Assessing the Impact of 3D Printing Adoption on the Supply Chain

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Abstract

With the rapid development of technology, we are entering a New Industrial Revolution – many believe disruptive technology will change the manufacturing industry, ushering in the new 'Age of 3D printing (3DP)'. D'Aveni (2013) once pointed out that 'businesses all along the supply, manufacturing, and retailing chains [will need] to rethink their strategies and operations'. Indeed, on the one hand, 3DP technology is changing the competitive dynamics of production based on traditional economies-of-scale into production based on economies-of-one. Meanwhile, 3DP technology can effectively help consumers to fulfil their personalized requirements with regard to the final product. Therefore, 3DP as a disruptive technology creates new opportunities and challenges for our supply chain system in product design, production, distribution, and logistics procecces. Although a great deal of existing research pays attention to 3DP technology adoption from a case study perspective, little research has been directed at how to adopt this disruptive technology – 3DP technology – to improve product customization and overall supply chain performance. Therefore, this PhD research addresses the gap that exists between the 3DP adoption market and the 3DP adoption research. The result of this PhD research offers the new insight about 3DP adoption strategies to the 3DP technology adopter (target at the manufacturer and the logistics vendor in this research), along with access to 3DP products and users which still have not widely adopted this new technology. This research investigates the question, '*What are the impacts of 3DP adoption on the supply chain?*' via three different quantitative research models.

Firstly, this research studies the impact of the logistics vendor's 3DP adoption on a single two-layer supply chain with one traditional manufacturer and one logistics vendor. The main results are as follows: (1) that the logistics vendor can benefit from 3DP adoption to better

restructure the supply chain. At the same time, there exists a situation in which the traditional manufacturer also benefits from this kind of 3DP adoption. (2) There exist conditions under which the logistics vendor can use this 3DP adoption as a threat to influence the traditional manufacturer's decisions in order to gain financial benefits. (3) The cost reductions and product customization improvements of the 3DP product do not always contribute to a better financial performance or higher consumer satisfaction.

Next, based on the first two-layer supply chain model, we investigate the traditional manufacturer's manufacturing strategy in terms of traditional manufacturing, traditional flexible manufacturing and 3DP, and explore the impacts of different strategies on the manufacturing decisions of the traditional manufacturer and on the logistics vendor's profit. Through numerical examples, we show that: (1) Adoption of 3DP is not always able to bring more profit to the logistics vendor. Specifically, if the traditional manufacturer has already used flexible manufacturing technology (traditional flexible manufacturing and/or 3DP), the logistics vendor can gain more profits if s/he provides a product delivery service only. (2) When it comes to cost reduction and product customization improvement, the traditional manufacturer should not use both traditional flexible manufacturing technology and 3DP manufacturing technology together for high value products. (3) Full 3DP product adoption is still not yet a beneficial strategy for the integrated supply chain.

Lastly, we explore and compare the logistics vendor's optimal models of collaboration with third-party 3DP professionals and the traditional manufacturer, obtaining optimal pricing strategies for both the traditional manufacturer and the logistics vendor, and maximized profits under different scenarios. The key findings are as follows: (1) Traditional manufacturer cannot always gain more profits under a self-3DP production model – it depends on the 3DP product cost, product design quality, and the product design authorization fee. (2) The logistics vendor cannot gain more profits if s/he chooses to produce the 3DP product using third-party 3DP product design while the traditional manufacturer already has 3DP production line. This finding implies that for those 3DP enabled logistics vendors (for example, UPS), it is not profitable to participate in the market competition where the traditional manufacturer already has TM (traditional manufactured) production and 3DP production (e.g. GE). (3) Although some research points out that 3DP is the future of some industries, our findings here indicate that compared to the hard-revolution (replace the whole TM production with 3DP production), adding 3DP production into the manufacturing system is a more profitable soft-landing plan for integrated supply chain development.

Preface

This dissertation is the result of my own work and includes nothing which is the outcome of work done in collaboration except as declared in the Preface and specified in the text. It is not substantially the same as any that I have submitted or is being currently submitted for a degree or diploma or other qualification at Northumbria University or any other University or similar institution except as declared in the Preface and specified in the text. It does not exceed the prescribed word limit for the relevant Degree Committee.

Elements of this work have previously been submitted in collaboration, specifically:

Yu Xiong, Gendao Li, Hui Lu (2018). Impacts of 3DP Technology on the Supply Chain. OR59 Conference, Loughborough, UK, Thursday 14 September 2017.

Yu Xiong, Hui Lu, Gendao Li, Yu Zhou. Game-changer or Threat: the Impact of Logistcs Vendor asoption of 3D Printing on the Supply Chain, Transportation Research Part E: Logistics and Transportation Review, under revision.

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My most sincere thanks go to my parents, **Shikang LU & Mei ZHUANG,** who have been a constant source of support and encouragement for my PhD dream. I am also incredibly thankful to my husband **Tianwei SUN** for his invaluable love, encouragement, and support throughout my three-year PhD life. Most importantly, I would like to thank my newborn son **Yiyan SUN** who is the most wonderful gift I can have in my life. I am looking very much forward to a happy future with you.

Author's Declaration

I declare that the work contained in this thesis has not been submitted for any other award and that it is all my own work. I also confirm that this work fully acknowledges opinions, ideas and contributions from the work of others. I am the sole author of this thesis.

Any ethical clearance for the research presented in this thesis has been approved. Approval has been sought and granted by the University Ethics Committee on 12 October, 2016.

I declare that the Word Count of this Thesis is 66, 498 words

I authorise Northumbria University to lend and reproduce this thesis to other institutions or individuals for the purpose of scholarly research.

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Chapter 1 Introduction

The *de facto* standard terminology – '3D printing', also known as 'additive manufacturing' – has been defined by ISO/ASTM 52900:2015 (ASTM F2792) as the subtractive and formative manufacturing process of joining materials, layer upon layer, to make a wide variety of customized objects from 3D model data through the deposition of a material by 'printing' technologies (fusing, extruding, jetting, photo-curing, laminating materials) (ISO/ASTM 52900:2017, 2017). This disruptive manufacturing technology was once primarily used for modelling, prototyping and tooling. Therefore, early research in this domain called it rapid prototyping technology.

Supply chain has been defined as a network between a system which try to produce a product or service to the end consumer, it including all the involved organizations, activities, informations, and resources (Zangiacomi, Fornasiero, Franchini, & Vinelli, 2017; D. Zhang, 2006). Thus, in the supply chain management research, the improvement of the supply chain is an enhancement activity to change the performance of a system (including raw material purchasing, product design, production, logistics, customer order fulfilment, after-sale service, etc.) from the *status quo* to a new level (Evans, 1993; Handyside, 1997). For the purpose of sharpen competitive advantage, supply chain improvement is becoming more important and therefore it is always essential in supply chain management (Wohlers Associates, 2018). The importance of making improvements in supply chain management has also been highlighted by several previous studies from increase production efficiency (e.g., low cost/high quality) (Womack and Jones, 1996) to improve customization (e.g. high customer service/short product delivery). The improvement of production and service are two key competitive weapon (Boyaci & Gallego, 2010; Waller & Fawcett, 2014; Xiao &

Yang, 2008). In particular, bringing improvements in product and service are essential for meeting the market challenges (Farahani, Rezapour, Drezner, & Fallah, 2014) and a central topic to ensure the competitiveness of the supply chain management (Farahani et al., 2014). Due to its short production time, low cost and high quality, 3DP technology is the new manufacrturing technology which can improve the product and service (Gao et al., 2015). Thus, it stars to be widely adopted by the commercial market for the production of parts going into the final products (e.g. jewellery, footwear, and personal accessories) (Wohlers Associates, 2018). This disruptive 3DP technology continues to offer tremendous untapped potential for the improvement of manufacturing, especially in terms of production customization. Therefore, there has been gradually increasing research focusing on 3DP technology development. However, study of the impact of 3DP adoption on the supply chain is lacking and what exists is mainly concentrated on 3DP and manufacturing industry reports and academic quantitative analysis on this topic remains insufficient.

What are the impacts of the disruptive 3DP technology on the traditional logistics industry? Due to the complexity of the impact of this disruptive technology on the supply chain, a great deal of related research has been conducted to evaluate the impacts of 3DP adoption on the traditional supply chain, such as in terms of product design and technology (Gao et al., 2015; Long, Pan, Zhang, & Hao, 2017; Ross et al., 2018; Strange & Zucchella, 2017; Thompson et al., 2016), production cost models (Baumers, Dickens, Tuck, & Hague, 2016; Ruffo & Hague, 2007; Ruffo, Tuck, & Hague, 2006; Westerweel, Basten, & Houtum, 2018), supply chain management (Hannibal & Knight, 2018; Holmström, Holweg, Khajavi, & Partanen, 2016; Khajavi, Partanen, & Holmström, 2014; Long et al., 2017; Mellor, Hao, & Zhang, 2014; Thompson et al., 2016; Weller, Kleer, & Piller, 2015), and 3DP intellectual property issues (IP) (Bradshaw, Bowyer, & Haufe, 2010; Esmond & Phero, 2014; Wilkof, 2016). The advantages of 3DP technologies have created new opportunities and challenges. However, most of the previous studies are limited to individual quantitative conceptual case study analysis, and little research has provided a comprehensive qualitative review on the actual impact of 3DP and its potential future impact on the supply chain.

In addition, many existing studies have demonstrated that 3DP could be used to improve the manufacturer's production performance, but most fail to explore the possibility of a non-manufacturer's 3DP adoption and the impact of this possibility (Attaran, 2017; Baumers et al., 2016; S. Ford & Despeisse, 2016; Khajavi et al., 2014). Moreover, reports by both Wohlers Associates (2018) and Ernst & Young (2016) concluded that 3DP technology will cause manufacturing production in low-cost countries (e.g. China, Vietnam, Turkey) to return to North America and Europe for the purpose of saving logistics costs and locating production near to the market. In the long term, this strategy will result in decline in the requirement for shipments and air cargo. Lower demand for shipment and warehousing will force logistics to transform. Integrating the 3DP service into the traditional logistics service is a possibility and this possibility has not been fully assessed yet, whilst quantitative analysis of the impact of the logistics vendor's 3DP adoption is rare. Therefore, the prime motivation of this study is to fill this research gap by systematically assessing the possibility of 3DP adoption by the logistics vendor as well as the impact of this kind of 3DP adoption on the supply chain.

After the logistics vendor adopts the 3DP technology, with the customer's increasing requirement for product customization, what would be the best manufacturing strategy for the traditional manufacturer? Product customization has been recognized as one of the most important attributes of business success since the early 1980s (Macchion, Fornasiero, & Vinelli, 2017; Shamsuzzoha et al., 2013; Zangiacomi et al., 2017). With the rapid development of technology, product customization has become progressively more complex over the last few decades. The reasons for the complexity of customization can be grouped into three major streams: Firstly, to rapidly respond to dynamic customization needs and satisfy changing customer preferences with regard to customization, many companies are outsourcing their product design or high-customization production to professional product design/manufacturing companies in order to ensure high product design quality and customization levels (Ernst & Young, 2016; Hannibal & Knight, 2018; Wohlers Associates, 2018). Thus, modern products with high customization require the manufacturer to show more flexibility and to have capabilities for high-customization product design. Secondly, customization is also extremely dynamic and difficult to forecast, due the fact that a consumer's requirements and standards for customization are fully unpredictable (Liechty, Ramaswamy, & Cohen, 2003; Takagoshi & Matsubayashi, 2013). Thirdly, as a consequence of manufacturing technology development, there are more strategies available to improve product customization and fulfil the consumers' customization requirements (e.g. flexible manufacturing strategy, agile manufacturing strategy, etc.) (Dong, Shi, & Zhang, 2017).

Meanwhile, the development of 3DP technology also provides possibilities to those non-manufacturers (the logistics vendor, the retailer) to be the 'maker' of high-customization products (Grandhi, Magar, & Roberts, 2013; Wohlers Associates, 2018). But, the adoption of 3DP technology does not force the traditional manufacturer to fully replace his/her current traditional manufacturing production with 3DP production. Khajavi et al. (2014) used the case of a spare part supply chain and explored the strategy of combining 3DP and traditional manufacturing technology. Dong et al. (2017) and Rehnberg & Ponte (2018) also conducted research on the combination of new 3D printing production and traditional production and suggested that the future of manufacturing production should be dynamic, reconfigurable, and innovative. For the aforementioned reasons, it is becoming increasingly important to assess the impact of 3DP technology on the traditional manufacturer's manufacturing strategy (Ernst & Young, 2016; Ryan, Eyers, Potter, Purvis, & Gosling, 2017; Wohlers Associates, 2018).

Therefore, this PhD research focuses on the question, 'What is the impact of 3DP adoption on the supply chain?' More specifically, this research seeks to develop three stylized models to assess the impact of 3DP adoption. The project 1) explores the possibility of the logistics vendor's 3DP adoption; 2) helps the manufacturer to evaluate different manufacturing strategies to improve product customization; and 3) investigates and compares the logistics vendor's different 3DP adoption strategies and, in turn, aims to produce some insights into the future development of manufacturing strategy and 3DP adoption.

This chapter presents an introduction to the research and the rationale for the methodology used in this study. The following section presents the research background (Section 1.1), and then the research motivations are given in Section 1.2. These are followed by the research objectives and research questions in Section 1.3, research contributions in Section 1.4, and research structure in Section 1.5.

1.1 Research background

This section will introduce the research background of the 3DP industry and its adoption status.

1.1.1 The 3DP Industry

3DP is fast evolving into a capability employed to manufacture unique and highly customized product designs and tools. Its impact ranges from incremental capability and financial improvements to radically new customer value propositions. The 3DP market is rapidly maturing as the myriad of 3DP technologies evolve, disrupting traditional business models in a wide variety of industries. According to (Wohlers Associates, 2018), the 3DP industry has continued to grow over the past decade: the average growth rate of the worldwide revenues generated by all accounted products and services over the last 29 years is 26.6%. In 2017, the 3DP industry grew 21% to $7.336 billion compared to 17.4% growth in 2016 ($6.063 billion) and 25.9% growth in 2015 ($4.816 billion). This represents a bounce-back of industry expansion after a slight softening of industry growth in 2016. The 3DP industry is expected to continue to show strong growth over the coming years (Ernst & Young, 2016; Pooley, 2013). Wohlers Associates (2018) forecasts that the sale of 3DP products and services will exceed $11.7384 billion worldwide in 2018 and it is expected to reach $27.3026 billion in 2023 (Figure 1-1).

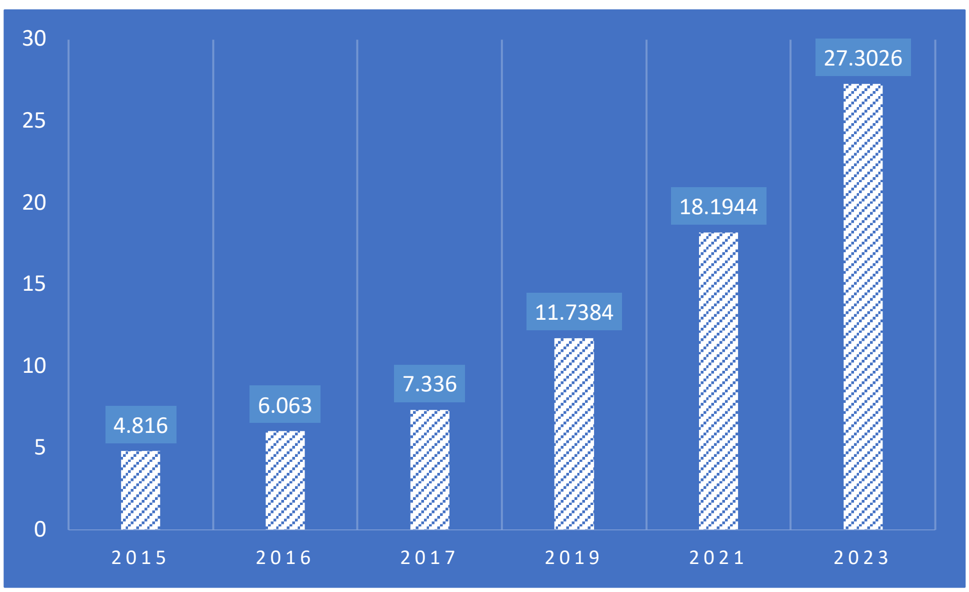


Figure 1-1 Worldwide 3DP Annual Revenue ($ Billion) (Wohlers Associates, 2018)

The 3DP industry is both multifaceted and dynamic. It is made up of a diverse ecosystem of designers, material suppliers, design tool creators, system manufacturers, consumers, and other groups. The ever-changing consumer requirements and market needs drive the development of new products, materials, processes, and standards. Constant innovation results in perpetual motion in the 3DP industry. Drivers of 3DP industry development constantly tailor the tools at hand to satisfy their needs and push boundaries to meet new market requirements with new business models (Ernst & Young, 2016). As the capabilities of the technology continue to grow, 3DP applications are spreading to previously untouched industries and regions, such as the cornea (Newcastle University, 2018) and housing (Cowan, 2018).

1.1.2 The 3DP Adoptions

The following section gives introduction about the current status about 3DP adoptions.

3DP Adoption by Industry

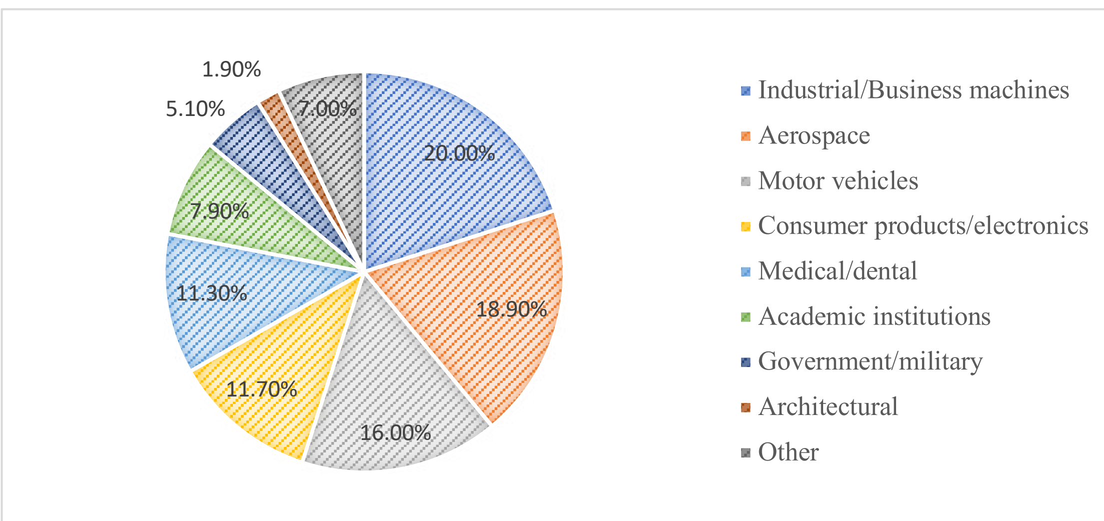


Figure 1-2 2017 3DP Adoption by Industry (Wohlers Associates, 2018)

According to the survey conducted by (Wohlers Associates, 2018) (which included 64 3DP system manufacturers, 19 materials and desktop 3D printer producers, and 92 3DP service providers), as shown in Figure 1-2 the leading industrial sector for 3DP adoption is still industrial/business machines (20.00%) for the fifth consecutive year, having grown by 1.2% since 2015. 3DP adoption under this category includes office equipment (e.g., computers, printers and routers) and industrial automation equipment (e.g., CNC machines and robots). The aerospace industry, as an early adopter of 3DP, is the runner-up growing by 0.7% in 2017, whilst 3DP adoption in motor vehicles grew by 1.2% since 2016 and ranks third place. Interestingly, the consumer products/electronics category, which covers a wide range from small kids' toys to all kinds of home electronics, is reaching the tipping point of adoption growth. 3DP technology actually accelerates product development by enabling rapid design iteration and optimization for the companies in those industries. For example, Hewlett-Packard's Jet Fusion 500/300 series 3D printers offer highly customized multi-colour protective phone covers (Figure 1-3) (Hewlett-Packard, 2018).

Figure 1-3 HP 3D Printed Mobile Phone Covers (Hewlett-Packard, 2018)

Although the volumes in the automotive and the consumer products/electronics industries are typically too high for the series production of most parts, some exceptions are beginning to emerge. For examples, Daimler Trucks is now producing spare parts by 3DP for its large trucks (Watkin, 2017) and Mini Cooper is starting to offer highly customized car parts for numerous MINI models over the course of 2018 via its 'MINI Yours Customised' project (Overall, 2017). In addition, individual consumers can order various final part products, including jewellery, home decorations, art, footwear, and all types of accessories from online 3DP providers, such as Shapeways, i.materialize, and Thingiverse. According to Wohlers Associates (2018), 3DP final part production is a topic of interest worldwide, and momentum is experiencing impressive growth (Figure 1-4). Therefore, 3DP technology can be used to facilitate the incorporation of small features and to consolidate many parts into one, offering a new market development opportunity in sectors with high product customization.

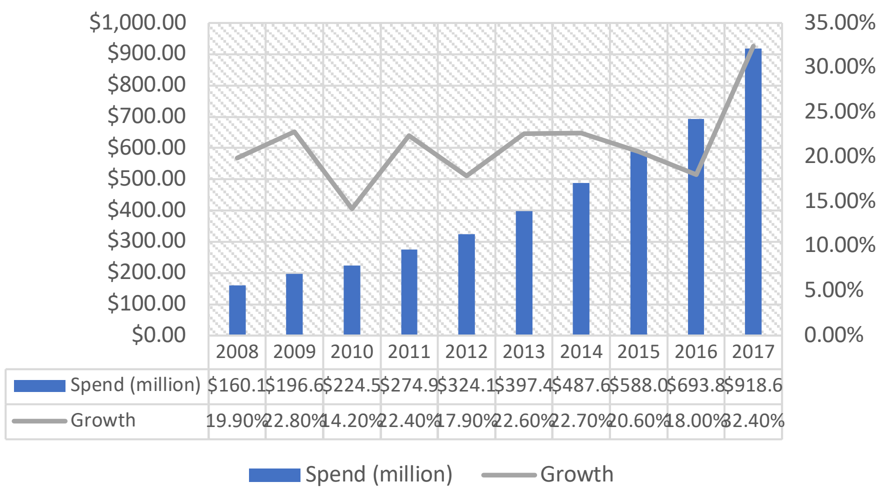


Figure 1-4 Market Development of 3DP Final Parts Production (Wohlers Associates, 2018)

3DP Adoption by Region

From the comprehensive 3DP adoption data tracked from 1988 to 2017 by Wohlers Associates (2018) (Figure 1-5), the U.S. continues to lead in 3DP adoption by a large margin, followed by China, Japan, and Germany. The U.S. segment decreased from 36.8% in 2016 to 35.9% in 2017 while China's segment grew from 10.3% to 10.6% over the same period.

Although North America is still leading in 3DP adoption and technological research, 3DP in the Asian Pacific is growing at a high speed.

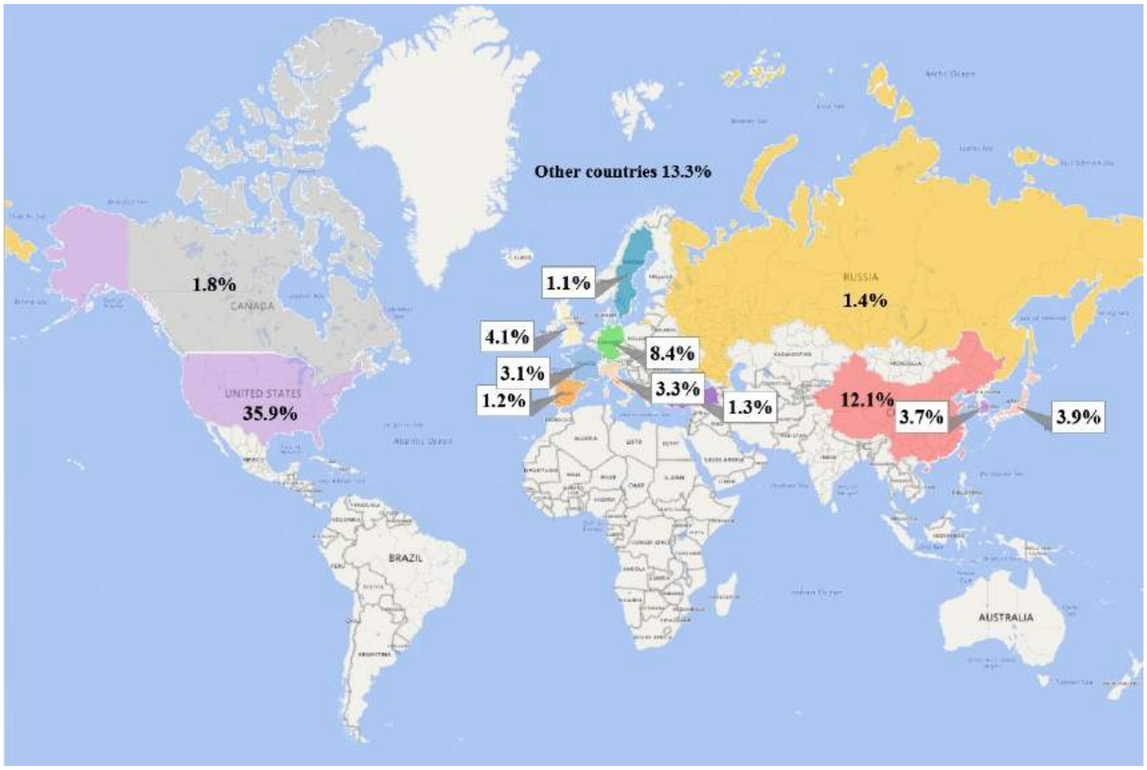


Figure 1-5 3DP Adoption by Region (Wohlers Associates, 2018)

Indeed, the 3DP industry is receiving ever-increasing active government support for the development of 3DP technologies and implications, as they realize the potential and importance of 3DP development to the new industrial revolution, as well as for sustainable development (Gebler, Schoot Uiterkamp, & Visser, 2014; Kellens, Mertens, Paraskevas, Dewulf, & Duflou, 2017). For instance, the U.S. government has established funding for 3DP research projects by several national organizations, including the National Science Foundation (NSF), National Institutes of Health (NIH), Department of Defense (DoD) and Department of Energy (DOE). The European Union also sets up 3DP research project funding as far back as the late 1980s and this funding has successfully support 3DP related research (e.g. 3DP database for the management of product design, 3DP virtual support platform for small or medium-sized enterprise on 3DP facility management) with more than €220 million funding from 2007 to 2017 (Wohlers Associates, 2018). Meanwhile, Asian countries have also put much effort into 3DP research and development. For example, the Chinese government treats 3DP as one of the vital supporting industries in its 13th Five-Year Plan for Economic and Social Development (Central Compilation and Translation Press, 2016). Therefore, 3DP has become an established set of technologies and is on the cusp of having broad impacts across most regions, industries, supply chains, and even end markets.

New Trend of 3DP Adoption

First of all, the market for individual 3DP products is increasing and custom/semi-custom products are gaining in popularity. According to Wohlers Associates (2018), both sales of low-priced desktop 3D printers and the market for 3DP services have increased significantly. Figure 1-6 illustrates the sales of 3D printers priced less than $5, 000 from 2007 to 2017. The growth in unit sales continued at a substantial rate, increasing by 24.7% to an estimated 528,952 machines, representing $610.5 million with 31.5% growth from 2007 to 2017. The growth rate of unit sales in 2016 was 49.9%, and the revenues were $464.2 million. Meanwhile, the scope of 3DP services has expanded tremendously. The estimated market for this sector was $2.690 million in 2017, which represented an increase of 23.8% from $2.173 million in 2016 (Wohlers Associates, 2018). It includes conventional service providers that have been in business since the early 1990s, 3DP marketplaces and communities such as Shapeways, i.materialise, and Sculpteo, online print networks such as 3D Hubs, and independent 3D print shops (e.g., UPS 3D printer shops). The 3DP service provider may be an individual with one desktop 3D printer selling parts locally. At the other end of the spectrum are 3DP system manufacturers and 'mega' service providers known as service bureaus, jog shops, or contract manufacturers. They have more than 100 industrial machines and maintain a global selling and service network. In summary, how to integrate personal 3DP market demand with the 'mega' 3DP services is a new question for the further development of the 3DP industry.

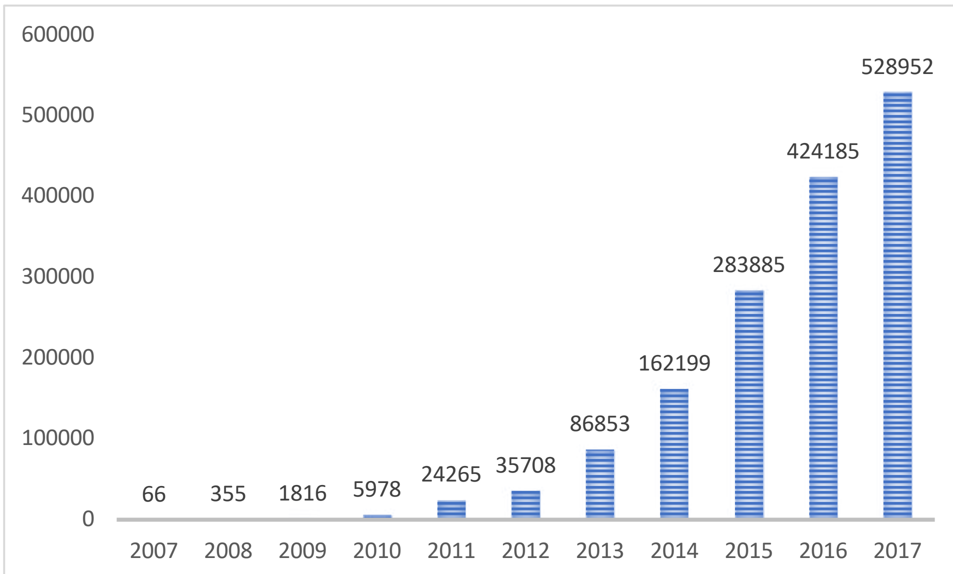


Figure 1-6 The Sales Quantity of Desktop 3D Printers (Wohlers Associates, 2018)

Another point needing attention is that not only traditional manufacturers, but also other supply chain players are exploring the possibility of 3DP adoption strategies. Among 500 buyers surveyed by UPS, 42% would like to switch business to a supplier with 3DP service in the next 3-5 years (UPS, 2017). The leading companies eager to be first movers in the 3DP race have begun leveraging this potentially disruptive manufacturing technology. This leveraging activity is evident in a variety of industrial sectors, especially consumer goods, such as the personalized running shoes pioneered by Adidas AG and Nike Inc, the personalized headphones manufactured by Normal Earphones, and the customized chocolates produced by Hershey (Pooley, 2013; Sher & Tutó, 2015). More interesting, even some logistics vendors among these companies are adopting this technology; for example, the global logistics vendor UPS launched 3DP service for small plastic products in the U.S. market in early 2014 and extended this business to the Asian and European markets in 2017 (UPS, 2015, 2017). On the one hand, logistics vendors can use 3DP as a game-changer to redefine their roles as not only deliverers but also makers. Not only does the 3DP service's built-in logistics network create a new revenue stream, but by giving the end consumer more flexibility in product customization, it attracts more attention to itself. On the other hand, logistics vendor can use 3DP as a threat to upset traditional manufacturers, meaning that its adoption equips them with a powerful bargaining tool to strengthen their logistics business. In summary, 3DP is evolving and/or revolting the traditional manufacturing industry. However, how to adopt 3DP or how to combine 3DP into traditional manufacturing system are questions needing assessment.

1.2 Research Motivation

The rationale behind this thesis is of twofold: the needs of assessing the impact of new 3D printing manufacturing technology adoption on the supply chain and the limited number of studies looking into this topic. The needs of assessing the impact of new 3D printing manufacturing technology adoption on the supply chain generate from various perspectives.

Firstly, the 3DP industry has continued to grow over the past decades. According to Wohlers Associates (2018) 3DP industry report, the average growth rate of the worldwide revenues generated by all accounted products and service over the last 29 years is 26.6% and the 3DP industry grew 21% to $7.336 billion in 2017. The sale of 3DP products and services is be expected to reach $27.3026 billion in 2023. This is a huge and fast developing industry under today's slack economic environment. Besides, some governments are continue to investment the new development of the 3DP industry, such as US, China, Germany, and Japan. There is a need to provide some industry insights to them to help make more suitable laws and regulations (such as IP law).

Secondly, apart from the economic development of 3DP industry, from the technology perspective, the new development of the 3DP manufacturing technology is changing the competitive dynamics of production from traditional economies-of-scale into economies-of-one. For example, GE is using 3D printing manufacturing technology for some of their engine parts production instead of traditional manufacturing production (Kellner, 2018). Because the 3DP manufacturing technology provides the possibility of develop high-customized engine parts and it allows any design changes before or during the ‘printing’ process. Most importantly, the applications of 3DP are spreading to previously untouched industries, especially consumer product industry, like shoes (Adidas), toys (Toys ‘R’ Us), and fashion accessories industry (earrings, rings) (Ernst & Young, 2016; Wohlers Associates, 2018). Therefore, 3DP is providing more and more new production possibilities to the supply chain development, not only limited to medical or aerospace industry. Thus, there is a need to review 3DP industry based on the new updated 3DP industry developments.

Thirdly, the product customization is an increasingly important factor on manufacturing production and it reflects the consumer shopping behaviour. 3DP can effectively help consumers to fulfil their personalized requirement on product function or product preference (Despeisse et al., 2017; Gebler et al., 2014). Therefore, 3DP drives manufacturing innovation by rethinking product design optimizing production and logistics for a new type product customization. For example, if you want to use your dad as the model to create a new small super hero statue as your dad’s birthday gift, 3DP might be the most convenience and fastest technology for you to do this. How to use 3DP manufacturing technology to improve the product customization and what is the impact of the 3DP adoption on the supply chain and product customization are two important questions which need to be addressed.

Fourthly, the introduction of 3DP has proven to be a 'game-changer' to the supply chain structure. For instance, the 3DP technology enabled less-assembly concept, which means, by using 3DP, some product could be 'print-as-one', therefore, the product delivery requirements would be reduced (Halassi, Semeijn, & Kiratli, 2019; Wohlers Associates, 2018). This is a big challenge to those delivery service companies, such as UPS and DHL. However, from another perspective, the 3DP has less requirements on production setups, for example, to some plastic product production, one printer and one produce design are the only things needed for production. Therefore, 3DP can enable everyone to be a new 'manufacturer', those logistics vendors who fears the threat of 3DP on their traditional delivery service are starting to explore the possibility of to be 3DP adopter. For example, UPS is already doing 3DP business since 2015 (UPS, 2015). Therefore, what is the actual impact of the logistics vendor's 3DP adoption on the supply chain? How about the performance of such adoption? Should the other logistics vendors start to engage the new 3DP service and how? What should the manufacturer to cope with such competition from the new 'manufacturer'? Those are interesting questions need to be evaluated as well.

Lastly, despite the importance of assessing the new 3DP adoption attracted by the sector, most of the existing research on 3DP, however, is limited on qualitative study or case study for a specific 3DP technology (see details in Chapter 2). Besides, for those studies about topic mass customization and technology disruption, they have ignored the uniqueness of 3DP manufacturing technology on customization disruption. There are still some gaps in this research domain. First, numerous studies have concentrated on individual 3DP technology adoption by the traditional manufacturer. However, little research has focused on investigating the possibility of the non-traditional manufacturer (e.g. logistics vendor) adopting 3DP technology, how the non-manufacturer could adopt 3DP, and what is the impact of non-manufacturer's 3DP adoption on the traditional manufacturer and the supply chain. In addition, the 3DP technology, as a disruptive technology, could be used to improve the product customization. However, little research has focused on integrating the mass customization theory and technology disruption theory to analyze what is the impact of the 3DP adoption on the supply chain and the traditional manufacturing system. Last, in the related 3DP adoption research domain, a great deal of research has employed a qualitative research methodology to analyze the 3DP adoption performance, such as a case study or empirical study approach (R. Huang et al., 2017; Ivan & Yin, 2018; Niaki & Nonino, 2017b). This thesis has been focused on possibility analysis for different types of 3DP adoption. Therefore, it would provide a different analysis about the 3DP adoption on the supply chain from a quantitative research perspective. In view of the aforementioned research gaps, there is a need to explore the question: 'What is the impact of 3DP adoption on the supply chain?'

Therefore, the prime motivation of this research is the need to deeply understand the current situation, in order to find insights and analysis tools that will assist in maximizing the potential of this 3DP market. The immediate derivatives from the prime motivation were secondary motivations relating to the factors influencing 3DP adoption by the logistics vendor and the traditional manufacturer, including cost, price, market demand, and the level of customization of the 3DP production. The actions that were set for examination of these factors were:

1. To review the current industry status of 3DP, in order to know inside-out its potential as a new value added service for the logistics vendor;

2. To study mass customization methods and paradigms as a reference for advancing approaches to strategies in the products market;
3. To evaluate the adoption plans for the logistics vendors and traditional manufacturer; and
4. To study the impact of 3DP adoption on the supply chain structure.

1.3 Research Objectives and Questions

This PhD thesis proposes analytical models to investigate the impact of 3DP adoption. Developing models for consumer product and purchase choice processes is a prevailing research method in supply chain and operational management. According to Blackwell, Miniard, & Engel (2006), there are five stages of consumer product choice processes, including recognizing need, searching for information, evaluating product alternatives, making a purchase decision and the post-purchase stage. Our models incorporate the first four steps. We follow existing theoretical models in the dual product competition research domain by considering that parameters such as production cost and product price determine consumers' choice of final product. Note that these models have been proved by previous studies. Basically, the consumer's decisions are a trade-off between the consumer surplus and the product price (González-Maestre & Granero, 2018).

In particular, this study focuses on assessing the impact of 3DP adoption on the supply chain. One of the main starting points concerns the possibility of 3DP adoption by the logistics vendor. The overall major research questions in the pervious study focuse on why and how the logistics vendor adopts 3DP as a part of their business. Further study and exploration naturally revealed that different adoption plans exist in this market, and each one of them has different impacts on the supply chain structure. The primary objectives of this thesis, therefore, are:

1. To develop an analytical model to investigate the supply chain following a logistics vendor's adoption of 3DP – one that explicitly models customization;
2. To explore the impact of the logistics vendor's use of 3DP on the supply chain; and
3. To examine potential 3DP service adoption plan for the logistics vendor.

Besides the primary research objective, this thesis also seeks to study what kind of actions the traditional manufacturer could take:

4. To develop another analytical model to evaluate the supply chains of traditional manufacturer who also adopts 3DP or adopts a highly flexible and customized manufacturing line in view of the market competition; and
5. To explore the impact of each manufacturing strategy on the supply chain.

Out of an initial spatial understanding of the possibility of 3DP adoption by the logistics vendor and the traditional manufacturer, these vendors' use of 3DP thus poses many challenges in the supply chain and raises several unanswered questions and sub-questions that warrant empirical investigation:

Q1. What are the impacts of a logistics vendor's 3DP adoption on the supply chain?

Q1.1. Under what conditions will a logistics vendor use 3DP as a game-changer to compete directly with the manufacturer?

Q1.2. Under what conditions will a logistics vendor use 3DP as a threat to bargain with the manufacturer?

Q1.3. What is the impact of a logistics vendor's 3DP adoption on the consumer?

Q2. What kind of manufacturing strategy should the traditional manufacturer take to cope with 3DP adoption by the logistics vendor?

Q2.1. Under what conditions will the traditional manufacturer also adopt 3DP?

Q2.2. Under what conditions will the traditional manufacturer use flexible manufacturing to compete with 3DP?

Q2.3. What are the impacts of the traditional manufacturer's different manufacturing strategies on the supply chain structure?

Q3. What is the best 3DP adoption plan for the logistics vendor?

Q3.1. Under what conditions will a logistics vendor choose to outsource the product design to a third-party 3DP design company?

Q3.2. Under what conditions will a logistics vendor choose to purchase the product design from the original traditional manufacturer?

Q3.3. What are the impacts of different logistics vendor's 3DP adoption strategies on the relationship between the logistics vendor and traditional manufacturer?

1.4 Research Contributions

Turning to the existing research on 3DP, mass customization and technology disruption, compared to the existing studies, this thesis is among the first to draw on those two theories to develop analytical models to assess the impact of different 3DP adoption strategies on the supply chain. This thesis thus provides a different perspective on the disruptive 3DP technology adoption literature on the following highlights.

Firstly, although pervious studies (such as (Dong et al., 2017; Song & Zhang, 2018)) show that the 3DP manufacturing could be used to improve the manufacturing performance on flexible production and supply chain inventory management, this thesis indicated that there are also encouraging signs in logistics vendor's 3DP adoption. Thus, this thesis extends the findings from previous studies, which are more or less focus on the traditional manufacturer's 3DP adoption strategies.

Secondly, following a serial of critical model analysis on the logistics vendor's 3DP adoption, the traditional manufacturer's 3DP adoption and the logistics vendor's 3DP adoption strategies, this thesis argues from the extension of the current 3DP research to include the logistics vendor and the traditional manufacturer's collaboration and competition relationship analysis on 3DP adoption (product, service, product design). This is borne out of the fact that when the logistics vendor or the traditional manufacturer starts to consider the 3DP adoption, the production cost of different type of manufacturing technology, the product customization level, the cost of logistics delivery, the product design cost, and the product pricing strategies should be the critical internal considerations. Most importantly, the collaboration and competition relationship between the logistics vendor and the traditional manufacturer should be another important external consideration. This is an echo to our technology disruption theory. Thus, for the purpose of improving the supply chain efficiency and effectiveness, the existing 3DP research, mass customization, and technology disruption research need to be extended.

Lastly, since 3DP is a continued developing manufacturing technology, the possibility of adopting this technology can be very complex. There is a need to review and assess this research topic based on the new development and changes in 3DP adoption. This thesis proposes a series of different 3DP adoption strategies for the logistics vendor and manufacturer to follow in order to achieve a better 3DP adoption.

In addition, it also generates several practical contributions by providing the following managerial insights.

The first model develops a stylized quantitative model that incorporates the logistics vendor's adoption of 3DP technology, identifies the conditions under which the logistics vendor will use 3DP as a game-changer or threat, and analyzes the impact of this adoption on both supply chain partners and consumers. It derives the observation that although the logistics vendor benefits from 3DP adoption, the cost reduction on 3DP products cannot always contribute to the logistics vendor's overall revenue because a portion of his/her revenue still derives from shipping the TM product for the manufacturer. This finding helps the logistics vendor on deciding which 3DP product should be provided and which 3DP product should do cost reduction.

The second model develops another analytical model to evaluate how the traditional manufacturer can adopt 3DP technology, defines the conditions 1) under which the traditional manufacturer should fully replace traditional manufacturing technology with 3DP and 2) under which the traditional manufacturer should combine 3DP with its traditional flexible manufacturing technology. It points out that although 3DP technology can be used to improve product customization, it cannot always increase the traditional manufacturer's profit; under some conditions, the traditional manufacturer's flexible technology can bring more profit than the 3DP manufacturing technology. These findings help the traditional manufacturer on the decision of flexible manufacturing technology strategy.

The third model develops another theoretical model to define the best 3DP adoption plan for the logistics vendor, and it compares the logistics vendor's potential 3DP engagement strategies and identifies the conditions under which the logistics vendor should provide a 'printing' and product design service as opposed to 'printing' only but with outsourcing of the product design service to a 3DP professional or traditional manufacturer. It concludes that collaboration with the traditional manufacturer for 3DP product design is sometimes the best 3DP adoption strategy for the logistics vendor. Most interestingly, we also demonstrate that the dictum that high customization and low-price leads to more consumers does not always hold true. This model gives the guidelines to the logistics vendor on the detailed 3DP adoption strategy.

Most importantly, those managerial insights also provide guidelines to those policymakers to develop the 3DP industry-related policy or regulations. In particular, this thesis shows the need for the policymakers and the 3DP companies/developers to have an understanding on the 3DP industry in order to mitigate the complexity and clean the barriers of further 3DP industrialized adoption.

1.5 Research Structure

Chapter 1 is introduction, which introduces the research background, motivations, and contributions of this research. Meanwhile, it also states the research objectives and outlines the specific research questions.

Chapter 2 reviews the different forms of research on 3DP, mass customization and technology disruption that have been conducted already. It provides a more detailed understanding of 3DP technology, mass customization and technology disruption, and then discusses in a deep discussion about the uniqueness of 3DP adoption. It also critically evaluates previous research on the problems, issues and challenges of 3DP adoption.

Chapter 3 introduces the methodology for the study. In order to select the most appropriate research method, this chapter first describes the classic quantitative and qualitative research methodology and then gives the reasons for the selection of analytical modelling for this research.

Chapter 4 focuses on adoption of 3DP by the logistics vendor. It studies the first analytical model to investigate the possibility of 3DP adoption by the logistics vendor. It also provides a more detailed model analysis and interpretations of the findings.

Chapter 5 illustrates the adoption of 3DP by the traditional manufacturer. It discusses the second model concerning the traditional manufacturer's 3DP adoption strategy. It compares different 3DP adoption strategies and then gives the recommended 3DP adoption strategy for the traditional manufacturer.

Chapter 6 proposes logistics vendor's 3DP engagement strategies. It explores and compares the logistics vendor's different 3DP engagement strategies. It also lists the suggested 3DP adoption models for the logistics vendor under different market structures.

Chapter 7 is the conclusion. It outlines the conclusions of the research and provides answers to the research questions. It also lists the limitations of this research and highlights recommended avenues for future studies.

Chapter 2 Literature Review

This chapter discusses the literature and theoretical context performed in the research domain, which underpin this thesis. The review aims to highlight the important gaps within this body of literature. To achieve this, this chapter is structured as follows: Section 2.1 outlines the existing studies on supply chain improvement managemenet research, especially on the proposed research area – 3DP supply chain research. Given that mass customization and technology disruption have been integral to the development of the supply chain. Section 2.2 provides a brief review of mass customization in the context of manufacturing industry and then presents an analysis on how the technology disruption influence the supply chain development in Section 2.3. Finally, Section 2.4 provides the conclusions of this literature review and summarizes the research challenges and gaps.

Overall, this chapter concludes that while the 3DP adoption has brought uncertainty to the supply chain development, the analysis in this chapter provides evidence to the necessity of assessing the impact of 3DP adoption in the supply chain.

2.1 3DP Supply Chain Research

After 3DP was first pioneered by Charles Hull in the late 1980s (Rylands, Böhme, Gorkin, Fan, & Birtchnell, 2016), the impressive development on 3DP technology and 3DP industry had inspired and informed the 3DP research, and equally the research findings offered insights on this development.

Despite the fact 3DP supply chain research is important to the supply chain development, a large number of existing studies in this domain in the past decades (list in Appendix A) were sporadic, and it is amongst the most under-researched areas in various 3DP manufacturing processing technology analysis and case. The focus of this section narrows to have an overview of the existing 3DP research and to identify the research gaps. After reviewing 37 related research articles in 3DP research domain (Appendix A), we have found that the majority of the studies focus on product technology (Section 2.1.1), production cost (Section 2.1.2), supply chain management (Section 2.1.3), and Intellectual Property (Section 2.1.4). Moreover, there are few works in the literature related to business models and industry review for 3DP (Figure 2-1).

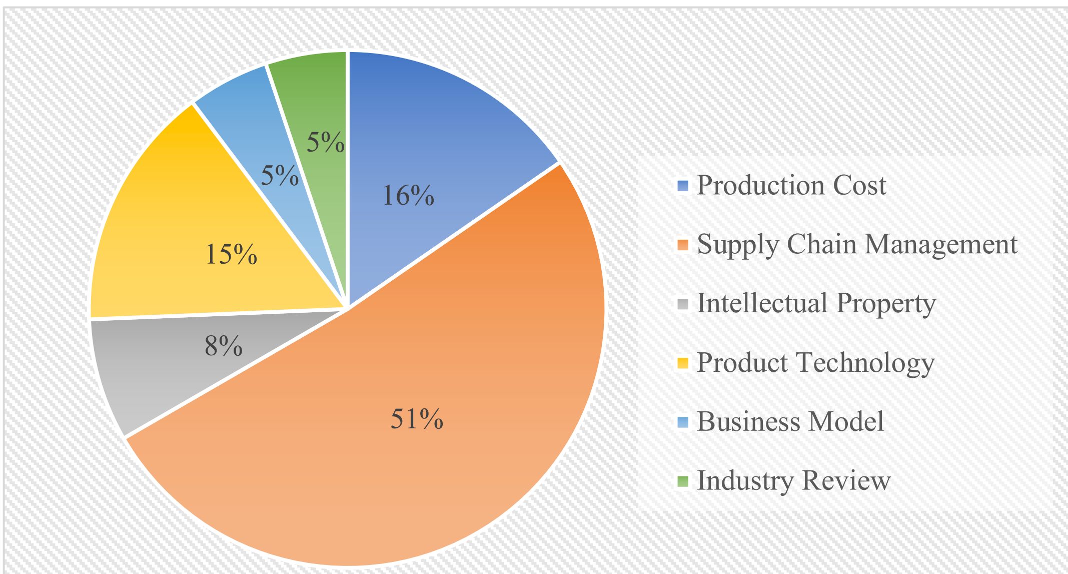


Figure 2-1 Classification of Related Studies by Research Perspectives

Although different perspectives of the 3DP have been identified and discussed by pervious studies, the impact of 3DP adoption in the supply chain remains unclear. In particular, at least four main perspectives of the 3DP research which have been identified by previous studies. They are outlined in following sub-sections.

2.1.1 Product Technology

Different 3DP technology processes build and consolidate layers in different ways, but in general, 3DP manufacturing technology consists of three basic processes: (1) computerizing the 3D solid model based on the different design requirements and then converting into a standard 3DP file format; (2) sending the 3DP file to a 3D printer; and (3) 'printing' the product layer by layer on the 3D printer (Woodson, Alcantara, & Nascimento, 2019).

With the ever-increasing number of raw materials and technologies that 3DP could use, 3DP emerges as a potentially disruptive technology which is very likely to replace the traditional manufacturing technology in long term. Therefore, this gives rise to a growing concern over how to using the new 3DP technology and how to combine the new 3DP technology into current manufacturing system. According to Berman (2012), because there is no tooling constraints, 3DP enables small quantities of highly customized goods to be manufactured with relatively low production cost. The product design can also change and update anytime and small batch production is also economical. Berman (2012) has also indicated that the manufacturer might have huge change-over costs on productions time, production costs, and materials. In particular, from Berman's perspective, the concern is that as 3DP technology can improve certain characteristics of the product (quality, product customization level, etc.) and help the traditional manufacturer to fulfil the consumers' increasingly complex and dynamic product customization requirements. But adopting the new 3DP technology which would in turn brings more challenges on manufacturing and production management to the traditional manufacturer. Arguably, Berman (2012) concludes those ideas by literature review methodology which need more cases or data support.

This perspective was later popularized by a number of research herein and they tried to examine it by empirical study, case study. or conceptual study, comparing the 3DP technology with the traditional manufacturing technology and then identifying the advantages and disadvantages of the 3DP technology. 3DP manufacturing technology has the following perceived advantages in terms of *Flexibility* and *Efficiency*:

(1) *Flexibility*: By using 3DP technology, it is possible to design and produce a product with varying and complex property components (Hofmann et al., 2014; Mohammed, Cadd, Peart, & Gibson, 2018). The new achievement of technology helps 3DP technology to couple it with other constituent technologies in the wave of industry 4.0 (Strange & Zucchella, 2017). For example, web 2.0 applications, the platforms where customers can purchase and share data, help the consumer generate new joint value-add through co-creation (Gao et al., 2015). In comparison to the traditional manufacturing design process, 3DP has the potential to enhance the capability to produce geometrically more complex components (Hofmann et al., 2014; Mohammed et al., 2018).

(2) *Efficiency*: Traditional manufacturing technology requires different resources such as cutting machines, assembly machines, and coolants (Ernst & Young, 2016; Strange & Zucchella, 2017; Wohlers Associates, 2018). 3DP manufacturing does not require those additional resources, which effectively reduces the initial investment for multi-location start-ups and product design (Long et al., 2017; Ross et al., 2018; Thompson et al., 2016; Xu, Meteyer, Perry, & Zhao, 2015). Furthermore, 3DP can use raw materials efficiently by building product layer by layer with little leftover materials. However, during the traditional manufacturing processes, a large amount of material might need to be removed (Mohammed et al., 2018). In addition, because the 3DP

process has less requirements on assembly, and thus, the production lead time could be reduced (Ross et al., 2018; Sanchez, Boudaoud, Muller, & Camargo, 2014).

However, 3DP manufacturing technology still cannot fully replace the traditional manufacturing technology yet, especially in product quality and mass production. Hofmann et al. (2014) provide an empirical study on the 3DP gradient metal alloys production, by comparing with the traditional manufacturing technology. This research concludes that although the new 3DP technology demonstrates a better performance over the traditional manufacturing technology on less unwanted phases and high product quality, the 3DP manufacturing technology has drawbacks in unit product cost and design complexity. Studies comparing the traditional manufacturing with the other 3DP manufacturing technology provide similar findings showing the studied 3DP manufacturing technology has the potential to (1) reduce the energy consumption and improve the design of parts geometry but it requires more resource on layer thickness and drying control (Xu et al., 2015); (2) reduce process lead time, cost, and steps, but it has strict requirements on consumer engagement in product design phase (Mohammed et al., 2018); and (3) reduce the need for highly skilled prosthetists, lower the production costs and improve the product customization level. However, it still needs a further development on production accuracy (Ross et al., 2018).

Following this perspective, a 3DP-enabled supply chain is more profitable and its has the flexibility to produce a higher customization level product with high product quality at low cost (Ernst & Young, 2016; Strange & Zucchella, 2017; Wohlers Associates, 2018). Meanwhile, the advantages of the 3DP product technology pointed out the possibility of the non-manufacturer’s possibility of adopting 3DP but the backwards highlighted the necessity for analysis on the 3DP adoption which help to achieve an optimal system performance.

2.1.2 Production Cost

However, the 3DP research under production cost perspective findings has showed a different review of the impact of 3DP adoption. The research under this sub-stream investigates the production costs required by 3DP manufacturing, compares with traditional manufacturing production costs and then proposes a new cost model for the new 3DP manufacturing technology. Therefore, this perspective consideres that cost might be the most crtical consideration of 3DP adoption. The most classic studies are conducted by Ruffo et al. (2006) and Ruffo & Hague (2007). Both studies use the previous Hopkinson-Dickens model as the base and then build up a new cost model for the new 3DP production. Different from the 3DP research on the technology perspective, these two study focused on the cost element analysis. The first study finds out that the indirect costs plays an essential a role in modern 3DP production cost models. The later one reports that apart from of the direct and indirect costs for the production, the simultaneous production strategy for different parts is also an critical consideration to the 3DP production cost model. As Figure 2-2 shows, this approach of work mainly aims to identify the breakeven point of the traditional manufacturing technology and current 3DP manufacturing technology and then forecast the future breakeven point for the new developing 3DP manufacturing technology. At last, the research uses the breakeven points analysis as a reference to reshape the supply chain structure and plan the development of the next 3DP manufacturing technology in view of the cost model of the 3DP. This perspective has also received a considerable amount of recognition (Holzmann, Breitenecker, Soomro, & Schwarz, 2017; Khajavi et al., 2014).

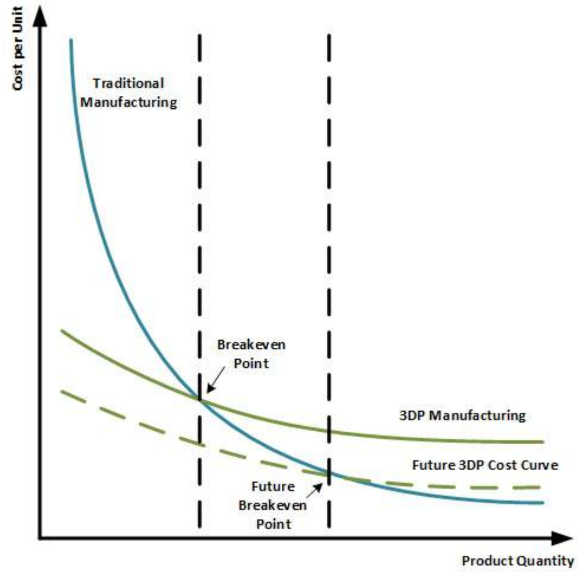


Figure 2-2 The Effect of Lower Unit Product Cost on the 3DP Breakeven Point, adopted from Basiliere (2017)

Apart from building up the cost model, researchers under this perspective also focused on conducting the impact analysis of one or several detailed cost element(s) on the total cost model, such as the energy consumption and environmental impact, the economies of scale, the production lead time, etc (Gebler et al., 2014; Gutowski et al., 2009; S. H. Huang, Liu, Mokasdar, & Hou, 2013).

As for energy consumption and environmental impact analysis for the 3DP production, manufacturing processes requires energy, and the average industry energy demand of the U.S. is one-third of the total consumption (S. H. Huang et al., 2013). Although the manufacturing industry is successful in reducing energy intensity in the past decades, the analysis about energy consumption on the manufacturing technology is a challenging but necessary task. Gutowski et al. (2009) have conducted an analytical study on this topic for the purpose of having a closer look at electricity usage of the manufacturing processes. The results of their study have showed that by comparing with the traditional manufacturing processes, the new manufacturing process has a better performance on producing finer dimensions and smaller scales, but the electricity consumption during the production phase is larger. However, the authors also acknowledges that the product produced by the new manufacturing processes requires less energy consumption during the use phase. Later, Gebler et al. (2014) also examine this matter by using cost model to evaluate the environmental impacts of the 3DP manufacturing technology quantitatively. Their results show that 3DP manufacturing technology has the potential for the cost reduction and decouple energy and CO_2 emissions during the production process. Most importantly, this research reveals that there is no a uniformly quantitative tool to help the 3DP manufacturing technology adopter to evaluate the impacts of new 3DP manufacturing technology on the manufacturing system. Therefore, although the new 3DP technology is perceived to have less production cost, it is still necessary to conduct a more thorough analysis.

The new development of the 3DP manufacturing technology is changing the competitive dynamics of production from traditional economies-of-scale into economies-of-one. However, many researchers and companies argue that the new economies-of-one 3DP manufacturing technology could only provide the high-customization to the consumer and it has shortcoming on achieving the competition advantages of economies-of-scale, such as high volume, low unit cost, and high variety (Ernst & Young, 2016; Wohlers Associates, 2018). Baumers et al. (2016) once study this research topic by analysing the enablers and barrier of the 3DP manufacturing adoption. Their research has observed that economies-of-scale is not a barrier of the 3DP manufacturing technology adoption, but it is achievable with the new 3DP manufacturing technology. The authors also identify that the how to successfully transform the manufacturing technology from traditional to 3DP is an important issue. Thus, more scientific evidence and sophisticate tools are needed to determine the 3DP manufacturing technology's performance, correctness, and practicality.

Although the new 3DP manufacturing has the clear advantages on the production lead time (less assembly, less delivery between processes), academic research still shows the interests on investigating this matter. Westerweel et al. (2018) have developed a decision-making model to test and compare the lifecycle costs of two different components. The outcome of their model shows that the by using the 3DP manufacturing technology, the production lead time is reduced which also contributes to the cost reduction on logistical costs, product design costs, and production costs. It is possible that the 3DP manufacturing can reduce the production lead time and contribute to the cost reduction within the manufacturing processes, but, once the entire supply chain system is considered, 3DP manufacturing technology might not have an edge over the traditional manufacturing technology in terms of production cost.

In this sense, which is different from product technology research perspective, cost model analysis of 3DP adoption should be implemented with an emphasis on the detailed cost elements, as they can be improving continuously and always have longer-lasting outcomes. As such, no firm conclusion can be drawn at this time and the research under this perspective is limited. Thus, there is a need to conduct such research to assess the performance of production cost on the manufacturing system level, the logistics system level, and the supply chain system level.

2.1.3 Supply Chain Management

In a supply chain, material flow forward from suppliers through various stages toward the end consumer requires the effort of various companies that form the manufacturing supply chain. Those companies might include raw material suppliers, original equipment manufacturers, distributors, retailers, and logistics vendors. Several studies have confirmed that the new 3DP manufacturing technology has the potential to reduce the number of stages in the traditional manufacturing supply chain (Holmström, Partanen, Tuomi, & Walter, 2010; S. H. Huang et al., 2013; Petrick & Simpson, 2014). In detail, 3DP manufacturing technology could improve the supply chain efficiency from two perspectives: (1) to improve the product design with less components and less material consumption and (2) to manufacture the product near to the end consumers (Ernst & Young, 2016; Wohlers Associates, 2018). Thus, the new 3DP manufacturing technology has the potential to simplify the supply chain to be shorter (less assembling, warehousing, shipping, and packaging processes) and efficient (less production/transportation lead time, less material consumption, and higher product customization level). Several studies listed below have examined the actual effect of using 3DP manufacturing in the supply chain.

Tuck, Hague, & Burns (2007) have once investigated how the new 3DP manufacturing technology could reshape the supply chain management paradigms and integrate with traditional lean and agile supply chain management strategy with three different case studies. Their research points out that the new 3DP manufacturing technology could improve the performance of traditional lean and agile supply chain. Firstly, the new 3DP manufacturing technology could improve the efficiency of a lean manufacturing supply chain through Just-In-Time (JIT) and waste elimination. The 3DP manufacturing only requires the product design and raw materials in order to produce a complex component. Thus, the need of machine setup and changeover, assemblies, and material transportation will be reduced. This in turn results in a reduction of material distribution and inventory holding. Secondly, the new 3DP manufacturing technology also can improve the responsiveness of an agile supply chain. The 3DP manufacturing technology pushes the supply chain transfer to the production model to be ‘Made-to-Order’ and ‘Near-to-Market’, which makes it economical to customize product to meet individual consumer’s requirements in a short lead time of production and product delivery.

This perspective of study is further extended by the studies with focused on testing the what is the impact of the 3DP manufacturing technology on the a particular supply chain process, including product design (Gibson, Rosen, & Brent, 2015; Liao, Wu, Huang, Kao, & Lee, 2014), manufacturing process (Holmström et al., 2010; Hsiao, Lorber, Reitsamer, & Khinast, 2018; Mellor et al., 2014; Oettmeier & Hofmann, 2016), logistics (Song & Zhang, 2018), manufacturing distribution design (Bogers, Hadar, & Bilberg, 2016), product and service customization management (Berman, 2012; Niaki & Nonino, 2017a; Rehnberg & Ponte, 2018), transportation (Attaran, 2017; Song & Zhang, 2018), sustainability management (Gebler et al., 2014; S. H. Huang et al., 2013), and manufacturing strategy (Dong et al., 2017; Hannibal & Knight, 2018; Long et al., 2017; Rayna & Striukova, 2016; Ruffo, Tuck, & Hague, 2007; Weller et al., 2015).

Literature reviewed by Ruffo et al. (2007), Huang et al. (2013), Niaki & Nonino (2017a), (Long et al., 2017) argues that although the 3DP manufacturing technology has not been widely adopted by industries yet mainly because of the concern of the manufacturing system changeover cost, the new developed 3DP manufacturing technology has the potential to overcome this difficulty by delivering highly customized products with low costs in terms of production, inventory, and transportation. Likewise, conceptual studies by Holmström et al. (2010), Petrick & Simpson (2014), Waller & Fawcett (2014), Bogers et al. (2016), Attaran (2017), Hannibal & Knight (2018), Hsiao et al. (2018), and Rehnberg & Ponte (2018) have suggested that the new 3DP-enabled manufacturing supply chain could improve system visibility and reduce the number of factors affecting the quality of the supply chain, such as freight, delivery lead time, and inventory levels. For example, Holmström et al. (2010) have suggested that the 3DP manufacturing could improve the service level and reduce the inventory holdings by either centralized the 3DP production by the Original Equipment Manufacturer (OEM) or distributed the 3DP production near the final market. In addition, several other empirical analyzes have used surveys or case studies to assess decision making for sourcing (Ruffo et al., 2007), logistics (Petrick & Simpson, 2014; Song & Zhang, 2018), inventory (Liu, Huang, Mokasdar, Zhou, & Hou, 2014), and manufacturing (Dong et al., 2017; Oettmeier & Hofmann, 2016). However, most of them only focus on a specific aspect of the supply chain process cost. For example, Liu et al. (2014) have made a case study comparison of a TM versus a 3DP supply chain and focused only on inventory cost. This study concludes that 3DP supply chain can provide more flexibility on the inventory management. Furthermore, there are a few studies investigating 3DP development for a particular country. For instance, based on a series of business case analyzes, Long et al. (2017) revealed that under a continued and centralized manufacturing structure, TM has advantages with economies-of-scale whereas 3DP has advantages with economies of one (high customization). Finally, Ernst & Young (2016) and Wohlers Associates (2018) are two research groups who timely produce a comprehensive review of the current status of 3DP technology development, 3DP supply chain management and future trends of 3DP industry, which provide the industry background information to all the 3DP technology developers, 3DP technology adopters, 3DP industry researcher and relevant policymakers.

Although the 3DP technology has increased in popularity in recent years, most of the literature on this research perspective remains limited to examine its potential adoption by the traditional manufacturers through qualitative studies methods (literature view, conceptual study, and empirical study). Meanwhile, the 3DP manufacturing technology is constantly evolving and the 3DP technology is expanding to other pervious untouched industries, so it is necessary to revisit and explore the 3DP manufacturing technology and its adoption strategy periodically – in light of the fact that it provides the foundation that guides on development and adoption of the new 3DP technology in the supply chain (Walter, Holmström, & Yrjölä, 2004; Wohlers Associates, 2018). Compared with the previous literature, our thesis provides several quantitative decision-making tools and yields new insights into the impact of the different 3DP adoption on supply chain management. To the best of our knowledge, this study is the first to investigate the 3DP adoption strategies of the logistics vendor and the traditional manufacturer.

2.1.4 3DP and Intellectual Property

With an increasing amount of 3DP adoption, primarily by small firms and individuals, how to protect IP is becoming an increasingly important research topic. 3DP makes it easy for customers to copy and reproduce products. For example, 3DP technology makes it easy to copy the product design (a CAD file) and 're-print' it anywhere (Wilkof, 2016). Bradshaw et al. (2010) have analyzed the current IP legislation and case law related to 3DP, including copyright, patents, trademarks, and passing off. They find that the majority of the UK's 3DP individual users use 3D printers only for personal use without the constraints of IP. But still some commercial users might use 3DP printing technology to re-make the product. Therefore, the authors acknowledge that the current regulations and laws are out of date, so there is a need to fully analyze the current 3DP related IP usage and then set up standard IP constraints for the 3DP industry specifically.

Later on, Esmond & Phero (2014) have noted that the 3DP actually presents the new and unique challenges to the IP protection. After a review on the current 3DP related legal landscape, the authors conclude that the it is grateful that 3DP technology brings the opportunities to the 3DP inventors and designers to innovatively design and create innovative complex products, but the 3DP technology also potentially provides the possibility of wide spreading 'IP theft'. Wilkof (2016) also carries out a study to explore the 3DP related IP issues by a conceptual study. He analyzes the 3DP industry revolution and the related legal developments on this area and then proposes two different principle components of patent protection. The first principle component is the creation of the patent right. The author summarizes and reviews the various components within the 3DP system, including materials manufacturers, developers, end users (private and commercial), creators and aggregators of 3DP design file, fulfilment platforms, 3DP service providers, and printer/scanner manufacturers. Then, he points out the key issue for the creation of the patent strategy is whether or not all the patentable subjects are claimed. The second principle component, enforcement of a registered patent, is focusing on the IP protection issue between the IP owner and the third-party users. The advantage is that this strategy can protect the patent owner's IP right. But it is difficult to identify the why the third-party uses the patent, for commercial purpose or for private purpose. For example, the third-party only use the patent for private propose, and this is an exception of IP protection scope. Therefore, how to protect the IP right in the 3DP adoption is still, and well remain, a work-in-progress that merits a detailed assessment.

2.1.5 3DP Research - Summary

Today's marketplace is competitive and dynamic. The development of breakthrough technologies and customers' different expectations towards product and service customization are changing the type of market competition from competitive independent firms to competitive supply chains (Boyaci & Gallego, 2010; Rezapour, Farahani, Dullaert,

& Borger, 2014; D. Zhang, 2006). The 3DP technology is a crucial factor that makes it possible for different companies to be able to compete as an integral part of the supply chain. Naturally, efficient coordination by an individual company of the form of its supply chain requires better management of its manufacturing strategy throughout the supply chain structure.

According to Ernst & Young (2016) and Wohlers Associates (2018), experts from different industries believe that 3DP technology with its many advantages over traditional manufacturing technology (Table 2-1) will become an essential manufacturing technology in the manufacturing process for both industrial and commercial products in the near future. Therefore, there is a need to analyze 3DP adoption and assess the impact of different types of adoption on the supply chain from a strategic, tactical and operational perspective.

Table 2-1 Comparison between Traditional Manufacturing and 3DP Manufacturing

		TM	**3DP**
Product Design and Technology	Time to Market	Long	Short
	Customization	Standard design, but the raw material range is large	Mass personalization, but the raw material range is small
	Design Improvement	Limited to production settings	Complex design
	Cost	High, especially for moulding	Low
Supply Chain Management	Flexibility	Need retooling	No tooling
	Speed	Low, manufacturer-centric	High, reduced assembly process and consumer-centric
	Productivity	High volume, mass production	Low volume ramps up production

	Cost	Economics of scale	Economics of one, eliminates raw material waste
	Quality	Relatively high for certain products	Eliminates the bottleneck of manual operations
	Distribution	Closer to production	Zero distribution, closer to market, low inventory risk
	Logistics	Depends on the supply chain network, centralized	On-demand logistics decentralized
	Marketing	Push	Pull, expanded customer base

Much of the 3DP research in the literature can be characterized as case study research focusing on analyzing the potential advantages of 3DP as a manufacturing technology and outlining some typical costs and trade-offs associated with the systems and investments. Despite the extensiveness of the investigations in the literature and the industry reports, most of them are still limited to qualitative conceptual studies and case studies. For instance, Berman (2012) has evaluated the impact of 3DP technology on separate product designs for manufacturing as well as the possibilities with regard to setting up 3DP production sites near to the end-user market via decentralization. More recently, Oettmeier & Hofmann (2016) have identified absorptive capacity and compatibility as the most influential factors determining the outcome of the 3DP adoption decision in 195 firms, but observed no significant concerns among these companies about 3DP adoption. Hence, this research stream has produced many studies on 3DP, which offer insights into 3DP's potential for enabling non-manufacturers to enter the product competition arena as new manufacturers, and the factors influencing their adoption decision could be classified into three categories: technological, organizational, and internal/external (Figure 2-3) (Saberi, Yusuff, Zulkifli, &

Ahmad, 2010). On the one hand, 3DP has not yet reached a mature level, so it is still unclear whether it is a worthwhile investment to disrupt TM, especially for non-manufacturers that use 3DP to reduce manufacturing and logistical costs. On the other hand, because 3DP technology is continuously evolving, adoption strategies need to be revisited periodically. Therefore, there is a need of conducting a comprehensive and updated research about the impact of 3DP on the supply chain.

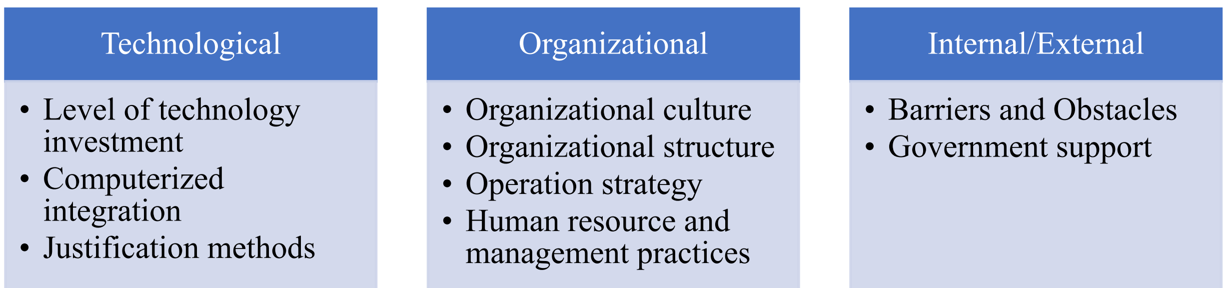


Figure 2-3 Factors Affecting the Adoption of 3DP (Saberi et al., 2010)

In addition, all of the studies discussed point out that 3DP, being assembly free, might pose a threat to traditional logistics, and especially to the upstream supply chains, although some argue against this conclusion. For instance, as we state above, 3DP service adoption might not need distribution infrastructure. If a company considers 3DP adoption, it could piggyback onto the efficient in-country infrastructure. Consequently, delivery between facilities is reduced (Rezapour et al., 2014; Wohlers Associates, 2018). On the other hand, manufacturers can also use the distribution infrastructure built by e-commerce leaders like Amazon and Alibaba or outsource to in-country logistics vendors like UPS and DHL (O'Toole, 2014; Pooley, 2013; UPS, 2016, 2017). 3DP might be a game-changer for companies with delivery capability, especially logistics vendors, because for some kinds of product, the retailers either cease to exist or become 'shop windows' for the manufacturer. Thus, the logistics vendor emerges as a means of raw material delivery for the manufacturer only. However, at the same time the logistics vendor can transform himself/herself into a 3DP-enabled manufacturer and delivery service provider (Manners-Bell & Lyon, 2012). Thus, 3DP is not necessarily solely a threat to logistics vendors – an aspect on which the research is still underdeveloped.

Table 2-2 Benefits of Adopting 3DP

Key Criteria	Consumer	Manufacturer
Digitalized System	Eased communication	More consumer data, predictable market forecasts
Simplified Production	Improved availability	Reduction in complexity and unnecessary stock
Increased Configurability	Improved flexibility and customization	Consumers trading up; enhanced consumer loyalty and satisfaction

The common denominator of all the reviewed references is that 3DP is reshaping the supply chain and provides benefits to consumers and manufacturers (Table 2-2). To our best knowledge, there is limited operations research analytically assessing the impacts of 3DP on the supply chain. Song & Zhang (2018) study the effect of 3DP adoption on spare part logistics management, and their research focus on the decision to 'stock or print.' Dong et al. (2017) compare the impact of 3DP and traditional flexible manufacturing technology on assortment and capacity strategy. Their results suggest that 3DP has excellent performance with regard to product variety and can always provide different implication strategies. Meanwhile, Westerweel et al. (2018) use lifecycle cost analysis to test the impact of 3DP on product design in a set of numerical experiments and cases from two different companies. Their results show that component reliability and production costs are two factors which outweigh the design cost in specific supply chain structures.

Unlike the above research, our research explores the scenario of a non-manufacturer (in our case, a logistics vendor) beginning to offer 3DP services. Instead of limiting to the discussion about how the manufacturer adopts the 3DP technology, we also discuss the possibilities and potential strategy for the logistics vendor that considers 3DP adoption as well.

2.2 Mass Customization

As discussed in the previous subsection, 3DP is a powerful technology which could satisfy the consumer's unique and personalized requirements with regard to the product. Therefore, once a company starts to consider 3DP adoption, one crucial question is how to select an efficient 3DP adoption strategy to improve the consumer's experience of customization.

2.2.1 Background of Mass Customization

The development of supply chain management system in production can be summarized from the Craft Production to Mass Production, and then during the last few decades to Mass Customization and 3DP supply chain (Figure 2-4). In pre-industrial period, craft production is the main manufacturing method. The Craft Production is small-scale and mainly involved manual work with or without the aid of tools (Patty & Denton, 2010). It requires highly skilled and experienced workers (Clarke, 2005). Craft Production has the advantages of manufacturing highly customized and flexible products but its main shortcomings are how to reduce the production cost, improve production lead time (Farahani, Rezapour, & Kardar, 2011). For example, before the introduction of Mass Production, the Ford only could build no more than 1, 000 cars every year and each of those cars is produced individually and separately by numbers of costly skilled workers (Koren, 2010), Later, Craft Production is replaced by Mass Production which could manufacture products in large quantity, short production time, and consistent quality (Hobbs, 2004). Therefore, in contrast to Craft Production, Mass Production is a high-quantity production system which uses large and dedicated machines which was first developed for high-quantity car assembly-line (Tuck et al., 2007). In late 1913, Ford Motors introduced a moving assembly-line at the Highland Park Plant to reduce the production lead time and maintain the product quality by standardized processes (H. Ford, 1926). It was the new milestone of mass production development. By using the mass production line, the Ford's model-Ts' output increased to 500, 000 in 1915 (H. Ford, 1926). Later, in 1940s, Toyota Production System was the new development of the mass production, which combined the advantage of craft production and the mass production (Slack, Chambers, & Johnston, 2007). However, mass production also has major short-comings. For example, the mass production machines are large and expensive, and the machine change-over time is long and the relative cost is expensive (Hu, 2013). Therefore, the drawbacks of mass production highlighted the necessity for improvements which could achieve an appropriate balance among cost, quality, and flexibility (Ohno, 1988).

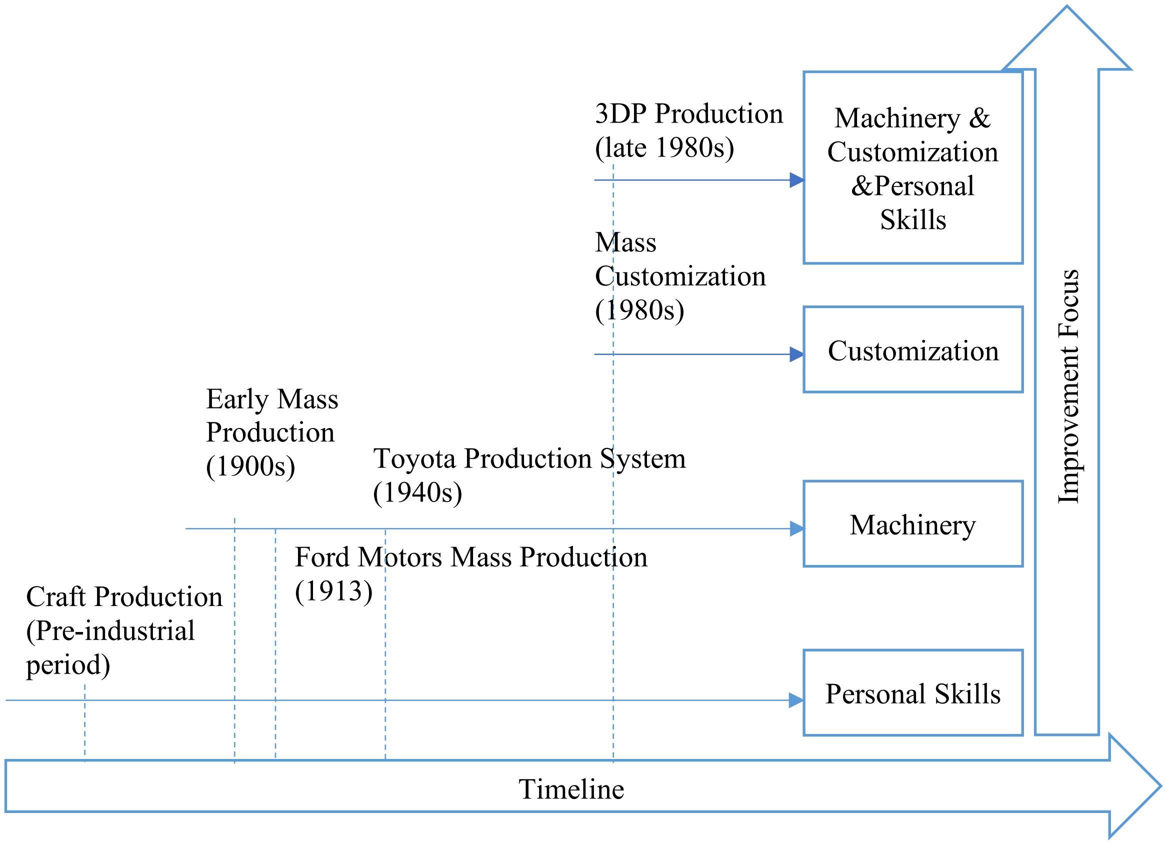


Figure 2-4 The Timeline of Manufacturing System Developments

Mass customization emerged in the 1980s. It is a continuous improvments at Toyota Production System which has the ability to provide individually designed products and services to every consumer through high process flexibility, agility, and integration (Da Silveira, Borenstein, & Fogliatto, 2001; Davis, 1989). Therefore, by using information technology, flexible processes, and organizational structures, the mass customization has the ability to mix cusonumers' individualization with product/service variety and process standardization (Westbrook & Williamson, 1993). A major point of orientation in the mass customization debate is determining the level of individualization characterizing the mass customized product or services. According to Hart (1995) 'the solution of this contention lies in careful determination of the range in which a product/service can be meaningfully customized, and how individuals make options upon this range'. Several researchers developed a continuous framework to 'measure' the level of mass customization in product/service design, fabrication, assembly, and delivery processes (Gilmore & Pine, 1997; Lampel & Mintzberg, 1996). Gilmore & Pine (1997) used empirical study to identify four customization levels as: collaborative (communication between designers and consumer), adaptive (product design can be modified), cosmetic (the final product can be packaged for individual consumer's specific requirements), and transparent (the products are adapted to individual needs). While, Lampel & Mintzberg (1996) proposed five mass customization strategies based on the level of customization in design, fabrication, assembly, and distribution processes, namely, pure standardization, segmented standardization, customized standardization, tailored customization, and pure customization (Figure 2-5). Later, by using case study research method, (Spira, 1993) developed a similar study on defining the customization level in four processes: packging, services, custom work, and assembly. At the same time, Westbrook & Williamson (1993) used the literature review method to summarized those mentioned work and proposed eight generic levels of mass customization ranging from pure strandardization to pure customization, including standardization, usage, package and distribution, additional custom work, assembly, fabrication, and design. All of those studies built up the foundation of the mass customization research.

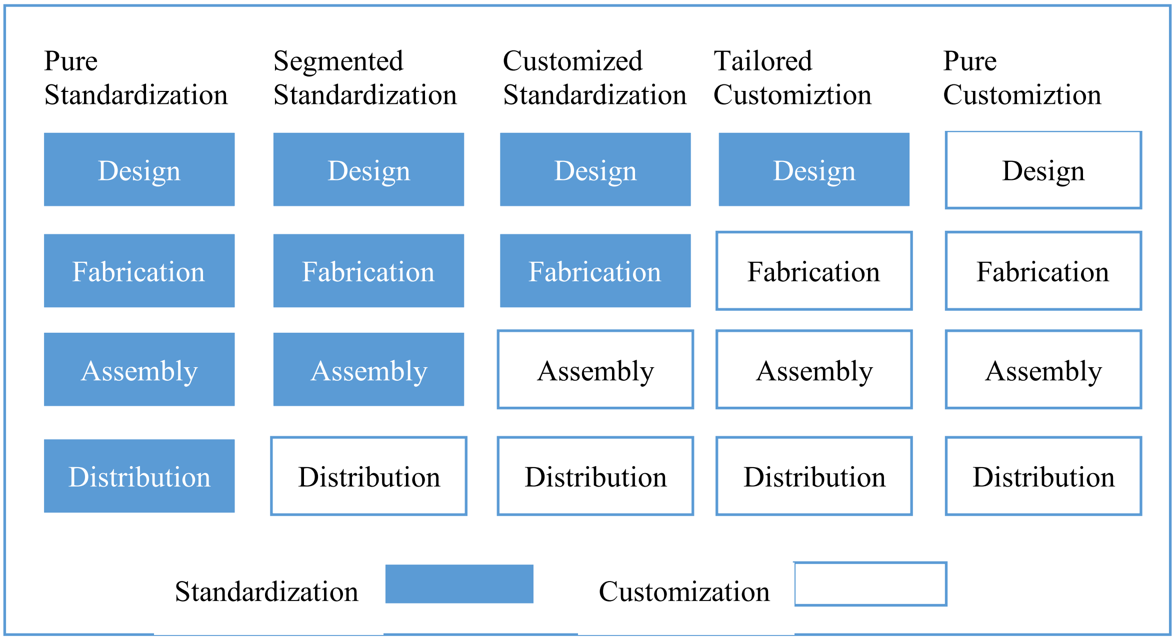


Figure 2-5 Mass Customization Strategies (Lampel & Mintzberg, 1996)

The literature on mass customization has significantly evolved over the last decades. The major studies focused on analyzing the economics of mass customization, success factors (customer demand, markets, value chain, technology, etc.), and enablers (methodologies, processes, order elicitation) of mass customization, as well as the consumer-manufacturer interaction (Fogliatto, Da Silveira, & Borenstein, 2012). These factors and enablers of mass customization were detailed investigated by Cavusoglu, Cavusoglu, & Raghunathan (2007), Jiang, Lee, & Seifert (2006), and Novshek & Thoman (2006) through modelling studies and case studies. In summary, studies under this perspective suggested that the manufacture can improve the level of mass customization by premium prices for customized products, postponement the differentiation activities, gather more updated market information (Z. Chen & Wang, 2007; M. Zhang & Tseng, 2007). Meanwhile, the consumers also improve their willingness-to-pay by having more access in design and production phase (Fiore, Lee, & Kunz, 2003, 2004; Xu et al., 2015).

The most current literature on this topic only qualitatively emphasizes the need to set up the right supply chain systems for customization (see (Macchion et al., 2017; Shamsuzzoha et al., 2013; Zangiacomi et al., 2017), as well as references herein). For instance, (Shamsuzzoha et al., 2013) focused on identifying the proper ICT (information and communication technology) to help SMEs' (Small and Medium Enterprises) collaboration on customized product design. They selected two SMEs, one textile and apparel company and one footwear company, and then implemented a proposed innovative methodological approach for facilitating the processes of creating and managing the collaborative networks on them. Their case studies results indicated that information sharing plays in critical role in improving the overall mass customization level. Besides, Zangiacomi et al. (2017) designed a footwear industry supply chain that combines orthopedic fashion footwear with custommization design to test the importance of consumer engagement in production design, while Shamsuzzoha *et al.* (2013) focused on identifying the proper balance between the product design and manufacturing processes. Macchion et al. (2017) then used historical data on a shoe producer to assess the impacts of the different supply chain configurations (e.g., production quantities and order delivery lead time) used by this company during the transition from traditional to customized production. The majority of the work, however, is still limited to discussions of how and when the manufacturer should involve customization in its production design. Because of the development of manufacturing technology, a broader organizational and economic implications of new mass customization should be discussed at a timely manner.

2.2.2 Mass Customization vs. 3DP

Some studies have compared and contrasted 3DP technology with traditional mass customization (Azadian, Murat, & Chinnam, 2015; Baumers et al., 2016; Berman, 2012).

According to (D. Eyers & Dotchev, 2010; Rangaswamy & Wind, 2001), unlike 3DP, mass customization is mainly archived by either using a different combination of pre-assembled products or using a particular delayed differentiation strategy (postponing the final process of production). Table 2-3 lists some examples. Take shoes as instance, mass customization for shoes focuses on providing different choice of colours for customer. However, by 3DP technology, the customer not only can have a pair of personalized shoes, s/he also can be involved into the design phase and provide his/her own ideas.

Table 2-3 Examples of Mass Customization and 3DP

Product	Mass Customization	3DP
Shoes	Different choice of colours and materials	Personalized shoes design fits to individual's feet size
Milk Tea	Different choice of topping, sugar level, and ice level.	Personalized vitamins fit to individual nutritional needs
Smart Phone	Different choice of colours, size of hard drive, and keyboard language	Personalised colours and graphics design fit to individual's preferences
Car	Different choice of colours, seats, accessories, etc.	Personalized colours, artwork, and body shapes fit to individual's preferences and measurements
Medical Treatment	Different drug combinations	Personalized medicine fits to individual's DNA

Furthermore, this perspective is further extended to the supply chain integration study, as supply chain integration requires process changes (Fahimnia, Farahani, Marian, & Luong, 2013; Tuck et al., 2007). For instance, Berman (2012) draws a sharp distinction between mass customization and 3DP (Table 2-4). He compares the differences between mass customization and 3DP and concludes that mass customization requires a high supply chain integration but the 3DP is readily available for supply chain integration. A very similar finding can be found in one of (Song & Zhang, 2018)'s studies. They argue that mass customization indeed relies on a high degree of supply chain integration because mass customization requires short system change over time, low product inventory levels and fast goods delivery. Also, it requires expensive tooling in small batch production. In contrast, 3DP neither requires tooling nor imposes the pressure of minimum batch sizes, but rather uses CAD digital files to print objects through melting a variety of materials by different printers. Therefore, 3DP can support mass customization with regard to design, materials and even location.

Table 2-4 Comparison between Mass Customization and 3DP (Berman, 2012; Song & Zhang, 2018)

Characteristic	Mass customization	3DP
Manufacturing Method	Different combination of pre-assembled parts	Product based on different designs (CAD file)
Supply Chain Integration	High integration	3D printer readily available
Product Range	Computers, shoes, watches	Prototypes, dental crowns

However, on the other hand, not only do 3DP and mass customization share specific economic characteristics, such as the aim to minimize inventory risk and improve capital management (Berman, 2012), but 3DP technology also integrates customization and manufacturing processes (Y. Chen, 2016) as an all-in-one solution. It thus enables direct communication between the manufacturer and final consumer by digital design files. Most important, 3DP technology also provides freedom of production design which could benefit the whole supply chain system. That is, in addition to allowing consumers to design and produce their design-to-need products (Rayna & Striukova, 2016), 3DP can help manufacturers gain more competitive advantages by continuously improving on customization and personalization (Wohlers Associates, 2016). Design-to-point 3DP supply chains, in contrast, together with digital technology (e.g., the Internet of Things (IoT), the Cloud), provide more possibilities for manufacturing customized products at a reasonable cost (Cai et al., 2014). The latter can provide the supply chain with a cost-effective option for fulfilling consumers' sporadic and unique demands. Therefore, all the relevant literature states that, based on a digital platform, 3DP helps the manufacturing paradigms move forward towards personalization by personalized product and service design and achieving manufacturing-to-demand goals (Figure 2-6).

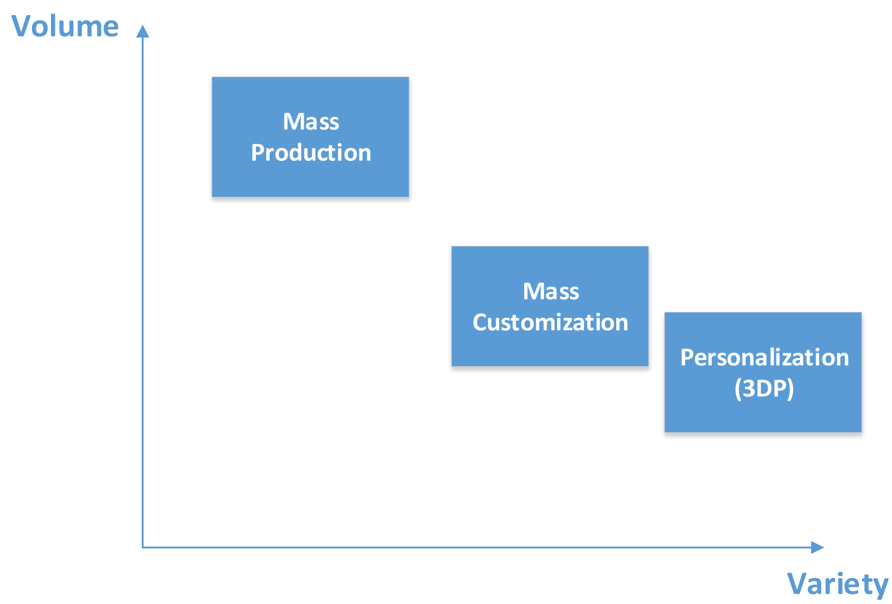


Figure 2-6 Mass Production, Mass Customization, and Personalization (3DP) (Cai et al., 2014; Rayna & Striukova, 2016; Wohlers Associates, 2016)

2.2.3 Mass Customization - Summary

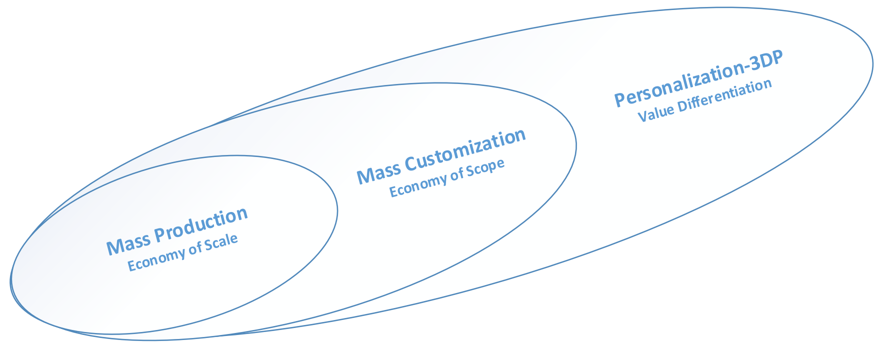


Figure 2-7 Revolution of Manufacturing Paradigms (Hu, 2013)

Due to the uniqueness of the processes, 3DP is driving the next wave of mass customization (Figure 2-7). 3DP together with other new technologies (e.g., IoTs, Block Chain, Cloud, etc.) is enabling further levels of mass customization to deliver attractive growth and margins to those companies that are pioneering new market opportunities or rejuvenating the stagnant industry (Cai et al., 2014).

Most mass production products are manufactured by one or few pre-defined product characteristics and the mass customization products are set upon combining pre-determined choices from a finite set of options. Compared to mass production and mass customization, 3DP-enabled personalization mainly focuses on value differentiation for the individual consumer. But all three paradigms with their different strengths (Table 2-5) co-exist in the current supply chain. For example, mass production focuses on direct production for some stable market demand, and so it utilizes the economy of scale. However, mass customization not only focuses on the economics of scope by providing more differentiated outputs but also tries to achieve economies of scale to maximize profits. In addition, personalized 3DP not only tries to achieve all of the goals mentioned, but it even seeks to decentralize its production and involve consumers in the product design process to tailor its product and satisfy individual consumer needs.

Table 2-5 Mass Production, Mass Customization, and Personalization (3DP) (Hu, 2013)

	Production goals	Strengths	Consumer involvement	Production methods
Mass Production	Economy of scale	Quality, cost	Buy	Different type of manufacturing technology, push
Mass Customization	Economy of scale and scope	Quality, cost, variety	Buy and Choose	Reconfigurable manufacturing, pull
Personalization (3DP)	Economy of scale, scope, and value	Quality, cost, variety, efficiency	Buy, choose and design	Manufacturing-to-demand, manufacturing-to-market

Combined with our discussion in the 3DP Research section, it can be seen that 3DP-enabled personalization is set to reshape the current supply chain from manufacturer-centric to consumer-centric (Figure 2-8) (Bogers et al., 2016; Koren, 2010). Following the literature, personalization should be built into the course of the 3DP adoption, but not treated as the only one consideration. Both personalized product and service can improve the customization.

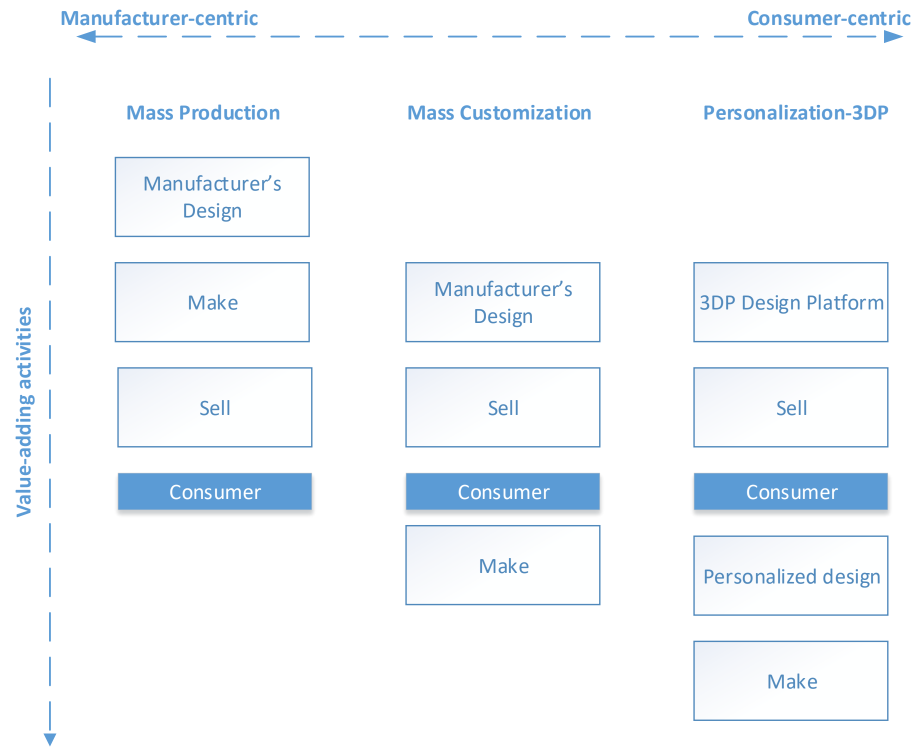


Figure 2-8 From Manufacturer-centric to Consumer-centric (Bogers et al., 2016; Koren, 2010)

These three different manufacturing technologies provide different options to the manufacturer. However, how to make decisions with regard to choosing and mixing the right paradigms for the right product is still an open question so far. As seen earlier, the literature throws a serial of frameworks describing different levels of customization/personalization might contributes to the overall supply chain performance (Berman, 2012; Franke, Schreier, & Kaiser, 2009; Hu, 2013; Takagoshi & Matsubayashi, 2013). However, these studies do not provide enough knowledge on how to determine the appropriate level of customization/personalization or 3DP for a specific product or service. High level customization/personalization or 3DP usually helps the manufacturers gain the competitive benefits but also results in high operational and investment cost (Da Silveira et al., 2001; Fogliatto et al., 2012). Also, it is evident that most of the research mentioned above is limited to quantitatively evaluating the possibility of the manufacturer including 3DP or mass customization into its current manufacturing system for a specific product, such as footwear in (Zangiacomi et al., 2017) and cloth in (Richardot, 2018). Therefore, there is a need to use a methodology for determining the appropriate level of customization/personalization or 3DP for a product or a service at generic level, e.g. involving customization/personalization or 3DP for production process only or production+ delivery processes together. The literature review on this section reveals that there is little contention on theoretical aspects concerning the practical implementation of mass customization/personalization and 3DP for manufacturer and most of them are drawn from limited case study or empirical study. There is a need to use a quantitative approach to assess this with hard evidence and data. Most importantly, the majority of the mass customization research is limited to analyze the manufacturer's strategies of improving mass customization performance, assessing the non-manufacturer's (in this study, the logistics vendor) mass customization/personalization or 3DP strategies and assessing the manufacturer's different combinations of mass customization choices (mass customization and/or 3DP) would be relevant contributions to the mass customization literature.

2.3 Technology Disruption

With accelerated developments of information technology, supply chains span the world with unprecedented complexities and uncertainties. These complexities and uncertainties not only increase the complexities of operation management, but also reduce visibility, which, in turn, makes technology disruption 'more vulerable to unforeseen disruptions' (Park, Min, & Min, 2016). Therefore, it is vital for companies to stay at the top of their business when technologies or markets change (Christensen, Raynor, & McDonald, 2015). Apple Inc. entered the personal computer industry quite late but successfully created the user-friendly portable computer market. However, IBM, which once dominated the mainframe computer market, missed the opportunity of emerging minicomputers. Recently, Marks & Spencer and House of Fraser announced the closure of many stores across the UK because they missed the excellent opportunity to enter the online shopping market (BBC, 2018a, 2018b). However, Amazon has taken advantage of online shopping and become one of the most successful companies in the world. All these cases highlight the necessity of adoption of the right technology at the right time, especially disruptive technology. Therefore, selecting the right 3DP adoption technology to improve consumer customization is one of the key issues for supply chain improvement. Although there is a body of theoretical papers on technology disruption strategy listed in below subsections (Section 2.3.1, 2.3.2, and 2.3.3), this paper adds to the extensive body of literature on 3DP printing disruption.

2.3.1 Disruption of Manufacturing Strategy

Manufacturing strategy could be identified as a critical research domain as lots of research rallies the actual benefits of the techniques in manufacturing systems (Dangayach & Deshmukh, 2001; Kim & Lee, 1993; Voss, 2005). Back in the late 1960s, Skinner (1969) is among the very first in this research domain. His work suggests that manufacturing strategy could be used to develop the competitive advantages by exploiting the manufacturing functions (e.g. the inventory management, logistics management). Later, Thomas, Hayes, & Wheelwright (2006) also give the definition of manufacturing strategy: it is a ‘consistent patter’ of decision making for how to improve or change the manufacturing function which also cohere with the overall company’s business strategy. Their theory points out that those companies that could bridge their competitive and manufacturing strategy attain superior performance. Therefore, manufacturing strategy reflects the organization’s business strategy and it brings advantages to the company’s competitiveness and business performance in long-term (Goldhar & Jelinek, 1985; Hill, 2009; Skinner, 1969; Swamidass & Waller, 1990). However, it is not easy to grasp the interrelationship between the business strategy and manufacturing strategy (Skinner, 1969).

Based on previous research, Thomas et al. (2006) propose a framework for manufacturing strategy by defining the business objectives first and then setting the manufacturing objectives accordingly, and lastly making structural and infrastructural decisions (Figure 2-9). Their research identifies several factors influencing the manufacturing strategy, including the cost, quality, dependability and flexibility. For example, the manufacturing cost has impact on the investment strategies (corporat/ebusiness objectives) and it also could influence the facilities/capacity planning (structural decisions) and workforce/production planning (infrastructural decisions).

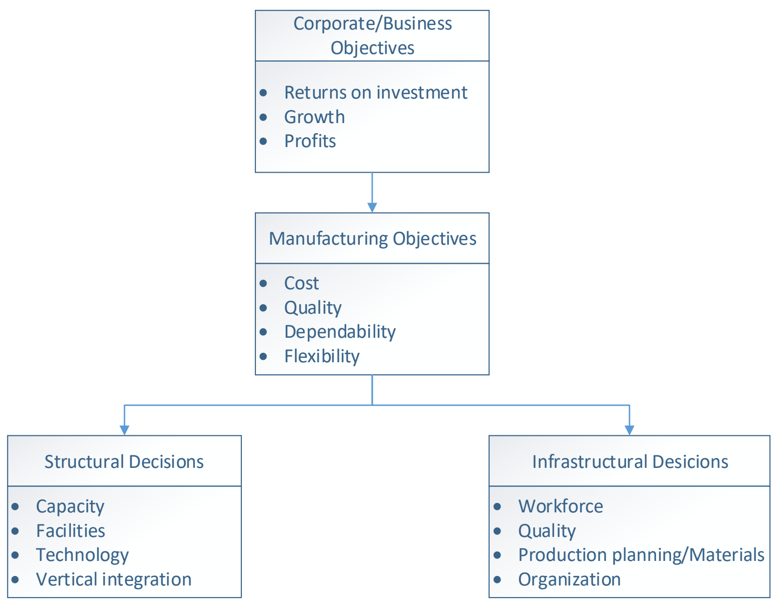


Figure 2-9 Manufacturing Strategy Framework (Thomas et al., 2006)

After this, (Frohlich & Dixon, 2001) revisit manufacturing strategy and analyze case studies from all over the world, proposing three new manufacturing strategies according to different business focus:

- Idlers: a lack of business strength on any competitive capabilities (mainly in South America)
- Servers: focus on service-based capabilities (mainly in Western Europe)
- Mass customization: focus on the competitive capabilities of low-price and production flexibility (in Asia Pacific)

(Voss, 2005) once comprehensively studies the paradigms of manufacturing strategies and how they can be applied to manufacturing processes and management. Three paradigms are proposed in his study: Competing through Manufacturing (key success factors, capability, order winners, etc.), Strategic Choices in Manufacturing (choice of process, approaches, infrastructure, etc.), and Best Practice (benchmarking, Total Quality Management, Continuous improvement, etc.). His study also concludes that a manufacturing strategy is an approach to business competition based on a company's capability, marketing strategy, and market demand.

2.3.2 Disruption of Supply Chain Management

Among all kinds of risks faced by companies, the supply chain disruption mainly arises from the inter-connected net flow of material, information, technology and cash. To a certain extent, all companies do not only link with those inter-connected net flow, but also rely on all the external sources and relationships. Therefore, they are consequently exposed to the risks of supply chain disruption (Pfeffer & Salancik, 1978). (Mitroff & Alpaslan, 2014) state that, among all Fortune 500 companies, there are only between 5% and 25% of them are prepared to manage disruptions. Therefore, how to effectively prevent and handle supply chain disruption has drawn increasing attention in both academia and industry. The research related to supply chain disruption can be categorized into two categories: conversion and new technologies.

In detail, the conversions include all kinds of traditional supply chain disruptions: poor communications, product quality issues, operational issues, delivery issues, and accidents or natural disasters (Chapman, Christopher, Jüttner, Peck, & Wilding, 2002; Levy, 1995; Mitroff & Alpaslan, 2014; Rice & Caniato, 2003; Riddalls & Bennett, 2002; Wu, Blackhurst, & O'Grady, 2007). More specifically, Levy (1995) once investigates physical flows in international supply chains with disruptions in the market demands and his research shows that disruption in a global supply chain can cause unexpected costs when the lead time of logisitcs delivery is long. Riddalls & Bennett (2002) simulate a production and inventory system and find that because of disruption the system became unstable and costly. Their research lists out disruptions can lead to a variety of costly issues to the supply chain systems, such as stock-outs, long lead time, and the poor consumer order fulfilment rate. In this area, some research has been conducted. For example, Rice & Caniato (2003) use a company survey and estimate the cost impact for a substantially disrupted supply chain network. Additionally, Wu et al. (2007) point out that in the supply chain system, any disruptions originating at a certain point might have the potential to pass such perturbations onto a wider range (including subsequent tiers or branches) with a possible amplifications. However, many companies, especially some small and medium enterprises (SMEs), are unable to forecast or quantify the relevant cost of supply chain disruptions.

The literature related to the supply chain disruption of new technologies indicates that 1) the evolutionary technological system is punctuated by discontinuous changes, and 2) the significant breakthrough in technological progress is relatively rare (Christensen et al., 2015). As shown in Figure 2-10, products/services improve over time with customer demand trajectories in order to chase higher business performance. The incumbent companies introduce more top performance products/services for the high-end market for higher profitability (Wohlers Associates, 2018). However, they lose the low-end market. This leaves an opportunity for the entrants on a disruptive trajectory to have a better offering and to move upmarket with better financial performance. Therefore, the right disruptive technology at the right time leads to a new change in the supply chain structure as well.

Figure 2-10 Disruptive Innovation Model (Christensen et al., 2015)

Nowadays, technological supply chain disruption includes the Internet of Things (IoT), 3DP, self-driving vehicles, collaborative robotics, the urbanization or airbnb'ing of delivery, and drones. 'Logistics currently is ripe for technology-driven disruption.' says Greg Hewitt, CEO of DHL Express U.S., which provides door-to-door transport of international express documents and goods to and from 220 countries and territories (Gresham, 2016, P. 2).

- Internet of Things (IoT): IoT is a physical-objects-based network which could be used to collect, monitor, and exchange real-time data/information. Currently, IoT is one of the most disruptive technologies in supply chains. It drives unprecedented visibility and remote operation, and influences logistics decision-making on production, storage, and shipment.

- 3DP technology: 3DP provides the possibility of printing any product once the design file is ready. Due to 3DP technology, the complexity of the supply chain could be dramatically simplified. For instance, GE adopts 3DP for producing fuel nozzles for jets. The nozzles contain more than 40 components. This adoption changes the previous extensive supply chain into a single factory based supply chain (Kellner, 2018).

- Self-driving vehicles: Driverless cars have the potential to reduce labour costs and increase efficiency, and this is a new game-changer for the logistics industry.

- Collaborative robotics: This is a breakthrough for the supply chain through the use of artificial intelligence and sensors. These robots can handle automated tasks or work alongside humans, for example by unloading trucks or packing and shipping goods within the warehouse.

- Urbanization or shared delivery: The urbanization of delivery is currently a favoured technique for utilizing space among innovative startups that want to provide same-day service at a cost that can compete with traditional logistics vendors. Shared-delivery can also use space in the rooms as the delivery site.

- Drones: Drones could deliver goods to the dedicated destinations by pre-set routings.

Thus, technological supply chain disruption is a threat to the logistics industry (e.g. allowing reductions on delivery) and the manufacturing industry (e.g. cost reductions on traditional production and high efficiency of the new manufacturing technology). Besides, technological supply chain disruption results in new power changes within the supply chain.

2.3.3 Strategy Selection for Technology Disruption

Skinner (1969) summarized the critical criteria in manufacturing strategy, including facility administration, plant and equipment, product design, production planning and control, labour management and schedule, etc. After that, Hayes & Wheelwright (1979) conducted similar research on this topic and detailed the key selection criteria and proposed a new decision-making matrix based on the process/product and quality/cost (Figure 2-11). For example, automobile assembly belongs to *connected line flow* in the process phase and *few major products, higher volume* in the product phase. Therefore, automobile assembly is a high dependability-cost process.

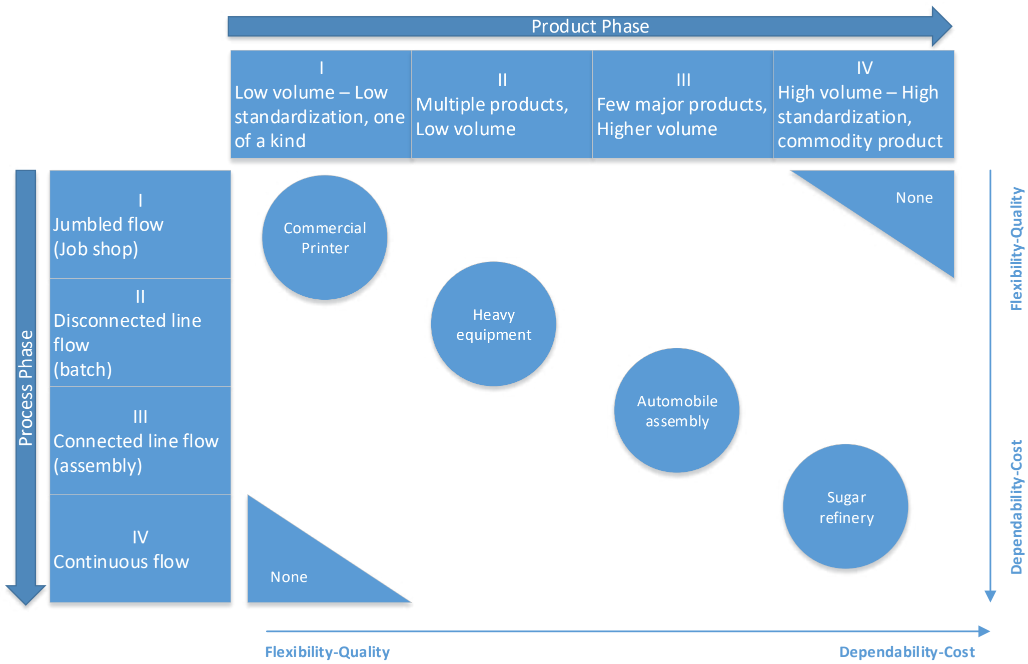


Figure 2-11 Product-Process Matrix for Strategy Selection (Hayes & Wheelwright, 1979)

Later on, approaches to strategy selection were developed by many researchers. One classic work was a taxonomy model proposed by Kim & Lee (1993). They evaluate the decision to select different manufacturing strategies by technical flexibility and complexity and group the production systems into four categories: intermittent, concurrent, degenerate, and continuous (Figure 2-12).

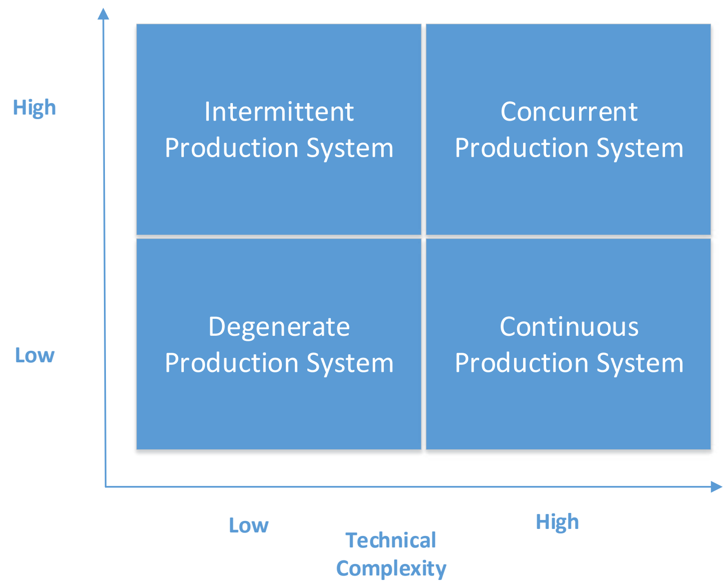


Figure 2-12 Product Systems Analyzed for Technical Flexibility and Complexity (Kim & Lee, 1993)

2.3.4 Technology Disruption - Summary

In the whirlwind of technological advances, however, it is easy to lose sight of where the value lies', notes Doug Waggoner, CEO of Echo Global Logistics, a Chicago-based logistics service provider (Gresham, 2016, P. 2). Therefore, technology disruption equals to breakthrough, there has to be purpose and strategic design – actual usefulness – for the technology to take hold and influence business strategy.

Despite the fact that the awareness among practitioners and academies is increasing and the external environment, especially the technological environment, is changing, the concept of disruption is still mainly limited to cost-related research analysis(Park et al., 2016; Riddalls & Bennett, 2002; Wu et al., 2007; Xia, Yang, Golany, Gilbert, & Yu, 2004). Meanwhile, the rapid development of breakthrough 3DP technology emphasizes the importance of research on technological disruption, especially for the logistics and manufacturing industry. However, due to the uniqueness of 3DP technology, 3DP technology disruption is not limited only to process change: it provides opportunities not only for the manufacturer but also for other supply chain players (e.g. the logistics vendor) to rethink their 3DP adoption strategies and options. 3DP technology brings more options to the supply chain to improve the overall system customization and profitability. This research area has rarely been touched upon. Therefore, this study focuses on analyzing the possibilities of different disruptive 3DP technology adoption strategies and seeks to update research in this stream.

2.4 Chapter Summary

‘Technology is easy; high-school students can build mobile apps at night, and they're pretty darn good,’ Waggoner (CEO of Echo Global Logistics) says. ‘But technology for technology's sake is not enough.’ (Gresham, 2016, P. 2).

A company’s competitive determinants are not only limited to quality, efficiency, and flexibility. Now, customization or personalization are new competitive dimensions. Consumers are becoming much more discerning and selective when purchasing. For any product to be successful, high attractiveness to the consumers is a new key factor. Therefore, how to provide the right product to fulfil the consumers’ existing and unspoken wishes, needs and requirements and how to delight consumers are becoming critical issues for supply chain development. A term that has been coined to describe such supply chains is ‘bespoke’, which focuses on rapid ‘manufacturing-to-order’ with greater choice and more customized features (Figure 2-13) (Asiabanpour, Mokhtar, & Houshmand, 2008).

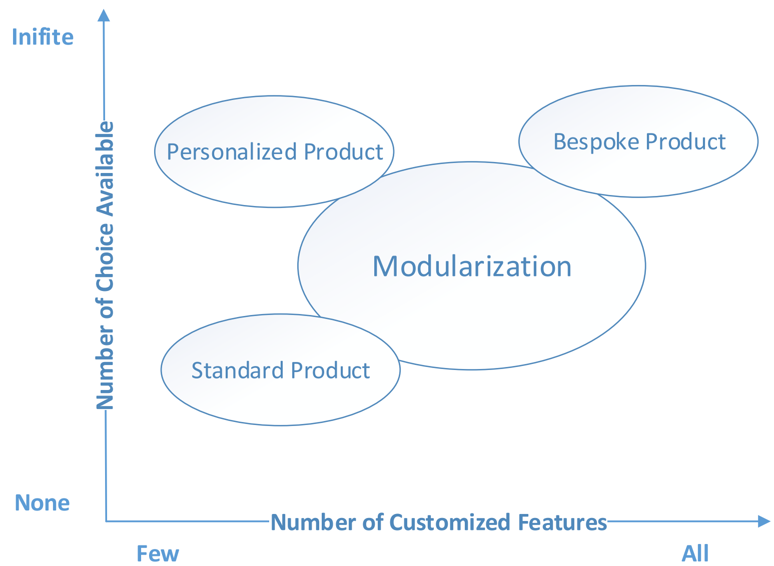


Figure 2-13 Types of Customization (Asiabanpour et al., 2008)

In addition, a new production supply chain that would always start and end with customers and be focused on them throughout is required. Therefore, companies do not only need to assess the trade-offs among cost, quality, efficiency, and flexibility, but also need to analyze the impact of the customization and new technology disruptions upon them (Figure 2-14).

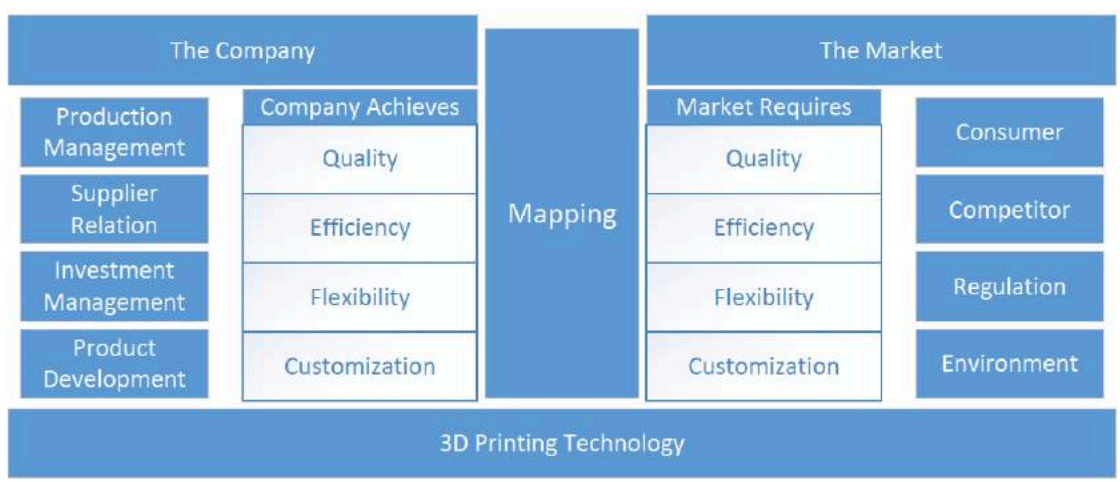


Figure 2-14 Company Competitiveness (Upton, 2008)

As we have discussed above, the disruptive 3DP technology is a potential approach to improve companies' competitiveness from the perspective of technology and customization (Wohlers Associates, 2018). But because of the uniqueness of 3DP technology and the new development in this area, how to adopt 3DP is becoming a critical question to all the supply chain members – not only the 'makers' and 'customers', but also the 'middle-men' (e.g. the logistics vendor).

This chapter reviews existing literature to scope the research domains and identifies both the need and the gap for assessing the impact of 3DP adoption on the supply chain.

Section 2.2 reviews the current studies related to 3DP adoption. These studies mainly concentrate on the advantages and cost structure of individual 3DP technology.

From the research methodology perspective, many studies are still limited to quantitative conceptual studies and case studies. In addition, little 3DP research has focused on examining the possibility of 3DP adoption by 'non-manufacturer' in particular.

In order to explore why customers want to use new 3DP technology, Section 2.3 investigates some more details about mass customization and also compares the mass customization with 3DP technology. Based on the review, several useful research which highlights key differences between the mass customization and the 3DP, such as manufacturing method, supply chain integration, and product range (Berman, 2012; Y. Chen, 2016; Rayna & Striukova, 2016; Wohlers Associates, 2016). However, there is still a need to evaluate the possibility of how to use 3DP technology to improve the overall product customization level and what are the impacts on the supply chain accordingly are.

Subsequently, Section 2.4 presents technology disruption on manufacturing and supply chain management. This section of literature review helps us understand the methodology of technology disruption and how to strategically select the right disruptive technology. Numerous criteria have been found: 1) flexibility, 2) quality, 3) dependability, and 4) cost. However, due to the uniqueness of 3DP technology on manufacturing production and process, there is a need to comprehensively review the adoption strategy for the new disruptive technology – 3DP technology.

To summarize, our study contributes to the literature by comprehensively analyzing 3DP adoption strategies and the impacts on supply chain management in the context of both mass customization and technology disruption. In addition, this study also extends the existing literature on manufacturing strategy choice (traditional manufacturing, traditional flexible manufacturing, and 3DP manufacturing) and collaboration between traditional manufacturers and logistics vendors.

Chapter 3 Methodology

The first two chapters outlined the scope and background of this research and also presented a review of relevant works. Although the previous studies have explored the possibility of 3DP adoption, very few studies have concentrated on the quantitative assessment of the possibility of 3DP adoption by the logistics vendor or the impacts of 3DP adoption by the logistics vendor on the supply chain. To this end, this research attempts to develop three different models to assess the 3DP adoption strategy, not only for the logistics vendor but also for the traditional manufacturer.

According to (Robson & McCartan, 2015), identifying the research methodology is one of the most important base stones for conducting any piece of research. Methodology could be a set of detailed tasks or procedures which are designed to meet the research aims (Easterby-Smith, Thorpe, & Lowe, 2002). This chapter is designed to provide a review on the methodological basis for this research. Therefore, in the following sections a comprehensive overview of the classical research methodology is provided and the specific research methodologies which was selected for this thesis is explained in detail. In detail, this chapter begins with a brief analysis of the all types of research methodology in operation and management research in Section 3.1. The focus then shifts to have an in-depth discussion and comparison among the qualitative and quantitative research methods in Section 3.2. Next, game theory is introduced in Section 3.3 as a theoretical perspective from which to explore the role of game theories in 3DP adoption, and then attention is also paid to identifying the most suitable game theories for this thesis. Section 3.4 describes the research method selected in this research. The final Section 3.5 gives an summary of this chapter.

3.1 Research Methodology

Research methodology could be defined as a tactics of probes, and normally, it contains research design and data collection plan (Luczun, 1989). The means of setting the research design and choosing research methodologies has huge impacts on the research framework, process design and data collection methodology. In additon, selecting appropriate research methodologies for the particular research project influences the reliability of the research outcomes (Patten & Patten, 2018). Therefore, selecting a suitable research methodology plays a critical role in the research development stage. Thus, this chapter tries to go through related research methodology theories and, in turn, choose appropriate research methodologies for exploring all the designed research questions.

In general, research methodologies could be splited into qualitative methodologies and quantitative methodologies (Creswell, 2013). Qualitative methodologies are those used by researchers to develop a theory or pattern by making knowledge claims from constructivist perspectives (i.e., the different meanings of individual experiences and thoughts). Conversely, quantitative methodologies are those used by researcheres primarily claims to develop knowledge from post-positivist perspectives (such as the testing of theories and sophisticated analyzes), and the researcher sually use different strategies of methodologies (such as experiments, observations, questionnarios, etc.) to collect data for analytical analysis (Creswell, 2013). In the subsections below, more details concerning qualitative and quantitative research methodologies are provided.

3.1.1 Qualitative Methodology

Traditionally, qualitative methodologies can be defined as research strategies that usually attempt to describe or translate certain natural phenomena in our daily life; they are not only quantification of the data collected and analysis (Maanen, 2018; Neuman, 2005). Qualitative methodologies have been widely used in academia because they can be used to explore and investigate the deeper meaning of any discoveries. More precisely, qualitative methodologies tend to investigate the importance of the research subjects and our experiential social life (Patten & Patten, 2018). Also, qualitative methodologies can capture individuals' behaviours and reactions in a complex world as the research results (Sugawara & Nikaido, 2014). Consequently, the results assist researchers to gather further understanding from the different participants' perspectives. Therefore, qualitative methodology could be used to identifying and summerize the possible relationships, direct/indirect causes and effects, and dynamic processes in the research design development stage (Brannen, 2017). The most classical and widely adopted qualitative methodologies are interviews, observations, focus groups, case studies, and simulations.

3.1.2 Quantitative Methodology

Quantitative methodology usually involves the enumerative induction processes and it can be regarded as a research strategy that emphasizes the quantification of data (Creswell, 2013; Neuman, 2005). The key advantages of quantitative methodology are ease of control and data precision. The ease of control could be achieved through the sampling and data collection design, and accuracy of data could be improved through quantitative and reliable measurement (Tashakkori, A. & Teddlie, 1998). Meanwhile, quantitative methodologies can help the researcher to get statements about causation, because the researcher could demonstrate the direct causal effect of a variable on the other variables by removing or controlling the value of that variable (Brewer, Newman, & Benz, 2006).

In addition, quantitative methodologies provide the service of the deductive test for assumptions and the collected quantitative data also could be used for stable statistical analysis (Brannen, 2017). Therefore, quantitative methods produce knowledge based on a much scientific and solid basis, comparing to qualitative methodologies. The most fundamental and common quantitative methodologies are questionnaire surveys, interview surveys, and experiments.

3.1.3 Comparing Qualitative and Quantitative Methodologies

According to Brennen (2018), qualitative research methodologies are usually used to get an in-depth understanding of a particular social phenomenon, whereas the quantitative methodologies are employed to make quantifiable 'easy-to-generalize' statement. For instance, the former research methodologies (qualitative) are used if the research target is not clearly defined and the questions of respondents are open (e.g. interviewing). By contrast, if the research target is clear-cut and the questions used to collect research data require systematic and clear answers, quantitative methodologies might be more appropriate (e.g. close-ended questionnaire). In summary, qualitative methodologies are usually associated with analytic induction, but quantitative methodologies are linked with enumerative induction. Table 3-1 lists out the key differences between the qualitative and quantitative methodologies (Brannen, 2017)

Table 3-1 Differences between Qualitative and Quantitative Methodologies (Adapted from Brannen, 2017)

	Qualitative Methodologies	Quantitative Methodologies
Objects	Theory emergent for contextual understanding	Theory testing for generalization
Research setting	Natural	Artificial
Data	Words, rich and deep data from the understanding of meaning	Numbers, hard and reliable data from the system behaviour

3.1.4 Mixed Methodology

Although both qualitative and quantitative methodologies have distinct advantages, they also have undeniable limitations. The primary criticism of qualitative methodologies is related to the concern of adequate validity and reliability. Because of the nature of qualitative data and its origin in contexts, it is difficult to adopt traditional standards of reliability and validity. Meanwhile, qualitative methodologies also have the limitation on the time requirements of data collection and analysis. In addition, many researchers are concerned that their behaviours during data collection could influence participants' individuality (Brannen, 2017; Brewer et al., 2006; Tashakkori, A. & Teddlie, 1998). Quantitative methodologies, on the other hand, they could successfully play as philanthropic endeavours that try to explore the system behavior and human condition. However, they fails to consider such as human's unique ability of interpreting their own experiences, constructing their own thoughts and reactions (Brannen, 2017). Therefore, because of the original restriction and the human control of variables, quantitative methodologies are often used to 1) produce common and trivial findings of consequence under defined scenarios and 2) predict the future trends based on the analysis of current practices.

Because of those afore-mentioned limitations of qualitative and quantitative methodologies, mixed methodologies have been applied as a combined method to overcome these limitations. Researchers usually use mixed methodologies to claim base knowledge on practical cases (and is thus, for example, consequence-oriented, problem-centered, and pluralistic) (Creswell, 2013). They employ strategies that include concurrent or sequential data collection for the purpose of assessing the research problems. The research results of mix methodologies consist both qualitative and quantitative information because the data collected for the mix methodologies involve both numeric information and text information (Sugawara & Nikaido, 2014). Figure 3-1 displays how the quantitative methodologies approach has been employed in this study. The next section will offer introductions and understandings of the fundamental research methodologies in more detail.

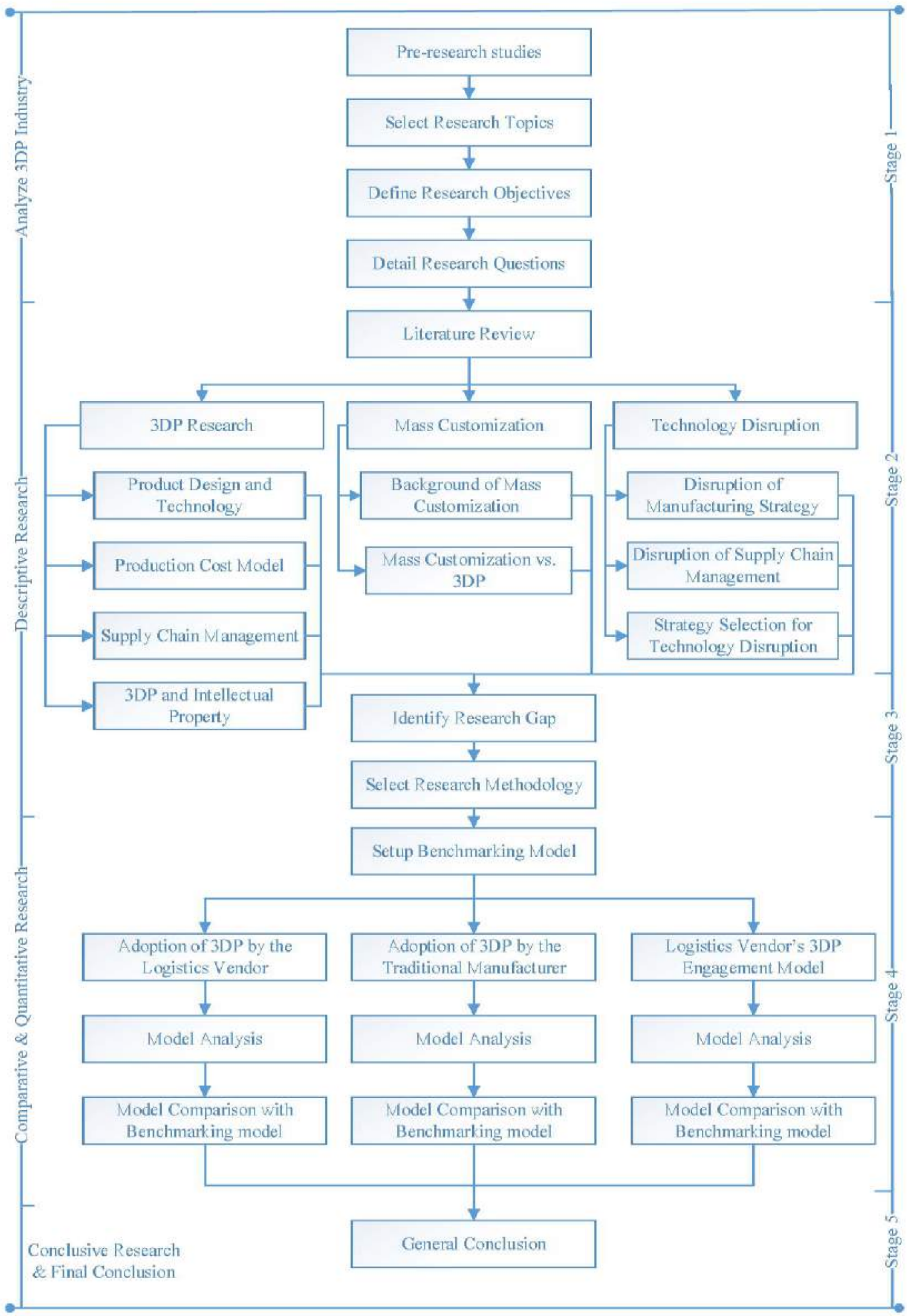


Figure 3-1 Framework of Quantitative Methodologies Used in this Thesis

3.2 Research Methods

As described in previous sections, various qualitative and quantitative methodologies could be applied for different research purposes. The subsections below illustrate features of related research methods in the 3DP research and then explain the reason about the selection of the research methods used in this research.

According to Croom (2009), the academic research process is a approach which methodically involves procedures to design research, gather or generate data, interpret and analyze the data, and then make conclusions. Different research process might have different sequence of procedures and different patterns (Maanen, 2018). The 3DP research as a part of the supply chain management research, it is a broadd field and may cover many issues and can be carried out using different research designs to collect and analysis the data (Hensley, 1999; Yin, 2003). Based on the source of data used and the approach taken to generate knowledge, the reviewed 3DP supply chain research listed in Appendix A could be broadly classified as empirical research, interpretive research and axiomatic research (Figure 3-2) (Croom, 2009).

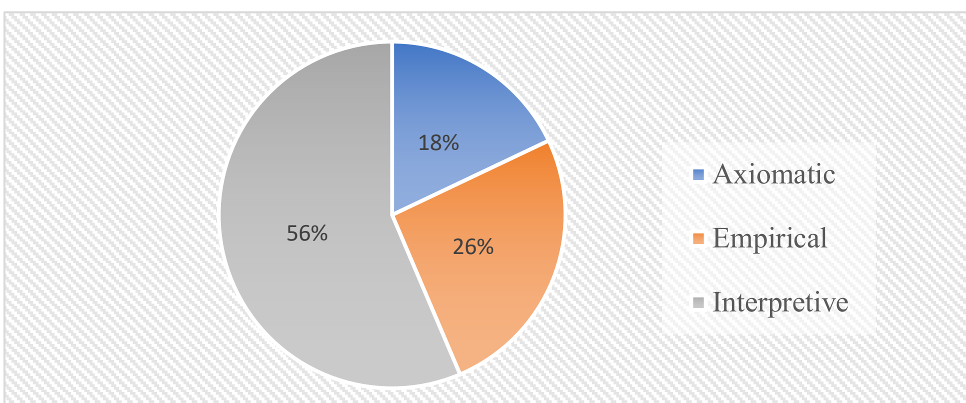


Figure 3-2 Classification of Related Studies by Research Method

3.2.1 Interpretive Research

Interpretive research is a reality-driven approach which uses the data collected from case studies, previous studies, and industry reports to descriptively summarize or improve existing knowledge about the defined research topic (Craighead & Meredith, 2008; Croom, 2009; J. R. Meredith, Raturi, Amoako-Gyampah, & Kaplan, 1989). Therefore, this kind of research is more inductive and subjective (J. Meredith, 2002; J. R. Meredith et al., 1989). The most used tools for the interpretive research in 3DP supply chain research are interview, questionnaire, and case study.

Interview is one of the most common and popular methods for data collection. It helps researchers to gather the accurate and inclusive data from interviewees' personal experience and then have a deeper understanding on a particular problem (Akeroyd & Burgess, 2006). It is particularly appropriate for research which targets to evaluate or summarize a group of people's thoughts and attitudes towards a particular issue or phenomenon (Easterby-Smith et al., 2002). Also, an interview provides flexibility to gathering large amounts of data regarding a wide range (Stanton, Salmon, Walker, Baber, & Jenkins, 2013). It can either be conducted through face-to-face chat or by other communication tools (e.g. by telephone, face-time, or Skype). Meanwhile, interview could be used for elicitation of information from one interviewee or a group of individuals. Group interview (also called focus group interview) can provide an efficient approach to investigate and compare different people's experiences, attitudes, reactions and opinions under the same scenario (Akeroyd & Burgess, 2006). According to the forms of the interview, Edwards & Holland (2013) categorize interviews into four different types: *structured interviews, unstructured interviews, standardized open-ended interviews,* and *semi-structured interviews.* Interview offers a flexible way to the academia to collect data regarding a wide range of subjects (Stanton et al. 2013). For example, (Wohlers Associates, 2018) interviewed more than 100 3DP companies to gather the data about the current situation of the 3DP supply chain development.

However, interviews also have some limitations. First, interview is time-consuming. For example, the interview construction, data collection and transcribing data processes are laborious. Second, it is difficult to access the reliability and validity of the interview methodology. Third, the quality of the collected data is entirely upon the interviewer's individual skill and the interviewees' individual quality (Stanton et al., 2013). Last, because the interviewer can fully direct and control the whole process of interview. Thus, they cannot ensure the data collected during the interview can be treated statistically (Dickinson, 2015).

Questionnaire is another most common research methodologies used in academic studies on 3DP supply chain research (Bogers et al., 2016; Esmond & Phero, 2014; Wohlers Associates, 2018). Because the research about the 3DP supply chain research is rare, questionnaire is one of the best method to collect data from the reality. Fink (2015) defines questionnaire as 'a structured schedule of questions which is usually self-completed by the respondent'. Therefore, questionnaires are widely preferred by the researchers who try to gather people's preferences and opinions on particular events or cases. Traditionally, questions listed in questionnaires could be differentiated into two types: *question of fact* and *question of opinion* (Brewer et al., 2006). Question of fact contains biographical details, such as age, gender, occupation. However, question of opinion usually targets on gathering respondents' opinions and/or attitudes toward a particular issue. In addition, questions can also be categorized as closed-ended and open-ended questions (Table 3-2 lists out some examples). Regarding open-ended questions, they cannot be answered with a direct 'yes' or 'no', or with a specific piece of information. Stanton, Young, et al. (2013) summarise the types of both closed-ended and open-ended questions including multiple choice, rating scales, ranking orders, pair associate, open-ended questions, open questions, and filter questions.

Table 3-2 Comparison of Closed-ended and Open-ended Questions

	Question of Fact	Question of Opinion
Closed-ended Question	Question: What is your occupation? Answer: Student	Question: Are you satisfied with your current employer? Answer: Yes / No
Open-ended Question	Question: Could you please give an introduction about your hometown? Answer: a paragraph	Question: What do you think about 3DP manufacturing? Answer: a paragraph

Fink (2015) once summarizes the advantages of the questionnaire into four major points: 1) the overall cost of conducting questionnaire is cheap, comparing with other methods; 2) the data collection process is less time-consuming; 3) the respondents are more likely to express their opinions and attitude under the anonymous style; and 4) by using a questionnaire, the researcher can direct the respondents to focus on the research objective and questions. In the same vein, Stanton, Young, et al. (2013) point out that a questionnaire also provides the flexibility and possibility to gathering large scale data from large participant population. For example, Ernst & Young (2016) and Wohlers Associates (2018) are two industry report, questionnaire is the best research method for both to dervie the industry data from more than one hundred 3DP companies globally.

The main limitations of the questionnaire can also be outlined as following. First, if the number of valid responses is low, questionnaire results may be distorted. For example, participant might not return the questionnaire because they are unable to complete the questionnaire (Fink, 2015). Second, although the data collection process is less time-consuming, the questionnaire design, questionnaire pilot, and raw data analysis are quite time-consuming. Last, questionnaires sometimes can only offer limited output because of the limited scope of the designed questions (Dickinson, 2015).

Normally, a case study is a preferred research method when the researchers want to understand some 'how' and 'why' questions, and/or when the researchers have little control over events, or when the researchers target to assess a contemporary real-life phenomenon. Yin (2003) defines case study as an investigation which studies a 'contemporary phenomenon' of a particular real-life event. Thus, we can define a case study as an inquiry that retains the holistic and meaningful data of the complex reality for inspection. In addition, a case study can also be applied to investigation processes, relationships or experience of a particular phenomenon and offers an in-depth understanding of the case in a specific instance (Kane, 2002). More importantly, a case study can also combine with other research methodologies to gather the various sources of data from real-life events for study. Thus, the case study approach can provide more reliable results. Also, documentation, archival records, interviews, direct observations, participant-observations, and physical artefacts are six commonly used resources to carry out case studies (Yin, 2003). By using case study research methodology, the researchers can focus on one or few cases and get the opportunities to understand the subtleties and intricacies. Also, the case study methodology encourages the researchers to embrace a variety of other research methodologies to enhance the reliability of the research outcomes. Furthermore, when the researcher has less control over the event, case study is an appropriate research method for investigating natural phenomena. In Berman (2012)'s research, he involves questionnaire, interview into the case study method to help gather data from the reality. On the other hand, the case study methodology also has some drawbacks. By using case study, it is difficult for researchers to produce fair results based on the investigated cases. Because case study research tends to analyae protracted elements over a certain period, therefore, the presence of a study could lead to the observer effect.

3.2.2 Empirical Study

Although empirical research is also a reality-driven research approach, different from interpretive research, it uses deductive methods with data collected from real external cases (e.g. observation data derived from the field) to describe phenomena and test if the assumed causal relationships between relevant variables hold in reality (Craighead & Meredith, 2008; Creswell, 2013; Yin, 2003). Therefore, empirical study research can be both descriptive and normative (Wacker, 2002).

A descriptive empirical study is initially used to create a model which can adequately present the actual relationships between objectives in the real world. Thus, a descriptive empirical study leads to an understanding of the processes going on in reality. Examples include product modularity strategy research (Hofmann et al., 2014; Mohammed et al., 2018; Ross et al., 2018; Sanchez et al., 2014) and multiobjective (MO) search (Holmström et al., 2016; Liao et al., 2014; Liu et al., 2014; Tuck et al., 2007). Normative empirical study research is primarily used to develop strategies, guidelines, and policies to improve the performance of current system. The existent amount of this type of research method is minimal. The classical example of this type of research is Mellor et al. (2014) and Oettmeier & Hofmann (2017). Comparing to the other research methods, the verification procedure of a normative empirical study is usually not very strong. For any study with a longitudinal design, if a specific change occurs during the verification stage, it is difficult to investigate the changes. In the other word, control on all relevant variables all the time is impossible for a normative empirical study. Traditionally, empirical studies can be classified into experimental research, empirical statistical research, and empirical case studies. Table 3-3 lists some details about these three sub-categories.

Table 3-3 Differences and Similarities between the Empirical Study Sub-Categories (Wacker, 2002)

	Experimental Design	Statistical Sampling	Case Studies
Definition Development	The conceptual definitions usually require new, more measurable concepts	The conceptual definitions come from the literature; new constructs are developed to represent the theoretical concept	The conceptual definitions come from the literature; new relationships need new definitions
Domain Limitations	Experimental design with specified and limited settings	Experimentally developed analytical statistical models	Developed from certain cases studies
Relationship Creation	Proposing limited relationships between variables for experiment	Using the theories suggested by the other statistical studies	Combining connections discovered from the case under study
Theory Predictions	Prediction from the experimental design and statistical experimental results	Prediction based on other studies results; samples statistical analyzes for relevance	Supported by case studies
Contributions	Investigates and verifies causal relationships between variables	Tests the theory by studying the statistical relationships and validates the existence of those relationship in larger populations or different circumstances	Investigates and develops complex relationships between variables and try to propose a new model/theory

Empirical experimental research tries to study relationships between variables by 'manipulating controlled treatments to determine the exact effect on specific dependent variables' (Yin, 2003). This research method mainly targets on capturing the causality between variables, and it is also known as 'field experiments' (Bertrand & Fransoo, 2002; J. Meredith, 2002). However, this research method is rarely used in our research since it has strict requirement on the case environment that it shall eliminate contamination effects (J. R. Meredith et al., 1989). As we all know, unusually, the 3DP adoption system is an open system, and it does not seem possible to place controls in some specific experiments to assess if one change could cause a particular result. For instance, measurements of production line performance might be different for different product production lines.

The second sub-category of research method is empirical statistical research, and this research method aims to empirically validate the propsoed theoretical relationships or models in larger size samples from actual business cases or in another circumstances. Therefore, the researchers would prefer this research method if the research issues are complex. An example could be Liu et al. (2014). They use empirical statistical research to evaluates the impact of AM in the aircraft spare parts industry (including conventional supply chain, a centralized AM supply chain, and a distributed AM supply chain). Generally, this research method uses interviews (structured/unstructured) or surveys to collect primary data or directly uses company's historical secondary data/information for statistical analyzes. Each of these research methodologies tends to statistically analyze the data collected from relevantly large size external samples. Thus, the empirical statistical research methodology offers empirical support for developing and testing the theoretical relationships between variables in large samples or different empirical cases (Meredith et al., 1989).

The last sub-category is the empirical case study which initially tries to explore and investigate insightful relationships within a limited size of empirical cases. Because the number of the test empirical case is limited, researchers can use this method to identify new empirical relationships by using a large number of different variables. In general, empirical case study is an appropriate research method for analyzing organization performance across time and offers new dynamic dimension to the development of relevant theory. It includes field research and action research (Walker, Chicksand, Radnor, & Watson, 2015; Zanardini, Bacchetti, Zanoni, & Ashourpour, 2016). A typical example of the empirical case study is Mohammed et al. (2018). In this study, the authors observe a patient's process of using 3DP technology to create prosthesis and then try to identify the best manufacturing strategy procedures of manufacture and purchase this kind of product.

3.2.3 Axiomatic Research

Last, axiomatic research is a model-driven method (Stigum, 1990) using mathematical models and 'abstract' data (i.e., assumptions or manipulated data rather than empirically observed data) to improve existing knowledge or try to find out an optimal solution for the defined problems (Swamidass, 1986; Swamidass & Waller, 1990; Wacker, 2002). Thus, it is different from an empirical study in that it uses deductive methods to arrive at theories (Croom, 2009). The most commonly used methods are analytical modelling and simulation (Wacker, 2002).

Analytical modelling is different from an empirical study because it uses deductive methods to arrive at theories (Swamidass, 1986; Swamidass & Waller, 1990; Wacker, 2002). The most commonly used methods are logical, mathematical, and/or mathematical-statistical tools, as shown in Table 3-4.

Table 3-4 Differences and Similarities between the Analytical Research Sub-Categories (Wacker, 2002)

	Conceptual	Mathematical	Statistical
Definition Development	Conceptual definitions or new definitions	Conceptual definitions from the relevant literature	Conceptual definitions from the relevant literature
Model Creation	Logically developed model	Mathematically developed model without stochastic error terms	Create mathematical statistical models based on the other relevant studies; limited error terms
Theory Predictions	Based on logical analysis; uses empirical evidence from case studies	Mathematically deduced predictions; predictions based on mathematical calculations or simulated results	Mathematically and logically derived predictions from the model and then use empirical evidence from other relevant case studies
Contributions	Develops new logical relationships for conceptual models	Investigate the mathematical conditions and explore the proposed theoretical relations	Integrate the other methods to assess a single empirical theory

First, analytical conceptual research attempts to provide new insightful findings to traditional research issue through developing a logical relationship model. In detail, it comprises new insights which derived from the process of logically developing relationships between the focused concepts and then systematically builds up an 'internally consistent theory' accordingly (Arns, Fischer, Kemper, & Tepper, 2002). Usually, it uses case studies to illustrate the researchers' conceptualizations. For example, the researcher might use his/her own experience to formulate concepts and describe and explain relationships from experiences to develop theory – we call this introspective research. Gutowski et al. (2009) adopt this research method in their study, and they use their previous experience in thermodynamics to help them form the framework to characterize and analyze the material and energy resources in the supply chain process. Another example is conceptual modelling. In the case, firstly, researcher usually posits a deduced relationship mental model. Next, this research methodology uses a framework to capture the essence of the system for investigation. A typical example for this research is Muir & Haddud (2018). They first set up the research framework to build up the internal relationship between the 3DP product and the consumer's willingness to pay, and then they use questionnaire to collect data to test their assumed framework. The last example is hermeneutics analytical conceptual research which infers facts from observation (Maskell, Heath, & Walker, 2014).

The second sub-category is analytical mathematical research which focuses on identifying and developing sophisticated relationships between narrowly defined concepts through a new mathematical model, and also studying how the model's behaviour under different conditions and scenarios. The analytical mathematical models are usually built on formal or pre-tested logic and tested by artificially generated data (Croom, Romano, & Giannakis, 2000). The research in this sub-category usually translates the relationships in to mathematical models and gives derivatively or computably numerical examples. Thus, analytical mathematical research does not need any external data for theory testing; it normally uses deterministic or simulated data instead. It includes reason/logical deductive theorem proving, normative analytical modelling, prototyping and physical modelling research, experimentation and simulation (Luczun, 1989; Mula, Peidro, Díaz-Madroñero, & Vicens, 2010; Voudouris & Consulting, 2003). Ruffo et al., (2006, 2007) use this research method to compare the 3DP production with the traditional manufacturing production, which helps them to easily conduct a serial of comparisons among all the involved cost elements for analysis.

The last sub-category is analytical statistical research, which integrates analytical mathematical research and empirical statistical research into a single combined theory (Moorthy, 2006). It is different from the mathematical method, because its explicated models are built for future empirical studies. Meanwhile, because it uses external data, the random variability of those data might bring the measurement errors to the relationship investigations for the considered variables. Thus, this research method serves larger and more integrated models studies (Wacker, 2002). In Dong et al. (2017)'s study, they develop analytical mathematical research to compare the performance of different assortment and capacity decisions. While, in (Song & Zhang, 2018)'s research, they use this research method to analyze the impact of 3DP adoption on the logistical cost and product variety.

In summary, analytical modelling has been widely applied in most of the initial research in operations. It normally is regarded as typical operational research method, and it is also the basis of initial management consulting and operations research. Initially, analytical modelling was used to solve real-life problems in management and operations research rather than develop scientific knowledge. Later, from the 1960s to the 1990s, analytical modelling focused on more idealized problems. Therefore, it is in line with a more theoretical research stream and departs from an empirically-orientated research stream. After that, analytical modelling shifted in its research direction to explanatory and predictive theory development (Arns et al., 2002; Bertrand & Fransoo, 2002; Gross, Erkal, Lockwood, Chen, & Spence, 2014).

Simulation is labeled as one of the most popular research methods for analyzing complex and dynamic processes and systems by academic researchers (Axelrod, 1997). It offers possibilities to the researchers to study an actual case/system and then predict its future performance under foresighted artificial scenarios (Vorst, Beulens, & Beek, 2000). Simulation could be built up on the assumed inherent complexity of a given research issue. Therefore, simulation is the most appropriate research method if the researchers intend to investigate the different system behaviour under different fabricated scenarios. Meanwhile, simulation also offers the channel to the researchers if they concentrate on research issues by looking backword across history and then exploring the 'moving forward' research issues (Dooley, 2002). In detail, the purposes of using simulation as research method could be categorized into: system performance analysis, system future trends prediction, academic theory exploration and proof, business case study, even entertainment (Axelrod 1997). By composing a model with structure and rules, simulation modelling tries to compare different system outputs which derived from different system settings (e.g. different structure and rules). Based on those output comparisons, researchers can deduce what might happen in the reality if they change one small element or rule. For example, some simulation studies tends to explore the most cost-less and efficient scheduling of logistic delivery, assembly shops, and production flow lines combinations (Deal, 2012). Meanwhile, when it is costly or impossible to conduct experimentation on the actual system, simulation is a substitute method (Axelrod, 1997). Therefore, we do usually find out that simulation is widely used by the business companies as a decision-aid on investment analysis, business performance diagnosis, and business strategy decision-making assessment. Simulation could be used to mimic all the uncertainty and randomness of the project into the model for exploring, which, in turn, may reduce the risk of investment to the company.

There are several advantages of using simulation as the research method. First of all, simulation allows the researchers to understand a system or an issue by simulating the system behaviours, interactions and potential conflicts. Second, the simulation provides the accesses to the researchers to define the correctness and improvement of a system design; therefore, the researchers could imitate the different strategy choices in a convenient and safe way. Moreover, simulation can also provide the practical feedback of any system changes. This helps researchers to gain further understanding of the system. Last but not least, simulation can also be used to explore the possibilities of certain potential solutions of a particular issue and even conduct comparisons among them. Despite some advantages of simulation outlined above , simulation, like other research methods, does have defects. For example, simulation cannot fully well fit into a specific dynamic system, and it is difficult for the simulation to capture and simulate all those unexpected and/or new raised issues which might occur in reality.

3.3 Game Theory

Game theory has been widely used as a mathematical and logical tool for analyzing situations involving conflict and cooperation. Since the game theory developed by (von Neumann & Morgenstern, 1944), it has been widely applied in diverse research domain, such as politics, sports, business, management, and auctions, etc. (Bräuer & Buscher, 2018; H. Huang, He, &

Chen, 2018; Muggy & Heier Stamm, 2014; Xiao & Yang, 2008). Based on those new applications, game theory has enjoyed a significant development, including the non-cooperative static games and dynamic games (Nash, 1949), and cooperative games (Aumann, 1959) etc.

This research is designed for the supply chain management research on the competition game between the logistics vendor's 3DP product and the traditional manufacturer's product. After reviewing the relevant paper on this topic, we find out that although there are many game theories, Nash equilibrium, Bertrand and Cournot equilibrium, and Stackelberg equilibrium are the most used game theories to discuss two-player competitions (Cachon & Netessine, 2004; Leng & Parlar, 2005; J. Li, Wang, & Cheng, 2010; Taleizadeh, Noori-Daryan, & Tavakkoli-Moghaddam, 2015; Taylor, Kwasnica, Reilly, & Ravindran, 2019; Xiao & Yang, 2008). Thus, in following sub-sections, we focus on the introduction of these three game theory concepts.

3.3.1 Nash equilibrium

In a supply chain system, when each players would choose a feasible strategy to maximize value (called best response function), 'an outcome appears as the specific payoffs to all players'(Leng & Parlar, 2005). Here, if the players could choose their strategies at the same time, a Nash equilibrium applies (Nash, 1949). Nash equilibrium is also applicable when the players cannot communicate (Shubik, 1985). Consider a two-palyer game where Player 1 and Player 2 attempts to maximize their respective objective function $f_1(x_1, x_2)$ and $f_2(x_1, x_2)$, $x_1 \in X_1$ and $x_2 \in X_2$. Under the Nash equilibrium, the player 1 and player 2's strategies (x_1^N, x_2^N) are satisfied:

$$f_1(x_1^N, x_2^N) \geq f_1(x_1, x_2^N) \; and \; f_2(x_1^N, x_2^N) \geq f_2(x_1^N, x_2)$$

Where, $x_1^N = \max_{x_1 \in X_1} f_1(x_1, x_2^N)$ and $x_2^N = \max_{x_2 \in X_2} f_2(x_1^N, x_2)$ (Nash, 1949).

Thus, when $x_1 = x_1^N$ and $x_2 = x_2^N$, the players' strategy must satisfy,

$$\frac{\partial f_1(x_1, x_2^N)}{\partial x_1} = 0 \; and \; \frac{\partial f_2(x_1^N, x_2)}{\partial x_2} = 0$$

Nash equilibrium is a 'self-fulfilling prophecy' (Cachon & Netessine, 2004). In detail, a player tries to guess another player's strategy with payoff maximization. The best scenario is that strategies can be used to maximize every single player's payoff. If the such Nash equilibrium does not exist, at least one player has to choose non-payoff maximizing strategy (Nash, 1949).

3.3.2 Cournot Competition and Bertrand Competition

Cournot and Bertrand competition models are usually used to simulate and analyze the homogenous product competition under the Nash equilibrium, where the players set up their strategy in production quantity or product price simultaneously (Sulber, 1995; Wambach, 1999). In detail, the Cournot game assumes that each players in the game decide the his/her production quantities, taking as given quantity to the competitors (Cournot, 1897). The resulting equilibrium is a Nash equilibrium in product quantity and the resulting price is the competitive price which is above the marginal cost (Sulber, 1995). Thus, take the two players competition game as example, under the Cournot competition, q_1 and q_2 denote the production quantities chosen by the player 1 and player 2, the players' strategy shall satisfy,

$$\frac{\partial f_1(q_1, q_2^C)}{\partial q_1} = 0 \; and \; \frac{\partial f_2(q_1^C, q_2)}{\partial q_2} = 0$$

However, the Bertreand game assumes that each players sets up his/her product price first and the resulting equilibrium is a Nash equilibrium in product price (Walras, 1883). Here, the price equals to the marginal cost (Cachon & Netessine, 2004). So, under the Bertrand competition, p_1 and p_2 denote the product price chosen by the player 1 and player 2, when $p_1 = p_1^B$ and $p_2 = p_2^B$, the players' strategy shall satisfy,

$$\frac{\partial f_1(p_1, p_2^B)}{\partial p_1} = 0 \; and \; \frac{\partial f_2(p_1^B, p_2)}{\partial p_2} = 0$$

3.3.3 Stackelberg Equilibrium

Stackelberg is a duopoly model for the competition analysis in a leader-follower environment, the player who has more power over the downstream players in the system and then chooses the strategy before others, a Stackelberg equilibrium applies (von Stackelberg, 1935). For example, if a company can launch a product with new functions before the other competitors, we assume that company has the market leader position. Therefore, 1) the leading company sets the marketing strategy first; 2) then the followers chooses their best response to the leading company's strategy; 3) in return, the leading company optimizes his/her objective functions (e.g. profit). Take a two-player game as an example again, Player 1 is the leader and Player 2 is the follower. Their objective functions are $f_1(x_1, x_2)$ and $f_2(x_1, x_2)$. First, Player 1 choose a strategy x_1; then Player 2 tries his/her best response function to determine the response $x_2^R(x_1)$; last, Player 1 optimizes his/her objective function $f_1(x_1, x_2)$ with the constraint $x_2 = x_2^R(x_1)$, that is,

$$f_1(x_1^S, x_2) \geq f_1(x_1, x_2)$$

In other word, the follower's strategy must satisfy $x_2^R(x_1)$: $\frac{f_2(x_1,x_2)}{\partial x_2} = 0$, and then the leader's strategy could be determined by

$$\frac{df_1(x_1, x_2^R(x_1))}{dx_1} = \frac{\partial f_1(x_1, x_2^R(x_1))}{\partial x_1} + \frac{\partial f_1(x_1, x_2)}{\partial x_2}\frac{\partial x_2^R(x_1)}{\partial x_1} = 0$$

So, under this game, the leading player can always can have Nash equilibrium with a better payoff.

3.3.4 Game Theoretical Applications in Product Competition Research

As mentioned in the front of this subsection, the emphasis on market competition and cooperation in supply chains make game theories become a primary tool for analyze the interactions among the decision makers (Cachon & Netessine, 2004). The Cournot, Bertrand, and Stackelberg games discussed above are the most applicable and efficient approaches used to model the defined problems in the supply chains in terms of obtaining the optimal strategies under a non-cooperative game scenario (Leng & Parlar, 2005). The game theoretical applications in product competition research include inventory management (Parlar, 1988; Xiao & Yang, 2008), production and pricing competition (Song & Zhang, 2018), product/service quality management (Cohen & Whang, 1997), advertising problem (Z. Huang, Li, & Mahajan, 2002), and new product introduction strategy (Dong et al., 2017). In supply chain management problems involving competition arise in either horizontal (e.g. duopoly channel for two players channel) or vertical channels (Leng & Parlar, 2005).

In an early work conducted by Parlar (1988), he used the Cournot game theory to develop a model to simulate and analyze the market competition between two retailers. In his model, he found out the Nash equilibrium and suggested that cooperation between these two retailers can share more profit together (Cohen & Whang, 1997) applied Stackelberg game theory for product life cycle analysis in the vertical competition between the manufacturer and independent service operator. Later, both Z. Huang et al. (2002) and Xiao & Yang (2008) use Stackelberg game theory to analyze the co-op advertising game in a two-layer (one manufacturer and multiple retailers) and the inventory management problem in a three-layer (a distributor, a manufacturer, and a retailer). Recently, Dong et al. (2017) considered a Cournot game for making the production strategies of two different flexible manufacturing technology. While, Song & Zhang (2018) also used Cournot game theory to develop a mathematical model to discuss the problems in product purchasing and delivery.

In summary, under a non-cooperative game scenario, the Cournat game and Bertrand game could be used to simulate and analyze the product competition in horizontal channels, because both game theory have constraints on ‘make the strategy at the same time’. However, when one player has certain more market power over the other the players or the players have upstream and downstream relationship (vertical channel, duopoly channel), Stackelberg game the most suitable game theory for competition and cooperation analysis.

3.4 Research Method Selection

In the afore-listed sections, both research methods and game theories have been reviewed and discussed. For the selection of the most suitable research methods for this research, there were four stages in the research method selection process (Figure 3-1). Firstly, the research background, research objectives, and research questions were assessed and conceptualized. Secondly, research gaps in the literature were identified. Thirdly, the research method was selected according to the specialties of the 3DP technolgy adoption status. Fourthly, the most appropriate game theories were selected. Lastly, the research was planned and executed.

Based on our introduction in Chapter 1 and literature review in Chapter 2, we have identified three different research topics:

- the impact of 3DP adoption by the logistics vendor;
- the possibilities of the traditional manufacturer's 3DP adoption strategy; and
- the logistics vendor's 3DP engagement plan.

These objectives aim to explore the management strategy for 3DP adoption and compare the predicted 3DP adoption strategies. Although the advantages of 3DP can immensely benefit supply chain development, the use of 3DP is not industrialized yet. Therefore, it is difficult to carry out qualitative research for this thesis if we aim to produce a forecast for a future business model or analyze a new business strategy. This leaves us to choose quantitative modelling research. Quantitative modelling can be used to obtain solutions within a structured model and derive management insight from a defined model. Based on some assumptions, it also produces knowledge about the behaviour of the specific variables in the models. In addition, quantitative modelling can also use other mathematic, statistic, or computerized tools (e.g. system optimization or queuing theory) to get an understanding about 1) how to manipulate certain variables in the model and 2) what are the behaviour of the target variables in the model (Bertrand & Fransoo, 2002).

Furthermore, at this stage, an empirical study is not an appropriate approach for our 3DP adoption research here, because we aim to derive a new 3DP adoption strategy and its relevant impacts on supply chain management. Therefore, this thesis uses the analytical mathematical modelling method. This method can help us to simulate and predict the system behaviour and test the variables accordingly. However, empirical and simulation research both rely on the actual case information and data. Empirical study research aims to develop a model based on the observations in reality. In addition, simulation research is used in cases where the model or the research question is too complicated for formal mathematical analysis (e.g., wider variety). This thesis not only seeks to adequately describe the causal relationships associated with 3DP adoption and improve the current 3DP adoption strategy but also to investigate possible 3DP adoption strategies and test the effects of relevant variables. Therefore, analytical modelling is the selected research method for this thesis.

In this research, we focus on analysis of the situations in which the strategies of two players (the traditional manufacturer and the logistics vendor) affect each agent's payoff. In each model, we discuss the non-cooperative and cooperative relationship between the two players -- the traditional manufacturer and the logistics vendor. Thus, under the non-cooperative situation, depending on the channel power of the traditional manufacturer's and/or the logistics vendor's in the market, they could choose the strategies (set up the product price in this research) by different order. When they share the same channel power, they might choose the a feasible strategy simultaneously, we use Bertrand equilibrium for this scenario. In addition, as the 3DP product is produce-by-demand, Cournot equilibrium is not suitable to use here. When the traditional manufacturer is still the market leader and the logistics vendor is the follower in the product market, the strategy for each player can be determined by the Stackelberg solution.

According to the standard research procedure developed by Mitroff, Betz, Pondy, & Sagasti (1974) (Figure 3-3), the basic research approaches are 1) Reality, Problem, Situation, 2) Conceptual Model, 3) Scientific Model, and 4) Solution. Meanwhile, the general steps between them are:

1) Conceptualization;

2) Modelling;

3) Model solving; and

4) Implementation.

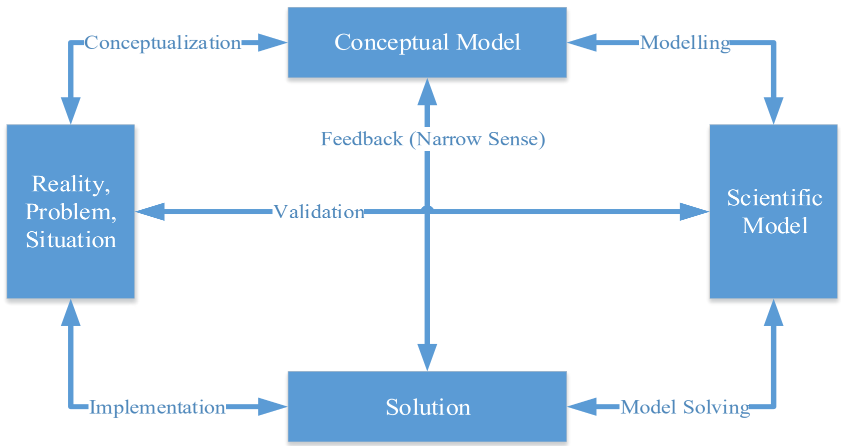


Figure 3-3 Modelling Approaches (Mitroff et al., 2008)

The first step is conceptualization; based on the relevant cases, we made a conceptual model of the systems which we select to study. Then, according to the study of the related literature and industry reports, we made decisions about which variables needed to be included and considered in the model, and what was the scope of the research and model to be addressed. Then, we built up the quantitative model and defined a causal relationship between the variables at step 2. The next step was model solving. Based on the selected game theory, we used mathematics to find out the optimal solution for the system and a system sensitive and comparative analysis was conducted. The last step was the implementation cycle; in this step, we summarized our proposed strategy for 3DP adoption and how a new research model might be built up based on the proposed model. Moreover, the feedback flow between the Conceptual Model and the Solution approach was used to improve the conceptual model and the solution, whilst the information about the 'Reality, Problem, Situation' was used to improve and validate our 'Scientific Model'.

In line with the research objectives of this thesis, the modelling steps for each research objective were mapped onto five steps for the modelling part:

1) Conceptual model of the research problem;
2) Mathematical model of the research problem;
3) Solution;
4) Proof of the solution (sensitive and comparative); and
5) Managerial insights.

Below further details of the research procedure are provided for Stage 4 (Figure 3-4).

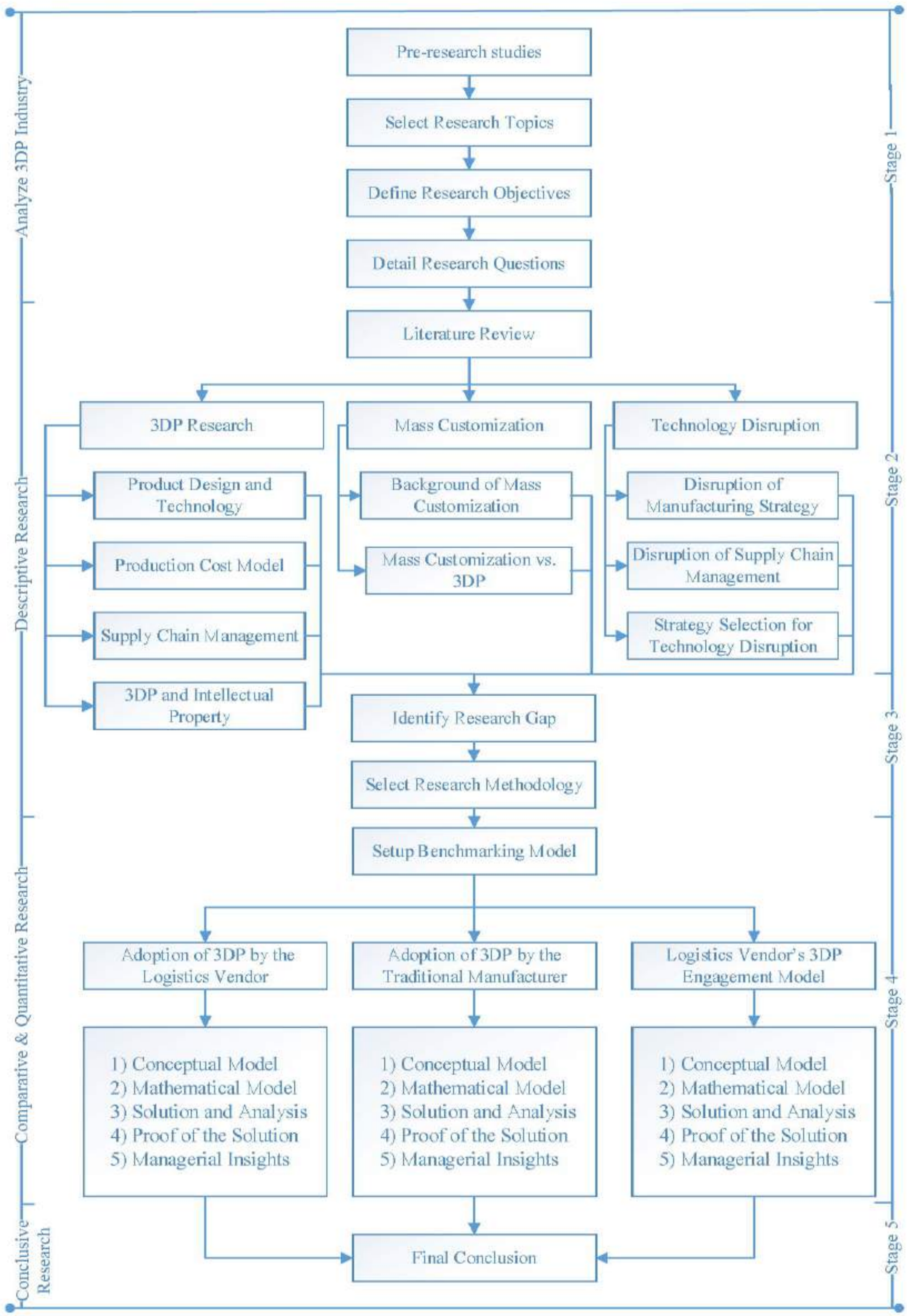


Figure 3-4 Detailed Research Procedure

3.5 Chapter Summary

This chapter has focused on selecting the most adequate methodology for this research. Both qualitative and quantitative methodologies have been systematically reviewed and discussed for selecting the suitable research methodologies for the research objectives and research questions. More specifically, this chapter has concentrated on the importance of the research methodology selection and design for this research. The research methodology selection is considered to be appropriate for this study; analytical mathematical modelling is selected to provide understanding of the impacts of 3DP adoption on the supply chain. More precisely, this research uses mathematical modelling to find an optimal solution for different 3DP adoption strategies. In addition, by comparing these different 3DP adoption strategies, this research seeks to identify what kind of strategy, actions, and policies should be implemented to improve supply chain performance.

The following chapters present three different models which address objectives 1 - 3 in this research:

- a model for investigating the impact of 3DP adoption by the logistics vendor;
- a model to explore the possibilities of the traditional manufacturer's 3DP adoption strategy; and
- a model for evaluating the logistics vendor's 3DP engagement plan.

Chapter 4 Adoption of 3DP by the Logistics Vendor

This chapter proposes a model for studying the impact of 3DP adoption on a supply chain by a logistics vendor. Specifically, this model considers a two-layer supply chain with one logistics vendor and a traditional manufacturer. Here, the logistics vendor, the goods delivery provider of the TM product, who simultaneously sells a 3DP product with a high level of customization to compete with the traditional manufacturer. By comparing the TM system and the new 3DP manufacturing system, this model finds that the logistics vendor can benefit from 3DP adoption to better restructure the supply chain. At the same time, there exists a situation in which the traditional manufacturer also benefits from this kind of 3DP adoption. This model then identifies the conditions under which the logistics vendor can use this 3DP adoption as a threat to influence the traditional manufacturer's decisions to gain financial benefits. After that, an analysis of the impact of this 3DP adoption on consumer surplus is presented together with additional insights on how both the manufacturer and the logistics vendor can better manage this 3DP adoption to maximize cost reduction and product customization level selection. Interestingly, the comparisons show that cost reductions and improvements in customization options for the 3DP product do not always contribute to better financial performance or higher consumer satisfaction.

The remainder of this chapter is organized as follows: Section 4.1 presents the introduction; Section 4.2 describes the problem and develops the model; Section 4.3 analyzes the model with regard to the impact of 3DP on supply chain members' optimal business decisions; After that how the logistics vendor can use 3DP adoption as a threat to influence the manufacturer's decisions and the actual impact of 3DP on consumer surplus is presented in Section 4.4; Section 4.5 concludes by discussing the practical implications of the findings. For readability, all the proofs are listed at Appendix A.

4.1 Introduction

According to the report issued by Wohlers Associates (2018), the 3DP industry has continued to grow with an average annual growth rate of 26.6% over the past 29 years and its revenue for 2017 was $6.063 billion, having grown 21% since 2016. 3DP is making significant progress towards becoming a mainstream option for series production. Without the requirement for tools (e.g. moulds and dies), 3DP is capable of producing items with complex shapes and geometric features in small batch sizes. It allows production of highly customized and complex features, as well as the consolidation of many parts into one. Moreover, of the 1,500 buyers surveyed by UPS, 42% would like to switch to a supplier with 3DP service in the next 3-5 years (UPS, 2017). As a result, companies become increasingly aware that TM technologies may be replaced by 3DP, and leading companies that have begun leveraging this potentially disruptive manufacturing technology are eager to be the first movers to switch their manufacturing mode to 3DP.

3DP technology has been adopted in a variety of industrial sectors, including aerospace, automation, medical supplies, as well as in production of some consumer goods, such as the personalized running shoes pioneered by Adidas AG and Nike Inc., the personalized headphones manufactured by Normal Earphones, and the customized chocolates produced by Hershey (DHL, 2016; Sher & Tutó, 2015). Even some logistics vendors among these companies are adopting this technology. For example, the global logistics vendor UPS launched 3DP service for small plastic products in the U.S. market in early 2014 and extended this business to the Asian and European markets in 2017 (UPS, 2014, 2017). Meanwhile, as we discussed in the Literature Review chapter, 3DP technology also potentially reduces product shipment needs, and this puts pressure on the logistics industry. Therefore, the new

3DP adoption by the logistics vendor (like UPS) puts the logistics industry in the centre of the ring.

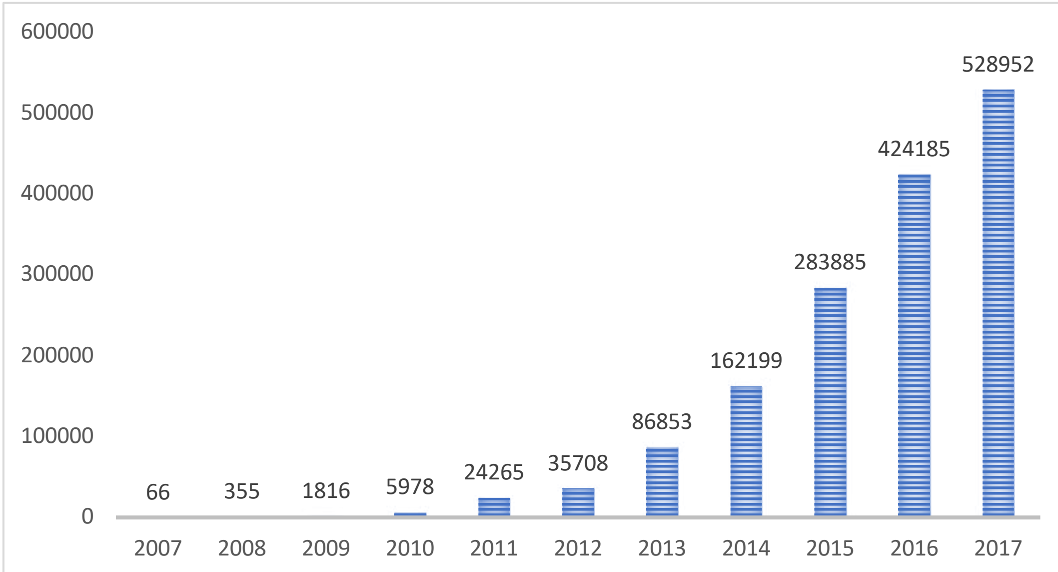


Figure 4-1 Number of Desktop 3D Printer Sales (Wohlers Associates, 2018)

The logistics vendor is both referee and corner. On the one hand, the market demand for desktop 3D printers is continually growing at a strong rate (Figure 4-1). In 2017, unit sales of desktop 3D printers (priced lower than $5, 000) increased by 24.7% to 528,952 machines and the average unit sales over the past 3 years has increased by 49.7%. The non-industrial and decentralized market demand for 3DP has dramatically increased, which offers a great opportunity for logistics vendors to use their built-in logistics networks to centralize these 3DP commercial market demands and create a new revenue stream just like UPS did. More importantly, this kind of 3DP service based on the delivery network of logistics vendors can improve the customization and flexibility of the product (UPS, 2016). Logistics vendors will compete with traditional manufacturers in the market, as 3DP adoption equips them with a powerful bargaining tool to strengthen their logistics business. However, the adoption of 3DP also poses many challenges in the management of supply chains and raises several unanswered question *'what are the impacts of a logistics vendor's 3DP adoption on the supply chain?'* and the sub-questions as below.

Q1.1. Under what conditions will a logistics vendor use 3DP as a game-changer to compete directly with the manufacturer?

Q1.2. Under what conditions will a logistics vendor use 3DP as a threat to bargain with the manufacturer?

Q1.3. What is the impact of a logistics vendor's 3DP adoption on the consumer?

The primary goals of this model are (i) to develop a stylized model to investigate the supply chain following a logistics vendor's adoption of 3DP – one that explicitly models product customization; and (ii) to explore the impact of the logistics vendor's use of 3DP on the supply chain. The supply chain we consider comprises a single manufacturer who provides a TM product directly to the end consumers and a logistics vendor who handles all associated delivery services. At the same time, however, because of 3DP adoption, the logistics vendor can also provide the end consumers with a 3DP product having the same function but a higher level of customization. In this scenario, both the traditional manufacturer and the logistics vendor need to determine the prices of their products (traditional product, logistics service, and 3DP product) to maximize their overall profits. This model simulates the problem using both a Bertrand and a Stackelberg game so as to cover different market powers. Although in practice the traditional manufacturer is usually the leading company with more bargaining power, the increasing importance of the customization provided by 3DP technology could give the logistics vendor equal or more bargaining power than the traditional manufacturer.

This model makes four major contributions to the literature: it develops a stylized model that incorporates adoption of 3DP technology by the logistics vendor, identifies the conditions under which the logistics vendor will use 3DP as a game-changer or threat, and analyzes the impact of this adoption on both supply chain partners and consumers. It also generates several managerial insights, including the observation that although the logistics vendor can always benefit from game changing 3DP adoption, the cost reduction on 3DP products cannot always contribute to the logistics vendor's overall revenue because a portion of his/her revenue still derives from shipping the TM product for the manufacturer. In fact, even though the logistics vendor can increase profits by using 3DP adoption as a threat to influence the traditional manufacturer's business, a supply chain structure is possible in which the logistics vendor's 3DP adoption helps the traditional manufacturer gain greater profits. The results of this model also demonstrate that the dictum that high customization and low-price lead to more consumers does not always hold true.

4.2 Problem Description

This section introduces the consumer choice, channel pricing decisions, as well as the notation, for the benchmarking model when a TM product is sold by the traditional manufacturer, and the 3DP model when a TM product is sold by the traditional manufacturer and a 3DP product is sold by the logistics vendor simultaneously (Figure 4-2). The interactions between the traditional manufacturer and the logistics vendor are modeled using the classical Bertrand and Stackelberg game theory.

4.2.1 Traditional Manufacturing System – Benchmarking Model

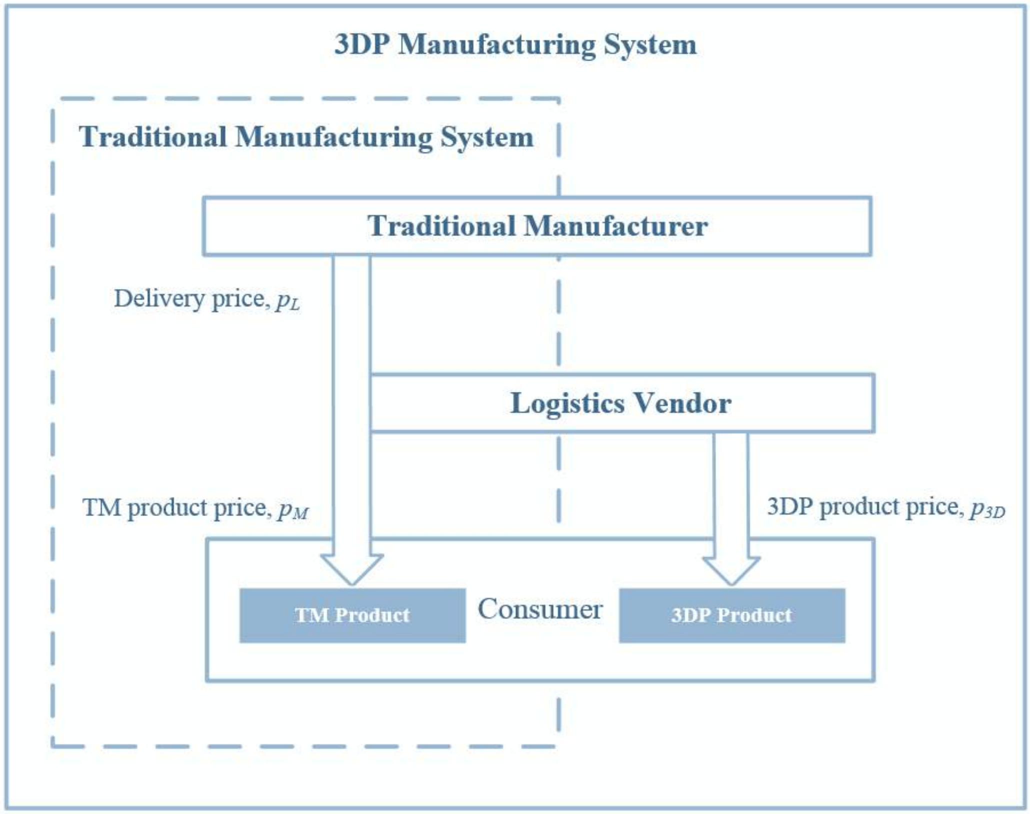


Figure 4-2 Model Structure

As our benchmark, this model simulates a TM system in which one manufacturer provides TM products to the consumer and one logistics vendor takes responsibility for product delivery (Figure 4-2). It thus begins as a typical supply chain in which the manufacturer sells products directly to the consumer. Following Agrawal *et al.* (2012) and Ferguson and Toktay (2006), for analytic simplicity, this model assumes that consumers are heterogeneous in the valuation of the product and the willingness-to-pay (or consumption value) is v and uniformly distributed within the market size (or consumer population) from 0 to 1, with a density of 1 (Figure 4-3). Because the product customization level of the TM product is lower than that of the 3DP product (Baumers et al., 2016; Gibson et al., 2015), the consumer values the former less, designated by αv, where the value of parameter α is the consumer's value discount for the customization level of the product. For simplicity, the product customization level of the 3DP product has been set to 1 and the product customization level is developed with $0 < \alpha < 1$.

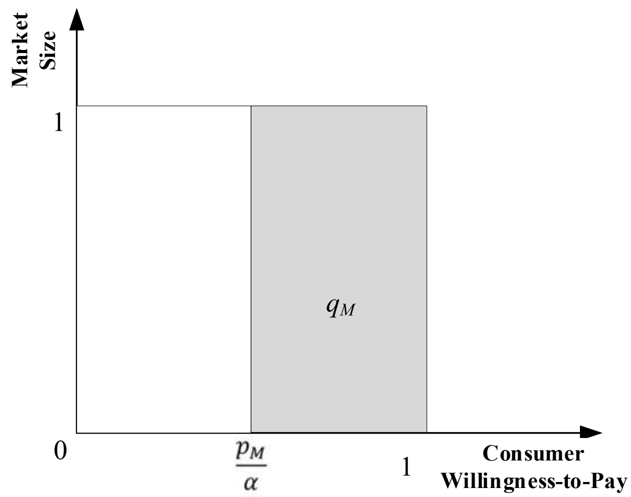


Figure 4-3 Distribution of Willingness-to-Pay

Given the assumptions and the definitions in Table 4-1, therefore, in the Benchmarking model, the traditional manufacturer offers the TM product with production customization level α at price p_M. Then, a consumer with valuation αv would derive a net consumer surplus of $\alpha v - p_M$ by buying the TM product. This model also assumes that the TM product is not available for sale elsewhere, so when willingness-to-pay satisfies $U_M = \alpha v - p_M \geq 0$, the consumer will buy the TM product. Therefore, all consumers with willingness-to-pay in the interval $\left[\frac{p_M}{\alpha}, 1\right]$ buy the TM product. In summary, consumer demand for the TM product in the Traditional Manufacturing system is $q_M = 1 - \frac{p_M}{\alpha}$, for $0 \leq p_M \leq 1$. Meanwhile, the logistics vendor provides all the relevant delivery services for the TM product at price p_L.

Table 4-1 Definitions of Parameters

Parameter	Definition
α	Consumer value discount for the TM product customization level, $0 < \alpha < 1$.
p_i	$i \in \{M, 3D, L\}$, the unit selling price for a TM product or a 3DP product, and the price charged by the logistics vendor to deliver a TM product for the traditional manufacturer, $0 < p_i < 1$.
c_i	$i \in \{M, 3D, L\}$, the unit manufacturing cost for a TM or a 3DP product, and the associated unit cost for the logistics vendor to deliver a TM product, $0 < c_i < 1$.
q_i	$i \in \{M, 3D\}$, the sales quantity for the TM and 3DP products, $0 < q_i < 1$.
$\prod i$	$i \in \{M, L\}$, the manufacturer's or the logistics vendor's profit, $\prod_i \geq 0$.

To simplify the analysis without loss of generalizability (Mussa & Rosen, 1978), we consider two kinds of cost in the TM system: TM production cost and logistics delivery cost, meaning that the profit for each can be expressed as

$$\prod\nolimits_{3DN} M(p_M) = (p_M - c_M - p_L)q_M = (p_M - c_M - p_L)\left(1 - \frac{p_M}{\alpha}\right) \tag{4.1}$$

$$\prod\nolimits_{3DN} L(p_L) = (p_L - c_L)q_M = (p_L - c_L)\left(1 - \frac{p_M}{\alpha}\right) \tag{4.2}$$

where $p_M - c_M - p_L > 0$ and $p_L - c_L > 0$ respectively, to ensure that both parties obtain positive margins.

The logistics vendor sets its delivery price first (e.g. fixed delivery charges by parcel size, weight, and requirements for delivery time), after which the traditional manufacturer prices the TM product. The traditional manufacturer sets the predetermined TM price and maximizes his/her profits given in Equation (4.1) with the consideration of the delivery price. The logistics vendor gives his/her response from the traditional manufacturer's pricing strategy and maximizes the logistics profits given in Equation (4.2). Thus, each firm tries to get the maximized profit independently.

PROPOSITION *4-1.* *In the traditional manufacturing system, under Nash-equilibrium, the maximum profit for the traditional manufacturer is* $\prod_{3DN}^{*} M(p_M) = \frac{(-\alpha+c_L+c_M)^2}{16\alpha}$ *and the maximum profit for the logistics vendor is* $\prod_{3DN}^{*} L(p_L) = \frac{(-\alpha+c_L+c_M)^2}{8\alpha}$ *and the maximum profit for the supply chain is* $\prod_{3DN}^{*} TMS(p_M, p_L) = \frac{3(-\alpha+c_L+c_M)^2}{16\alpha}$ *. These profits are maximized by* $p_M^* = \frac{1}{4}(3\alpha + c_L + c_M)$*,* $p_L^* = \frac{1}{2}(\alpha + c_L - c_M)$ *and* $q_M^* = \frac{\alpha - c_L - c_M}{4\alpha}$.

Previous studies have discussed whether the higher price, sales volume and profits are lower than that of vertically integrated channels, also known as 'double marginalization' (Chiang, Chhajed, & Hess, 2003; Spengler, 2002). This model explores double marginalization by new disruptive technology – 3DP, which is different from the previous studies in this research domain (which focus on supply chain interaction and design, profit sharing, quantity discounts, promotions, etc.) (Chiang et al., 2003; Desiraju & Moorthy, 2008; Gerstner & Hess, 2008; Jeuland & Shugan, 2008; Lal, 2008).

Thus, in the 3DP manufacturing system, if the two firms are vertically integrated, the profit of the supply chain could be determined by

$$\prod_{3DN} TMS(p_M) = (p_M - c_M - c_L)q_M = (p_M - c_M - c_L)\left(1 - \frac{p_M}{\alpha}\right) \qquad (4.3)$$

where $p_M - c_M - c_L > 0$.

PROPOSITION ***4-2.*** *In the traditional manufacturing system, under Nash-equilibrium, the maximum profit for the supply chain is* $\prod_{3DN}^{*} TMS = \frac{(-\alpha+c_L+c_M)^2}{4\alpha}$*, which is maximized by* $p_M^* = \frac{1}{2}(\alpha + c_L + c_M)$ *and* $q_M^* = \frac{\alpha - c_L - c_M}{2\alpha}$.

This proposition gives the optimal decisions of the traditional manufacturing system.

4.2.2 3DP Manufacturing System

Before the complete analysis of this 3DP manufacturing system, the question of how to model consumer choice when there are two different product customization levels but the same product function needs to be discussed first. In the 3DP manufacturing system (Figure 4-2), the logistics vendor adopts 3DP and provides a customized 3DP product at price p_{3D} to the market, thereby competing with the traditional manufacturer's TM product. Therefore, the consumer receives utilities U_M ($U_M = \alpha v - p_M$) from the TM product and U_{3D} ($U_{3D} = v - p_{3D}$) from the 3DP product. A consumer buys a product if and only if the received unit utility is positive.

Market Demand in the 3DP Manufacturing System

If a new type of 3DP product is also sold in the market by the logistics vendor at price p_{3D}, then the consumer surplus for the 3DP product is $v - p_{3D}$. If consumers can buy either the TM product or the 3DP product, their decision depends on the comparison of the consumer surplus derived from the TM and 3DP product, $\alpha v - p_M$ versus $v - p_{3D}$. All consumers whose willingness-to-pay satisfies $\alpha v - p_M \geq 0$ would consider buying the TM product from the traditional manufacturer. The marginal consumer whose valuation v_M equals $\frac{p_M}{\alpha}$ is indifferent to buying from the traditional manufacturer and may not buy at all. Equivalently, consumers whose valuation meets $v - p_{3D} \geq 0$ would choose the 3DP product. The marginal consumer whose valuation v^{3D} equals p_{3D} is indifferent to buying the 3DP product. Lastly, if $\alpha v - p_M \geq v - p_{3D}$, then the consumer prefers to buy the TM product. The consumer whose valuation v^D equals $\frac{p_{3D}-p_M}{1-\alpha}$ is indifferent between the two products, and if the valuation greater than this value, the consumer switches and buys the 3DP product.

Therefore, in the case where $v^M < v^{3D}$, then $v^M < v^{3D} < v^D$. All the consumers with valuations in the interval $[v^D, 1]$ would like to buy the 3DP product, and all those in the interval $[v^M, v^D]$ would choose the TM product, and those consumers whose valuations are located in the interval $[0, v^M]$ leave the market. In the case where $v^M > v^{3D}$, no consumers want to buy the TM product and all consumers whose valuations locate in the interval $[v^{3D}, 1]$ buy the 3DP product.

Because the consumers' valuation is uniformly distributed, the TM and 3DP product demands correspond to pricewise-liner demand functions:

$$q_M = \begin{cases} \dfrac{\alpha p_{3D} - p_M}{(1-\alpha)\alpha} & \text{if } p_{3D} \geq \dfrac{p_M}{\alpha}, \\ 0 & p_{3D} < \dfrac{p_M}{\alpha}, \end{cases} \tag{4.4}$$

$$q_{3D} = \begin{cases} 1 - \dfrac{p_{3D} - p_M}{1-\alpha} & \text{if } p_{3D} \geq \dfrac{p_M}{\alpha}, \\ 1 - p_{3D} & p_{3D} < \dfrac{p_M}{\alpha}. \end{cases} \tag{4.5}$$

Figure 4-4 illustrates the demand functions of these two products. The 3DP product's price becomes more price elastic when the 3DP product is less than $\frac{p_M}{\alpha}$ as demonstrated in Figure 4-4(b), because the logistics vendor can lose consumers to the TM product delivery. The value of $\frac{p_M}{\alpha}$ corresponds to the broader price in the 3DP manufacturing system, which is also influenced by the product delivery price. If the price of the 3DP product is high, some price sensitive consumers will choose the TM product although they cannot enjoy some of the value associated with product customization $(1-\alpha)v$.

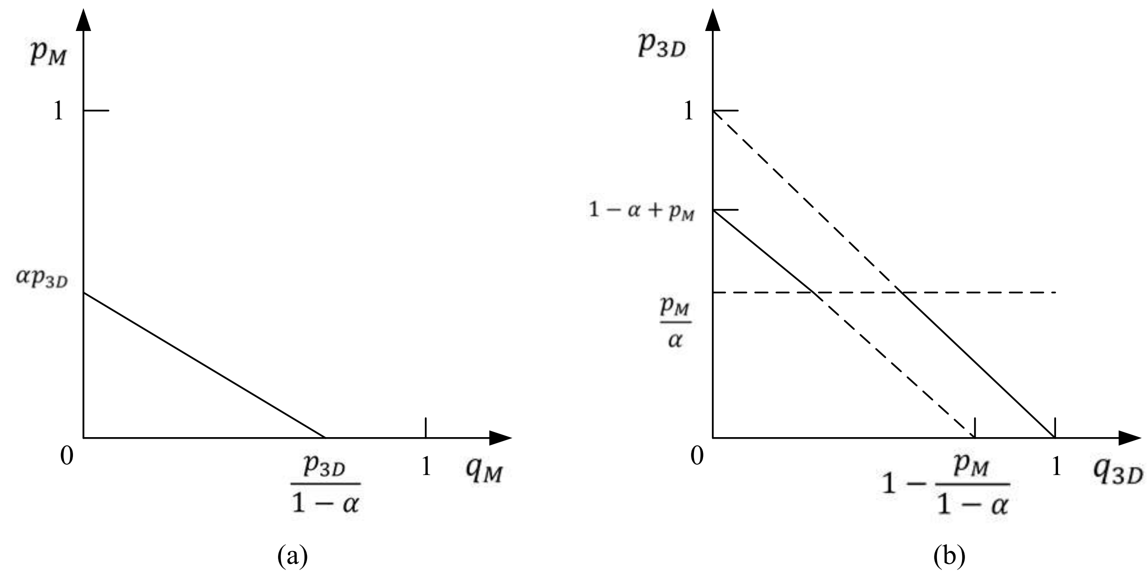


Figure 4-4 Demand Function of the TM and 3DP Product

Optimal Decisions in the 3DP Manufacturing System

In the new 3DP system (Figure 4-2), the logistics vendor adopts new 3DP technology and offers the 3DP product on the market. With the advantages of 3DP technology, this vendor can fully utilize its delivery capacities and integrate them with 3DP service. Because UPS delivery tracks are likely to be equipped with 3D printers in the near future (Grazia Speranza, 2018; Manners-Bell & Lyon, 2012; Wohlers Associates, 2018), this model assumes the delivery charge of a 3DP product to be zero. However, because in practice most manufacturers are still outsourcing their goods delivery process to third-party logistics vendors (Pooley, 2013), the manufacturer's and logistics vendor's profits could be formulated respectively:

$$\prod_{3D} M(p_M) = (p_M - c_M - p_L)q_M \tag{4.6}$$

$$\prod_{3D} L(p_{3D}, p_L) = (p_L - c_L)q_M + (p_{3D} - c_{3D})q_{3D} \tag{4.7}$$

Meanwhile, the profit for the vertically integrated supply chain is

$$\prod_{3D} SC(p_M, p_{3D}, p_L) = (p_M - c_M - c_L)q_M + (p_{3D} - c_{3D})q_{3D} \tag{4.8}$$

To ensure that both have non-negative margins, we again set $p_M > c_M + p_L$, $p_L - c_L > 0$ and $p_{3D} - c_{3D} > 0$.

Compared to the TM product, if the 3DP product shows significant advancements not only in the product customization level but also in the product price ($p_{3D} < \frac{p_M}{\alpha}$), then the consumers will choose to buy the 3DP product without any doubt. Because this model aims to determine whether adding a new 3DP business is a profitable new business strategy for the logistics vendor under a product competition and service cooperation environment, this scenario is excluded in this model.

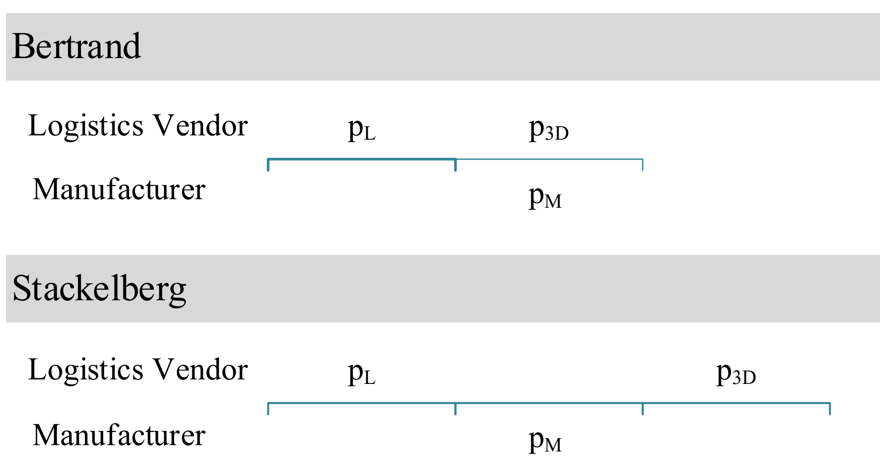


Figure 4-5 Pricing Sequence in the Bertrand and Stackelberg games

Therefore, if $p_{3D} \geq \frac{p_M}{\alpha}$, to model the different decision sequences in the new 3DP manufacturing system, there are two types of game to consider, the Bertrand (we use letter 'B' as the index for Bertrand game throughout the thesis) and the Stackelberg game (we use letter 'S' as the index for Stackelberg game throughout the thesis) (see Figure 4-5). The games have the following sequence of moves. As discussed above, the third-party logistics vendors usually have predefined standard delivery service charges for different weights, sizes, and delivery lead times. Therefore, in the first step, the logistics vendor always determines the logistics price p_L for the TM product – no matter the game.

In the Bertrand game, this model assumes the traditional manufacturer and logistics vendor have equal market bargaining power, so in step 2, they set up p_M and p_{3D} separately but simultaneously to maximize their own profit.

In the Stackelberg game, in contrast, the traditional manufacturer acts as Stackelberg leader, and taking the logistics vendor's behaviour into consideration, sets the product price p_M to maximize its profit in the second step. In the last step, the retailer, as a follower, decides the 3DP product price p_{3D} to maximize its profit, given the traditional manufacturer's decision.

To be certain that the game is perfect, this model uses backward induction to first analyze the decisions at the final step followed by the decisions at earlier steps. This model does not consider a scenario in which the logistics vendor sets p_{3D} first because of its later entrance into the market.

Bertrand

PROPOSITION ***4-3.*** *In the decentralized 3DP manufacturing system, under Bertrand-Nash-equilibrium, the maximum profit for the traditional manufacturer is* $\prod_{3DB}^{*} M(p_M) = -\frac{(2+\alpha)^2(-\alpha c_{3D}+c_L+c_M)^2}{(-1+\alpha)\alpha(8+\alpha)^2}$ *and the maximum profit for the logistics vendor is*

$\prod_{3DB}^{*} L(p_{3D}, p_L) = \frac{1}{4(\alpha-1)\alpha(8+\alpha)}((-1+\alpha)\alpha(8+\alpha) + \alpha(-8+\alpha(3+\alpha))c_{3D}^2 - 2\alpha c_{3D}(-8+7\alpha+\alpha^2-4c_L-4c_M) - 4(c_L+c_M)^2)$, *which are maximized by optimal price* $p_M^* = \frac{\alpha(8+\alpha)+\alpha(4+\alpha)c_{3D}+4c_L+4c_M}{2(8+\alpha)}$, $p_L^* = \frac{\alpha(8+\alpha)-\alpha^2 c_{3D}+2(4+\alpha)c_L-8c_M}{2(8+\alpha)}$ *and* $p_{3D}^* = \frac{8+\alpha+(8+3\alpha)c_{3D}-2c_L-2c_M}{2(8+\alpha)}$. *The optimal market demand for the TM and 3DP product is* $q_M^* = -\frac{(2+\alpha)(\alpha c_{3D}-c_L-c_M)}{(-1+\alpha)\alpha(8+\alpha)}$ *and* $q_{3D}^* = \frac{-8+7\alpha+\alpha^2-(-8+\alpha+\alpha^2)c_{3D}-6c_L-6c_M}{2(-1+\alpha)(8+\alpha)}$.

In the integrated 3DP manufacturing system, under Bertrand-Nash-equilibrium, the maximum profit for the supply chain is $\prod_{3DB}^{*} SC(p_M, p_{3D}) = -\frac{-(-1+\alpha)\alpha+\alpha c_{3D}^2+(c_L+c_M)^2-2\alpha c_{3D}(1-\alpha+c_L+c_M)}{4(-1+\alpha)\alpha}$, *which is maximized by optimal price* $p_M^* = \frac{1}{2}(\alpha + c_L + c_M)$ *and* $p_{3D}^* = \frac{1}{2}(1+c_{3D})$. *The optimal market demand for the TM and 3DP product is* $q_M^* = \frac{-\alpha c_{3D}+c_L+c_M}{2(-1+\alpha)\alpha}$ *and* $q_{3D}^* = \frac{1-\alpha-c_{3D}+c_L+c_M}{2-2\alpha}$.

Stackelberg

PROPOSITION ***4-4.*** *In the decentralized 3DP manufacturing system, under Stackelberg-Nash-equilibrium, the maximum profit for the traditional manufacturer is* $\prod_{3DS}^{*} M(p_M) = \frac{2(-2+\alpha)(-\alpha c_{3D}+c_L+c_M)^2}{(-1+\alpha)\alpha(8+(-5+\alpha)\alpha)^2}$ *and the maximum profit for the logistics vendor is* $\prod_{3DS}^{*} L(p_{3D}, p_L) = \frac{1}{4(-1+\alpha)\alpha(8+(-5+\alpha)\alpha)}((-1+\alpha)\alpha(8+(-5+\alpha)\alpha) + \alpha(-8+(9-2\alpha)\alpha)c_{3D}^2 - (-2+\alpha)^2(c_L+c_M)^2 + 2\alpha c_{3D}(-(-1+\alpha)(8+(-5+\alpha)\alpha) + (-2+\alpha)^2 c_L + (-2+\alpha)^2 c_M))$. *They are maximized by optimal price* $p_M^* = \frac{\alpha(8+(-5+\alpha)\alpha)-(-4+\alpha)\alpha c_{3D}+(-2+\alpha)^2 c_L+(-2+\alpha)^2 c_M}{2(8+(-5+\alpha)\alpha)}$, $p_L^* = \frac{\alpha(8+(-5+\alpha)\alpha)-\alpha^2 c_{3D}+(8+(-4+\alpha)\alpha)c_L-(-4+\alpha)(-2+\alpha)c_M}{2(8+(-5+\alpha)\alpha)}$ *and* $p_{3D}^* = \frac{8+(-5+\alpha)\alpha+(8-3\alpha)c_{3D}+(-2+\alpha)c_L+(-2+\alpha)c_M}{2(8+(-5+\alpha)\alpha)}$. *The optimal market demand for the TM and 3DP product is* $q_M^* = \frac{(-2+\alpha)(\alpha c_{3D}-c_L-c_M)}{(-1+\alpha)\alpha(8+(-5+\alpha)\alpha)}$ *and* $q_{3D}^* = \frac{(-1+\alpha)(8+(-5+\alpha)\alpha)+(8+(-7+\alpha)\alpha)c_{3D}-6c_L-6c_M-(-5+\alpha)\alpha(c_L+c_M)}{2(-1+\alpha)(8+(-5+\alpha)\alpha)}$.

In the integrated 3DP manufacturing system, under Stackelberg-Nash-equilibrium, the maximum profit for the supply chain is $\prod_{3DS}^{*} SC(p_M, p_{3D}) = -\frac{-(-1+\alpha)\alpha+\alpha c_{3D}^2+(c_L+c_M)^2-2\alpha c_{3D}(1-\alpha+c_L+c_M)}{4(-1+\alpha)\alpha}$, *which is maximized by optimal price* $p_M^* = \frac{1}{2}(\alpha + c_L + c_M)$ *and* $p_{3D}^* = \frac{1}{2}(1+c_{3D})$. *The optimal market demand for the TM and 3DP product is* $q_M^* = \frac{-\alpha c_{3D}+c_L+c_M}{2(-1+\alpha)\alpha}$ *and* $q_{3D}^* = \frac{1-\alpha-c_{3D}+c_L+c_M}{2-2\alpha}$. *Therefore, it is the same as the Bertrand-Nash-equilibrium – the channel power has no impact here.*

Full Adoption of 3DP

If $p_{3D} < \frac{p_M}{\alpha}$, then all the consumers only purchase the 3DP product, which means $q_{3D} = 1 - p_{3D}$ and $q_M = 0$. Therefore, the profit of the logistics vendor under a fully 3DP-based supply chain is

$$\prod\nolimits_{F3D} L(p_{3D}) = (p_{3D} - c_{3D})q_{3D} \tag{4.9}$$

Meanwhile, the optimal decisions under Nash-equilibrium are

$$p_{3D}^* = \frac{1}{2}(1 + c_{3D}) \tag{4.10}$$

$$q_{3D}^* = \frac{1}{2}(1 - c_{3D}) \tag{4.11}$$

$$\prod\nolimits_{F3D}^{*} L(p_{3D}) = \prod\nolimits_{F3D}^{*} SC(p_{3D}) = \frac{1}{4}(-1 + c_{3D})^2 \tag{4.12}$$

All the equilibrium optimal solutions for different supply chain systems have been summarized in Table 4-2.

Table 4-2 Equilibrium optimal solutions for Different Supply Chain Systems

Optimal Solutions	Decentralized Traditional Manufacturing System	Integrated Traditional Manufacturing System	Decentralized 3DP Manufacturing System (Individual Decision)		Integrated 3DP Manufacturing System (Vertically Integrated)	Fully 3DP-based Manufacturing System
			Bertrand	Stackelberg	Bertrand/Stackelberg	
p_L^*	$\frac{1}{2}(\alpha + c_L - c_M)$	-	$\frac{1}{2(8+\alpha)}(\alpha(8+\alpha) - \alpha^2 c_{3D} + 2(4+\alpha)c_L - 8c_M)$	$\frac{1}{2(8+(-5+\alpha)\alpha)}(\alpha(8+(-5+\alpha)\alpha) - \alpha^2 c_{3D} + (8+(-4+\alpha)\alpha)c_L - (-4+\alpha)(-2+\alpha)c_M)$	-	-
p_M^*	$\frac{1}{4}(3\alpha + c_L + c_M)$	$\frac{1}{2}(\alpha + c_L + c_M)$	$\frac{1}{2(8+\alpha)}(\alpha(8+\alpha) + \alpha(4+\alpha)c_{3D} + 4(c_L + c_M))$	$\frac{1}{2(8+(-5+\alpha)\alpha)}(\alpha(8+(-5+\alpha)\alpha) - (-4+\alpha)\alpha c_{3D} + (-2+\alpha)^2(c_L + c_M))$	$\frac{1}{2}(\alpha + c_L + c_M)$	-
p_{3D}^*	-	-	$\frac{1}{2(8+\alpha)}(8+\alpha + (8+3\alpha)c_{3D} - 2(c_L + c_M))$	$\frac{8+(-5+\alpha)\alpha + (8-3\alpha)c_{3D} + (-2+}{2(8+(-5+\alpha)\alpha)}$	$\frac{1}{2}(1 + c_{3D})$	$\frac{1}{2}(1 + c_{3D})$
q_M^*	$-\frac{1}{4\alpha}(-\alpha + c_L + c_M)$	$1 - \frac{1}{2\alpha}(\alpha + c_L + c_M)$	$-\frac{(2+\alpha)(\alpha c_{3D} - c_L -}{(-1+\alpha)\alpha(8+}$	$\frac{(-2+\alpha)(\alpha c_{3D} - c_L - c_M)}{(-1+\alpha)\alpha(8+(-5+\alpha)\alpha)}$	$\frac{-\alpha c_{3D} + c_L + c_M}{2(-1+\alpha)\alpha}$	-

q^*_{3D}	-	-	$\frac{1}{2(-1+\alpha)(8+\alpha)}(-8 \cdots + 7\alpha + \alpha^2 - (-8 + \alpha + \alpha^2)c_{3D} - 6(c_L + c_M))$	$\frac{1}{2(-1+\alpha)(8+(-5+\alpha)\alpha)}((-1 + \alpha)(8+(-5+\alpha)\alpha) + (8+(-7 + \alpha)\alpha)c_{3D} - 6c_L - 6c_M - (-5 + \alpha)\alpha(c_L + c_M))$	$\frac{1-\alpha-c_{3D}+c_L+ \cdots}{2-2\alpha}$	$\frac{1}{2}(1-c_{3D})$
$\prod M$	$\frac{1}{16\alpha}(-\alpha + c_L + c_M)^2$	-	$-\frac{1}{(-1+\alpha)\alpha(8+\alpha)^2} \cdots + \alpha)^2(-\alpha c_{3D} + c_L + c_M)^2$	$\frac{2}{(-1+\alpha)\alpha(8+(-5+\alpha)\alpha)^2}(-2 + \alpha)(-\alpha c_{3D} + c_L + c_M)^2$	-	-
$\prod L$	$\frac{1}{8\alpha}(-\alpha + c_L + c_M)^2$	-	$\frac{1}{4(\alpha-1)\alpha(8+\alpha)}((- \cdots + \alpha)\alpha(8+\alpha) + \alpha(-8+\alpha(3 + \alpha))c_{3D}^2 - 2\alpha c_{3D}(-8+7\alpha + \alpha^2 - 4c_L - 4c_M) - 4(c_L + c_M)^2)$	$\frac{1}{4(-1+\alpha)\alpha(8+(-5+\alpha)\alpha)}((-1 + \alpha)\alpha(8+(-5 + \alpha)\alpha) + \alpha(-8+(9 - 2\alpha)\alpha)c_{3D}^2 - (-2+\alpha)^2(c_L + c_M)^2 + 2\alpha c_{3D}(-(-1 + \alpha)(8+(-5+\alpha)\alpha) + (-2+\alpha)^2 c_L + (-2+\alpha)^2 c_M))$	-	$\frac{1}{4}(-1+c_{3D})^2$
$\prod SC$	-	$\frac{1}{4\alpha}(-\alpha + c_L + c_M)^2$	-	-	$-\frac{1}{4(-1+\alpha)\alpha}(-(\cdots + \alpha)\alpha + \alpha c_{3D}^2 + (c_L + c_M)^2 - 2\alpha c_{3D}(1 - \alpha + c_L + c_M))$	$\frac{1}{4}(-1+c_{3D})^2$

4.3 Model Analysis

This section comprehensively compares the TM and 3DP manufacturing systems from the perspective of optimal decisions and maximized profit and presents some interesting observations with regard to the research question: Under what conditions will a logistics vendor use 3DP as a game-changer to compete directly with the manufacturer?

4.3.1 Sensitivity Analysis

In this subsection, the impact of different costs and product customization on the optimal decisions is examined.

The Impact of Costs

PROPOSITION ***4-5.*** *In a 3DP-enabled decentralized market, no matter whether in Bertrand or in Stackelberg,*

(1) The optimal price of the logistics service decreases in the cost of the TM and 3DP product but increases in the cost of the logistics service;

(2) The optimal price of the TM product increases in all kinds of cost;

(3) The optimal price of the 3DP product increases in the cost of the 3DP product but decreases in the TM and logistics service cost;

(4) The optimal market demand for the TM product decreases in the cost of the TM product and the logistics service but increases in the cost of the 3DP product;

(5) The optimal market demand for the 3DP product increases in the cost of the TM product and the logistics service but decreases in the cost of the TM product.

PROPOSITION **4-5** indicates that if the associated cost of the TM product decreases, the TM price decreases for the purpose of increasing the market demand by attracting more price-sensitive consumers. This pushes the logistics vendor to use a high price regime to reduce its profit loss. However, if the cost of the 3DP product decreases, because the product customization level of the TM product is low, the traditional manufacturer has to set the price of the TM product as low as possible to keep its key competitive advantage on pricing. This result is congruent with the finding of other studies indicating that the lower product customization level, the lower consumer willingnesss to pay (Piller, Moeslein, & Stotko, 2004; Pine, 1993; Syam & Kumar, 2006). Meanwhile, the logistics vendor can increase the price of the logistics delivery at the beginning to reduce the traditional manufacturer's pricing advantage. Therefore, cost reduction of 3DP seems a good tool for the logistics vendor to use to leverage the market competition. In addition, the cost saving on the delivery service has a positive impact on the TM product pricing strategy but not on the logistics vendor's 3DP product pricing strategy. Therefore, the latter should be careful with regard to whether to reflect its cost saving in its logistics delivery service pricing.

PROPOSITION ***4-6.*** *In a 3DP-enabled integrated market, no matter whether in Bertrand or in Stackelberg,*

(1) Only the cost of the logistics delivery and the TM product can influence the TM product price, and the price of the TM product increases in both of them;

(2) The price of the 3DP product increases in the cost of the 3DP product;

(3) The market demand for the TM product decreases in the cost of the TM product and the logistics service but increases in the cost of the 3DP product;

(4) The market demand for the 3DP product increases in the cost of the TM product and the logistics service but decreases in the cost of the TM product.

Most of the findings of ***PROPOSITION*** **4-6** are the same as ***PROPOSITION*** **4-5**, because the traditional manufacturer and the logistics vendor are vertically integrated in this system. The only difference is that the cost reduction of the TM or 3DP product cannot influence the pricing strategy of the competitor.

PROPOSITION ***4-7.*** *In a 3DP-enabled decentralized supply chain,*

(1) The traditional manufacturer's profit decreases in the cost of the logistics delivery and the TM product but increases in the cost of the 3DP product;

(2) *The logistics vendor's profits decrease in the cost of the logistics delivery and the TM product; but, in the Bertrand-market,*

a. *If* $\frac{c_L+c_M}{\alpha} < c_{3D} < \frac{(-1+\alpha)(8+\alpha)-4(c_L+c_M)}{-8+\alpha(3+\alpha)}$, *it decreases in* c_{3D};

b. *If* $\frac{(-1+\alpha)(8+\alpha)-4c_L-4c_M}{-8+\alpha(3+\alpha)} < c_{3D} < 1$, *it increases in* c_{3D};

Meanwhile, in the Stackelberg-market,

a. *If* $\frac{c_L+c_M}{\alpha} < c_{3D} < \frac{-(-1+\alpha)(8+(-5+\alpha)\alpha)+(-2+\alpha)^2(c_L+c_M)}{8+\alpha(-9+2\alpha)}$, *it decreases in* c_{3D};

b. *If* $\frac{-(-1+\alpha)(8+(-5+\alpha)\alpha)+(-2+\alpha)^2(c_L+c_M)}{8+\alpha(-9+2\alpha)} < c_{3D} < 1$, *it increases in* c_{3D}.

In a 3DP enabled integrated supply chain, the total supply chain profit also decreases in the cost of the logistics delivery and the TM product; but,

a. *If* $\frac{c_L+c_M}{\alpha} < c_{3D} < 1-\alpha+c_L+c_M$, *it decreases in* c_{3D};

b. *If* $1-\alpha+c_L+c_M < c_{3D} < 1$, *it increases in* c_{3D}.

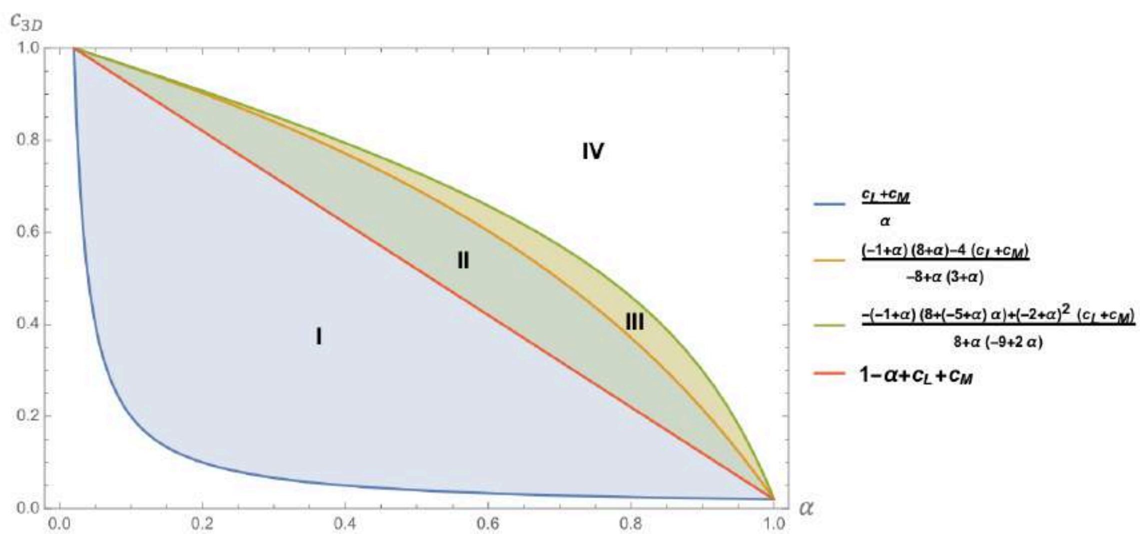


Figure 4-6 The Impact of the 3DP Cost in the Logistics Vendor's Maximized Profit and the Integrated Supply Chain (given $c_L = 0.01$, $c_M = 0.01$)

***PROPOSITION* 4-7** demonstrates that

(1) Reductions of the TM product's associated cost have positive impacts on the traditional manufacturer's profits as well as those of the logistics vendor and the total supply chain profitability. This finding is similar with the findings derived from the

research by Dong et al. (2017) and Berdine, DiPaola, & Weinberg (2019). The reasons behind this are obvious: when the product cost and/or the goods delivery cost reduce, the manufacturer tries to use a lower price to attract more price-sensitive consumers. As a result, the traditional manufacturer can gain more profits generated from the increased number of consumers despite those lost due to the unit price dropping. At the same time, the logistics vendor (who is without price advantages) finds that the reductions of the TM product cost and/or delivery service push it to use a high-price regime to compensate for its loss due to the decreased market size. Eventually, the logistics vendor can earn more profit from the increased unit price than the profit loss from the reduced market demand. Overall, the whole supply chain can achieve more profits. Therefore, cost reductions of the TM product and the logistics delivery are a win-win strategy for the traditional manufacturer and the logistics vendor and also a profitable strategy for the whole supply chain.

(2) (Liao et al., 2014) argue that the cost reduction of the 3DP production always can bring advantages to the 3DP user, However, our analysis here suggest that cost reduction of the 3DP product has a negative impact on the traditional manufacturer's profitability and its impact on the profitability of the logistics vendor and the supply chain depends on the cost level of the 3DP product.

(3) i) If the cost of the 3DP product is relatively high (Region III and IV for the decentralized Bertrand market, Region IV for the decentralized Stackelberg market, and Region II, III and IV for the integrated supply chain in Figure 4-6), cost reduction of the 3DP product offers some pricing advantages to the 3DP product and it pushes the traditional manufacturer to lower its TM product price as well. Therefore, some customization-sensitive consumers switch and buy the 3DP product, which results in

a decrease in the traditional manufacturer's profit and the logistics vendor cannot generate more profits from the increased consumer market than the loss of the low-price strategy. Overall, the supply chain also loses profit. ii) If the cost of the 3DP product is at a low level (Region I and II for the decentralized Bertrand market, Region I, II and III for the decentralized Stackelberg market, and Region I for the integrated supply chain in Figure 4-6), more customization-sensitive consumers switch to the 3DP product. Consequently, the traditional manufacturer loses more profit and the logistics vendor can gain more profits from the increased market demand than the loss of the low-price strategy. However, overall, the integrated supply chain benefits from this situation. Therefore, with this kind of cost structure (where the 3DP product cost is cheap), continued cost reduction of 3DP can help the logistics vendor to gain more profits by cannibalizing the TM product market, and the whole supply chain can be improved in this way.

PROPOSITION *4-8.* *In a fully 3DP-enabled market, the price of the 3DP product increases in the cost of the 3DP product; the market demand for the 3DP product and the profit of the logistics vendor and the supply chain all decrease in the cost of the 3DP product.*

The findings in the above proposition are intuitive for one certain product market. Cost reduction helps the logistics vendor to use a low pricing strategy to increase market demand, but the overall profits decrease due to the low unit margin.

The Impact of Product Customization Level

Unfortunately, the structure of the optimal decisions in Table 4-2 and the maximized profit functions for the traditional manufacturer and the logistics vendor are too complex to allow us to obtain direct insights into the impact of customization level on these optimal decisions. In this section, numerical tests are conducted to determine the relative performance of product customization sensitivity with regard to the optimal decisions under different market structures. To achieve this, a full factorial design was created with three different values for 3 different costs (c_{3D}, c_L, c_M) – namely, low, medium and high as Table 4-3 shows, followed by a depiction of the optimal prices and quantities for each parameter for different scenarios.

Table 4-3 Parameter Values in the Numerical Testing for the Impacts of Customization on Optimal Decisions in the 3DP as Game-changer Market

	c_{3D}	c_L	c_M
Low	0.3	0.01	0.01
Medium	0.6	0.01	0.01
High	0.9	0.01	0.01

PROPOSITION *4-9.* *In a 3DP-enabled decentralized market,*

(1) The optimal price of the logistics service, TM product, and the 3DP product increase in the TM product customization level;

(2) The optimal market demand increases in the product customization level of the TM product but the market demand of the 3DP product decreases in it;

(3) Both the traditional manufacturer's and the logistics vendor's maximized profit increase in the product customization level of the TM product.

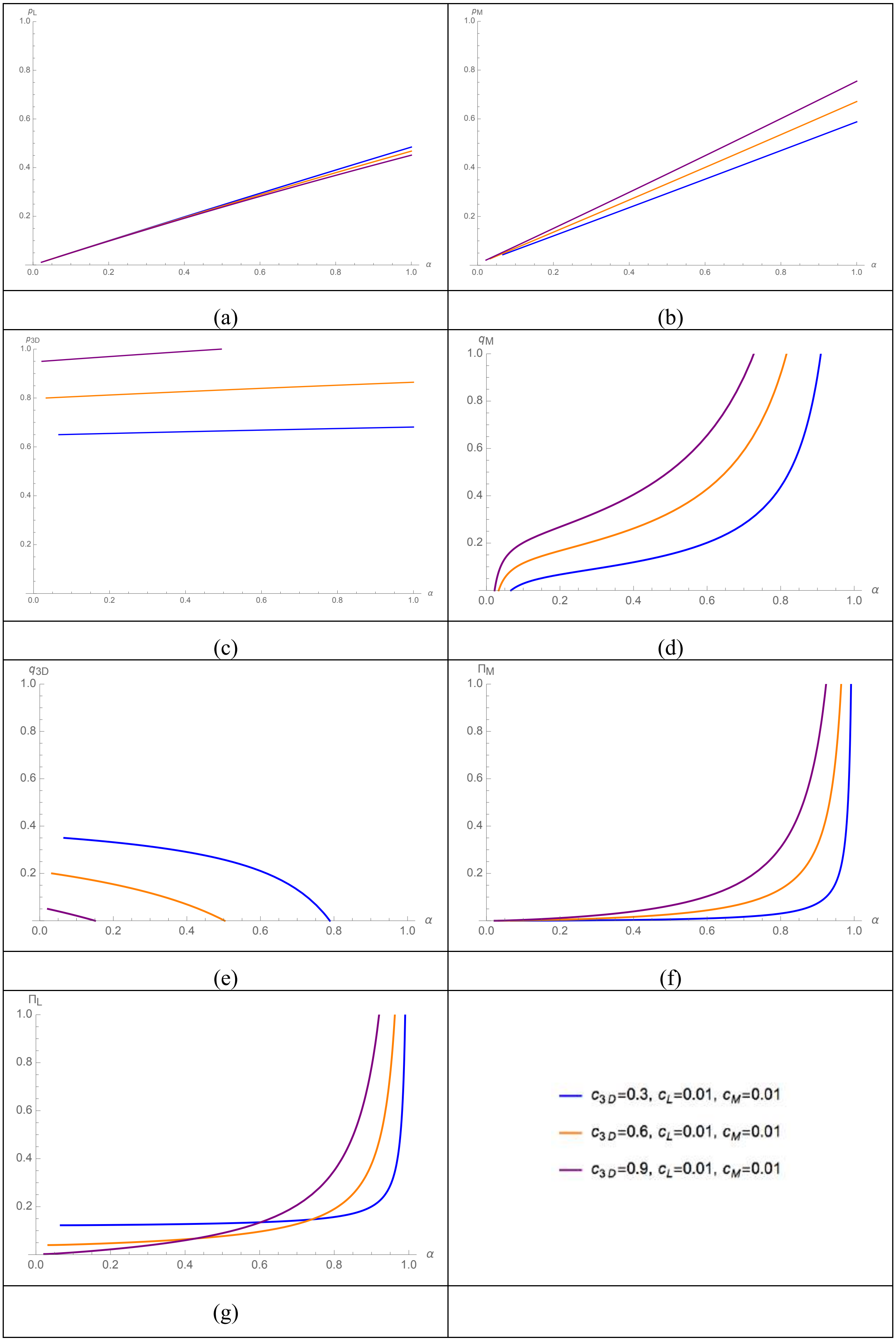


Figure 4-7 Impact of Product Customization on Optimal Decisions – Bertrand

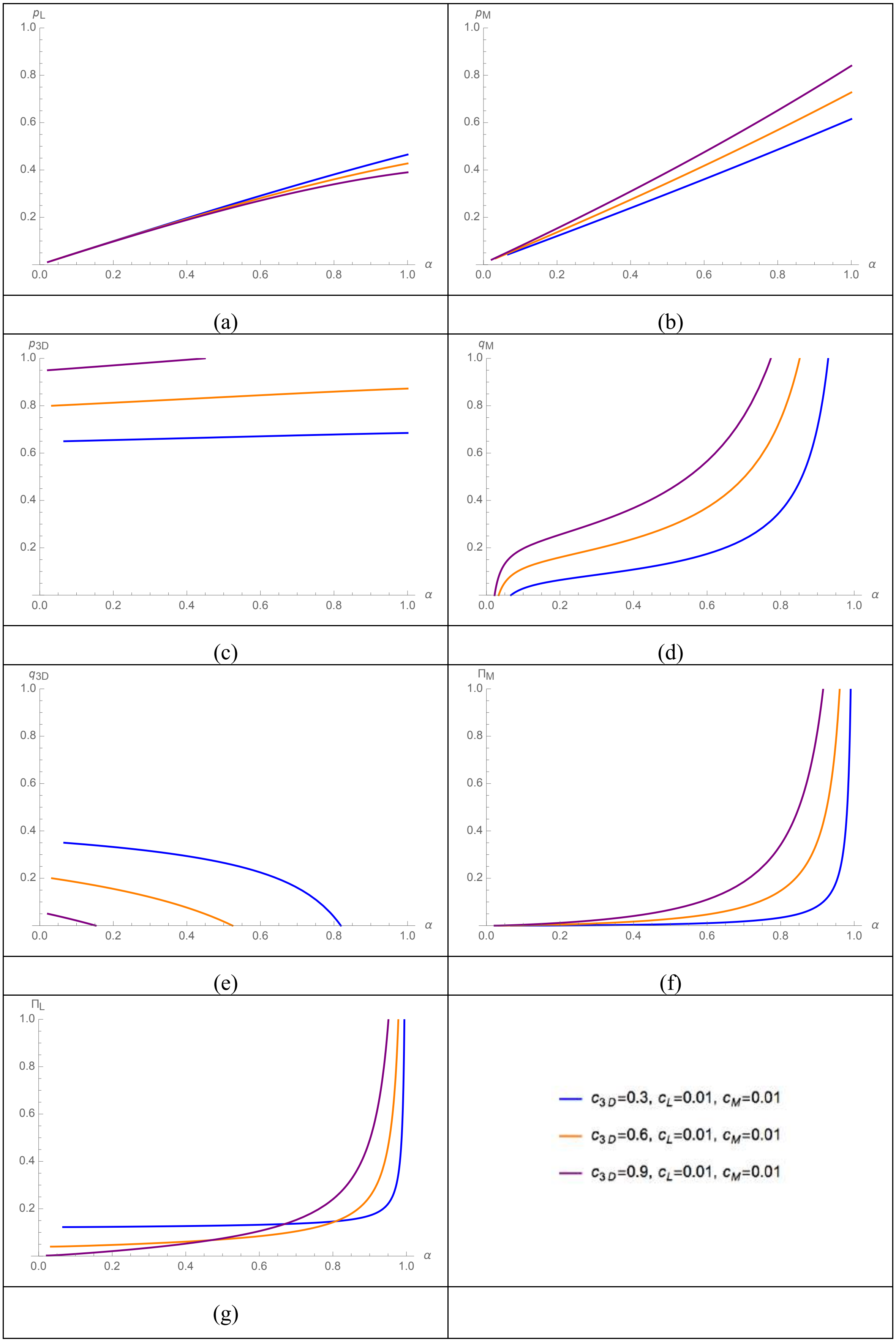


Figure 4-8 Impact of Product Customization on Optimal Decisions – Stackelberg

Figure 4-7 and Figure 4-8 demonstrate that no matter what the cost structure of the supply chain is, if the logistics vendor chooses to adopt a higher customization level 3DP technology (the difference between the customization level of the TM and 3DP product is larger, α is smaller), the optimal price of goods and services and the market demand for the TM product decreases, but the market demand for the 3DP product increases. On the one hand, due to the disadvantages of product customization, both the logistics vendor and the traditional manufacturer use a low-price regime for the logistics service and the TM product for the purpose of attracting more price-sensitive consumers. On the other hand, considering the low TM price, the logistics vendor also sets the price of the 3DP product as low as possible in order to increase market demand. Consequently, the market demand for the TM product reduces and the market demand for the 3DP product increases conversely. The traditional manufacturer loses profits on the low pricing strategy and low market demand. For the logistics vendor, although the market demand is increased by low pricing, the loss from low pricing cannot be compensated for by the new profit generated from the increased market demand. Therefore, surprisingly, in a decentralized market, increased customization cannot help either the traditional manufacturer or the logistics vendor to achieve better financial performance.

PROPOSITION *4-10.* *In a 3DP-enabled integrated market,*

(1) The optimal price of the TM product increases in the TM product customization level and there is no direct relationship between the TM product customization level and the price of the 3DP product;

(2) The optimal market demand increases in the product customization level of the TM product but the market demand for the 3DP product decreases in it;

(3) The overall supply chain's maximized profit increases in the product customization level of the TM product.

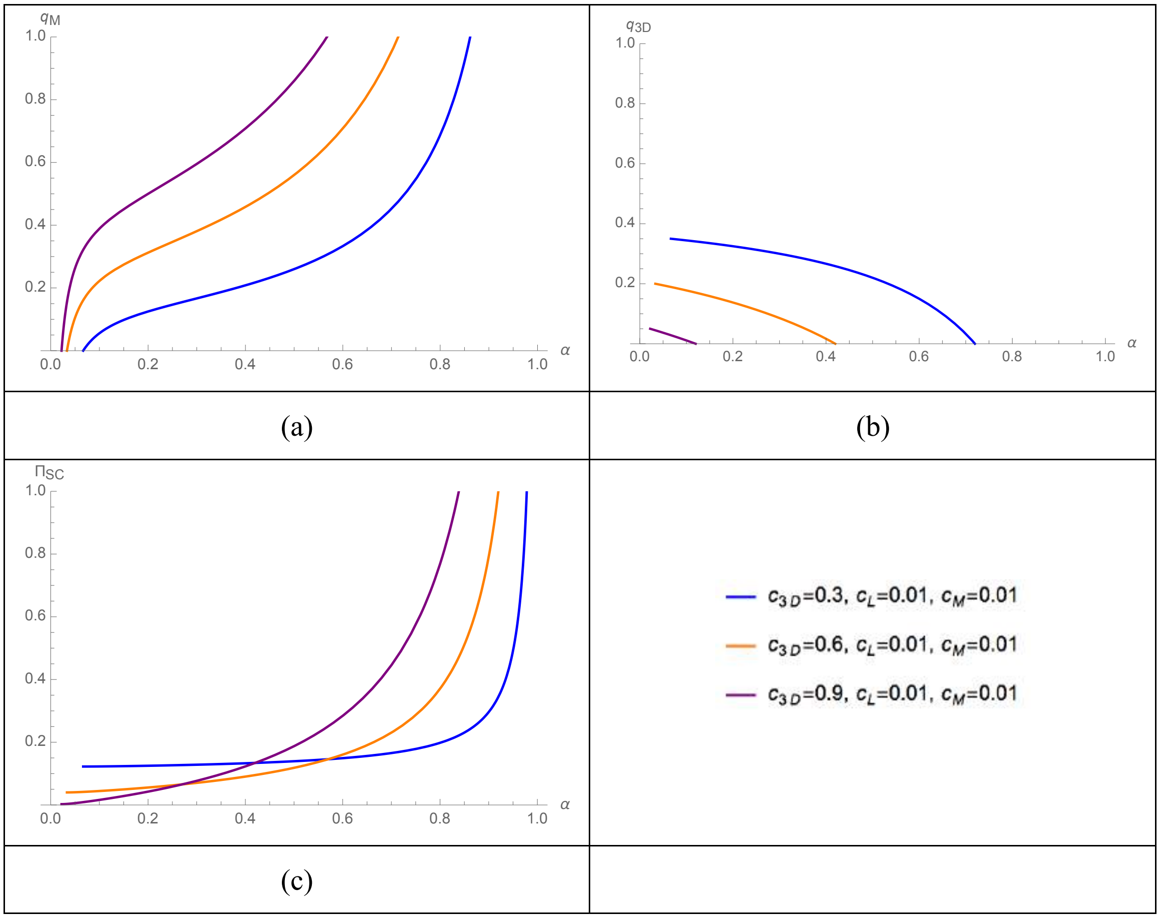


Figure 4-9 Impact of Product Customization on Optimal Decisions – Integrated Supply Chain

The findings in ***PROPOSITION* 4-10** (Figure 4-9) echo the findings in ***PROPOSITION* 4-9** and show that the improvement of the customization of the 3DP product (α becoming smaller) results in decreased market demand for the TM product but increased demand for the 3DP product, but the overall profitability of the supply chain is not improved as expected. This finding highlight that for the development of 3DP adoption by logistics vendors, some extra industrial level financial support is needed. This study explores what kind of support should be implemented below.

4.3.2 Comparative Analysis

As discussed in the introduction, the cost of the 3DP product is one of the most critical considerations to those companies that are currently thinking about 3DP adoption. Therefore, taking the cost of 3DP as a key consideration, this section tries to determine whether adding a new 3DP business is a profitable business strategy for the logistics vendor, while also assess the impact of 3DP adoption on the manufacturer's business by comparing the profitability and optimal decisions of the TM and Bertrand-3DP manufacturing systems.

PROPOSITION ***4-11.*** *In a decentralized Bertrand market, compared to the traditional manufacturing system, engaging a new 3DP service has*

(1) A positive impact on the logistics vendor's profitability;

(2) Its impact on the traditional manufacturer's business performance differs depending on the cost of the 3DP product. If the cost of the 3DP product is relatively low ($\frac{c_L+c_M}{\alpha} < c_{3D} \frac{c_L+c_M}{\alpha} + \frac{(\alpha+8)(\alpha-c_L-c_M)\sqrt{1-\alpha}}{4\alpha(2+\alpha)}$ *), the impact on the traditional manufacturer's profitability is negative; otherwise, if the cost of the 3DP product is higher, the traditional manufacturer can also gain more profits.*

The impacts on the optimal decisions of the traditional manufacturer and the logistics vendor are

(3) The optimal price of the TM product in the traditional and the new Bertrand 3DP manufacturing system show the following respective relationships:

a. The optimal price of the logistics service decreases;

b. The optimal price of the TM product decreases under the condition $\frac{c_L+c_M}{\alpha} < c_{3D} < \frac{8+\alpha+c_L+c_M}{8+2\alpha}$*, otherwise it decreases;*

c. The market demand for the TM product decreases only under the condition $\frac{c_L+c_M}{\alpha} < c_{3D} < \frac{-(-1+\alpha)(8+\alpha)+(11+\alpha)(c_L+c_M)}{4(2+\alpha)}$.

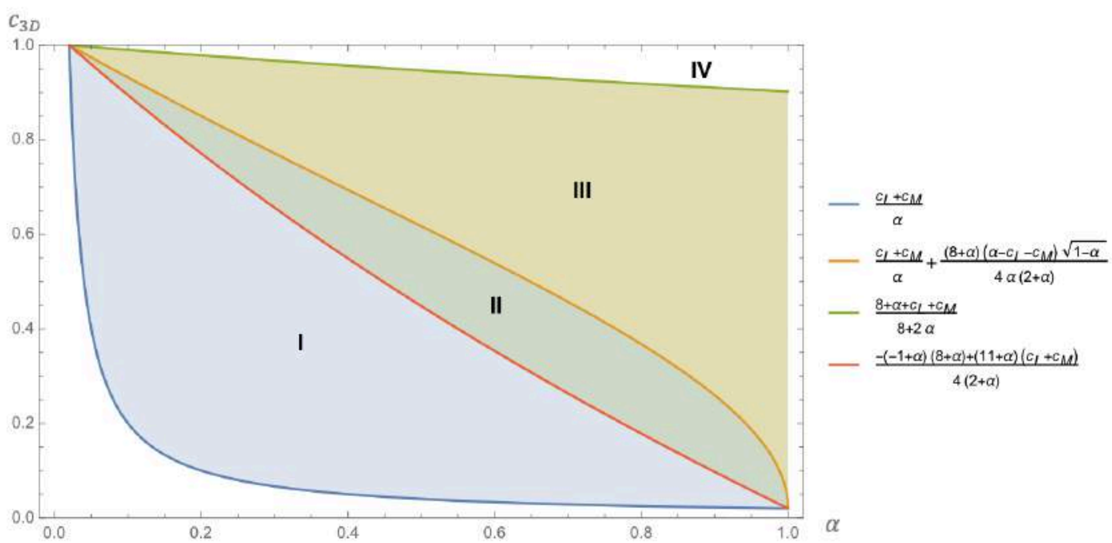


Figure 4-10 Decision Regions for the Comparison between the TM and Bertrand 3DP Systems

(given $c_L = 0.01$, $c_M = 0.01$)

PROPOSITION ***4-12.*** *In a decentralized Stackelberg-market, compared to the traditional manufacturing system, engaging a new 3DP service has*

(1) A positive impact on the logistics vendor's profitability;

(2) Its impact on the traditional manufacturer's business performance differs depending on the cost of the 3DP product. If the cost of the 3DP product is relatively low ($\frac{c_L+c_M}{\alpha} < c_{3D} < \frac{c_L+c_M}{\alpha} - \frac{\sqrt{2}(8+(-5+\alpha)\alpha)(\alpha-c_L-c_M)\sqrt{(-2+\alpha)(-1+\alpha)}}{8(-2+\alpha)\alpha}$ *), the traditional manufacturer cannot also benefit from it, but if the 3DP product cost is higher, the traditional manufacturer can also benefit.*

The impacts on the optimal decisions of the traditional manufacturer and the logistics vendor are

(3) The optimal price of the TM product in the traditional and the new Bertrand 3DP manufacturing system have the following respective relationships:

a. The optimal price of the logistics service decreases;

b. The optimal price of the TM product decreases under the condition $\frac{c_L+c_M}{\alpha} < c_{3D} < \frac{-8-(-5+\alpha)\alpha+(-3+\alpha)(c_L+c_M)}{2(-4+\alpha)}$*, but otherwise it increases;*

c. The market demand for the TM product increases only under the condition $-\frac{-(-1+\alpha)(8+(-5+\alpha)\alpha)+(-3+\alpha)^2(c_L+c_M)}{4(-2+\alpha)} < c_{3D} < 1$.

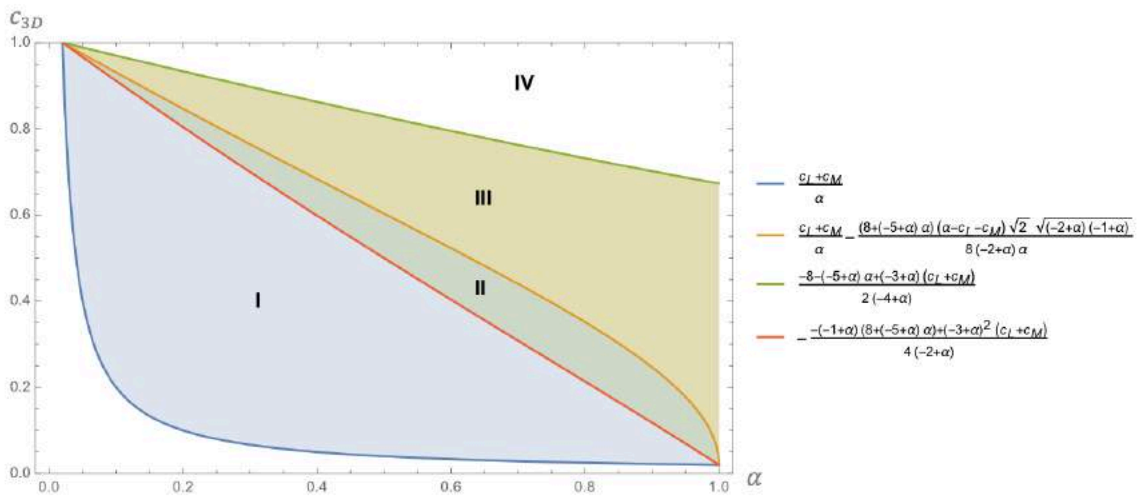


Figure 4-11 Decision Regions for the Comparison between the TM and Stackelberg 3DP Systems (given $c_L = 0.01$, $c_M = 0.01$)

PROPOSITION **4-11** and ***PROPOSITION*** **4-12** show the same result. In a decentralized market, offering a 3DP service is a beneficial strategical move for the logistics vendor but the impact of the new 3DP manufacturing service has different impacts on the traditional manufacturer's profits. Therefore, there exists a situation where the new 3DP adoption cannot bring more profits to both the logistics vendor and the traditional manufacturer, although the majority of the 3DP research suggested that 3DP adoption always contributes to the supply chain development (Despeisse et al., 2017; Dong et al., 2017).

In the new 3DP manufacturing system, the logistics vendor introduces a new 3DP product into the market. For the purpose of maximizing the profitability of the delivery service, the logistics vendor sets the price of the logistics delivery service with the expectation of increasing the TM market demand by a low TM product price strategy.

If the cost of the 3DP product is low (Region I and II in Figure 4-10 and Figure 4-11) the traditional manufacturer cannot gain more profits: 1) in Region I, the traditional manufacturer uses a low price-regime to keep its competitive advantages on price. However, the market demand for TM in this scenario decreases because some customization sensitive consumers switch and buy the 3DP product instead. Consequently, the low-price strategy results in financial loss for the traditional manufacturer. However, although the TM product delivery requirement reduces, the logistics vendor still benefits from the new 3DP business and achieves greater profitability. Overall, the whole supply chain gains more profits. 2) In Region II, for the same reason, the logistics vendor still uses a low-price regime. However, in this scenario, the cost of the 3DP product is slightly higher than in Region I, and so the price of the 3DP product is higher. Thus, the market demand for the TM product increases because the new price-sensitive consumers who previously entered the market to buy 3DP change and buy the TM product. Overall, the traditional manufacturer still loses profit with the low pricing strategy. But the logistics vendor benefits from increased profits from the high delivery requirement and the new 3DP product business. Therefore, for the whole supply chain system, profitability improves.

If the cost of the 3DP product is high (Region III and IV in Figure 4-10 and Figure 4-11), both the logistics vendor and the traditional manufacturer can benefit from 3DP adoption. 1) In Region III, although the cost of product delivery is low, since the cost of 3DP is high, the traditional manufacturer uses a low-price strategy for the purpose of increasing market demand. Therefore, the traditional manufacturer gains more profit through the increased market demand and the logistics vendor generates more profits on the new 3DP product and the increased product delivery requirements. 2) If the cost of the 3DP product is in Region IV, which is extremely high, the manufacturer uses a high-price regime to maximize its profit. In this region, the price of the 3DP product is extremely high (for high production cost products, the manufacturer usually uses a high price to ensure its margin is positive), some consumers previously intending to buy the 3DP product shift and buy the TM product. Therefore, both the traditional manufacturer and the logistics vendor enjoy the increased market demand for the TM product through product selling and goods delivery. Therefore, the whole supply chain gains more profits. In these kinds of market structures, adopting a new 3DP service is a win-win strategy for both the traditional manufacturer and the logistics vendor.

PROPOSITION *4-13.* *In a decentralized 3DP-enabled system, the logistics vendor can gain more profits in the Bertrand market than the Stackelberg market, but conversely the manufacturer can gain more profits in the Stackelberg market. Under system equilibrium, the optimal price of the logistics service and the market demand for the TM product is higher in the Bertrand market, but the optimal price of the TM and 3DP product, and the market demand for the 3DP product, are lower in the Bertrand market than the Stackelberg market.*

This proposition shows that the channel bargaining power plays an important role here. This result is somewhat consistent with the finding of D. R. Eyers & Potter (2015) indicating that channel power helps the company get market advantages (e.g. consumer prefer to buy the product manufactured by great brand). The logistics vendor can achieve greater profits by introducing a 3DP product into a market where he has equal bargaining power to the traditional manufacturer. But in market which is led by the traditional manufacturer, the logistics vendor's new 3DP business cannot bring him/her more profits. The reason behind this is straightforward: both of them use a low-price regime if they set the product price simultaneously which results in higher demand for the TM product. And under the Stackelberg game, the logistics vendor prices the 3DP product later and s/he uses a higher price for the purpose of maximizing market demand and the total profits but loses the profit generated from the conversional goods delivery service. Therefore, the logistics vendor can gain more profits from the logistics delivery service in the Bertrand market.

PROPOSITION ***4-14.*** *In an integrated supply chain, compared to the traditional manufacturing system, engaging a new 3DP service has a positive impact on total supply chain profitability; the optimal price decreases; the market demand for the TM product increases only under the condition* $\frac{-(-1+\alpha)\alpha+(1+\alpha)(c_L+c_M)}{2\alpha} < c_{3D} < 1$.

For the supply chain, after introducing the 3DP product to the market, the traditional manufacturer has to use a low-price strategy to keep its competitive advantage on price. When the cost of the 3DP product is high ($\frac{-(-1+\alpha)\alpha+(1+\alpha)(c_L+c_M)}{2\alpha} < c_{3D} < 1$), considering the price of the 3DP product, more price sensitive consumers choose to buy the TM product. Therefore, the supply chain benefits from the increased market demand for the TM product and the newly introduced 3DP business. However, if the 3DP product cost is low ($\frac{c_L+c_M}{\alpha} < c_{3D} < \frac{-(-1+\alpha)\alpha+(1+\alpha)(c_L+c_M)}{2\alpha}$), the logistics vendor can use a low-price strategy for the 3DP product. Consumers sensitive to product customization choose to buy the new 3DP product instead of the TM product. Thus, the supply chain loses profit from the TM product, but it can generate more profit from the new 3DP product service.

In the above section, this model investigates the scenarios in which the logistics vendor adopts 3DP technology and competes with the TM product in the market. However, in addition, the proposition below considers whether full adoption of the 3DP product by the logistics vendor is an option for him ($q_{3D} = 1 - p_{3D}$ and $q_M = 0$) by comparing the profitability of the logistics vendor in the traditional manufacturing system, a 3DP-enabled Bertrand and Stackelberg decentralized manufacturing system, and full 3DP by the logistics vendor.

PROPOSITION ***4-15.*** *In a decentralized supply chain, compared to the traditional manufacturing system, fully engaging a new 3DP service has a positive impact on the logistics vendor's profitability if* $0 < c_{3D} < \frac{1}{2}(2 + \frac{\sqrt{2}(\alpha - c_L - c_M)}{\sqrt{\alpha}}$*. The whole supply chain can achieve greater profits through the full 3DP strategy only if* $0 < c_{3D} < 1 + \frac{\alpha - c_L - c_M}{\sqrt{\alpha}}$*.*

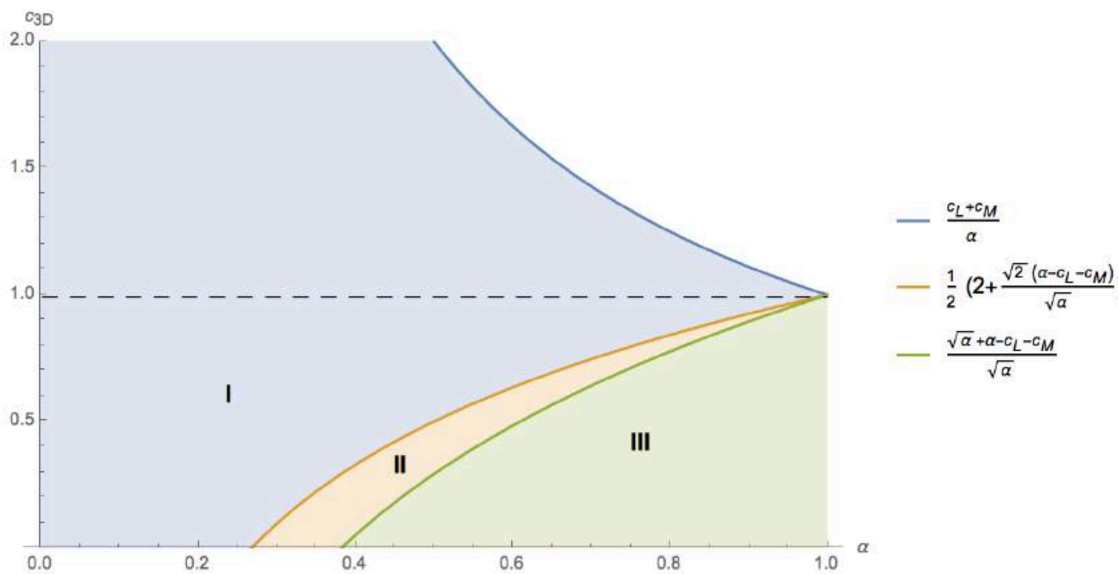


Figure 4-12 Decision Regions for the Full 3DP Strategy (given $c_L = 0.5$, $c_M = 0.5$)

In this subsection, this model uses $c_L = 0.5$, $c_M = 0.5$ as an example to simulate the decision regions in Figure 4-12. It indicates that when the cost of the 3DP product is low, not only the logistics vendor (Region II and III) but also the integrated supply chain (Region III) can gain greater profits due to the new 3DP business creating new market values.

4.3.3 3DP Adoption as a Threat

All the analysis so far have assumed that$q_{3D} \neq 0$, indicating that the logistics vendor offers the new 3DP product in order to compete with the traditional manufacturer in the market, and the results do in fact show that the vendor can use 3DP adoption as a game-changer to restructure the market and generate increased profits. This model therefore investigates what will occur if the logistics vendor simply uses 3DP adoption as a strategic threat and introduces no 3DP product onto the market. In our model we do not consider the cost of 3DP printer investment, because currently, the logistics vendors like UPS only focus on the low-cost 3DP printer business (UPS, 2015; B. Zhang, 2016). The logistics vendor needs only to claim it is going to launch 3DP products to threaten the manufacturer's TM product pricing strategy. Hence, in the next subsections, this model assumes $q_{3D} = 0$ and tests whether the logistics vendor can still earn more profit using this threat.

Optimal Decisions

PROPOSITION ***4-16.*** *In a decentralized Bertrand market, the maximum profits for the traditional manufacturer and the logistics vendor are* $\prod^*_{(q^*_{3D}=0,B)} M(p_M) = -\frac{(-1+\alpha)(2+\alpha)^2(-\alpha+c_L+c_M)^2}{\alpha(-8+\alpha+\alpha^2)^2}$ *and*$\prod^*_{(q^*_{3D}=0,B)} L(p_{3D}, p_L) = -\frac{(-4+\alpha)(2+\alpha)(-\alpha+c_L+c_M)^2}{\alpha(-8+\alpha+\alpha^2)^2}$*; they are maximized by* $p^*_{(q^*_{3D}=0,LB)} = \frac{(-4+\alpha^2)c_L+(-4+\alpha)(\alpha-c_M)}{-8+\alpha+\alpha^2}$, $p^*_{(q^*_{3D}=0,MB)} = \frac{\alpha(-6+\alpha(2+\alpha))-(2+\alpha)(c_L+c_M)}{-8+\alpha+\alpha^2}$, *and* $p^*_{(q^*_{3D}=0,3DB)} = -\frac{8-\alpha(3+2\alpha)+(2+\alpha)(c_L+c_M)}{-8+\alpha+\alpha^2}$. *The optimal market demand for the TM product is* $q^*_{(q^*_{3D}=0,MB)} = -\frac{(2+\alpha)(\alpha-c_L-c_M)}{\alpha(-8+\alpha+\alpha^2)}$.

In a decentralized Stackelberg-market, the maximum profits for the traditional manufacturer and the logistics vendor are $\prod^*_{(q^*_{3D}=0,S)} M(p_M) = \frac{2(-2+\alpha)(-1+\alpha)(-\alpha+c_L+c_M)^2}{\alpha(8+(-7+\alpha)\alpha)^2}$ *and* $\prod^*_{(q^*_{3D}=0,S)} L(p_{3D}, p_L) = -\frac{(-2+\alpha)^3(-\alpha+c_L+c_M)^2}{\alpha(8+(-7+\alpha)\alpha)^2}$ *; they are maximized by* $p^*_{(q^*_{3D}=0,LS)} = \frac{(4-3\alpha)c_L+(-2+\alpha)^2(\alpha-c_M)}{8+(-7+\alpha)\alpha}$, $p^*_{(q^*_{3D}=0,MS)} = \frac{\alpha(6+(-6+\alpha)\alpha)-(-2+\alpha)c_L-(-2+\alpha)c_M}{8+(-7+\alpha)\alpha}$, *and* $p^*_{(q^*_{3D}=0,3DS)} = \frac{8+\alpha(-9+2\alpha)-(-2+\alpha)c_L-(-2+\alpha)c_M}{8+(-7+\alpha)\alpha}$. *The optimal market demand for the TM product is* $q^*_{(q^*_{3D}=0,MS)} = -\frac{(-2+\alpha)(\alpha-c_L-c_M)}{\alpha(8+(-7+\alpha)\alpha)}$.

In an integrated supply chain, no matter whether a Bertrand or Stackelberg structure, the maximum profit for the supply chain is $\prod^{*}_{(q^{*}_{3D}=0)} SC = \frac{(-\alpha+c_L+c_M)^2}{4\alpha}$*, which is maximized by* $p^{*}_{(q^{*}_{3D}=0,MSC)} = \frac{1}{2}(\alpha + c_L + c_M)$ *and* $p^{*}_{(q^{*}_{3D}=0,3DSC)} = \frac{1}{2}(2 - \alpha + c_L + c_M)$*, and the optimal market demand for the TM product is* $q^{*}_{(q^{*}_{3D}=0,MSC)} = -\frac{-\alpha+c_L+c_M}{2\alpha}$.

Sensitivity Analysis

In this part, this study investigates the impacts of different costs and product customization levels on the new optimal decisions and the maximized profits.

Impact of Costs

PROPOSITION ***4-17.*** *If the logistics vendor uses 3DP as a threat, in a 3DP-enabled decentralized market, no matter whether in Bertrand or in Stackelberg,*

(1) The optimal price of the logistics service decreases in the cost of the TM product and the cost of the logistics service; but the optimal price of the TM and 3DP product increases in them;

(2) The optimal market demand for the TM product decreases in the cost of the TM product and the logistics service;

(3) The traditional manufacturer's and the logistics vendor's maximized profits decrease in the cost of the logistics service and TM product.

In a 3DP-enabled integrated market,

(4) The optimal price of the TM and 3DP product increase in the cost of the TM product and the cost of the logistics service;

(5) The optimal market demand for the TM product decreases in the cost of the TM product and the logistics service;

(6) The whole system's maximized profits decrease in the cost of the logistics service and TM product.

The above proposition demonstrates that the different costs involved have the same impacts on the optimal decisions as ***PROPOSITION*** **4-5**. Therefore, although the logistics vendor uses the 3DP service as a threat for the purpose of market competitiveness, the impacts of the cost reduction on the equilibrium system are the same.

Impact of Product Customization Level

Due to the complexity of the optimal decisions, closed-form solutions investigating the impact of product customization level are not achievable under this kind of supply chain system. Thus, in this section, this model uses numerical tests for analysis by creating three different values for 2 different costs, (c_L, c_M) namely low, medium, and high (Table 4-4), followed by a depiction of the optimal prices and quantities for each parameter for different scenarios.

Table 4-4 Parameter Values in the Numerical Testing of the Impacts of Customization on the Optimal Decisions for 3DP as a Market Threat

	c_L	c_M
Low	0.2	0.1
Medium	0.3	0.4
High	0.7	0.6

PROPOSITION ***4-18.*** *If the logistics vendor uses 3DP as a threat, in a 3DP-enabled decentralized market, no matter whether in Bertrand or in Stackelberg,*

(1) The optimal price of the logistics service and the TM product increase in the product customization level of the TM product, but the optimal price of the 3DP product decreases in it;

(2) The optimal market demand for the TM product increases in the TM product customization level;

(3) There exists a threshold value of the TM product customization level; the traditional manufacturer's maximized value first increases and then decreases;

(4) The maximized profit of the logistics vendor increases in the TM product customization level.

In a 3DP-enabled integrated market,

(5) The optimal price of the TM product increases in the product customization level of the TM product and the 3DP product price decreases in it;

(6) The optimal market demand for the TM product increases in the TM product customization level;

(7) The whole system's maximized profit increases in the TM product customization level.

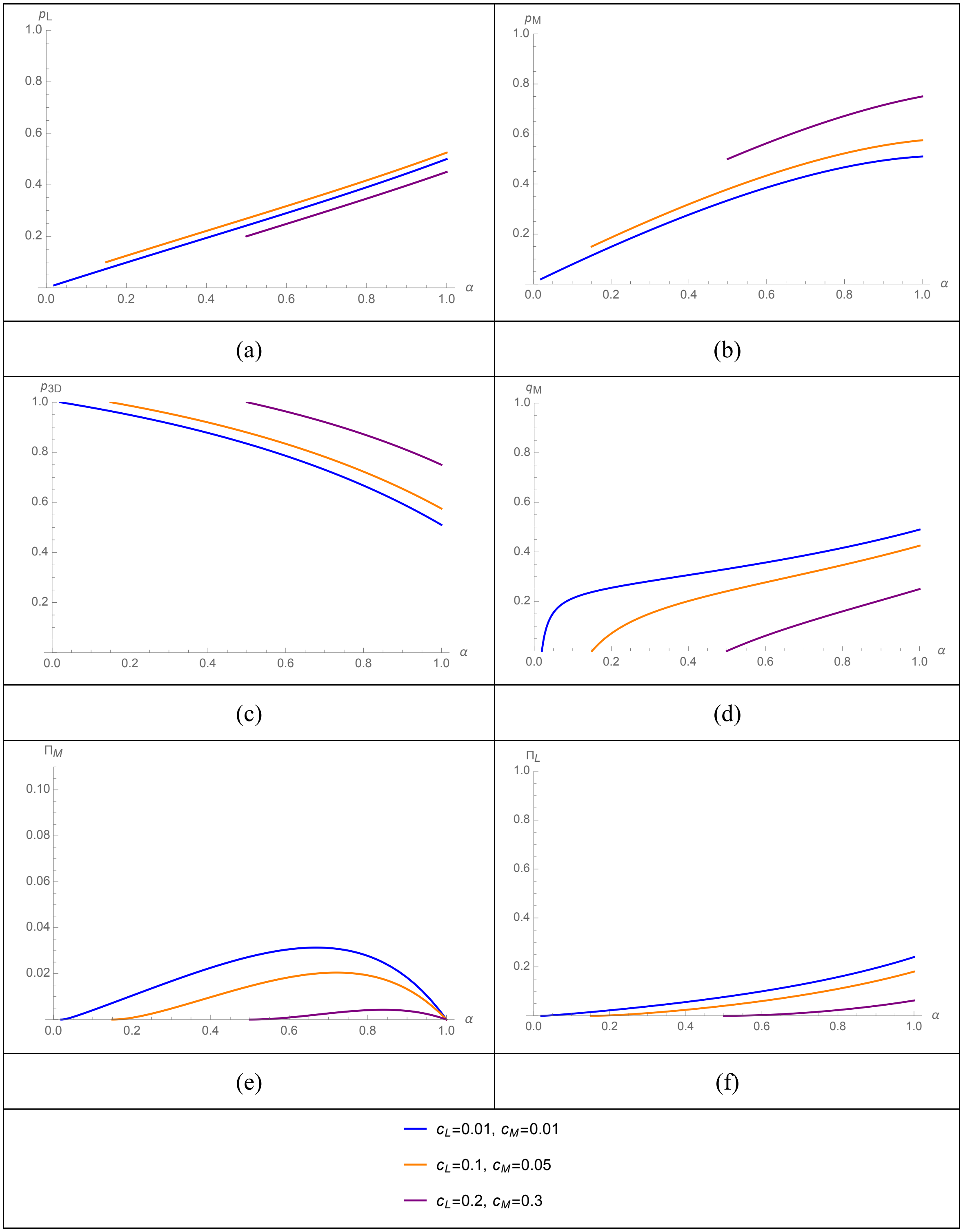


Figure 4-13 Impact of Product Customization on the Optimal Decisions – Bertrand

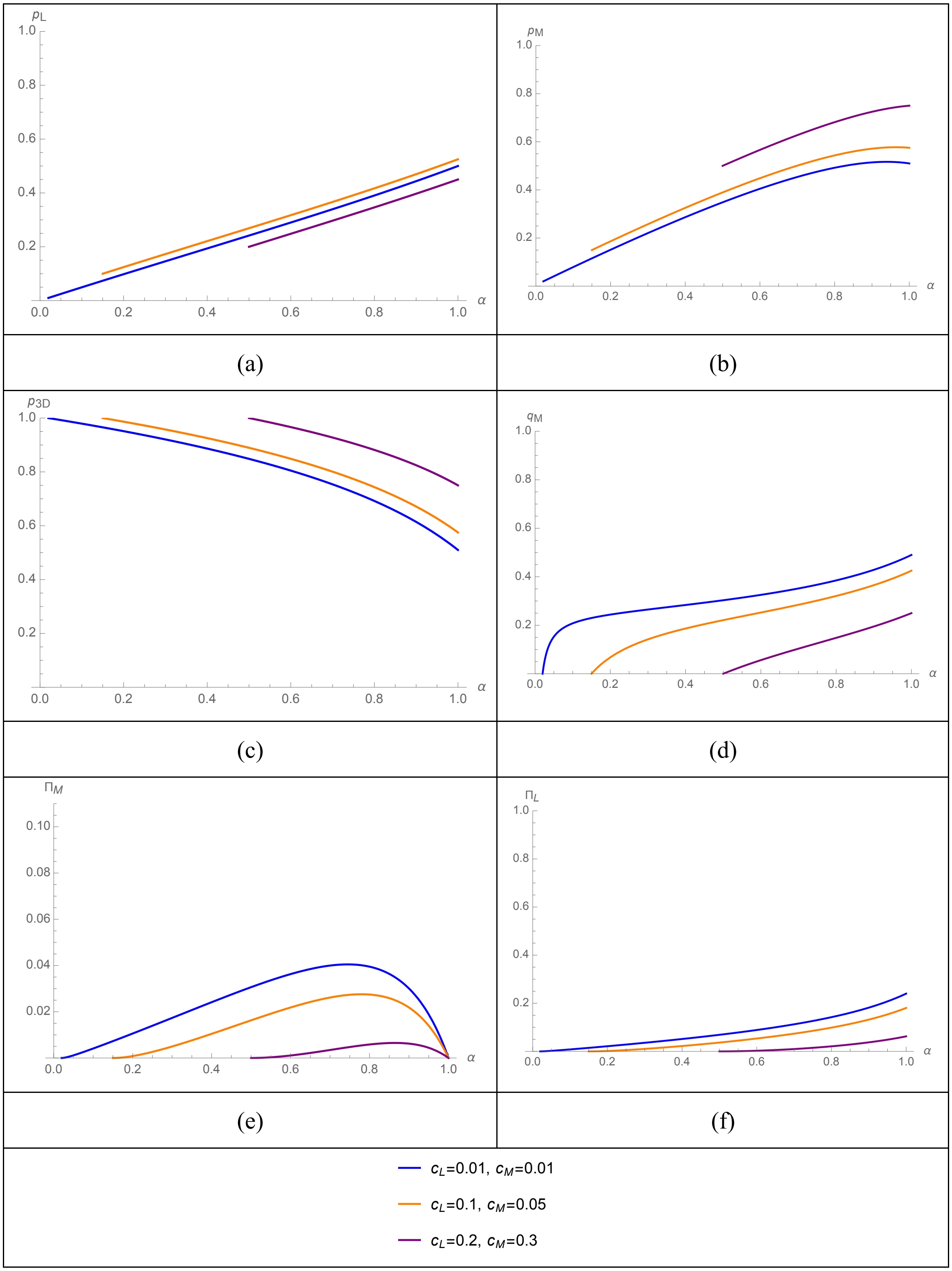


Figure 4-14 Impact of Product Customization on the Optimal Decisions – Stackelberg

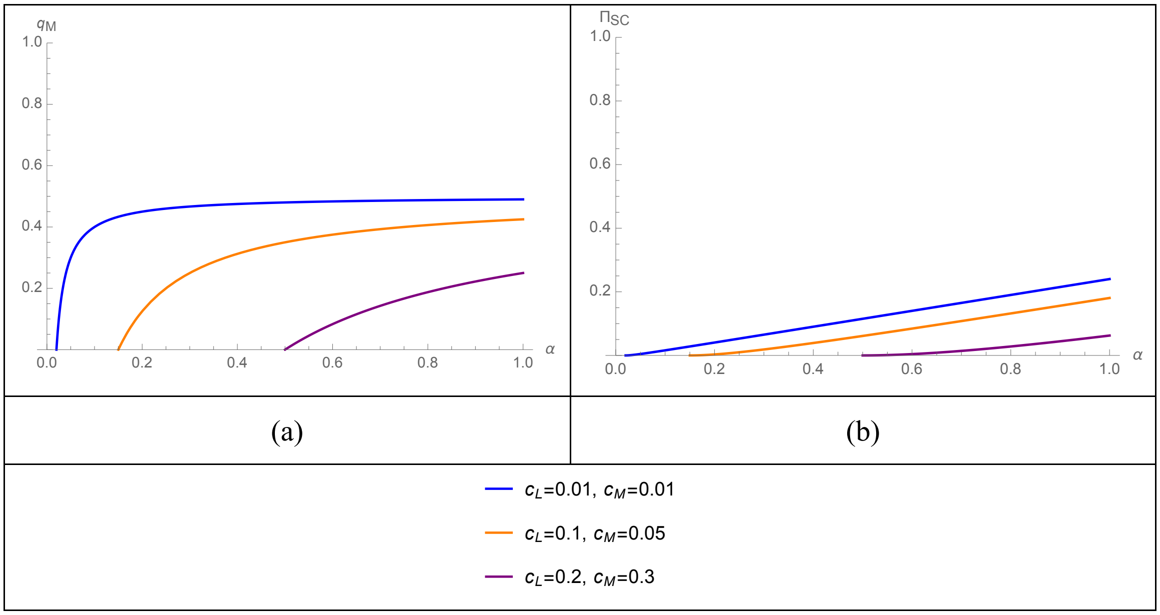


Figure 4-15 Impact of Product Customization on the Optimal Decisions – Integrated Supply Chain

The properties described in (1), (2), (5), and (6) are straightforward. Because lowering the TM product customization level results in a higher relative customization level of the 3DP product, the logistics vendor raises its 3DP product price for the purpose of creating a product image emphasising its uniqueness. Therefore, the traditional manufacturer has to use lower price to enhance its market competitiveness. Because there are some consumers sensitive to product customization who switch and buy the 3DP product, the actual equilibrium market demand for the TM product declines. Consequently, the logistics vendor loses its profits from traditional goods delivery. However, if the product customization level of the TM product is similar to that of the 3DP product, introducing a new 3DP product has a positive impact on the traditional manufacturer's profits. Although the traditional manufacturer uses a low-price regime and the market demand for the TM product drops, the logistics vendor also charges less for product delivery. Therefore, the unit margin of the TM product increases. However, if the customization level of the 3DP product is higher, the traditional manufacturer has to use a lower price to maintain its market share, but this results in less profit. Taking all these scenarios into consideration, if the logistics vendor uses a 3DP service with a higher customization level as a threat, both the market demand for and the price of the TM product drop, and the supply chain cannot achieve better profitability.

Comparative Analysis

This section compares the optimal decisions and maximized profits with those earned by the traditional manufacturer and the logistics vendor in the benchmarking system (traditional manufacturing system) and the 3DP-enabled Bertrand and Stackelberg system, yielding the following outcomes:

PROPOSITION *4-19.* *If the logistics vendor uses 3DP as a threat, in comparison with the traditional manufacturing system,*

(1) *The maximized profit of the logistics vendor increases;*

(2) *Under a Bertrand market, if* $0 < \alpha < -6 - \frac{25(1-i\sqrt{3})}{2(-109+12i\sqrt{26})^{1/3}} - \frac{1}{2}(1 + i\sqrt{3})(-109 + 12i\sqrt{26})^{1/3}$*, the maximized profit of the traditional manufacturer increases; otherwise, it decreases. Under a Stackelberg market, if* $0 < \alpha < \frac{14}{3} - \frac{97(1-i\sqrt{3})}{6(881+24i\sqrt{237})^{1/3}} - \frac{1}{6}(1 + i\sqrt{3})(881 + 24i\sqrt{237})^{1/3}$*, the maximized profit of the traditional manufacturer increases; otherwise, it decreases.*

(3) *The optimal price of the logistics delivery service and the TM product decrease;*

(4) *The market demand for the TM product increases.*

There are no differences in the optimal decisions and maximized supply chain profit at the integrated supply chain level.

So, if the logistics vendor uses 3DP as a threat, for the purpose of maximizing the actual profit from product delivery, the logistics vendor uses a low-price regime. Considering the low delivery service charge and the threat of the new 3DP product, naturally the traditional manufacturer decreases the price of the TM product and gains more price-sensitive consumers. Therefore, the logistics vendor can gain more profits from the increased use of its goods delivery service. However, if the customization level of the TM product is low, which means the 3DP product has a significant advantage in terms of its product customization level, the traditional manufacturer uses a lower TM product price and more price-sensitive consumers buy the TM product. Therefore, the profit of the traditional manufacturer increases. If the customization level of the TM product is high, the traditional manufacturer does not choose to sacrifice the unit price margin, which results in lower market demand for the TM product, compared to the previous scenario. As a result, the traditional manufacturer cannot gain more profits. Overall, the maximized profits and the optimal decisions stay at the same level, because there is no actual 3DP product to be found in the market.

PROPOSITION *4-20.* *If the logistics vendor uses 3DP as a threat, under the 3DP-enabled decentralized Bertrand manufacturing system,*

(1) If $\frac{c_L+c_M}{\alpha} < c_{3D} < \frac{(-1+\alpha)(8+\alpha)-6(c_L+c_M)}{-8+\alpha+\alpha^2}$*, the price of the logistics delivery and the profit of the logistics vendor decrease while the price of the TM and 3DP product, the market demand for the TM product and the traditional manufacturer's profit increase;*

(2) If $\frac{(-1+\alpha)(8+\alpha)-6(c_L+c_M)}{-8+\alpha+\alpha^2} < c_{3D} < \frac{(-1+\alpha)(8+\alpha)(-8+(-1+\alpha)\alpha)-2(-8+(-5+\alpha)\alpha)(c_L+c_M)}{(-8+\alpha+\alpha^2)(-8+\alpha(3+\alpha))}$*, the price of the logistics vendor and the profit of the logistics vendor increase but the price of the TM and 3DP product, the market demand for the TM product and the traditional manufacturer's profit decline;*

(3) If $\frac{(-1+\alpha)(8+\alpha)(-8+(-1+\alpha)\alpha)-2(-8+(-5+\alpha)\alpha)(c_L+c_M)}{(-8+\alpha+\alpha^2)(-8+\alpha(3+\alpha))} < c_{3D} < 1$*, the price of the logistics vendor increases but the price of the TM and 3DP product, the market demand for the TM product, the traditional manufacturer's profit, and the profit of the logistics vendor decline.*

Under the 3DP-enabled decentralized Stackelberg manufacturing system,

(4) If $\frac{c_L+c_M}{\alpha} < c_{3D} < \frac{(-1+\alpha)(8+(-5+\alpha)\alpha)-(-4+\alpha)(-3+\alpha)(c_L+c_M)}{-8+\alpha+\alpha^2}$*, the price of the logistics delivery and the profit of the logistics vendor decrease while the price of the TM and 3DP product, the market demand for the TM product and the traditional manufacturer's profit increase;*

(5) If $\frac{(-1+\alpha)(8+(-5+\alpha)\alpha)-(-4+\alpha)(-3+\alpha)(c_L+c_M)}{-8+\alpha+\alpha^2} < c_{3D} < \frac{-(-1+\alpha)(8+(-5+\alpha)\alpha)+(-3+\alpha)(-2+\alpha)(c_L+c_M)}{8+(-7+\alpha)\alpha}$*, the profit of the logistics vendor decreases while the price of the logistics delivery, the price of the TM and 3DP product, the market demand for the TM product and the traditional manufacturer's profit increase;*

(6) If $\frac{-(-1+\alpha)(8+(-5+\alpha)\alpha)+(-3+\alpha)(-2+\alpha)(c_L+c_M)}{8+(-7+\alpha)\alpha} < c_{3D} < \frac{(-1+\alpha)(-8+5\alpha)(8+(-5+\alpha)\alpha)-(-2+\alpha)(8+3(-3+\alpha)\alpha)(c_L+c_M)}{(8+(-7+\alpha)\alpha)(8+\alpha(-9+2\alpha))}$*, the price of the logistics vendor and the profit of the logistics vendor increase but the price of the TM and 3DP product, the market demand for the TM product and the traditional manufacturer's profit decline;*

(7) If $\frac{(-1+\alpha)(-8+5\alpha)(8+(-5+\alpha)\alpha)-(-2+\alpha)(8+3(-3+\alpha)\alpha)(c_L+c_M)}{(8+(-7+\alpha)\alpha)(8+\alpha(-9+2\alpha))} < c_{3D} < 1$*, the price of the logistics vendor increases but the price of the TM and 3DP product, the market demand for the TM product, the traditional manufacturer's profit, and the profit of the logistics vendor decline.*

Under the 3DP-enabled integrated manufacturing system,

(8) The overall profit of the supply chain decreases;

(9) There is no difference in the price of the TM product;

(10) If $\frac{c_L+c_M}{\alpha} < c_{3D} < 1-\alpha+c_L+c_M$*, the price of the 3DP product and the market demand for the TM product increase; if the cost of the 3DP product exceeds this level, the price of the 3DP product and the market demand for the TM product decrease.*

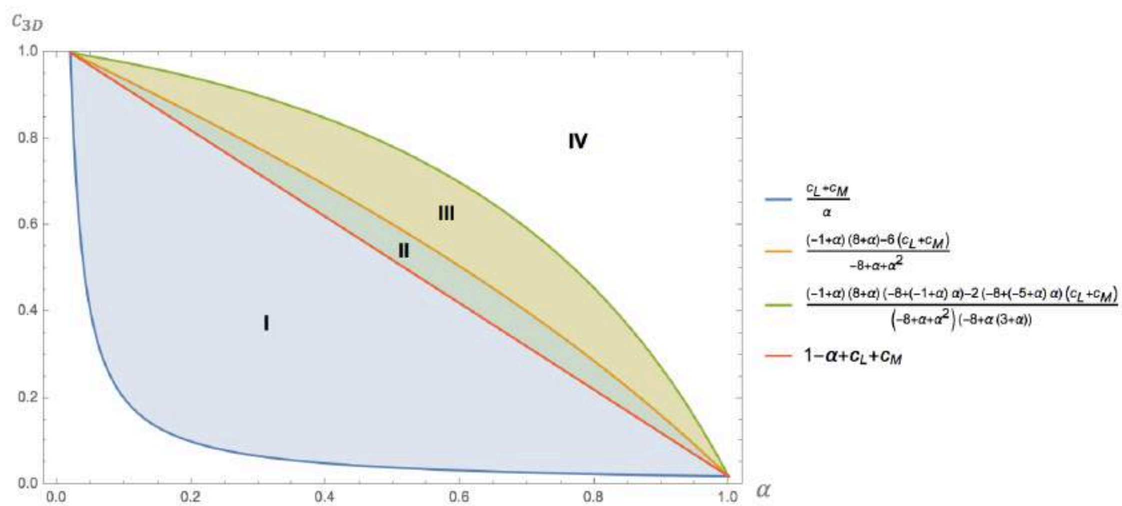


Figure 4-16 Comparison of the Bertrand Market under Different Threat Strategies (given $c_L = 0.01$, $c_M = 0.01$)

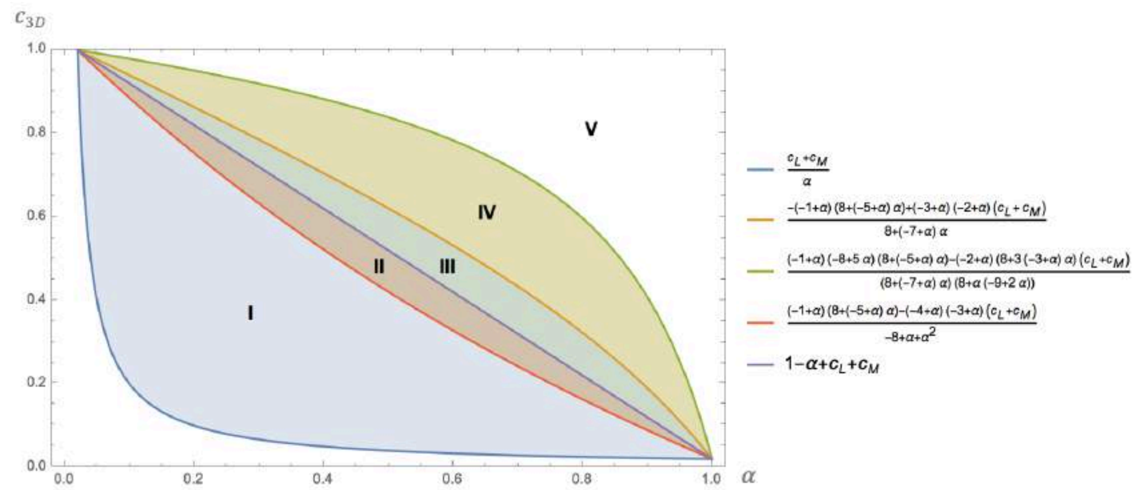


Figure 4-17 Comparison of the Stackelberg Market under Different Threat Strategies (given $c_L = 0.01$, $c_M = 0.01$)

In the decentralized market, when the cost of the 3DP product is low (Region I and II in Figure 4-16 or Region I in Figure 4-17), the logistics vendor uses a low price regime for its logistics delivery service for the purpose of increasing the demand for TM product delivery. Because the logistics vendor is not actually providing the 3DP product, it uses a high 3DP price strategy to push price-sensitive consumers to buy the TM product. This offers room to the traditional manufacturer to also use a high price regime for the purpose of maximizing its profit. Consequently, the traditional manufacturer gains more profits, but the logistics vendor loses profits due to the reduced margin per delivery. If the cost of the 3DP product is located in Region II and III in Figure 4-17 for the Stackelberg decentralized market, the logistics vendor uses a higher price for its delivery service for the purpose of maximizing its profits and this pushes the traditional manufacturer to use a high price to increase the product's profit margin. Then, the logistics vendor who prices the 3DP product later uses a high price regime to help the traditional manufacturer gain more price-sensitive consumers. These pricing strategies result in an increase in the traditional manufacturer's profit and a decrease in the logistics vendor's profit, because the logistics vendor cannot make profits from the 3DP product. If the cost of the 3DP product is located in Region III in Figure 4-16 or Region IV in Figure 4-17, the logistics vendor uses a higher price for the logistics delivery in order to achieve a greater margin per unit. The logistics vendor uses low pricing to irritate the traditional manufacturer into also using low TM pricing to attract more consumers to buy the TM product. But due to the low price of the 3DP product, some customization-sensitive consumers shift to buying the 3DP product. However, because there is no actual 3DP product, they leave the market. Therefore, the market demand for the TM product drops and the traditional manufacturer loses profits. However, the logistics vendor benefits from the high logistics delivery pricing strategy. Lastly, if the cost of the 3DP product is in Region IV in Figure 4-16 or Region V in Figure 4-17, the logistics vendor also uses a high price for the delivery service for the purpose of maximizing its actual profits. Both the logistics vendor and the traditional manufacturer use a low-price strategy in order to increase the market demand for the TM product among price-sensitive consumers. However, due to the low 3DP product price, more price-sensitive consumers shift to buying the 3DP product, but because they cannot buy the 3DP product from the logistics vendor, they then have to leave the market. As a result, not only the traditional manufacturer but also the logistics vendor loses profit under the sinking market demand.

For the integrated 3DP supply chain, because of the cooperation, the traditional manufacturer keeps the same price for the TM product. With regard to the logistics vendor, if the cost of the 3DP product is low (Region I in Figure 4-16 or Region I and II in Figure 4-17), the logistics vendor uses a high price regime to push more customers to buy the TM product. If the cost of the 3DP product is high (Region II, III, and IV in Figure 4-16 or Region III, IV, and V in Figure 4-17), the logistics vendor prices the 3DP product low for the purpose of attracting more consumers into the market, just in case they may buy the TM product after they find out there is not a 3DP product in the market. However, some price-sensitive consumers who previously entered the market to buy the TM product change and wish to buy the 3DP product and leave the market with empty hands, because there is no 3DP product in the market. Therefore, this strategy results in a decline in market demand for the TM product. Overall, because the supply chain cannot generate profit from the 3DP product, this threat strategy has a negative impact on the system's profitability.

4.4 Consumer Surplus

In this section, this model tries to assess the impacts of different types of 3DP adoption on the consumer surplus. The first part focuses on the analysis of the impacts and then investigates how consumers are affected by 3DP adoption.

For the traditional manufacturing system, there is only the TM product in the market. Therefore, by considering the individual consumer's expected surplus on the TM product (Mussa & Rosen, 1978),

$$CS_{3DN} = \int_{p_M^*}^{1} (\alpha v - p_M^*)\, dv$$

The optimal price of the decentralized TM product is $p_M^* = \frac{1}{4}(3\alpha + c_L + c_M)$, and therefore the consumer surplus is

$$CS_{3DND} = -\frac{1}{32}(-4 + 3\alpha + c_L + c_M)(\alpha(-2 + 3\alpha) + (-2 + \alpha)(c_L + c_M)) \tag{4.13}$$

In the integrated traditional manufacturing system, the optimal price of the TM product is $p_M^* = \frac{1}{2}(\alpha + c_L + c_M)$, and so the consumer surplus is

$$CS_{3DNI} = -\frac{1}{8}(-2+\alpha+c_L+c_M)(\alpha^2+(-2+\alpha)(c_L+c_M)) \tag{4.14}$$

Next, after the logistics vendor adopts 3DP, we derive the expected surplus in the 3DP manufacturing system from the total consumer perspective:

$$CS_{3D} = \int_{p_M^*}^{1} (\alpha v - p_M^*)\, dv + \int_{p_{3D}^*}^{1} (v - p_{3D}^*)\, dv$$

By considering the different games, we have the following. Under the decentralized Bertrand market, the optimal product prices are $p_M^* = \frac{\alpha(8+\alpha)+\alpha(4+\alpha)c_{3D}+4c_L+4c_M}{2(8+\alpha)}$ and $p_{3D}^* = \frac{8+\alpha+(8+3\alpha)c_{3D}-2c_L-2c_M}{2(8+\alpha)}$.

$$\begin{aligned} CS_{3DB} = \frac{1}{8(8+\alpha)^2}&((8+\alpha-(8+3\alpha)c_{3D}+2c_L+2c_M)^2-((-2+\alpha)(8+\alpha) \\ &+\alpha(4+\alpha)c_{3D}+4c_L+4c_M)(\alpha^2(8+\alpha)+(-2+\alpha)\alpha(4+\alpha)c_{3D} \\ &+4(-2+\alpha)c_L+4(-2+\alpha)c_M)) \end{aligned} \tag{4.15}$$

In the decentralized Stackelberg market, the optimal product prices are

$p_M^* = \frac{\alpha(8+(-5+\alpha)\alpha)-(-4+\alpha)\alpha c_{3D}+(-2+\alpha)^2c_L+(-2+\alpha)^2c_M}{2(8+(-5+\alpha)\alpha)}$,

and $p_{3D}^* = \frac{8+(-5+\alpha)\alpha+(8-3\alpha)c_{3D}+(-2+\alpha)c_L+(-2+\alpha)c_M}{2(8+(-5+\alpha)\alpha)}$.

$$\begin{aligned} CS_{3DS} = \frac{1}{8(8+(-5+\alpha)\alpha)^2}&((8+(-5+\alpha)\alpha+(-8+3\alpha)c_{3D}-(-2+\alpha)c_L \\ &-(-2+\alpha)c_M)^2-2(\alpha(8+(-5+\alpha)\alpha)-(-4+\alpha)\alpha c_{3D} \\ &+(-2+\alpha)^2c_L+(-2+\alpha)^2c_M)((-4+\alpha)\alpha c_{3D}-(-2+\alpha)(8 \\ &+(-5+\alpha)\alpha+(-2+\alpha)c_L+(-2+\alpha)c_M)) \\ &+\alpha(4(8+(-5+\alpha)\alpha)^2 \\ &-(\alpha(8+(-5+\alpha)\alpha)-(-4+\alpha)\alpha c_{3D}+(-2+\alpha)^2c_L \\ &+(-2+\alpha)^2c_M)^2)) \end{aligned} \tag{4.16}$$

For the integrated 3DP-enabled supply chain, the optimal product prices are $p_M^* = \frac{1}{2}(\alpha + c_L + c_M)$ and $p_{3D}^* = \frac{1}{2}(1 + c_{3D})$.

$$CS_{3D} = \frac{1}{8}(1 - 2c_{3D} + c_{3D}^2 - (-2 + \alpha + c_L + c_M)(\alpha^2 + (-2 + \alpha)c_L + (-2 + \alpha)c_M)) \quad (4.17)$$

Lastly, for the fully 3DP-based system, the expected surplus is,

$$CS_{F3D} = \int_{p_{3D}^*}^{1} (v - p_{3D}^*)\, dv$$

The optimal product price is $p_{3D}^* = \frac{1}{2}(1 + c_{3D})$.

$$CS_{F3D} = \frac{1}{8}(-1 + c_{3D})^2 \quad (4.18)$$

4.4.1 Sensitivity Analysis

In the following subsections, this model tests the impacts of the different costs and product customization levels on the consumer surplus under different market structures.

Impact of Costs

PROPOSITION *4-21.*

(1) In a decentralized or integrated traditional manufacturing market, the consumer surplus decreases in the cost of the TM product and the logistics service cost.

(2) In a decentralized Bertrand market, after the logistics vendor adopts 3DP technology,

a. If $c_{3D} > \frac{-24+\alpha(47-2\alpha(10+\alpha))}{8+\alpha(-13+2\alpha(2+\alpha))}$, *the consumer surplus decreases in the cost of the logistics delivery service and the TM product;*

b. If $c_{3D} < \frac{-24+\alpha(47-2\alpha(10+\alpha))}{8+\alpha(-13+2\alpha(2+\alpha))}$, *when* $c_M < \frac{-(8+\alpha)(3+2(-2+\alpha)\alpha)-(8+\alpha(-13+2\alpha(2+\alpha)))c_{3D}+(18-8\alpha)c_L}{-18+8\alpha}$, *the consumer surplus* *decreases in the cost of the logistics delivery service and the TM product; otherwise it increases in them.*

c. *If* $\frac{c_L+c_M}{\alpha} < c_{3D} < -\frac{(8+\alpha)(8+\alpha(11+\alpha(-6+\alpha(2+\alpha))))+2(8+\alpha(-13+2\alpha(2+\alpha)))(c_L+c_M)}{-64+\alpha(-48-41\alpha+6\alpha^3+\alpha^4)}$, *the consumer surplus decreases in the cost of the 3DP product; otherwise it increases in the cost of the 3DP product.*

(3) In a decentralized Stackelberg market, after the logistics vendor adopts 3DP technology,

a. *If* $c_{3D} > \frac{(3+(-3+\alpha)\alpha)(-8+\alpha(19+\alpha(-11+2\alpha)))}{8+\alpha(-19+\alpha(20+(-8+\alpha)\alpha))}$, *the consumer surplus decreases in the cost of the logistics delivery service and the TM product;*

b. *If* $c_{3D} < \frac{(3+(-3+\alpha)\alpha)(-8+\alpha(19+\alpha(-11+2\alpha)))}{8+\alpha(-19+\alpha(20+(-8+\alpha)\alpha))}$, *when* $c_M < \frac{1}{(-3+\alpha)(-2+\alpha)(3+(-3+\alpha)\alpha)\alpha}((8+\alpha(-19+\alpha(20+(-8+\alpha)\alpha)))c_{3D} - (3+(-3+\alpha)\alpha)((-1+\alpha)(8+(-5+\alpha)\alpha)+(-3+\alpha)(-2+\alpha)c_L))$, *the consumer surplus decreases in the cost of the logistics delivery service and the TM product; otherwise it increases in them.*

c. *If* $\frac{c_L+c_M}{\alpha} < c_{3D} < \frac{1}{-64+\alpha(48+\alpha(-41+\alpha(32+(-10+\alpha)\alpha)))}((8+(-5+\alpha)\alpha)(-8+(-1+\alpha)\alpha(5+(-5+\alpha)\alpha))+(-2+\alpha)(8+\alpha(-19+\alpha(20+(-8+\alpha)\alpha)))(c_L+c_M))$, *the consumer surplus decreases in the cost of the 3DP product; otherwise it increases in the cost of the 3DP product.*

(4) In an integrated 3DP-enabled market, the consumer surplus decreases in the cost of the TM and 3DP product and the cost of the logistics service.

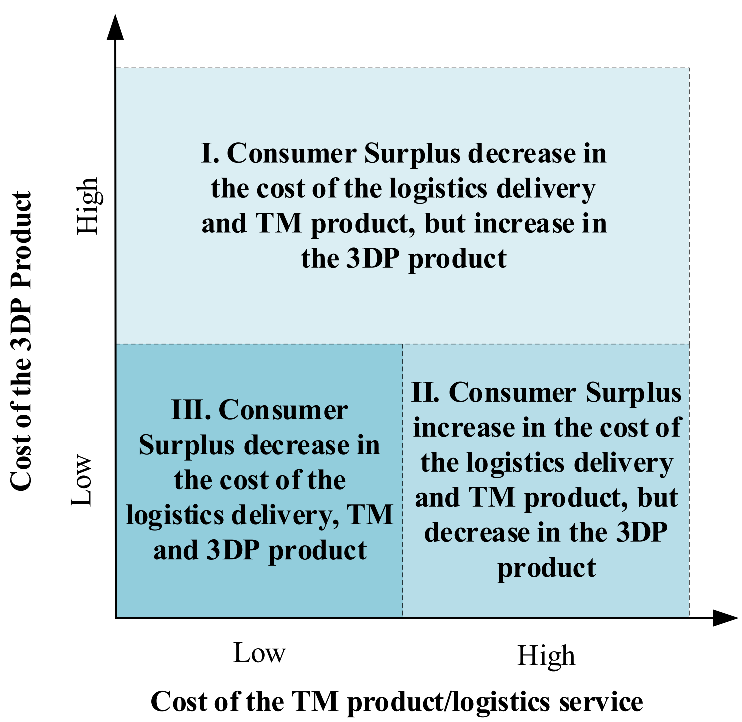


Figure 4-18 Impact of Costs on Consumer Surplus – Decentralized Market

In the traditional manufacturing market, the consumer surplus decreases in the cost of the TM product and the logistics delivery cost, because the optimal prices increase in these costs. This is also applicable to the integrated 3DP-enabled supply chain. Therefore, cost reduction helps the consumer gain more surplus, which is quite straightforward. However, in a decentralized market, after the logistics vendor introduces the 3DP product into the market, based on ***PROPOSITION* 4-5**, the TM product price increases in c_M, c_L and c_{3D}, whilst the 3DP product price decreases in c_M and c_L, but increases in c_{3D}. In ***PROPOSITION* 4-21**, there are three different market structures (Figure 4-18).

(1) When the cost of the 3DP product is high (Region I), if the cost of the TM product and delivery service reduce, for the purpose of maximizing the profit, the traditional manufacturer uses a low pricing strategy to increase market demand, but the logistics vendor uses a high price regime to increase the unit price margin. Therefore, the consumer can enjoy more surplus on the cost reduction of c_M and c_L, but loses surplus due to the cost reduction of c_{3D}.

(2) In Region II, the cost of the 3DP product is low but the cost of the TM product and the logistics service is high. Therefore, the consumer values the 3DP product less than Region I. Therefore, the cost reduction of the c_M and c_L contribute to the low TM product price, which results in a higher consumer surplus for the TM product, but consumers' willingness to pay for the 3DP product becomes lower. Thus, the consumer cannot benefit from the cost reduction on the TM product and the logistics delivery cost. However, if the cost of the 3DP product reduces, both the price of the TM and 3DP product reduce, and the consumer can enjoy more surplus.

(3) Under Region III, all the relevant costs are low. Cost reduction on the TM product and the logistics delivery service help the consumer generate more consumer surplus from the TM product, although the consumer surplus on the 3DP product drops due to the increase in the 3DP product price. Meanwhile, if there is a cost reduction of the 3DP product, it brings more consumer surplus because of the low price of both the TM and 3DP product.

PROPOSITION ***4-22.*** *In a fully 3DP-based system, the consumer surplus is increased in the cost of the 3DP product.*

It is straightforward that for a market only offering the 3DP product, a cost reduction results in the logistics vendor using a low pricing strategy to increase market demand and maximize the total profit.

Impact of Product Customization Level

Here, again due to the complexity of the consumer surplus functions, it is difficult to gain direct insights into how they are impacted by the product customization level. Therefore, this subsection also uses the numerical tests with the same settings as in Table 4-3 of section 4.3.1 for the 3DP-enabled system. For the traditional manufacturing system, another three different values for the cost of the TM product and the logistics delivery service at low, medium and high levels have been created as shown below:

Table 4-5 Parameter Values in the Numerical Testing of the Impacts of Customization on the Optimal Decisions under the Traditional Manufacturing Market and the Integrated 3DP-Enabled Supply Chain Market

	c_L	c_M
Low	0.1	0.15
Medium	0.2	0.35
High	0.3	0.4

PROPOSITION ***4-23.***

(1) *In a traditional manufacturing market and a 3DP-enabled integrated market, the consumer surplus increases in the TM product customization level;*

(2) *In a 3DP-enabled decentralized market, the consumer surplus is first concave in the TM product customization level and then convex in the TM product customization level.*

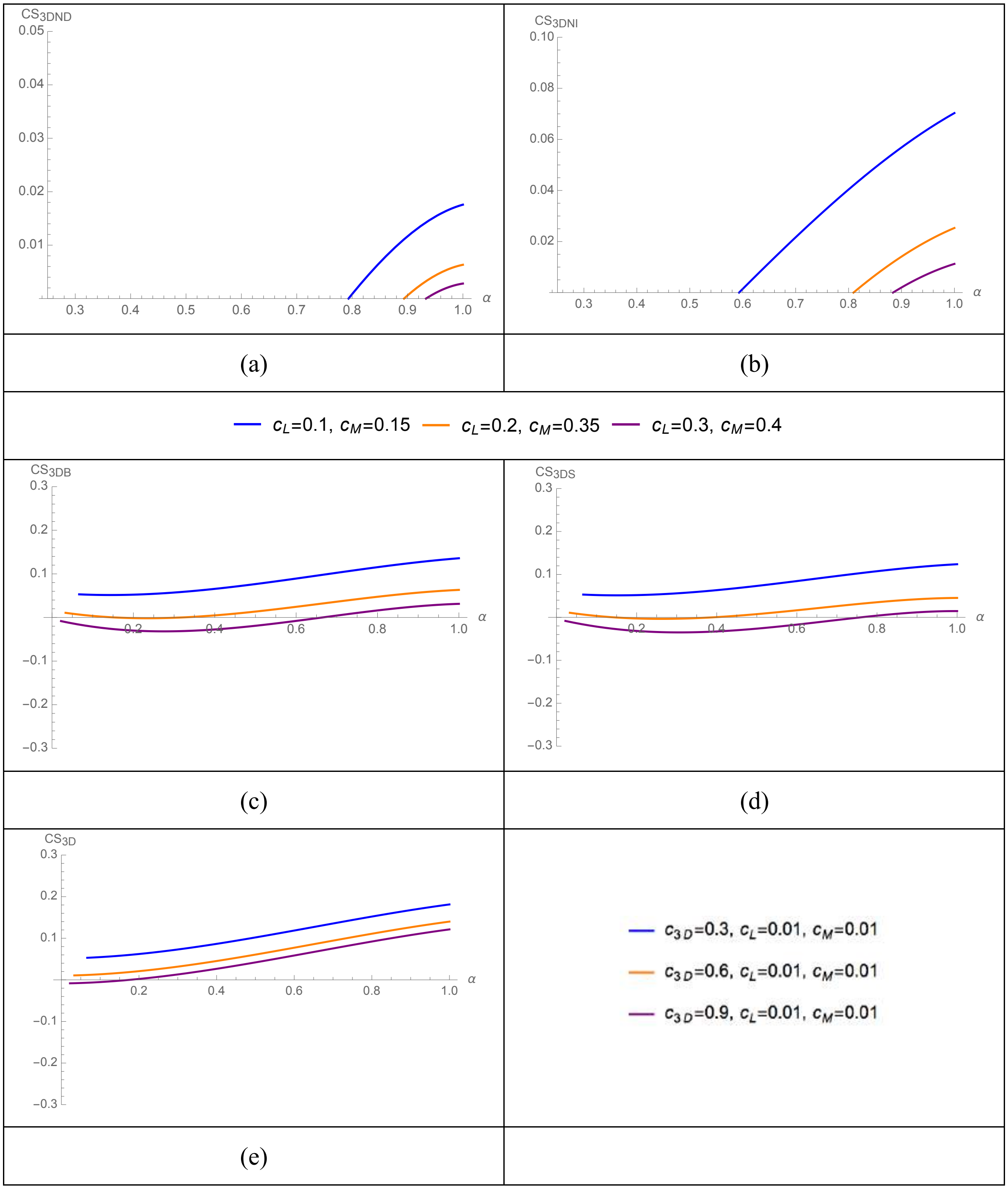


Figure 4-19 The Impact of the TM Product Customization Level on the Consumer Surplus

Firstly, it is obvious that in the traditional manufacturing system (Figure 4-19 (a) and (b)), the higher the customization level, the greater the consumer surplus. Secondly, in the 3DP-enabled decentralized supply chain (Figure 4-19 (c) for the Bertrand market and (d) for the Stackelberg market), according to *PROPOSITION* 4-9, the TM and 3DP product price increase in the 3DP product customization level. As such, the impact of the product customization level could be summarized into three different scenarios. When the customization level of the 3DP product is extremely low (the customization level of the TM product α is high; the customization level of the 3DP product and the TM product are similar), the improvement of the 3DP product's customization level results in the optimal price dropping, and therefore the consumer benefits from this 3DP product customization level improvement. If the logistics vendor continues to improve the product customization level of the 3DP product, although the prices of both products still decline, the consumer can generate less surplus from the TM product. Thus, the consumer gains less consumerization. If the product customization level of the 3DP product is extremely high, the consumer benefits from the improvements of the 3DP product customization level because the system can generate more surplus from the low-pricing strategy of both products, and this part of the increased surplus can cover the surplus lost in the decreased willingness to pay for the TM product. Lastly, in the integrated 3DP-enabled market, the improvement of the customization level of the 3DP product results in decreases in the TM and 3DP product price. However, the consumer can gain less surplus from the TM product, and therefore, overall, the customer never benefits from this 3DP product customization level improvement.

4.4.2 Comparative Analysis

This subsection focuses on comparing the consumer surplus between the different systems and obtained the following results.

PROPOSITION *4-24*.

(1) Under the decentralized supply chain, in a Bertrand market, the consumer benefits from this new 3DP adoption if the cost of the 3DP product is high; in a Stackelberg market, the consumer can gain more surplus only when the cost of the 3DP product is low; in general, the consumer enjoys more surplus under the Bertrand market than the Stackelberg market;

(2) Under the integrated supply chain, the consumer can benefit from 3DP adoption by the logistics vendor.

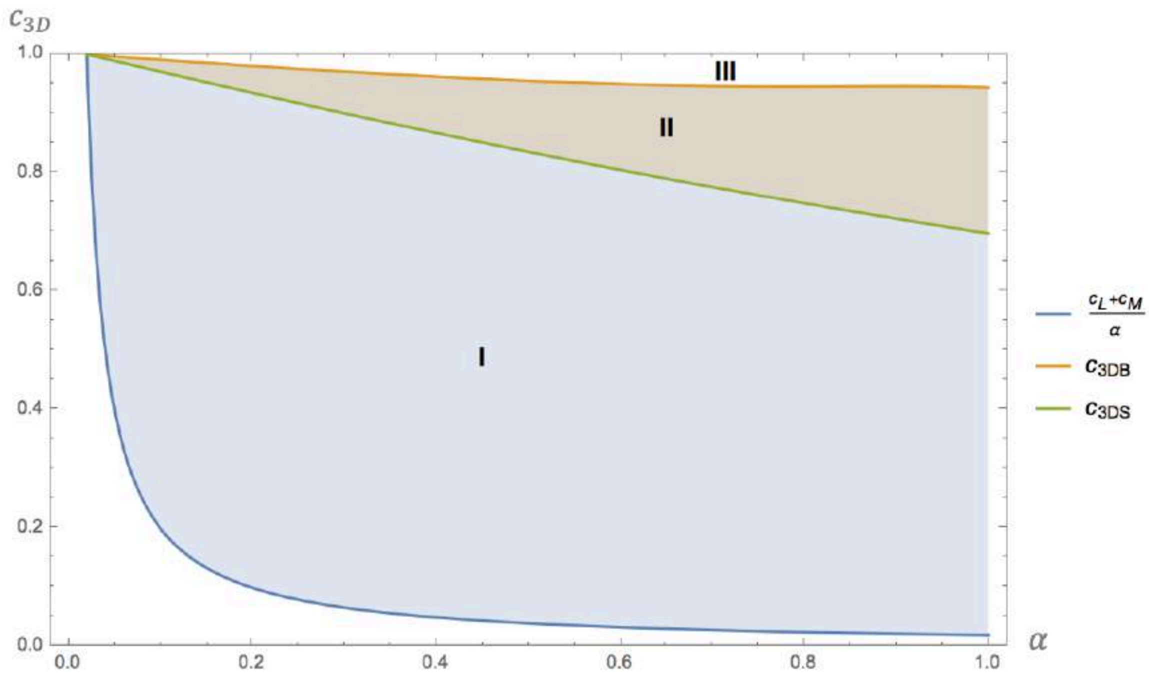


Figure 4-20 Decision Regions for the Comparison of Consumer Surplus – Decentralized Market (given $c_L = 0.01$, $c_M = 0.01$)

Note: the values of c_{3DB} and c_{3DS} are listed in the Proofs of Proposition 4-24.

PROPOSITION 4-24 indicates that, firstly, in a Bertrand market, if the cost of 3DP is low (Region I and II in Figure 4-20), the logistics vendor prices the 3DP product low and this pushes the traditional manufacturer to use a low-price regime to keep its pricing advantages. But the consumer cannot generate more surplus than the market with only a TM product. When the cost of the 3DP product is relatively high (Region III in Figure 4-20), the consumer can gain more surplus than the traditional manufacturing system, because the consumer can gain more consumer surplus from the 3DP product. Secondly, in a Stackelberg market, the logistics vendor prices the 3DP product later. Therefore, if the cost of the 3DP is low (Region I in Figure 4-20), the manufacturer sets the TM product price low to achieve a pricing advantage and the logistics vendor has to use a low pricing strategy. As a result, the consumer can gain more surplus. If the cost of the 3DP is high (Region II and III in Figure 4-20), the traditional manufacturer and the logistics vendor use a high product price on both products, which leads to less consumer surplus. Thirdly, because the logistics vendor prices the 3DP product later in the Stackelberg market, he sets the 3DP product price as high as possible. Therefore, the consumer surplus in the Stackelberg market is less than in the Bertrand market. Lastly, in an integrated market, after the introduction of a new 3DP product into the market by the logistics vendor, the consumer can benefit from the market pricing competition and the new consumer surplus from the 3DP product.

PROPOSITION ***4-25.*** *In a decentralized market, if the logistics vendor uses a fully 3DP-based strategy to replace the TM product, the consumer benefits only if the cost of the 3DP product is low (* $0 < c_{3D} < 1 - \frac{1}{2}\sqrt{-(-4+3\alpha+c_L+c_M)(\alpha(-2+3\alpha)+(-2+\alpha)c_L+(-2+\alpha)c_M)}$ *); otherwise, the consumer loses surplus. Compared to integrated market traditional manufacturing, the consumer benefits from the fully 3DP-based strategy.*

This proposition demonstrates that under a decentralized market, if the cost of the 3DP is low, the logistics vendor uses a low-price regime, and therefore the consumer can enjoy more surplus. Moreover, at the supply chain level, no matter the cost of the 3DP product, the fully 3DP-based strategy always brings more surplus to the consumer through the high product customization.

4.5 Chapter Summary

This chapter uses a model to rigorously investigate the impact of 3DP adoption by the logistics vendor on the supply chain, exploring specifically whether a logistics vendor can use this strategy to seize new business opportunities presented by this disruptive manufacturing technology. To do so, this model considers a change that is occurring in practice, which is receiving significant attention in the media, involving the logistics vendor reckoning with 3DP adoption (UPS, 2017). This model first presents a consumer behaviour model that captures the consumer response to the logistics vendor's 3DP product offering. Using this model, this study derives consumer demand, characterizes patterns of consumer behaviour, and factors them into the logistics vendor's and manufacturer's pricing and financial optimization problem. The following section summarizes important implications of this model analysis so that this model can help companies cope with the 3DP adoption. Several noteworthy implications are discussed below.

Managerial Insights

This model then presents a number of managerial insights on how pricing, cost reduction and product customization level impact the supply chain and then compares the situation before and after the logistics vendor adopts 3DP. The followings are the key insights:

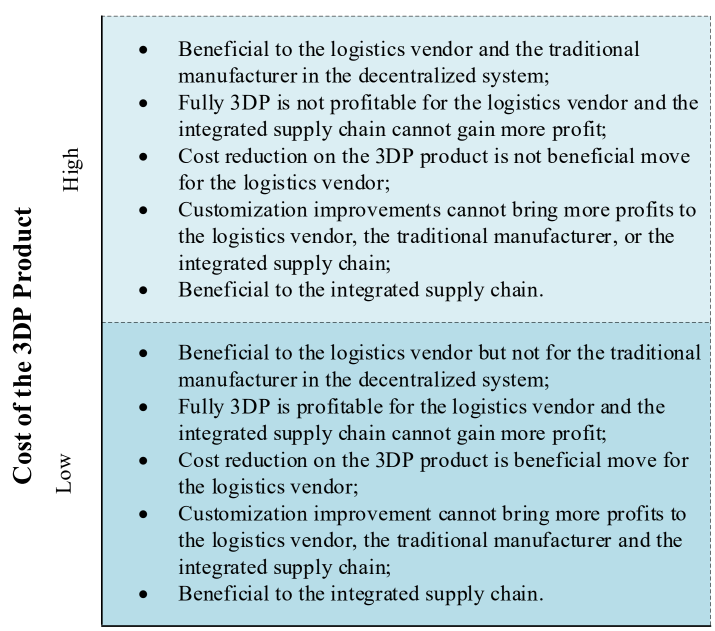


Figure 4-21 Impacts of 3DP Adoption on Profitability

Firstly, 3DP adoption can be used by the logistics vendor to restructure the supply chain (Pooley, 2013; Wohlers Associates, 2018). Pooley (2013) argues that traditional manufacturer might be the best user of the new 3DP technology because they have the advantages on product design and product quality control. Our results indicate that the logistics vendor can take a more active role, enhancing its financial performance and adjusting consumer expectations through this new manufacturing technology. This model also identifies a cost threshold below which 3DP product cost reduction provides more profits to the traditional manufacturer, meaning that the 3DP does not always have a negative impact on the TM industry. The manufacturer can also enjoy a windfall from the vendor's 3DP adoption, so that a win-win situation exists. The results listed in Figure 4-21 also show, however, that selecting a 3DP product with a high customization level does not always help to improve system profitability. In addition, the logistics vendor can achieve more profits in the decentralized Bertrand market than in the decentralized Stackelberg market. Therefore, the vendor must be careful in selecting which product should use 3DP technology; 3DP product customization level and product cost are two important factors, as explained in this chapter.

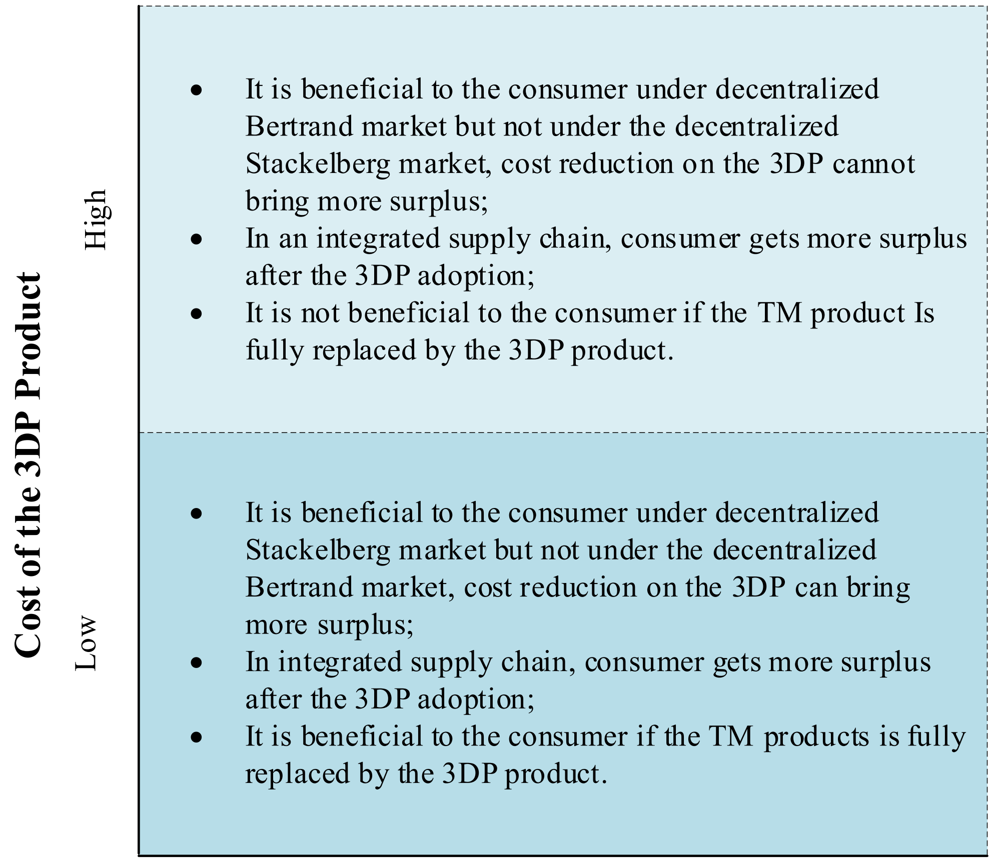


Figure 4-22 Impacts of 3DP Adoption on the Consumer Surplus

Secondly, the analysis in the consumer surplus section suggests that under a decentralized Bertrand market with a high 3DP cost, consumers can also benefit from such 3DP adoption (Figure 4-22). However, under a decentralized Stackelberg market, the consumer can only gain more surplus if the cost of the 3DP product is high. Additionally, the consumer can gain more surplus in the Bertrand market than the Stackelberg market. Therefore, the channel power plays an important role here. This model also shows that such 3DP adoption brings more surplus to the consumer under the integrated market. In addition, if the cost of the 3DP product is low, it is beneficial to the consumer if the logistics vendor can fully replace the TM product with the 3DP product. Thus, overall, 3DP adoption and cost reduction of 3DP are still future research directions for the 3DP industry. This result is congruent with the findings of other studies indicating that cost reduction of the 3DP would help the long-term development of 3DP technology (Ernst & Young, 2016; Wohlers Associates, 2018).

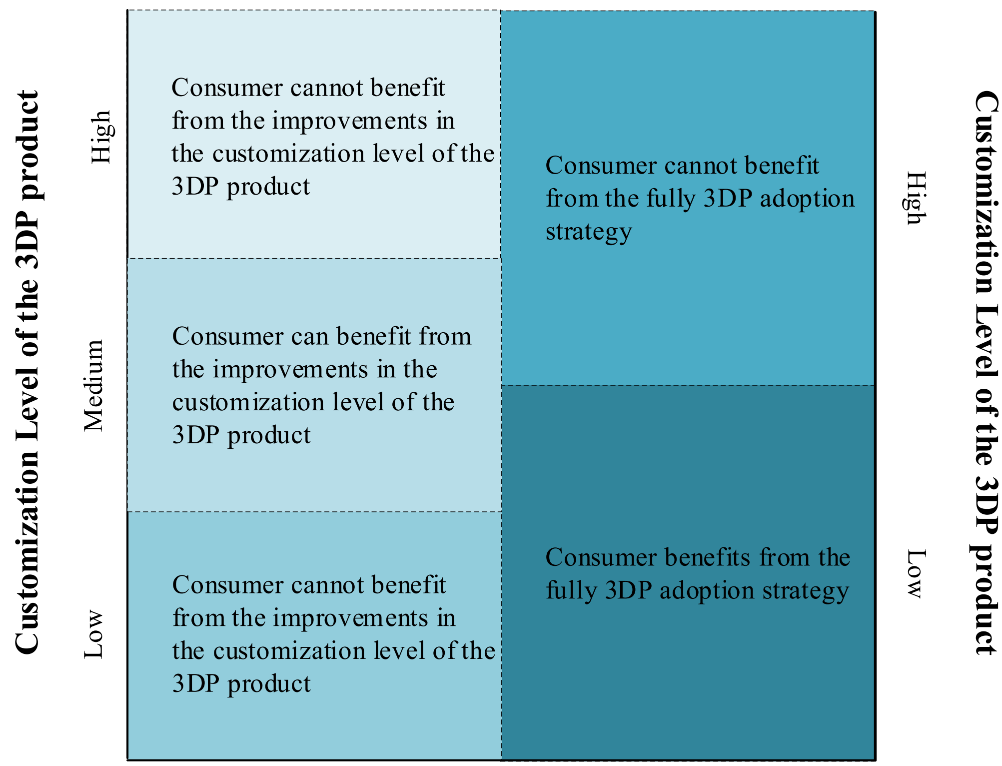


Figure 4-23 Impacts of the Product Customization Level on Consumer Surplus

Thirdly, as summarized in Figure 4-23 above, with regard to customization improvements, under the decentralized 3DP-enabled market, the consumer can only enjoy more surplus when the customization level of the 3DP product is neither extremely high nor low. However, if the logistics vendor uses a 3DP product to fully replace the TM product, the consumer benefits only if the customization level of the 3DP product is low. Therefore, selecting a higher customization level for the 3DP product is not beneficial to the consumer, although the most studies in the mass customization research suggested that the consumer willingness to pay would be increased by the high level of the product customization (Fiore et al., 2004; Pine, 1993; Takagoshi & Matsubayashi, 2013).

Product Customization Level of the 3DP product	Traditional Manufacturer	Logistics Vendor
High	N	N
Medium	Y	N
Low	N	Y

Figure 4-24 The Impact of using 3DP as a Threat

In addition, this model also investigates the possibility of using 3DP as a threat to influence the traditional manufacturer's business decisions, as Figure 4-24 demonstrates. It is beneficial to the logistics vendor to use this strategy only if the customization level of the 3DP product is low, because in this scenario the traditional manufacturer uses a low-pricing strategy to maintain its pricing advantage and thus increase market demand for the TM product. Therefore, the logistics vendor can gain more profits from the increased delivery service.

Theoretical Contributions

First, drawing upon the game theory, this chapter accesses the impact of the logistics vendor's 3DP adoption on the supply chain. Based on the analytical model, the research in this chapter confirms game theories (Bertrand and Stackelberg, specifically) indeed could be used for decision making on the 3DP adoption and derives guidelines about how to adopt 3DP technology.

Second, in 3DP adoption improvement, there exist two different strategies: (1) improving the customization level of the 3DP or (2) reducing the cost of the 3DP production (Dong et al., 2017). Unlike the other existing 3DP research literature which focuses on either improving the customization level of 3DP or reducing the cost of 3DP (Halassi et al., 2019; Wohlers Associates, 2018; Zeltmann et al., 2016), this paper attempts to examine those key variables of the 3DP adoption and the interaction among them.

Also, although some of the existing 3DP research literature (e.g. (Holmström et al., 2010; Mellor et al., 2014; Schröder, Falk, & Schmitt, 2015; Zanardini et al., 2016)) have attempted to determine the best 3DP adoption strategies, most of them neglect the possibility of a non-manufacturer's 3DP adoption using the analytical modelling. In particular, since the 3DP adoption has no requirements on tooling and workforce's skill, this study attempts to theorize that a non-manufacturer also can adopt the 3DP for the purpose of improving the supply chain.

Chapter 5 Adoption of 3DP by the Traditional Manufacturer

The previous model points out that under certain market structures, the traditional manufacturer loses its market share because of the logistics vendor's 3DP adoption. Therefore, this model still uses the two-layer supply chain (one traditional manufacturer and one logistics vendor) and seeks to explore what kind of manufacturing decisions the traditional manufacturer should take to cope with the threat of the logistics vendor's 3DP adoption. Typically, there are two options for the traditional manufacturer. One option is that the traditional manufacturer decides to upgrade its traditional technology to make it more flexible and offers alternative products with higher customization levels. Alternatively, believing that 3DP may revolutionize the manufacturing industry, the traditional manufacturer decides to adopt 3DP. Therefore, what is the best operations decision for the manufacturer? This chapter intends to answer this question, which has not yet been formally assessed.

The remainder of this chapter is organized as follows. Section 5.1 introduces the background and Section 5.2 describes the problem, sets up the benchmarking model, and derives the equilibrium under different market structures. Section 5.3 focuses on the analysis and comparisons of the traditional manufacturer's different traditional flexible manufacturing strategies, when only the logistics vendor provides 3DP product to the market. Section 5.4 analyzes and compares the benchmarking model with the traditional manufacturer's potential 3DP adoption strategies. Section 5.5 presents an extra technical analysis of the traditional manufacturer's traditional flexible manufacturing strategies and 3DP manufacturing strategies. Finally, Section 5.6 concludes this chapter by discussing the practical implications of the findings and suggesting potential avenues for future research. All the proofs of this chapter are detailed in the Appendix B-1.

5.1 Introduction

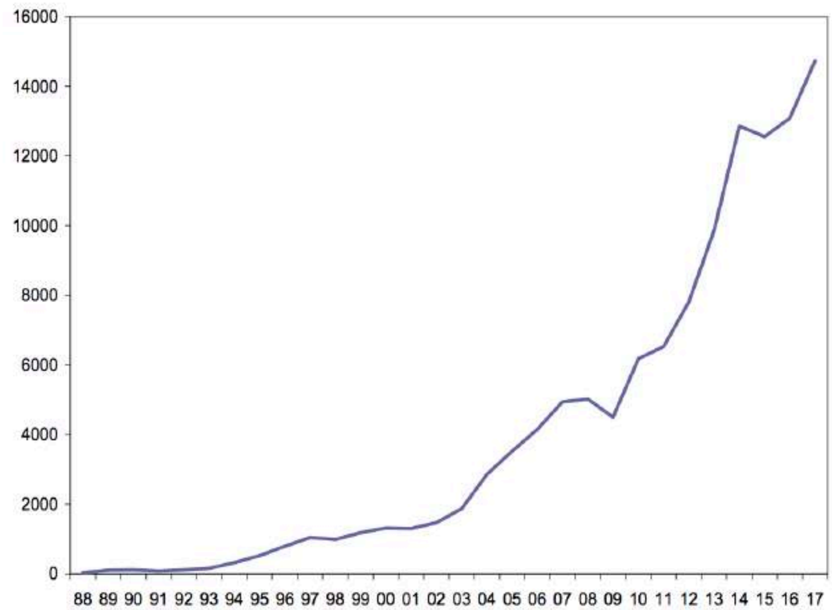


Figure 5-1 Industrial 3DP System Sales (Wohlers Associates, 2018)

According to a report by Wohlers Associates (2018) (Figure 5-1), the unit sales of industrial systems priced over $5,000 grew by 12.6% compared to a growth of 4.2% in 2016 and a decline of 2.3% in 2015. The average selling price of industrial 3DP systems decreased after increasing in 2016 and 2015. This may be due to a large increase in the number of traditional manufacturers now supplying industrial 3DP systems (e.g., GE, Airbus, Adidas, Ford, BMW), many of which are at the lower end of the cost spectrum. For instance, General Motors has successfully adopted 3DP technology for its smart parts manufacturing strategy and saves almost 49 times the amount of money that it initially invested in 3DP (Watkin, 2018). This is a typical example of fully successful 3DP adoption. The Mini Cooper (owned by BMW) started to offer 3DP personalized accessories and special equipment from 2018 (Figure 5-2) (MINI, 2018; Overall, 2017; Saunders, 2017). This 3DP product line is a part of MINI's current high customization production line and the entire delivery service is currently handled by DHL in the European market (MINI, 2018).

Figure 5-2 MINI Yours Customized 3DP Product Service (Saunders, 2017)

Considering the cost of replacing existing traditional manufacturing systems with 3DP manufacturing, the majority of companies are still choosing flexible manufacturing strategies, such as robots, computer controlled machines, and CNC (Computer Numerical Control) machines to improve the productivity of the whole manufacturing system and the customization level of their products (Faludi, Bayley, Bhogal, & Iribarne, 2015; Tang, Mak, & Zhao, 2016). Although these flexible manufacturing technologies are quite expensive, adopting the traditional flexible technology is still a common strategy the traditional manufacturer uses to improve the product customization level (Bogers et al., 2016; Hu, 2013). However, considering the speed of technology improvement and the changes in consumer demands, using a flexible manufacturing strategy might not be an absolutely sustainable alternative to the traditional manufacturing. In addition, as we already discussed in Chapter 3, currently, some logistics vendors (e.g. UPS) have put much effort into 3DP adoption for production-on-demand. Under certain conditions, the new 3DP product will cannibalize the TM product's market share and have a negative impact on the traditional manufacturer's profits. This finding motivates us to think about what kind of manufacturing strategy the traditional manufacturer can use to face the challenge from the new 3DP technology.

Therefore, this model considers a traditional manufacturer (like Mini) facing operational decisions with regard to the selection of flexible manufacturing technologies during the transition to 3DP manufacturing for car accessories. The situation is modelled within the market in which the logistics vendor has already adopted 3DP (i.e. UPS) and is using the 3DP product to compete with the TM product. Then, this model simulates the situation where the traditional manufacturer offers a 3DP product to the end consumer via 3DP adoption or the expensive traditional flexible manufacturing technologies. By comparing these different manufacturing technology decisions, this model aims at further investigation of the impact of 3DP adoption on the supply chain. Three more different scenarios are considered in which the traditional manufacturer can select a traditional flexible technology or a 3DP manufacturing technology to improve its product's customization level. In the other words, this model tries to glean managerial insights by exploring the research question '*what kind of manufacturing strategy should the traditional manufacturer take to cope with 3DP adoption by the logistics vendor?*' and the relevant sub-questions,

Q2.1. Under what conditions will the traditional manufacturer also adopt 3DP?

Q2.2. Under what conditions will the traditional manufacturer use flexible manufacturing to compete with 3DP?

Q2.3. What are the impacts of the traditional manufacturer's different manufacturing strategies on the supply chain structure?

The primary goals of this model are (i) to further develop our first model in Chapter 3 to investigate the supply chain following a traditional manufacturer's adoption of 3DP or traditional flexible manufacturing technology, whilst explicitly modelling customization. The model also aims (ii) to explore the impact of 3DP adoption on the traditional supply chain where the logistics vendor is already empowered by 3DP.

Overall, this model makes the following contributions. Firstly, it endogenizes the 3DP adoption decision under the 3DP enabled supply chain and develops a stylized model to study the interaction between traditional manufacturing, traditional flexible manufacturing technology and 3DP technology. Secondly, this model derives the conditions under which 3DP adoption by the traditional manufacturer is mutually beneficial or exclusively beneficial for the traditional manufacturer and/or the logistics vendor. Thirdly, this model analyzes the consumer surplus of different manufacturing decisions made by the traditional manufacturer. The results can help to inform the traditional manufacturer and the logistics vendor with regard to the adoption of new manufacturing technology and consumer behaviour research.

The results have important implications for both decision makers and policymakers. Understanding the adoption of 3DP, manufacturers can better focus their R&D efforts on projects that ideally perform both in their economic and environmental aspects. Moreover, the results support the traditional manufacturer in deciding which manufacturing technology strategy is profitable, and for which products it may be worth using 3DP technology. And for the logistics vendor, the results help provide further understanding of how to cope with the manufacturer's different manufacturing strategies and how to become involved in the manufacturer's new high customization manufacturing business. Logistics vendors might need to start to collaborate with the traditional manufacturer on certain 3DP services. From a policy-maker's point of view, these results highlight the fact that, at this stage, encouraging

3DP adoption through legislation ultimately aimed at improving manufacturing technology may in fact still have the inverse effect on traditional manufacturing. Therefore, it is a big challenge for the policymakers to find a way to not only improve the manufacturing industry overall performance but also further help the further 3DP technology's adoption.

5.2 Problem Description

In this model, we consider the period after the logistics vendor adopts 3DP, and in which the traditional manufacturer employs a new manufacturing strategy based on traditional manufacturing, traditional flexible manufacturing, and 3DP manufacturing. All three technologies (TM, TF, and 3DP) deliver the same product quality, but the costs are different due to the fixed aspects (i.e. product design, prototyping, machine setting, etc.) and variable aspects (i.e. materials, machines, tooling, labour, etc.). Both the traditional and the 3DP manufacturing technologies can provide the same product customization variants. In this model, we are interested in the manufacturing technology decisions for the traditional manufacturer; therefore, this model focuses on five different scenarios:

If the traditional manufacturer uses the flexible manufacturing strategy, there are two different supply chain structures:

Scenario 1: The traditional manufacturer produces a product using traditional manufacturing (TM) and traditional flexible manufacturing (TF), whilst the logistics vendor offers the 3DP product (Figure 5-6).

Scenario 2: The traditional manufacturer fully abandons the traditional manufacturing method for the purpose of improving product customization (Figure 5-10).

If the traditional manufacturer starts to use 3DP manufacturing technology, there are three different combinations:

Scenario 3: The supply chain where the traditional manufacturer sells three horizontally differentiated product variants in the market, the TM, the TF, and the 3DP product (Figure 5-12).

Scenario 4: Considering the cost of the flexible manufacturing system, the traditional manufacturer only uses 3DP manufacturing technology for high customization products (Figure 5-13).

Scenario 5: The traditional manufacturer fully switches to a 3DP manufacturing system (Figure 5-14).

Table 5-1 provides descriptions of all the parameters which are used in this chapter.

Table 5-1 Definitions of Parameters

Parameter	Definition
α	Consumer value discount for the TM product customization level, $0 < \alpha < 1$.
β	Consumer value discount for the TF product customization level, $\alpha < \beta < 1$.
p_i	$i \in \{M, FT, 3DM, 3DL\}$, the unit selling price for a TM product, a FT product or a 3DP product offered by the traditional manufacturer or the logistics vendor, and the price that is charged by the logistics vendor to deliver a TM, FT, or 3DM product for the traditional manufacturer, $0 < p_i < 1$.
FC_i	$i \in \{M, FT, 3DM, 3DL\}$, the fixed cost for a TM product, a FT product or a 3DP product that is offered by the traditional manufacturer or the logistics vendor, $0 < p_i < 1$.
VC_i	$i \in \{M, FT, 3DM, 3DL\}$, the variable cost for a TM product, a FT product or a 3DP product that is offered by the traditional manufacturer or the logistics vendor, $0 < p_i < 1$.
q_i	$i \in \{M, FT, 3DM, 3DL\}$, the sales quantity for the TM, FT, 3DM or 3DL products, $0 < q_i < 1$.

U_i	$i \in \{M, FT, 3DM, 3DL\}$, the utility of the TM, FT, 3DM or 3DL products.
$\prod_i$	$i \in \{M, L, SC\}$, the manufacturer's profit, or the logistics vendor's profit, or the supply chain's total profit, $\prod_i \geq 0$.

In line with the benchmark model in Chapter 4, this model sets the product customization level of the TM product lower than that of the TF and 3DP product. For simplicity, this model also sets the full customization level of the 3DP product to 1. Therefore, the consumer values the TM product less, as designated by αv, where $\alpha\,(0 < \alpha < 1)$ represents the customization level of the TM product. The higher the degree of customization the 3DP product variants have, the less the consumer values the TM product. Because the TF product can offer multiple product customization variants, how much the consumer values the TF product depends on the number of its variants βv $(\alpha < \beta < 1)$, which captures two features of the traditional flexible manufacturing technology. Firstly, the customization level of the TF product is higher than the TM product; and secondly, the customization level of the TF product is lower than the 3DP product (Wohlers Associates, 2018). Therefore, the net utilities of a consumer buying the TM, TF, and 3DP product from either the traditional manufacturer and/or the logistics vendor are $U_M = \alpha v - p_M$, $U_{TF} = \beta v - p_{TF}$, $U_{3DM} = v - p_{3DM}$, and $U_{3DL} = v - p_{3DL}$, respectively.

Because the traditional manufacturer's flexible manufacturing system might be developed on the traditional manufacturing system, referring the model settings by Dong et al. (2017), we separate the cost of different manufacturing technology into fixed cost and variable cost. This model assumes that the TM product can only offer one variant (in terms of product customization), the fixed and variable cost of the TM product are constant at F_M and V_M. However, this model separates the logistics delivery cost, p_L, from the manufacturing cost. Thus, the total cost of the traditionally manufactured product is $F_M + V_M + p_L$. The traditional flexible manufacturing technology can offer multiple product variants via customization. Differently, this model assumes that all variants are equally dissimilar and more flexible variants require more investment (Hu, 2013). The fixed cost and the variable cost of the traditional manufacturing technology are denoted by F_{TF} and V_{TF} respectively, and the variable cost of the product produced by traditional flexible manufacturing is higher than the traditionally manufactured product ($V_M < V_{TF}$) (Syam & Kumar, 2006), then the higher the customization level, the greater the variable cost. The variable cost of the traditional manufacturing product increases in the degree of TF product customization. Therefore, the cost of a TF product is $F_{TF} + \beta V_{TF} + p_L$ (Upton, 2008). Lastly, the 3DP manufacturing technology in this model is a new type of flexible manufacturing technology with fixed cost F_{3D} and variable cost V_{3D}. For the 3DP manufacturing technology, it is easy to prototype and design complex and high customization products; therefore, the unit variable cost V_{3D} does not increase dramatically (Smith, 2015). Nevertheless, this model assumes $V_{3D} > V_{TF} > V_M$ (Figure 5-3) because the cost of those products which are never 3D printed is still high (Smith, 2015; Wohlers Associates, 2018). Thus, the cost of the 3DP product is $F_{3D} + V_{3D}$. In addition, the fixed costs of the TF and 3DP product weakly decrease in their own product sales and there is no delivery cost for the logistics vendor, as we explained in Chapter 4.

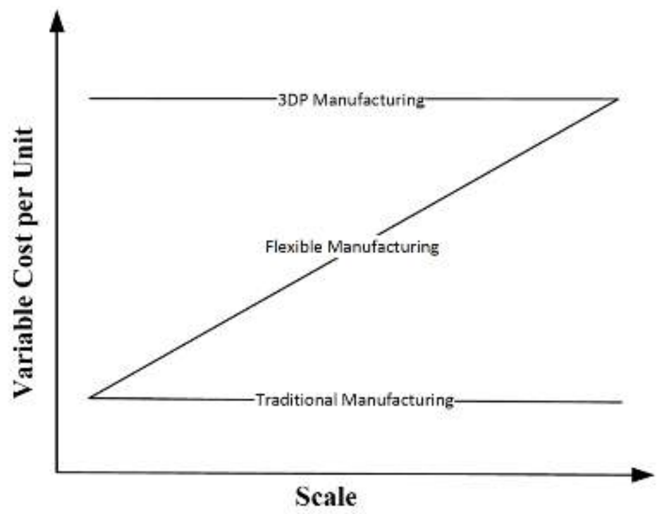


Figure 5-3 Variable Cost of Products Produced by three Different Manufacturing Methods

5.3 Benchmarking Model – 3DL Model

First of all, based on the structure we used in Chapter 4, because we invent new parameters, we recalculate the optimal decisions and the maximized profits of the benchmarking model.

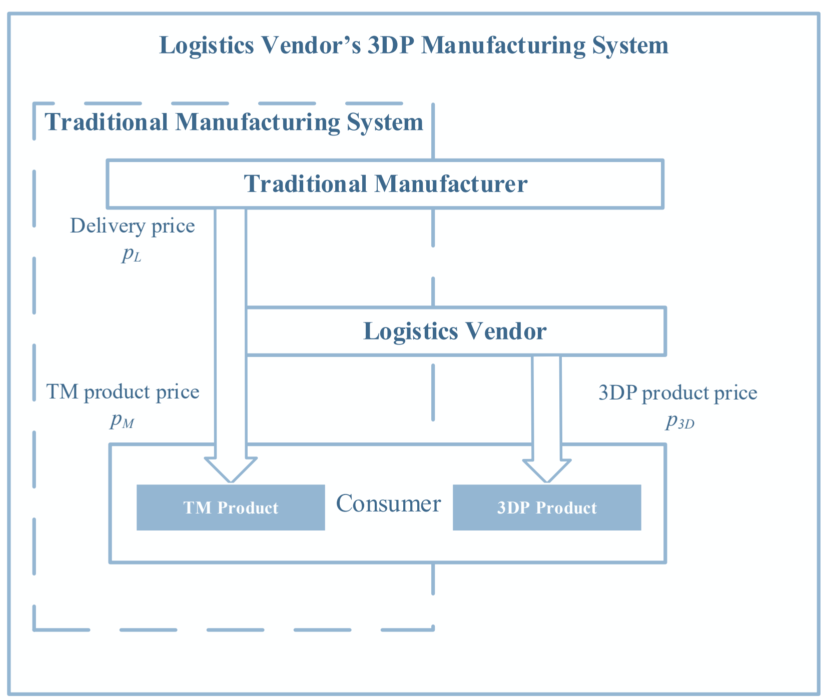


Figure 5-4 Benchmarking Model - TM3DL Model

Under the benchmarking model (Figure 5-4), where the logistics vendor adopts the 3DP technology ($p_{3DL} \geq \frac{p_M}{\alpha}$), the pricewise-linear demand functions for the TM and 3DP product are

$$q_M = \frac{\alpha p_{3DL} - p_M}{(1-\alpha)\alpha} \tag{5.1}$$

$$q_{3DL} = 1 - \frac{p_{3DL} - p_M}{1-\alpha} \tag{5.2}$$

The profit functions for the traditional manufacturer and the logistics vendor under the decentralized supply chain are

$$\prod\nolimits_{3DL} M(p_M) = (p_M - F_M - V_M - p_L)q_M \tag{5.3}$$

$$\prod\nolimits_{3DL} L(p_{3DL}, p_L) = (p_L - c_L) * q_M + (p_{3DL} - F_{3D} - V_{3D})q_{3DL} \tag{5.4}$$

And the profit for the vertically integrated supply chain is

$$\prod\nolimits_{3DL} SC(p_M, p_{3DL}, p_L) = (p_M - F_M - V_M - c_L)q_M + (p_{3DL} - F_{3D} - V_{3D})q_{3DL} \tag{5.5}$$

Here, this model also uses Bertrand and Stackelberg for the price decision sequence (Figure 5-5).

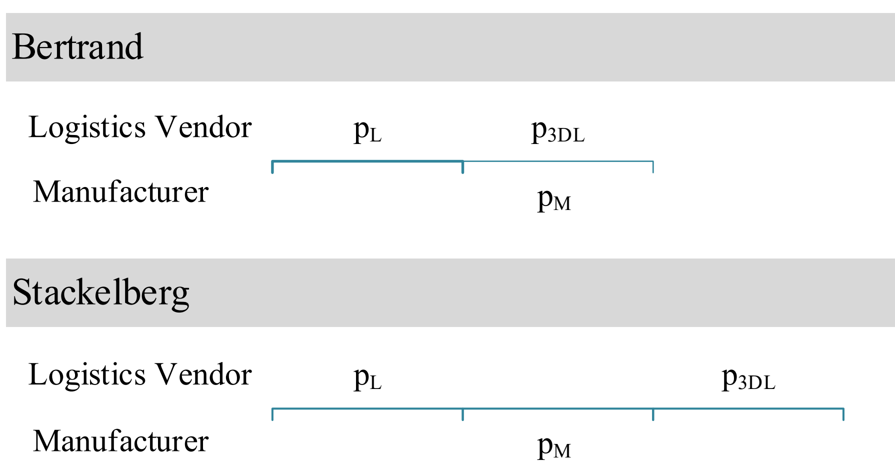


Figure 5-5 Pricing Sequence of the Logistics Vendor's 3DP Manufacturing System

PROPOSITION ***5-1.***

(1) In the decentralized 3DP manufacturing system, under Bertrand-Nash-equilibrium, the maximum profit for the traditional manufacturer is $\prod_{3DLB}^{*} M(p_M) = -\frac{(2+\alpha)^2(c_L+F_M-\alpha(F_{3D}+V_{3D})+V_M)^2}{(-1+\alpha)\alpha(8+\alpha)^2}$ *and the maximum profit for the logistics vendor is* $\prod_{3DLB}^{*} L\left(p_{3DL}, p_L\right) = \frac{1}{4(-1+\alpha)(8+\alpha)^2}\left(-(8+\alpha-2c_L+(-8+\alpha)F_{3D}-2F_M+(-8+\alpha)V_{3D}-2V_M)(-(-1+\alpha)(8+\alpha)+6c_L+(-8+\alpha+\alpha^2)F_{3D}+6F_M+(-8+\alpha+\alpha^2)V_{3D}+6V_M)+\frac{1}{\alpha}\left(2(2+\alpha)(-c_L-F_M+\alpha(F_{3D}+V_{3D})-V_M)(-\alpha(8+\alpha)+8c_L+8F_M+\alpha^2(F_{3D}+V_{3D})+8V_M)\right)\right)$ *, both of which are maximized by optimal price* $p_M^{*} = \frac{\alpha(8+\alpha)+4c_L+4F_M+\alpha(4+\alpha)(F_{3D}+V_{3D})+4V_M}{2(8+\alpha)}$*,* $p_L^{*} = \frac{\alpha(8+\alpha)+2(4+\alpha)c_L-8F_M-\alpha^2(F_{3D}+V_{3D})-8V_M}{2(8+\alpha)}$*, and* $p_{3DL}^{*} = \frac{8+\alpha-2c_L+(8+3\alpha)F_{3D}-2F_M+(8+3\alpha)V_{3D}-2V_M}{2(8+\alpha)}$*. The optimal market demand for the TM and 3DP product is* $q_M^{*} = \frac{(2+\alpha)(c_L+F_M-\alpha(F_{3D}+V_{3D})+V_M)}{(-1+\alpha)\alpha(8+\alpha)}$ *and* $q_{3DL}^{*} = -\frac{-(-1+\alpha)(8+\alpha)+6c_L+(-8+\alpha+\alpha^2)F_{3D}+6F_M+(-8+\alpha+\alpha^2)V_{3D}+6V_M}{2(-1+\alpha)(8+\alpha)}$.

(2) In the decentralized 3DP manufacturing system, under Stackelberg-Nash equilibrium, the maximum profit for the traditional manufacturer is $\prod_{3DLS}^{*} M(p_M) = \frac{1}{(-1+\alpha)\alpha(8+(-5+\alpha)\alpha)^2}\left((c_L+F_M-\alpha(F_{3D}+V_{3D})+V_M)(2(-2+\alpha)c_L-4(F_M+V_M)+\alpha(-2(-2+\alpha)F_{3D}+2F_M+(-4+\alpha(11+(-6+\alpha)\alpha))V_{3D}+2V_M))\right)$ *and the maximum profit for the logistics vendor is* $\prod_{3DLS}^{*} L(p_{3DL}, p_L) = \frac{1}{4(-1+\alpha)(8+(-5+\alpha)\alpha)^2}(((-1+\alpha)(8+(-5+\alpha)\alpha)-(-3+\alpha)(-2+\alpha)c_L+(8+(-7+\alpha)\alpha)F_{3D}+(-3+\alpha)(-2+\alpha)(-F_M+\alpha V_{3D})-6V_M-(-5+\alpha)\alpha V_M)(8+(-5+\alpha)\alpha+(-2+\alpha)c_L+(-8+(7-2\alpha)\alpha)F_{3D}-2F_M-16V_{3D}-2V_M+\alpha(F_M+(20+(-8+\alpha)\alpha)V_{3D}+V_M))+\frac{1}{\alpha}(2(-2+\alpha)c_L-4(F_M+V_M)+\alpha(-2(-2+\alpha)F_{3D}+2F_M+(-4+\alpha(11+(-6+\alpha)\alpha))V_{3D}+2V_M))(-\alpha(8+(-5+\alpha)\alpha)+(-4+\alpha)(-2+\alpha)c_L+8F_M+8V_M+\alpha(-6(F_M+V_M)+\alpha(F_{3D}+F_M+V_{3D}+V_M))))$ *, both of which are maximized by optimal price* $p_M^{*} = \frac{1}{2(8+(-5+\alpha)\alpha)}\left(\alpha(8+(-5+\alpha)\alpha)+(-2+\alpha)^2c_L+4F_M-(-4+\alpha)\alpha(F_{3D}-F_M+V_{3D}-V_M)+4V_M\right)$*,* $p_L^{*} = \frac{1}{2(8+(-5+\alpha)\alpha)}\left(\alpha(8+(-5+\alpha)\alpha)+(8+(-4+\alpha)\alpha)c_L-8F_M-8V_M-\alpha(-6(F_M+V_M)+\alpha(F_{3D}+F_M+V_{3D}+V_M))\right)$ *, and* $p_{3DL}^{*} = \frac{1}{2(8+(-5+\alpha)\alpha)}\left(8+(-5+\alpha)\alpha+(-2+\alpha)c_L+(8-3\alpha)F_{3D}-2F_M-2V_M+\alpha(F_M+(10+(-6+\alpha)\alpha)V_{3D}+V_M)\right)$*. The optimal market demand for the TM and 3DP product is* $q_M^{*} = -\frac{1}{2(-1+\alpha)\alpha(8+(-5+\alpha)\alpha)}\left(2(-2+\alpha)c_L-4(F_M+V_M)+\alpha(-2(-2+\alpha)F_{3D}+2F_M+(-4+\alpha(11+(-6+\alpha)\alpha))V_{3D}+2V_M)\right)$ *and* $q_{3DL}^{*} = \frac{1}{2(-1+\alpha)(8+(-5+\alpha)\alpha)}\left((-1+\alpha)(8+(-5+\alpha)\alpha)-(-3+\alpha)(-2+\alpha)c_L+(8+(-7+\alpha)\alpha)F_{3D}+(-3+\alpha)(-2+\alpha)(-F_M+\alpha V_{3D})-6V_M-(-5+\alpha)\alpha V_M\right)$.

(3) In the integrated 3DP manufacturing system, under Bertrand-Nash equilibrium, the maximum profit for the supply chain is $\prod_{3DLB}^{*} SC(p_M, p_{3DL}) = \frac{1}{4(-1+\alpha)\alpha}\left(-\alpha(-1+F_{3D}+V_{3D})(-1+\alpha-c_L+F_{3D}-F_M+V_{3D}-V_M)+(\alpha-c_L-F_M-V_M)(c_L+F_M-\alpha(F_{3D}+V_{3D})+V_M)\right)$ *, which is maximized by optimal price* $p_M^{*} = \frac{1}{2}(\alpha+c_L+F_M+V_M)$ *and* $p_{3DL}^{*} = \frac{1}{2}(1+F_{3D}+V_{3D})$ *. The optimal market demand for the TM and 3DP product is* $q_M^{*} = \frac{c_L+F_M-\alpha(F_{3D}+V_{3D})+V_M}{2(-1+\alpha)\alpha}$ *and* $q_{3DL}^{*} = \frac{1-\alpha+c_L-F_{3D}+F_M-V_{3D}+V_M}{2-2\alpha}$.

Above proposition presents the existing optimal decisions and the maximized profits of different market structures for the benchmarking model.

5.4 Traditional Manufacturer's Flexible Manufacturing Strategy

In this subsection, we describe the proposed model for the traditional manufacturer's flexible manufacturing strategy, derive the equilibrium under different supply chain structures, and present technical analysis for the comparison between the benchmarking model and the proposed models. At the end of the subsection, we conduct a further comparison among all the proposed models in this chapter.

If the traditional manufacturer introduces flexible manufacturing technology instead of 3DP technology, consumers can find three different products in the market: the TM and the TF product offered by the traditional manufacturer, and the 3DP product provided by the logistics vendor. The consumer has three purchase choices under different conditions:

(1) They buy the TM product when $U_M > U_{TF} > U_{3DL}$ and $U_M > 0$ or $U_M > U_{3DL} > U_{TF}$ and $U_M > 0$;

(2) They buy the FT product from the traditional manufacturer when $U_{TF} > U_{TM} > U_{3DL}$ and $U_{TF} > 0$ or $U_{TF} > U_{3DL} > U_M$ and $U_{TF} > 0$; and

(3) They buy the logistics vendor's 3DP product when $U_{3DL} > U_M > U_{TF}$ and $U_{3DL} > 0$ or $U_{3DL} > U_{TF} > U_M$ and $U_{3DL} > 0$.

Then, we can derive the inverse market demand functions as shown in Table 5-2. The market demand could be summarized into 4 different scenarios depending on the price of each product. Scenario II is the same as the benchmarking manufacturing system. Because this section focuses on the question of whether the traditional manufacturer could use traditional flexible manufacturing to compete with the logistics vendor's 3DP, this model only investigates scenario I in Section 5.4.1 and scenario III in Section 5.4.2.

Table 5-2 The Inverse Market Demand of the Traditional Flexible Manufacturing System

		q_M	q_{TF}	q_{3DL}
Scenario I	$\frac{p_M}{\alpha} < \frac{p_{TF}}{\beta} < p_{3DL}$	$\frac{\beta p_M - \alpha p_{\mathrm{TF}}}{\alpha^2 - \alpha\beta}$	$\frac{-p_{\mathrm{3DL}} + p_{\mathrm{TF}}}{-1+\beta} + \frac{-p_M + p_{\mathrm{TF}}}{\alpha - \beta}$	$1 + \frac{p_{\mathrm{3DL}} - p_{\mathrm{TF}}}{-1+\beta}$
Scenario II	$\frac{p_M}{\alpha} < p_{3DL} < \frac{p_{TF}}{\beta}$	$\frac{-\alpha p_{\mathrm{3DL}} + p_M}{(-1+\alpha)\alpha}$	0	$1 + \frac{p_{3DL} - p_M}{-1+\alpha}$
Scenario III	$\frac{p_{TF}}{\beta} < \frac{p_M}{\alpha} < p_{3DL}$	0	$\frac{-\beta p_{\mathrm{3DL}} + p_{\mathrm{TF}}}{(-1+\beta)\beta}$	$1 + \frac{p_{\mathrm{3DL}} - p_{\mathrm{TF}}}{-1+\beta}$
	$\frac{p_{TF}}{\beta} < p_{3DL} < \frac{p_M}{\alpha}$	0	$\frac{-\beta p_{\mathrm{3DL}} + p_{\mathrm{TF}}}{(-1+\beta)\beta}$	$1 + \frac{p_{3DL} - p_{TF}}{-1+\beta}$
Scenario IV	$p_{3DL} < \frac{p_M}{\alpha} < \frac{p_{TF}}{\beta}$	0	0	$1 - p_{3DL}$
	$p_{3DL} < \frac{p_{TF}}{\beta} < \frac{p_M}{\alpha}$	0	0	$1 - p_{3DL}$

5.4.1 TMTF3DL Model

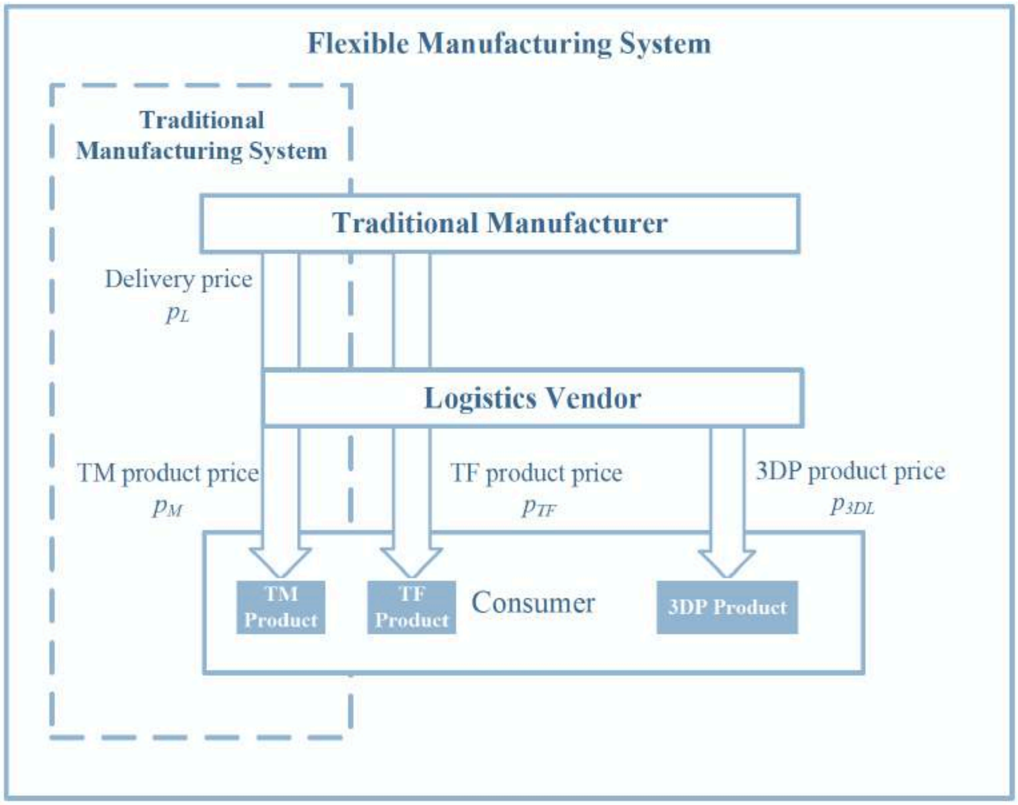


Figure 5-6 Flexible Manufacturing System -TMTF3DL Model

Under Scenario I (Table 5-2), the traditional manufacturer offers the TM and TF product and the logistics vendor offers the 3DP product with a high product customization level; for easy reference, we name it the TMTF3DL model. For example, most of the automotive companies (e.g. Nissan, Ford, Acura) are using CNC machines to improve the productivity and the efficiency of their manufacturing systems (Ernst & Young, 2016; Wohlers Associates, 2018). The profits of the manufacturer and logistics vendor could be formulated as Equation (5.6) and (5.7), respectively,

$$\prod\nolimits_{TF}^{M}(p_M, p_{TF}) = (p_M - F_M - V_M - p_L)q_M + (p_{TF} - F_{TF} - \beta V_{TF} - p_L)q_{TF} \tag{5.6}$$

$$\prod\nolimits_{TF}^{L}(p_{3DL}, p_L) = (p_L - c_L)(q_M + q_{TF}) + (p_{3DL} - F_{3D} - V_{3D})q_{3DL} \tag{5.7}$$

And the profit for the vertically integrated supply chain is

$$\prod_{TF} SC(p_M, p_{TF}, p_{3DL}) = (p_M - F_M - V_M - c_L)q_M + (p_{TF} - F_{TF} - \beta V_{TF} - c_L)q_{TF} + (p_{3DL} - F_{3D} - V_{3D})q_{3DL} \tag{5.8}$$

Considering the different market structures (Figure 5-7), next, this model seeks to derive the Bertrand equilibrium and Stackelberg equilibrium.

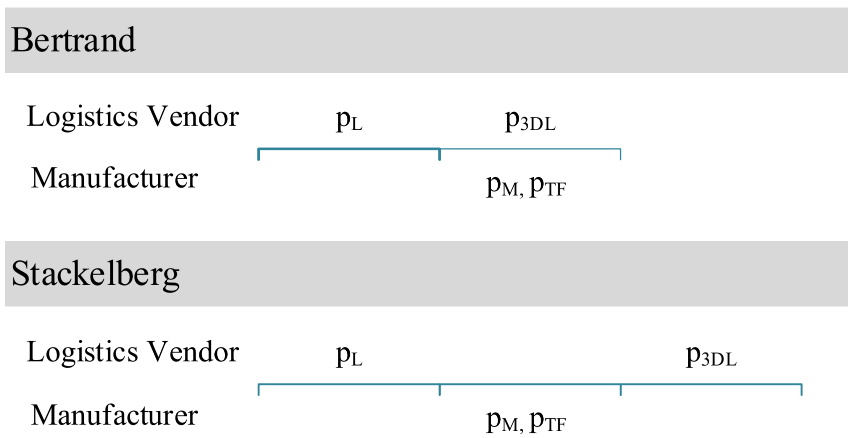


Figure 5-7 Pricing Sequence of Scenario I

PROPOSITION *5-2.*

(1) *In the decentralized 3DP manufacturing system, under Bertrand-Nash equilibrium, the maximum profits for the traditional manufacturer and the logistics vendor are shown in Equation (5.53) and (5.54) respectively. They are maximized by the optimal price in Equation (5.46), (5.47), (5.48), and (5.49). The optimal market demand for the TM, TF, and 3DP product are given in Equation (5.50), (5.51), and (5.52)(5.53).*

(2) *In the decentralized 3DP manufacturing system, under Stackelberg-Nash equilibrium, the maximum profit for the traditional manufacturer is shown in Equation (5.62) and the maximum profit for the logistics vendor is as in Equation (5.63), both of which are maximized by the optimal price given in Equation (5.55), (5.56), (5.57), and (5.58). The optimal market demand for the TM, TF, and 3DP product is given in Equation (5.59), (5.60), and (5.61).*

(3) *In the integrated 3DP manufacturing system, the maximum profit for the supply chain is given in Equation (5.70) , which is maximized by the optimal prices in Equation (5.64), (5.65), and (5.66). The optimal market demand for the TM and 3DP product are shown in Equation (5.67), (5.68), and (5.69).*

Because of the complexity of the structure of the optimal decisions, it is difficult to gain direct insights in the following comparisons. Therefore, this model had to use numerical tests to investigate the relative performance under different supply chain structures. A full factorial design of the cost has been created with three different groups – low-cost, medium-cost and high-cost supply chains, as Table 5-3 below shows. We use these supply chain settings for all of the following comparative analysis in this chapter.

Table 5-3 Parameter Values in the Numerical Testing for the Impacts of Product Customization Level

	TM product			TF Product			3DP product		Delivery product
	F_M	V_M	α	F_{TF}	V_{TF}	β	F_{3D}	V_{3D}	c_L
Low	0.01	0.01	0.1	0.025	0.02	0.2	0.1	0.03	0.01
Medium	0.05	0.05	0.2	0.1	0.25	0.4	0.3	0.3	0.01
High	0.1	0.08	0.3	0.3	0.3	0.6	0.6	0.35	0.01

For each cost group we refer to one special item which could be 3D printed by traditional manufacturing technology, traditional flexible manufacturing technology and 3DP technology. The cost structure of the supply chain with the low setting refers to Mini Cooper's car dashboard fascia (Figure 5-2), the medium setting uses 3DP Formula 1 race car aluminium alloy components as the reference (Figure 5-8), and the high setting is based on the cost structure for Honda's new configurable electric car body shell production (Figure 5-9) (Wohlers Associates, 2018).

Figure 5-8 3D Printed Formula 1 Race Car Aluminium Alloy Components (Wohlers Associates, 2018)

Figure 5-9 Honda's 3D Printed Electric Car Body (Ayre, 2016)

Based on these cost settings, in the tests of the impact of TM product customization, this model selects three different levels of TF product customization ($\beta = 0.2$, $\beta = 0.4$, $\beta = 0.6$). Following the same approach, in the numerical tests of the impact of TF product customization, another three different TM product customization levels were used for laboratory analysis ($\alpha = 0.1$, $\alpha = 0.2$, $\alpha = 0.3$).

For the purpose of understanding and comparing the impacts of different product costs and the different product customization levels on the overall results, the results about the test on each variate are listed in Appendix C-2.

5.4.2 TF3DL Model

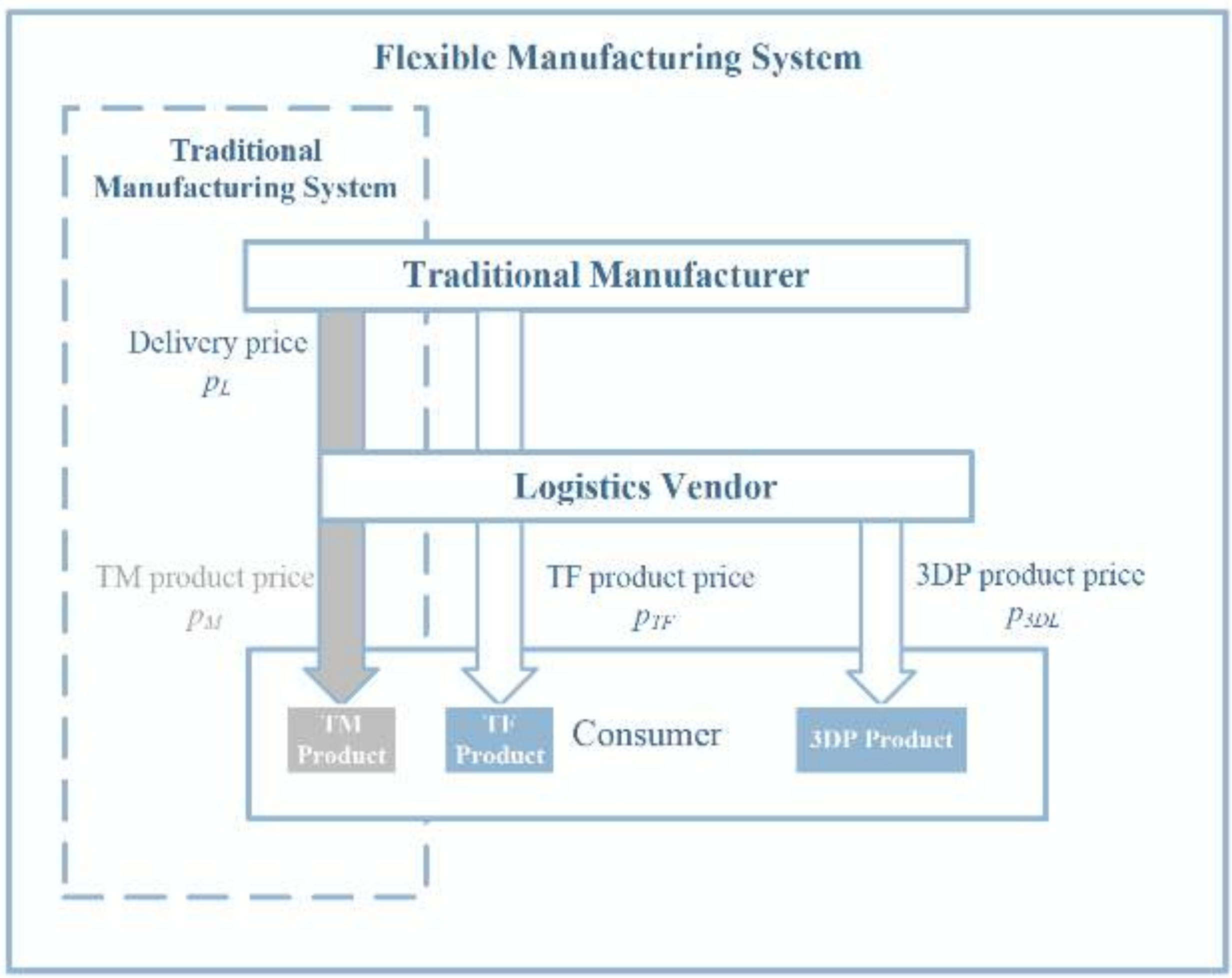


Figure 5-10 Flexible Manufacturing System -TF3DL Model

In scenario III (Table 5-2), the traditional manufacturer prices the TF product lower ($\frac{p_{TF}}{\beta} < \frac{p_M}{\alpha}$), and so the consumer chooses from two different high customization products, the TF and the 3DP product (Figure 5-10) – we call this the 'TF3DL' model. For instance, Boeing, Airbus, Rolls Royce, and GE are currently using CNC machining for assembly and subassembly fabrication and inspection services.

In this TF3DL model, the manufacturer's and the logistics vendor's profits could be re-formulated as in Equation (5.9) and (5.10) respectively,

$$\prod_{TF} M(p_{TF}) = (p_{TF} - F_{TF} - \beta V_{TF} - p_L) q_{TF} \tag{5.9}$$

$$\prod_{TF} L(p_{3DL}, p_L) = (p_L - c_L) q_{TF} + (p_{3DL} - F_{3D} - V_{3D}) q_{3DL} \tag{5.10}$$

And the profit for the vertically integrated supply chain is

$$\prod_{TF} SC(p_{TF}, p_{3DL}) = (p_{TF} - F_{TF} - \beta V_{TF} - c_L) q_{TF} + (p_{3DL} - F_{3D} - V_{3D}) q_{3DL} \tag{5.11}$$

By considering the different market structures (Figure 5-11), in the following discussion this model seeks to list the solutions for Bertrand-equilibrium and Stackelberg-equilibrium.

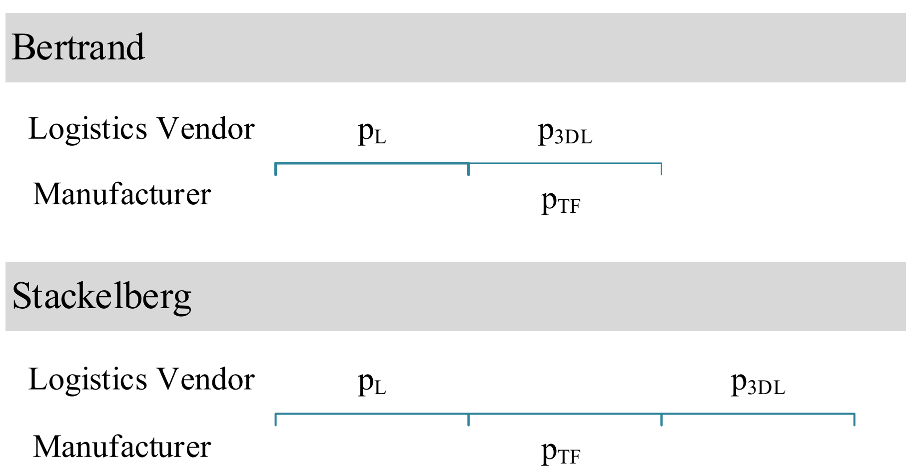


Figure 5-11 Pricing Sequence in Scenario III

PROPOSITION 5-3. *If the traditional manufacturing decides fully use TF product to replace TM product for the purpose of coping with the logistics vendor's 3DP technology,*

(1) In the decentralized 3DP manufacturing system, under Bertrand-Nash equilibrium, the maximum profits for the traditional manufacturer and the logistics vendor are given in Equation (5.76) and (5.77), respectively. They are maximized by the optimal

prices shown in Equation (5.71), (5.72), and (5.73), whilst the optimal market demand for the TM and 3DP product is given in Equation (5.74) and Equation (5.75).

(2) In the decentralized 3DP manufacturing system, under Stackelberg-Nash equilibrium, the maximum profit for the traditional manufacturer is shown in Equation (5.83) and the maximum profit for the logistics vendor is as in Equation (5.84), both of which are maximized by the optimal price given in Equation (5.78), (5.79), and (5.80). The optimal market demand for the TM and 3DP product are as in Equation (5.81) and Equation (5.82).

(3) In the integrated 3DP manufacturing system, the maximum profit for the supply chain is given in Equation (5.89), which is maximized by the optimal price as in Equation (5.85) and Equation (5.86). The optimal market demand for the TF and 3DP product is shown in Equation (5.87) and (5.88).

5.4.3 Comparison between the TF Enabled Models

In this subsection, we compare the outcomes in the TF enabled models (TMTF3DL and TF3DL) and identify the traditional manufacturer's best TF manufacturing strategy.

PROPOSITION *5-4*. *The traditional manufacturer is better off adding the TF product instead of fully replacing the TM product with the TF product in most cases, except*

(1) On the low supply chain setting, when the fixed TF product cost is extremely low;

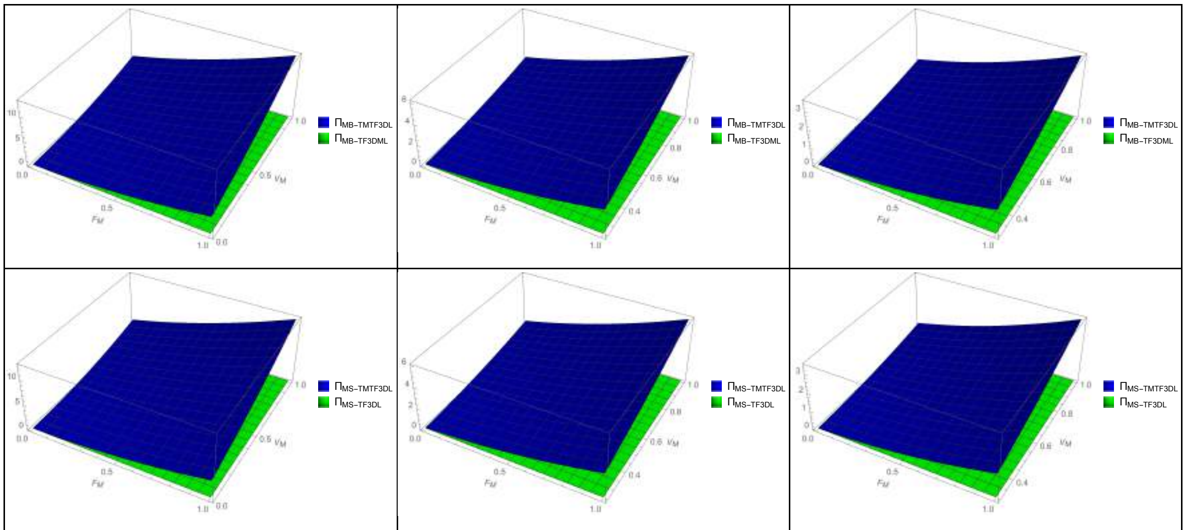
(2) On the high supply chain setting when a) the 3DP product costs are high under the Bertrand supply chain, or b) the 3DP product costs are sufficiently low or low under the Stackelberg supply chain.

In this supply chain structure, it is obvious that the traditional manufacturer can generate more profits by producing two products differentiated by customization level rather than only providing the TF product. This finding concurs with a majority of previous papers which suggest that the manufacturer should launch a wider range of products to fulfil consumer demands under certain conditions. For instance, (Dong et al., 2017) find it an inevitable trend for the traditional manufacturer to use flexible technologies to improve product variety. Considering the investment cost, adding one of the flexible technologies into the current TM production system is a more appropriate manufacturing strategy for the traditional manufacturer at this stage. The 3DP product sales become robust because the high price of the TF product mitigates the price disadvantage of the 3DP product. For example, consider the case of chain brands for clothing and shoes. Selling both the standard items and the highly customized item can help the traditional manufacturer cover a wider consumer base and the logistics vender can make more profit on the delivery service. However, on the low supply chain setting (where the cost structure of the product is not extremely high), if the costs of the TF product are located in a certain low range, fully using TF production is better for the traditional manufacturer (Table 5-5). A new TF product benefits the traditional manufacturer by a higher margin per product and more customization-sensitive consumers, even with valuation uncertainty.

Therefore, the key implications of this proposition are as follows. Firstly, intuitively, we expect a multiple product manufacturing strategy to be better than the TF product only, but this proposition suggests that for those products whose cost is not extremely high (e.g. phone covers, shoe soles), if the TF product investment is not expensive, fully engaging in TF production might be a good manufacturing strategy to cope with the logistics vendor's 3DP product competition. In practice, some companies only provide the customized product. For example, SATAIR only provides some highly-customized aeroplane parts to specified airline companies (e.g. Airbus) (SATAIR, 2018). Secondly, for high cost products, it is better to add the TF product instead of fully replacing the TM production. Rolls-Royce not only provides highly customized flight engines (the Trend serials) to the Airbus and Boeing airliners, but also provides the standard flight engine (Rolls-Royce, 2018).

Table 5-4 Traditional Manufacturer's Maximized Profit: Comparison by TM Product Cost – TMTF3DL and TF3DL

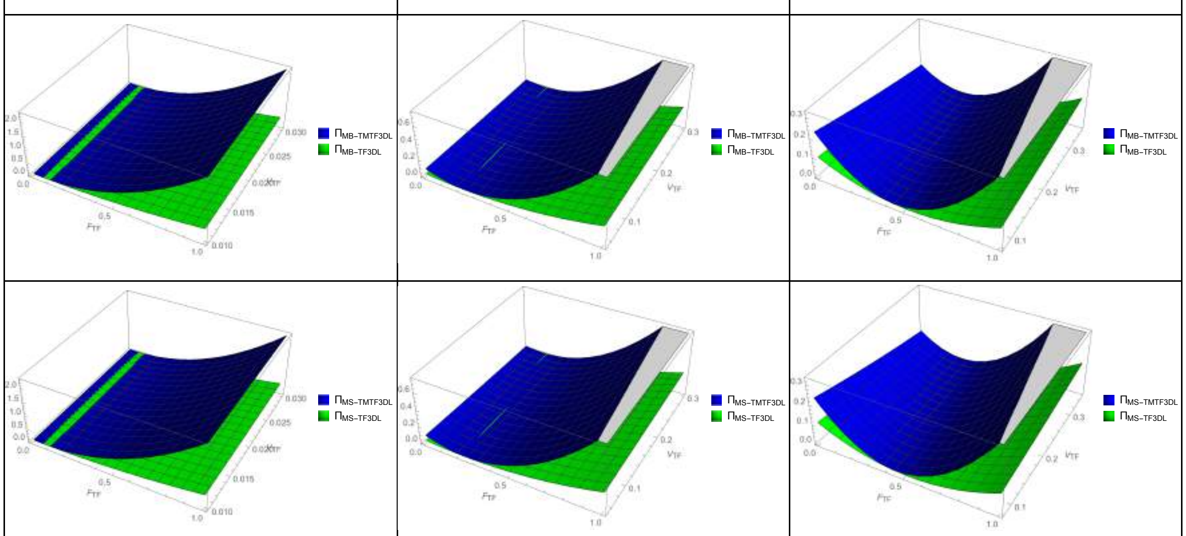
Low	Medium	High



	TM Product			TF Product			3DP Product		Delivery
	F_M	V_M	α	F_{TF}	V_{TF}	β	F_{3D}	V_{3D}	c_L
Low	-	-	0.1	0.025	0.02	0.2	0.1	0.03	0.01
Medium	-	-	0.2	0.1	0.25	0.4	0.3	0.3	0.01
High	-	-	0.3	0.3	0.3	0.6	0.6	0.35	0.01

Table 5-5 Traditional Manufacturer's Maximized Profit: Comparison by TF Product Cost – TMTF3DL and TF3DL

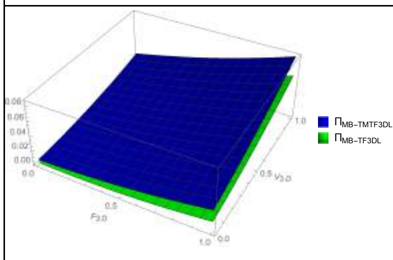
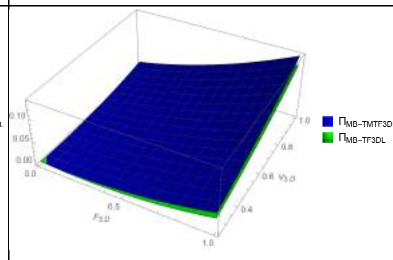
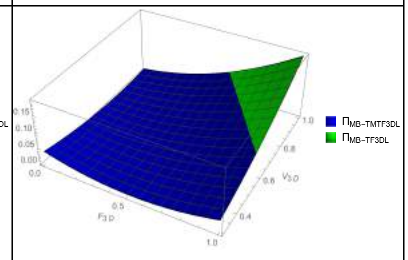
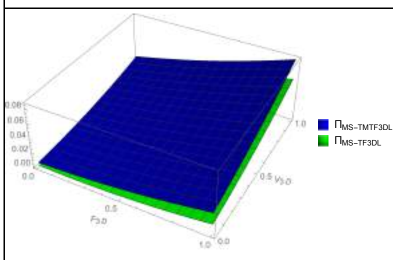
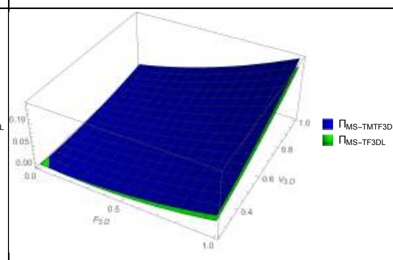
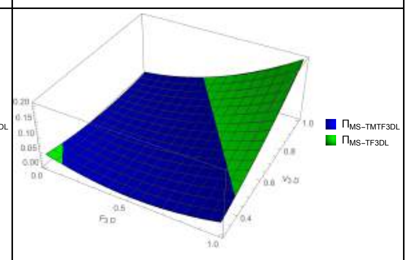
Low	Medium	High



	TM Product			TF Product			3DP Product		Delivery
	F_M	V_M	α	F_{TF}	V_{TF}	β	F_{3D}	V_{3D}	c_L
Low	0.01	0.01	0.1	-	-	0.2	0.1	0.03	0.01

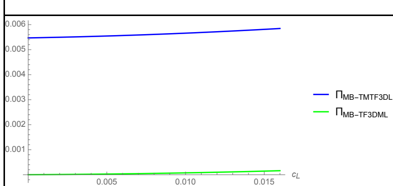
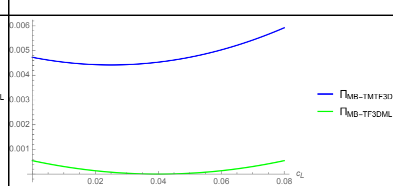
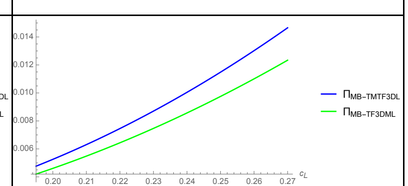
Medium	0.05	0.05	0.2	-	-	0.4	0.3	0.3	0.01
High	0.1	0.08	0.3	-	-	0.6	0.6	0.35	0.01

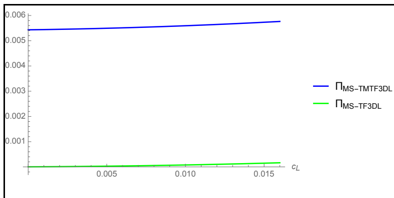
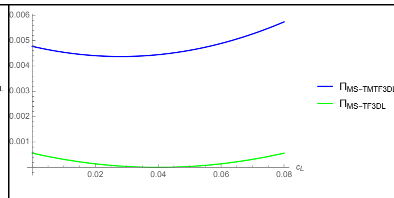
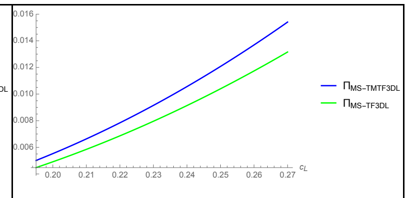
Table 5-6 Traditional Manufacturer's Maximized Profit: Comparison by 3DP Product Cost – TMTF3DL and TF3DL

Low	Medium	High
		
		

	TM Product			TF Product			3DP Product		Delivery
	F_M	V_M	α	F_{TF}	V_{TF}	β	F_{3D}	V_{3D}	c_L
Low	0.01	0.01	0.1	0.025	0.02	0.2	-	-	0.01
Medium	0.05	0.05	0.2	0.1	0.25	0.4	-	-	0.01
High	0.1	0.08	0.3	0.3	0.3	0.6	-	-	0.01

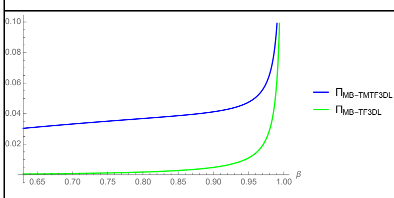
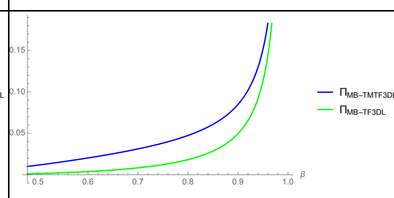
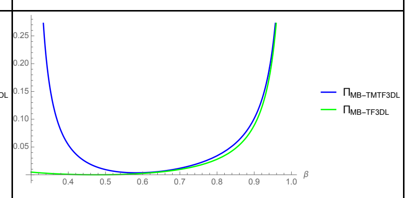
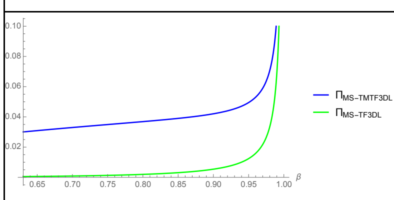
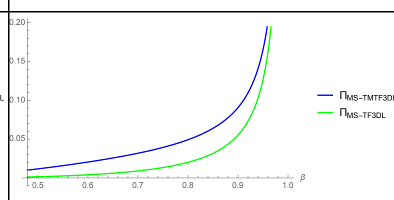
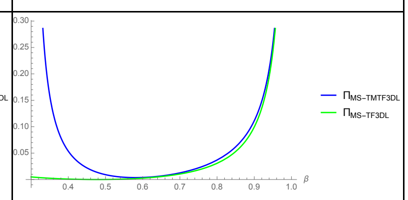
Table 5-7 Traditional Manufacturer's Maximized Profit: Comparison by Logistics Delivery Cost – TMTF3DL and TF3DL

Low	Medium	High
		

	TM Product			TF Product			3DP Product		Delivery
	F_M	V_M	α	F_{TF}	V_{TF}	β	F_{3D}	V_{3D}	c_L
Low	0.01	0.01	0.1	0.025	0.02	0.2	0.1	0.03	-
Medium	0.05	0.05	0.2	0.1	0.25	0.4	0.3	0.3	-
High	0.1	0.08	0.3	0.3	0.3	0.6	0.6	0.35	-

Table 5-8 Traditional Manufacturer's Maximized Supply Chain Profit: Comparison by TF Product Customization Level – TMTF3DL and TF3DL

Low	Medium	High
		
		

	TM Product			TF Product			3DP Product		Delivery
	F_M	V_M	α	F_{TF}	V_{TF}	β	F_{3D}	V_{3D}	c_L
Low	0.01	0.01	0.1	0.025	0.02	-	0.1	0.03	0.01
Medium	0.05	0.05	0.2	0.1	0.25	-	0.3	0.3	0.01
High	0.1	0.08	0.3	0.3	0.3	-	0.6	0.35	0.01

PROPOSITION 5-5.

(1) With the low supply chain setting, the logistics vendor can in general achieve better performance under the TF3DL model. However, if a) the TF product costs are high, or b) the fixed TF product cost is located within a certain low range, the logistics vendor can gain more profits under the TMTF3DL model.

(2) *With the medium supply chain setting, the logistics vendor gains more profit under the TF3DL model if a) the TF product costs are sufficiently low, b) the TF product costs are sufficiently low or high, c) the logistics delivery cost is high, or d) the TF product customization level is high. Otherwise, s/he can make more profit under the TMTF3DL model.*

(3) *With the high supply chain setting, the logistics vendor obtains more profit under the TF3DL model if a) the TF product costs are sufficiently low, b) the fixed TF product costs are sufficiently low or high, c) the logistics delivery cost is high, or d) the TF product customization level is extremely high. Otherwise, he/she can obtain more profit under the TMTF3DL model.*

We have several findings regarding this proposition, as illustrated in Table 5-9 to Table 5-13.

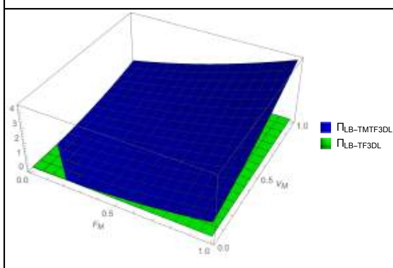
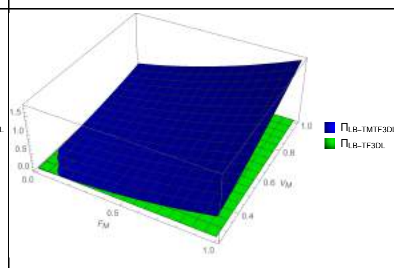
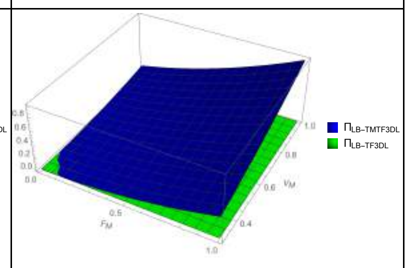
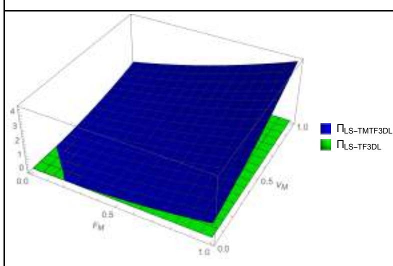
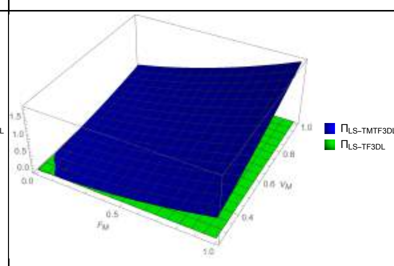
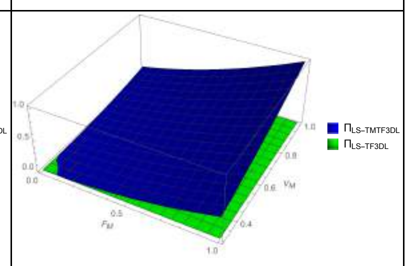
Firstly, we find that multi-product manufacturing does not always lead to more profit for the logistics vendor from increased goods delivery and increased 3DP product revenue. With all three supply chain settings, if the TM product costs are sufficiently low, the logistics vendor can achieve better financial performance under the TF3DL model. If the TM product costs are high, the logistics vendor can glean more profits under the TMTF3DL model (Table 5-9). On the one hand, if the TM product costs are low, the traditional manufacturer can achieve more TM product sales due to the price advantage. Therefore, the logistics vendor can make more profit on product delivery. On the other hand, the new TF product benefits the logistics vendor through a new stream of profit from TF product delivery. Meanwhile, based on our assumption, the TF product price is higher than that of the TM product. Therefore, the higher TF product cost (the higher TF price) also discourages price-sensitive switchers (Dong et al., 2017). Accordingly, the logistics vendor can gain more profits under the traditional manufacturer's TMTF3DL manufacturing strategy.

Secondly, product differentiation can help the traditional manufacturer achieve better financial performance. One of our conjectures is that the TF product always brings more profit to the traditional manufacturer because 1) it forces the traditional manufacturer to use a low-price strategy to attract more price-sensitive consumers and 2) it cannibalizes the 3DP product market. Therefore, it hurts the logistics vendor's business performance. However, if the price of the TF product is located between the TM and the 3DP product, it mitigates the product competition by the product similarity and gains a wider range of consumers. Thus, the logistics vendor can benefit from 1) the increased requirement for delivery of the TM and TF product and 2) the increased 3DP product business.

Thirdly, one might expect that the 3DP product costs play an important role in the logistics vendor's profitability. However, this proposition demonstrates that such an intuition does not hold. As depicted in Table 5-11 below, the logistics vendor can attain better performance in the TF3DL model under the low-cost supply chain setting rather than under the medium and high settings. In general, the traditional manufacturer's TMTF3DL manufacturing strategy helps the logistics vendor to gain a new profit stream from the TF product delivery. On the low supply chain setting, if the 3DP product costs are low, compared to the TMTF3DL model, the logistics vendor can make more profit on 3DP product sales under the TF3DL model because there is no low-price TM product. However, on the medium/high supply chain setting, the logistics vendor can achieve better profitability in the TMTF3DL model. This follows from the fact that if the costs of the TM product are high (such as for bicycle frames, aeroplane engines, etc.), the new TF product can lure some customization-sensitive and price-sensitive consumers. This contributes an increase to the logistics vendor's goods delivery business.

Lastly, on the high supply chain setting, the logistics vendor's profitability depends on the TF product customization level. Recall that β represents the customization level of the TF product. If the customization level of the TF product (β) is low, the logistics vendor cannot gain more profits under this scenario, due to the shrunken sales of the TM product. However, if the TF product customization level is slightly higher, the traditional manufacturer can glean more profits from the TF product sales. Therefore, the logistics vendor can make more profit from the TMTF manufacturing strategy because the positive effect on the product delivery business exceeds the negative effect of the decreased 3DP product sales.

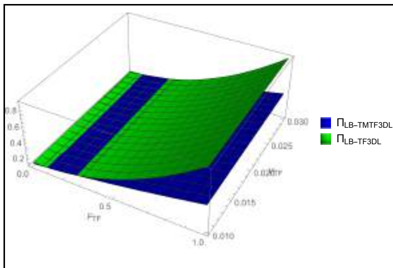
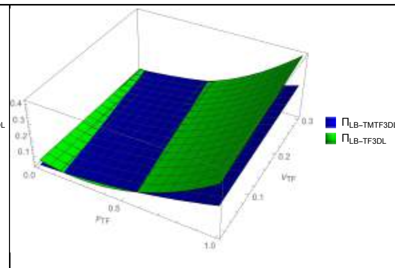
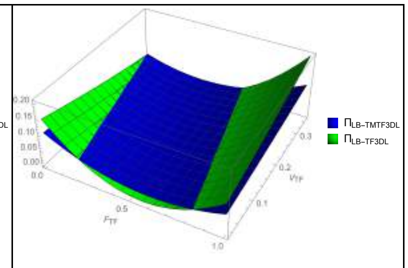
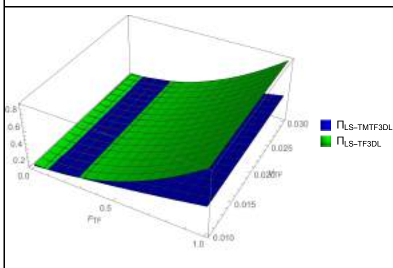
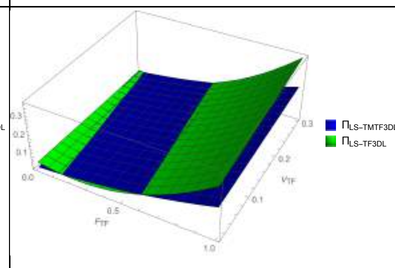
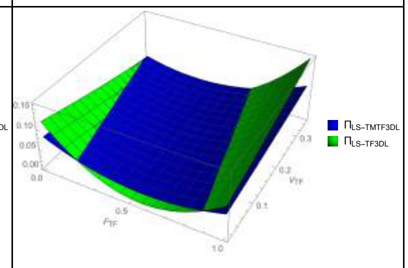
Table 5-9 Logistics Vendor's Maximized Profit: Comparison by TM Product Cost – TMTF3DL and TF3DL

Low	Medium	High
		
		

	TM Product			TF Product			3DP Product		Delivery
	F_M	V_M	α	F_{TF}	V_{TF}	β	F_{3D}	V_{3D}	c_L
Low	-	-	0.1	0.025	0.02	0.2	0.1	0.03	0.01
Medium	-	-	0.2	0.1	0.25	0.4	0.3	0.3	0.01
High	-	-	0.3	0.3	0.3	0.6	0.6	0.35	0.01

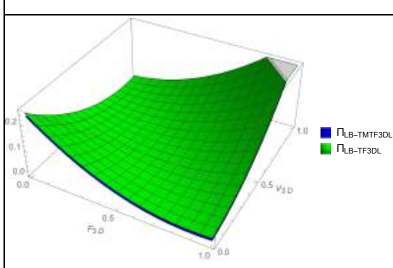
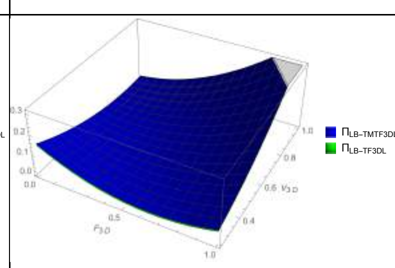
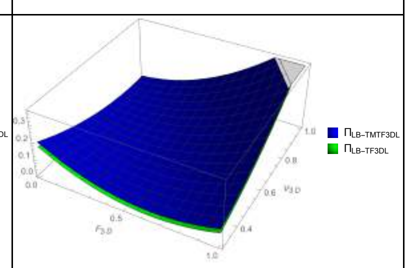
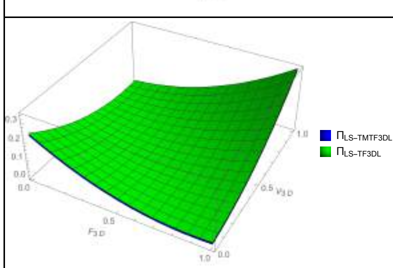
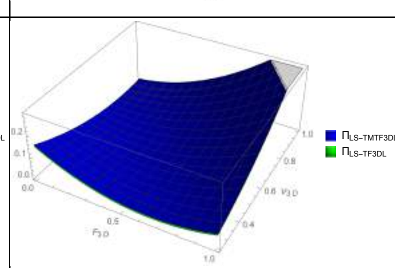
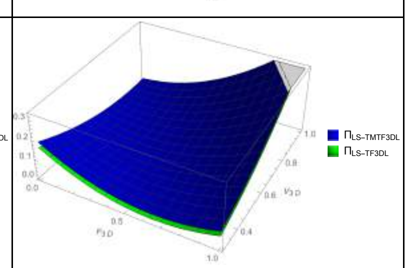
Table 5-10 Logistics Vendor's Maximized Profit: Comparison by TF Product Cost – TMTF3DL and TF3DL

Low	Medium	High

	TM Product			TF Product			3DP Product		Delivery
	F_M	V_M	α	F_{TF}	V_{TF}	β	F_{3D}	V_{3D}	c_L
Low	0.01	0.01	0.1	-	-	0.2	0.1	0.03	0.01
Medium	0.05	0.05	0.2	-	-	0.4	0.3	0.3	0.01
High	0.1	0.08	0.3	-	-	0.6	0.6	0.35	0.01

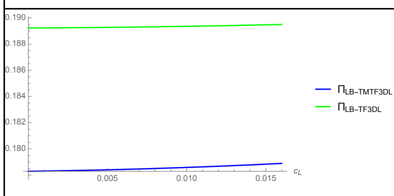
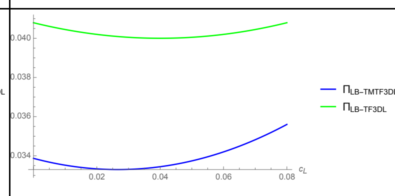
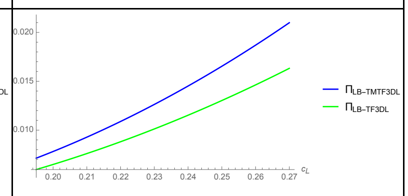
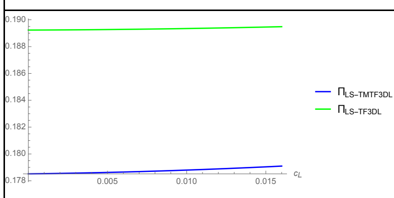
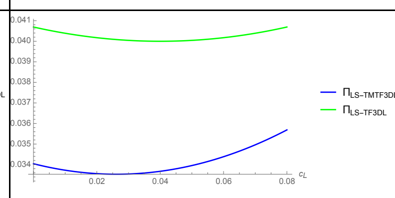
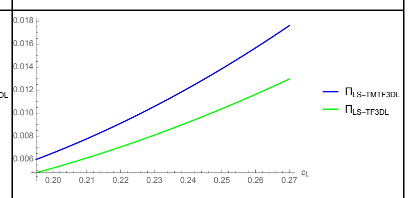
Table 5-11 Logistics Vendor's Maximized Profit: Comparison by 3DP Product Cost – TMTF3DL and TF3DL

Low	Medium	High
		
		

	TM Product	TF Product	3DP Product	Delivery

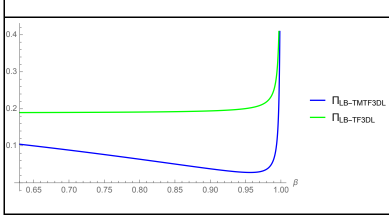
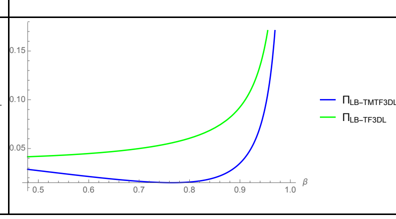
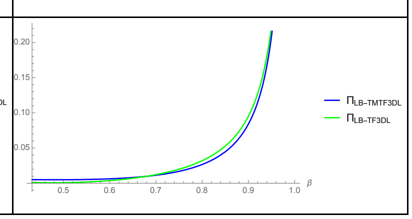
	F_M	V_M	α	F_{TF}	V_{TF}	β	F_{3D}	V_{3D}	c_L
Low	0.01	0.01	0.1	0.025	0.02	0.2	-	-	0.01
Medium	0.05	0.05	0.2	0.1	0.25	0.4	-	-	0.01
High	0.1	0.08	0.3	0.3	0.3	0.6	-	-	0.01

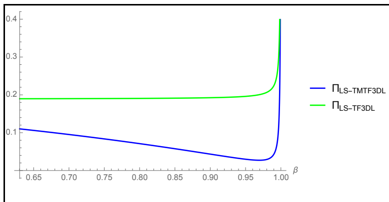
Table 5-12 Logistics Vendor's Maximized Profit: Comparison by Logistics Delivery Cost – TMTF3DL and TF3DL

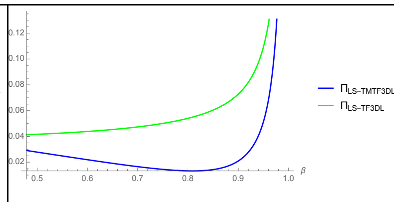
Low	Medium	High
		
		

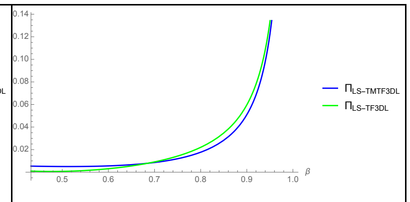
	TM Product			TF Product			3DP Product		Delivery
	F_M	V_M	α	F_{TF}	V_{TF}	β	F_{3D}	V_{3D}	c_L
Low	0.01	0.01	0.1	0.025	0.02	0.2	0.1	0.03	-
Medium	0.05	0.05	0.2	0.1	0.25	0.4	0.3	0.3	-
High	0.1	0.08	0.3	0.3	0.3	0.6	0.6	0.35	-

Table 5-13 Logistics Vendor's Maximized Supply Chain Profit: Comparison by TF Product Customization Level – TMTF3DL and TF3DL

Low	Medium	High
		







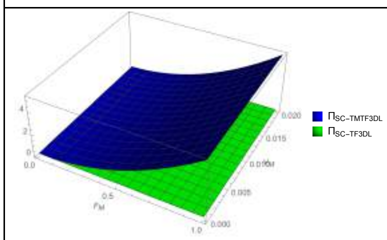
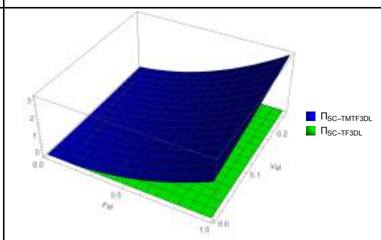
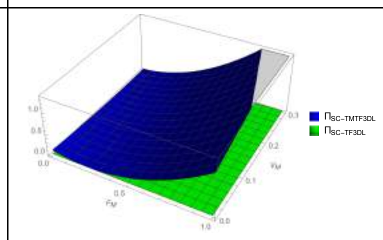
	TM Product			TF Product			3DP Product		Delivery
	F_M	V_M	α	F_{TF}	V_{TF}	β	F_{3D}	V_{3D}	c_L
Low	0.01	0.01	0.1	0.025	0.02	-	0.1	0.03	0.01
Medium	0.05	0.05	0.2	0.1	0.25	-	0.3	0.3	0.01
High	0.1	0.08	0.3	0.3	0.3	-	0.6	0.35	0.01

PROPOSITION 5-6. *In general, the traditional manufacturer's TMTF3DL manufacturing strategy contributes to the development of the integrated supply chain. However, on the low and medium supply chain settings, if the TF product costs are within a certain low range, the TF3DL strategy can help the development of the supply chain instead.*

One might expect that the integrated supply chain is always better off with the traditional manufacturer's TMTF3DL manufacturing strategy (Fahimnia et al., 2013; Koren, 2010; Upton, 2008). However, this proposition indicates that this does not always hold; there are two exceptions (Table 5-15), green area in low-cost setting and medium-cost setting supply chain profits comparison). On the low or medium supply chain setting, there exists a scenario where the integrated supply chain can generate more profits under the TF3DL model. This helps us to explain the 3DP jewellery production competition, and why some jewellery industries still focus only on highly-customized jewellery designs instead of both traditional standard jewellery production and highly-customized jewellery production together. Recall that the TF product customization level is higher than the TM product customization level. Therefore, the TF product is more attractive to those customization-sensitive consumers. If the TF product costs are extremely low, it cannibalizes the TM product and the integrated supply chain can make more profit on the 3DP product. If the TF product costs are high, it discourages price-sensitive switchers, and the integrated supply chain can benefit from more

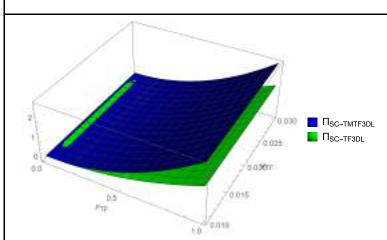
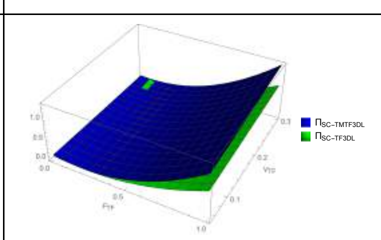
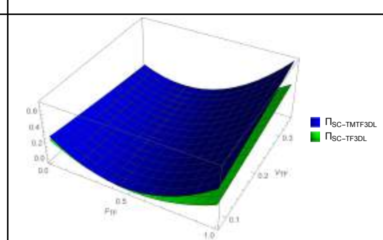
TM product business. However, if the TF product costs are located in between the other two products, the integrated supply chain's loss on the 3DP business exceeds the positive effect of increased TM product and TF product sales. Therefore, the integrated supply chain prefers the traditional manufacturer to choose the TF3DL manufacturing strategy for industry development.

Table 5-14 The Integrated Supply Chain's Maximized Profit: Comparison by TM Product Cost – TMTF3DL and TF3DL

Low	Medium	High
		

	TM Product			TF Product			3DP Product		Delivery
	F_M	V_M	α	F_{TF}	V_{TF}	β	F_{3D}	V_{3D}	c_L
Low	-	-	0.1	0.025	0.02	0.2	0.1	0.03	0.01
Medium	-	-	0.2	0.1	0.25	0.4	0.3	0.3	0.01
High	-	-	0.3	0.3	0.3	0.6	0.6	0.35	0.01

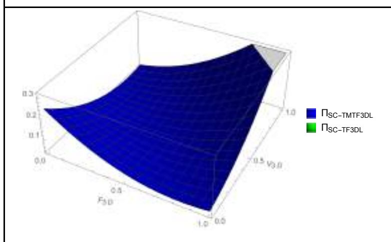
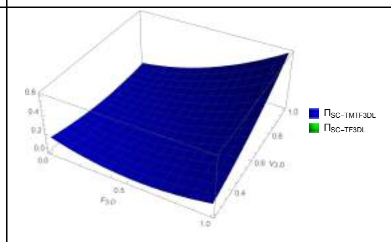
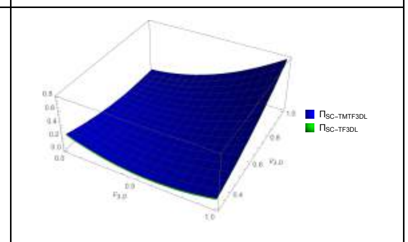
Table 5-15 The Integrated Supply Chain's Maximized Profit: Comparison by TF Product Cost – TMTF3DL and TF3DL

Low	Medium	High
		

	TM Product			TF Product			3DP Product		Delivery
	F_M	V_M	α	F_{TF}	V_{TF}	β	F_{3D}	V_{3D}	c_L

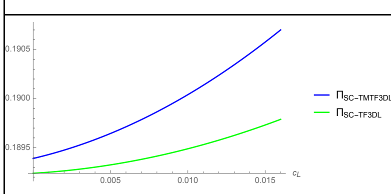
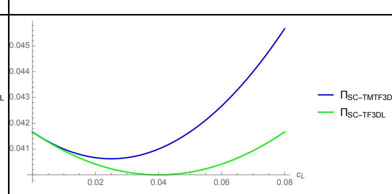
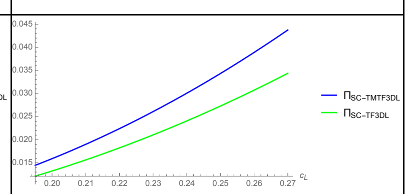
Low	0.01	0.01	0.1	-	-	0.2	0.1	0.03	0.01
Medium	0.05	0.05	0.2	-	-	0.4	0.3	0.3	0.01
High	0.1	0.08	0.3	-	-	0.6	0.6	0.35	0.01

Table 5-16 The Integrated Supply Chain's Maximized Profit: Comparison by 3DP Product Cost – TMTF3DL and TF3DL

Low	Medium	High
		

	TM Product			TF Product			3DP Product		Delivery
	F_M	V_M	α	F_{TF}	V_{TF}	β	F_{3D}	V_{3D}	c_L
Low	0.01	0.01	0.1	0.025	0.02	0.2	-	-	0.01
Medium	0.05	0.05	0.2	0.1	0.25	0.4	-	-	0.01
High	0.1	0.08	0.3	0.3	0.3	0.6	-	-	0.01

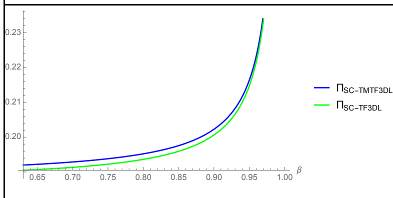
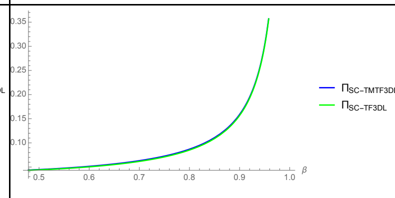
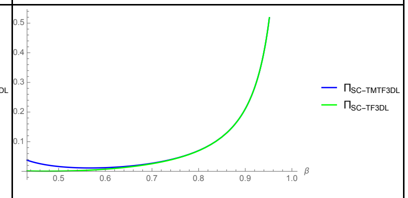
Table 5-17 The Integrated Supply Chain's Maximized Profit: Comparison by Logistics Delivery Cost – TMTF3DL and TF3DL

Low	Medium	High
		

	TM Product			TF Product			3DP Product		Delivery
	F_M	V_M	α	F_{TF}	V_{TF}	β	F_{3D}	V_{3D}	c_L
Low	0.01	0.01	0.1	0.025	0.02	0.2	0.1	0.03	-
Medium	0.05	0.05	0.2	0.1	0.25	0.4	0.3	0.3	-

High	0.1	0.08	0.3	0.3	0.3	0.6	0.6	0.35	-

Table 5-18 The Integrated Supply Chain's Maximized Supply Chain Profit: Comparison by TF Product Customization Level – TMTF3DL and TF3DL

Low	Medium	High
		

	TM Product			TF Product			3DP Product		Delivery
	F_M	V_M	α	F_{TF}	V_{TF}	β	F_{3D}	V_{3D}	c_L
Low	0.01	0.01	0.1	0.025	0.02	-	0.1	0.03	0.01
Medium	0.05	0.05	0.2	0.1	0.25	-	0.3	0.3	0.01
High	0.1	0.08	0.3	0.3	0.3	-	0.6	0.35	0.01

5.5 Traditional Manufacturer's 3DP Manufacturing Strategy

This subsection conducts a comprehensive comparative analysis of the simulated scenarios where the traditional manufacturer adopts 3DP technology and seeks to determine which manufacturing strategy decision is best for the traditional manufacturer with regard to traditional manufacturing, flexible manufacturing and 3DP manufacturing technology.

The rest of this sub-section is organized as follows. We present three different models for the traditional manufacturer's 3DP adoption plan, derive the equilibriums for each model, and then compare the proposed models with the benchmarking model. Finally, we offer a comprehensive comparison of all of the proposed models.

Because this model assumes the customization levels of the 3DP product offered by the traditional manufacturer and the logistics vendor are the same, the model focuses on the scenario in which the traditional manufacturer's 3DP has a price advantage $p_{3DM} < p_{3DL}$.

5.5.1 TMTF3DM Model

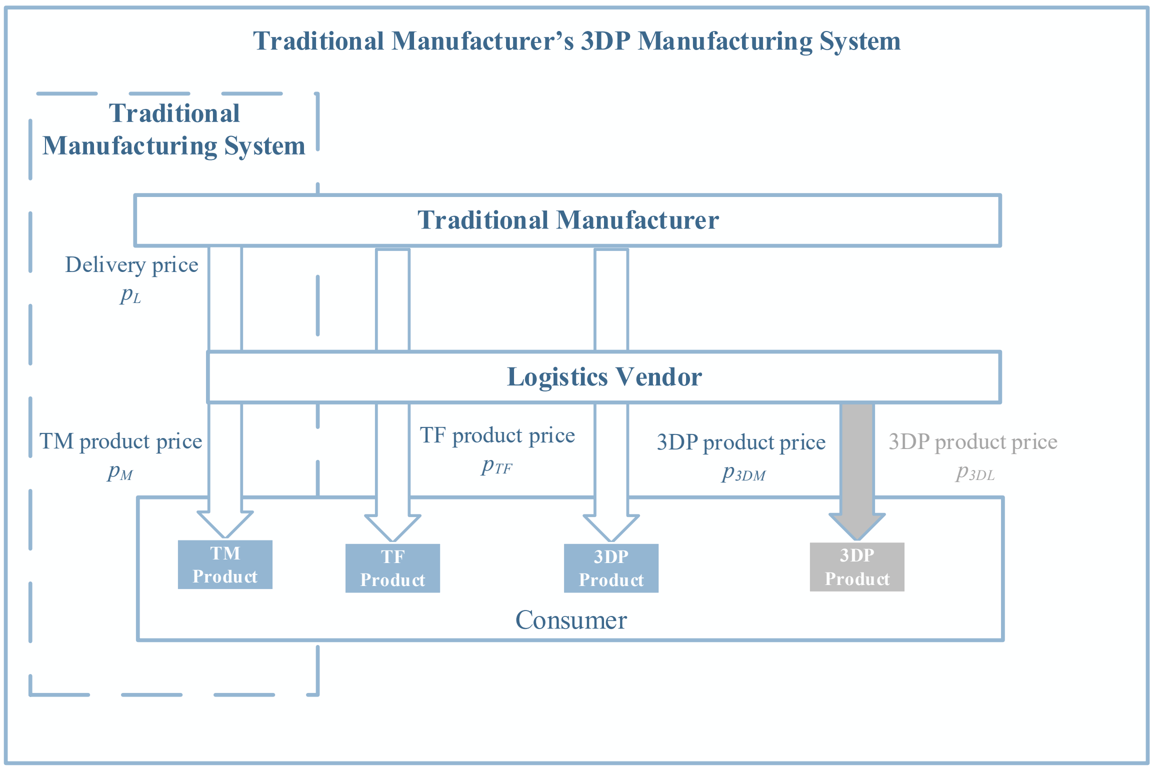


Figure 5-12 Traditional Manufacturer Adopts 3DP – Three Products-TMTF3DM Model

This model builds on Mini Cooper's practice, where Mini as the traditional manufacturer has three different production lines for its car accessories: a traditional manufacturing line, a traditional flexible manufacturing line and the new 3DP manufacturing line. Here, DHL is the logistics vendor for all of the parts delivery (MINI, 2018; Wohlers Associates, 2018).

Based on our analysis of the product market demand in Table 5-2, only when $p_{3DM} < p_{3DL}$ can the traditional manufacturer offer three products differentiated by customization level.

Therefore, the consumer purchases the TM product when $U_M > U_{TF} > U_{3DM}$ and $U_M > 0$ or $U_M > U_{3DM} > U_{TF}$ and $U_M > 0$. The consumer purchases the TF product when $U_{TF} > U_M > U_{3DM}$ and $U_{TF} > 0$ or $U_{TF} > U_{3DM} > U_{TM}$ and $U_{TF} > 0$, and s/he will buy the 3DP product when $U_{3DM} > U_M > U_{TF}$ and $U_{3DM} > 0$ or $U_{3DM} > U_{TF} > U_M$ and $U_{3DM} > 0$. Accordingly, we can derive the inverse market demand functions as follows.

$$q_M = \frac{\beta p_M - \alpha p_{\mathrm{TF}}}{\alpha^2 - \alpha\beta} \tag{5.12}$$

$$q_{TF} = \frac{-p_{\mathrm{3DM}} + p_{\mathrm{TF}}}{-1+\beta} + \frac{-p_M + p_{\mathrm{TF}}}{\alpha - \beta} \tag{5.13}$$

$$q_{3DM} = 1 + \frac{p_{\mathrm{3DM}} - p_{\mathrm{TF}}}{-1+\beta} \tag{5.14}$$

Accordingly, in the decentralized supply chain, the profit functions for the traditional manufacturer and the logistics vendor are

$$\begin{aligned}\prod\nolimits_{3DM} M(p_M, p_{TF}, p_{3DM}) \\ &= (p_M - F_M - V_M - p_L)q_M + (p_{TF} - F_{TF} - \beta V_{TF} - p_L)q_{TF} \\ &+ (p_{3DM} - F_{3D} - V_{3D} - p_L)q_{3DM}\end{aligned} \tag{5.15}$$

$$\prod\nolimits_{3DM} L(p_L) = (p_L - c_L)(q_M + q_{TF} + q_{3DL}) \tag{5.16}$$

And the profit for the integrated supply chain is

$$\begin{aligned}\prod\nolimits_{3DM} SC(p_M, p_{TF}, p_{3DM}) \\ &= (p_M - F_M - V_M - c_L)q_M + (p_{TF} - F_{TF} - \beta V_{TF} - c_L)q_{TF} \\ &+ (p_{3DM} - F_{3D} - V_{3D} - c_L)q_{3DM}\end{aligned} \tag{5.17}$$

Therefore, the traditional manufacturer decides the price of the three different products after the logistics vendor sets the delivery price.

PROPOSITION 5-7. *If the traditional manufacturer tries to offer a TM, TF and 3DP product at the same time,*

(1) In the decentralized 3DP manufacturing system, the maximum profit for the traditional manufacturer is given in Equation (5.97) and the maximum profit for the logistics vendor is as in Equation (5.98), both of which are maximized by the optimal

price shown in Equation (5.90), (5.91), (5.92), and (5.93). The optimal market demand for the TM and 3DP product is given in Equation (5.94), (5.95), and (5.96).

(2) *In the integrated 3DP manufacturing system, the maximum profit for the supply chain is shown in Equation (5.105), which is maximized by optimal price Equation (5.99), (5.100), and (5.101). The optimal market demand for the TM and 3DP product is given in Equation (5.102), (5.103), and (5.104).*

5.5.2 TM3DM Model

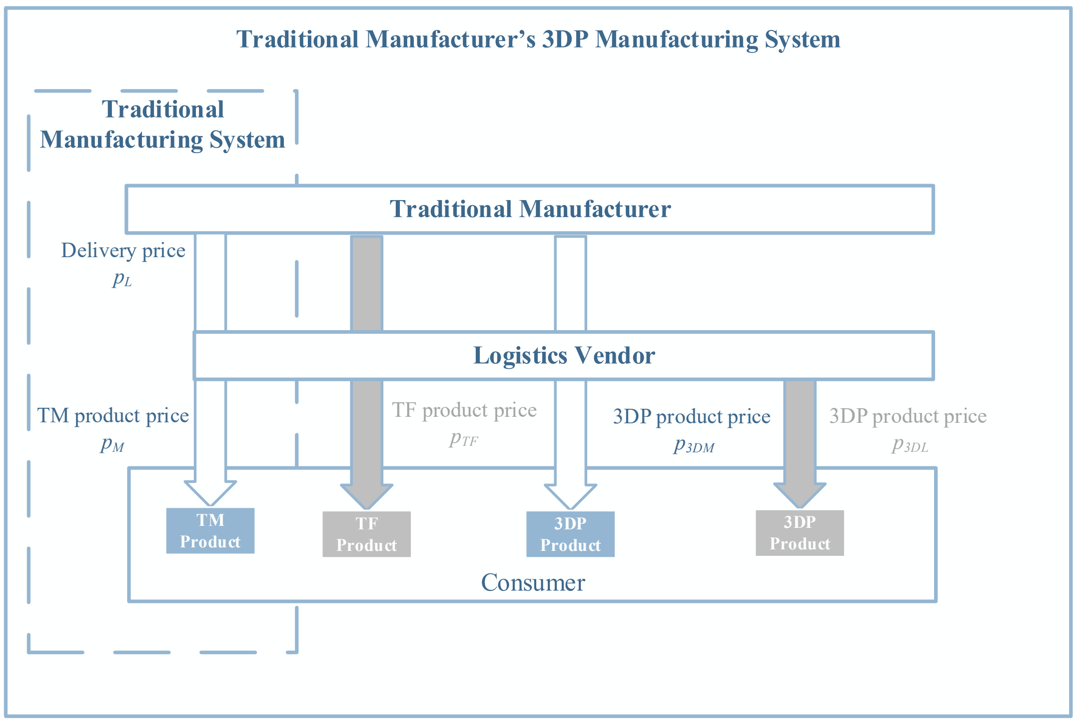


Figure 5-13 Traditional Manufacturer Adopts 3DP –-TM3DM Model

Because the overall cost of TF product production is higher than TM product production in practice, there exists the scenario in which the traditional manufacturer stops the TF product manufacturing line and fully transfers to 3DP production for products with a high customization level. For example, Formula 1 currently uses traditional manufacturing and 3DP manufacturing for the production of car parts (Wohlers Associates, 2018). In this subsection, we focus on this situation, in which the traditional manufacturer simultaneously offers the TM and the 3DP product with a price advantage of $p_{3DM} < p_{3DL}$.

Therefore, the consumer can find two different products in the market, the TM and the 3DP product, both offered by the traditional manufacturer. Therefore, market demand can be easily derived:

$$q_M = \frac{\alpha p_{3DM} - p_M}{(1-\alpha)\alpha} \tag{5.18}$$

$$q_{3DM} = 1 - \frac{p_{3DM} - p_M}{1-\alpha} \tag{5.19}$$

Accordingly, the profit functions for the traditional manufacturer and the logistics vendor are

$$\prod\nolimits_{3DM} M(p_M, p_{3DM}) = (p_M - F_M - V_M - p_L)q_M + (p_{3DM} - F_{3D} - V_{3D} - p_L)q_{3DM} \tag{5.20}$$

$$\prod\nolimits_{3DM} L(p_L) = (p_L - c_L)(q_M + q_{3DM}) \tag{5.21}$$

And the profit for the integrated supply chain is

$$\prod\nolimits_{3DM} SC(p_M, p_{3DM}) = (p_M - F_M - V_M - c_L)q_M + (p_{3DM} - F_{3D} - V_{3D} - c_L)q_{3DM} \tag{5.22}$$

PROPOSITION 5-8. *If the traditional manufacturer tries to offer a TM and 3DP product simultaneously,*

(1) In the decentralized 3DP manufacturing system, the maximum profit for the traditional manufacturer is given in Equation (5.111) and the maximum profit for the logistics vendor is as in Equation (5.112), both of which are maximized by optimal price Equation (5.106), (5.107), and (5.108). The optimal market demand for the TM and 3DP product is given in Equation (5.109) and (5.110).

(2) In the integrated 3DP manufacturing system, the maximum profit for the supply chain is given in Equation (5.117), which is maximized by optimal price Equation (5.113) and (5.114). The optimal market demand for the TM and 3DP product is calculated by Equation (5.115) and (5.116).

5.5.3 3DM Model

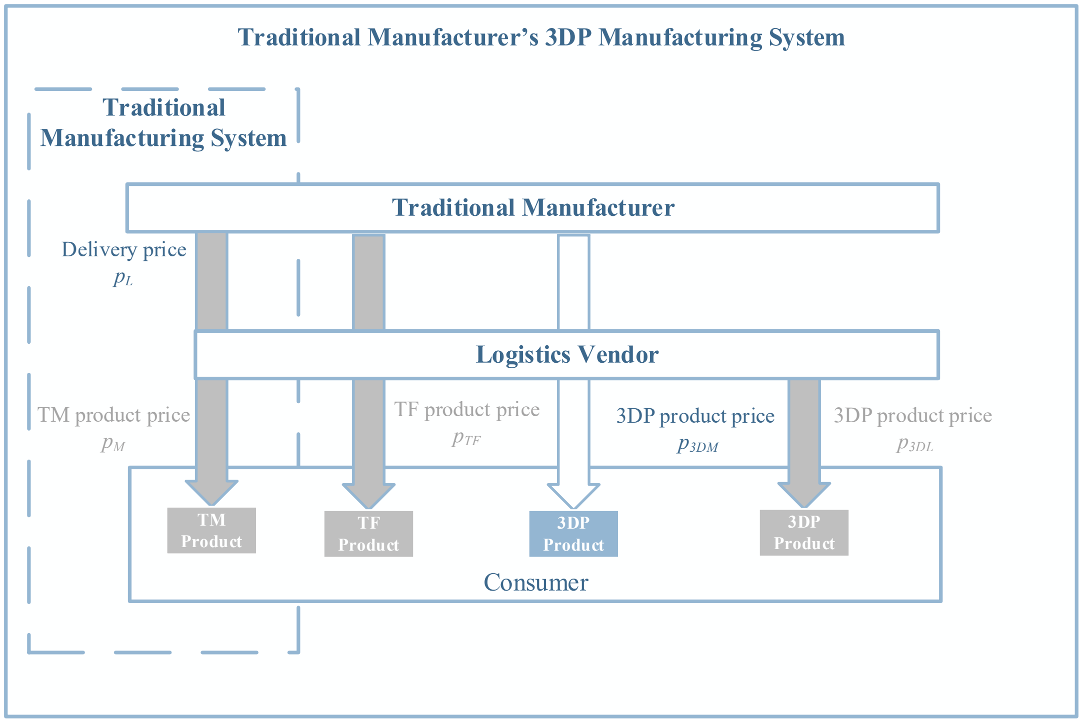


Figure 5-14 Traditional Manufacturer Adopts 3DP – 3DM Model

In this sub-section, this model tests the scenario in which the traditional manufacturer completely replaces its current manufacturing system with 3DP technology (e.g. LimaCorporate uses 3DP technology to produce orthopaedic products (Wohlers Associates, 2018)). Therefore, the market demand for the 3DP product is $q_{3DM} = 1 - p_{3DM}$, and the profit functions of the traditional manufacturer, the logistics vendor, and the integrated supply chain are

$$\prod\nolimits_{3DM} M(p_{3DM}) = (p_{3DM} - F_{3D} - V_{3D} - p_L)q_{3DM} \tag{5.23}$$

$$\prod\nolimits_{3DM} L(p_L) = (p_L - c_L)q_{3DM} \tag{5.24}$$

$$\prod\nolimits_{3DM} SC(p_{3DM}) = (p_{3DM} - F_{3D} - V_{3D} - c_L)q_{3DM} \tag{5.25}$$

PROPOSITION ***5-9.*** *If the traditional manufacturer tries to use a 3DP product to fully replace the TM product,*

(1) *In the decentralized 3DP manufacturing system, the maximum profit for the traditional manufacturer is* $\prod_{3DM}^{*} M(p_{3DM}) = \frac{1}{16}(-1 + c_L + F_{3D} + V_{3D})^2$ *and the maximum profit for the logistics vendor is* $\prod_{3DM}^{*} L(p_L) = \frac{1}{8}(-1 + c_L + F_{3D} + V_{3D})^2$*, which are maximized by optimal price* $p_L^* = \frac{1}{2}(1 + c_L - F_{3D} - V_{3D})$ *and* $p_{3DM}^* = \frac{1}{4}(3 + c_L + F_{3D} + V_{3D})$*. The optimal market demand for the 3DP product is* $q_{3DM}^* = \frac{1}{4}(1 - c_L - F_{3D} - V_{3D})$*.*

(2) *In the integrated 3DP manufacturing system, the maximum profit for the supply chain is* $\prod_{3DM}^{*} M(p_{3DM}) = \frac{1}{4}(-1 + c_L + F_{3D} + V_{3D})^2$*, which is maximized by optimal price* $p_{3DM}^* = \frac{1}{2}(1 + c_L + F_{3D} + V_{3D})$ *and the optimal market demand for the 3DP product is* $q_{3DM}^* = \frac{1}{2}(1 - c_L - F_{3D} - V_{3D})$*.*

Above proposition lists the optional decisions and the maximized profits functions for different market structure.

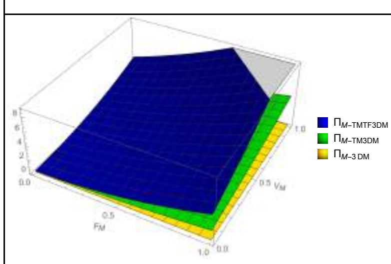
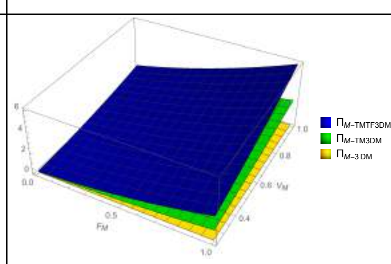
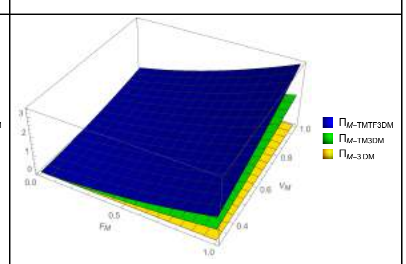
5.5.4 Comparisons over the 3DP Enabled Models

In this subsection, we compare the supply chain stakeholders' profit functions and the integrated supply chain's profitability, for the purpose of finding out which 3DP adoption strategy is the best strategy for the traditional manufacturer and what the impacts are for the logistics vendor's profitability and the overall supply chain's development.

PROPOSITION ***5-10.*** *The traditional manufacturer is always better off using the TMTF3DM strategy; the product costs and the TF product customization level have no impact on this manufacturing decision.*

According to Table 5-19 to Table 5-23, it is obvious that it is better to use the TMTF3DM manufacturing strategy because it helps the traditional manufacturer to cover a wider variety of consumer needs. There are two interesting findings there. Firstly, the product costs are not relevant to this decision. When the traditional manufacturer introduces the TMTF3DM manufacturing strategy, s/he uses a different pricing setting for each product. Therefore, as long as the costs of the different products are different, the price differences help the traditional manufacturer differentiate the TM, the TF, and the 3DP product in the market. Secondly, the TF product customization level also cannot influence the traditional manufacturer's manufacturing strategy here. Recall that the TF product customization level β is located between the TM product customization level α and the 3DP product customization level 1. Therefore, the introduction of the TF product makes the market expansion robut and it also can increases the overall profitability of the traditional manufacturer. This finding is different from the research result in (Dong et al., 2017)'s work. Their study still suggest that adopting traditional flexible manufacturing technology in addition to other manufacturing technology might reduce product variety. For those companies which have already put much effort into flexible manufacturing, it is time to seriously think about the advantages of 3DP production. This result also helps us to understand why MINI added a new 3DP production line into its current manufacturing system.

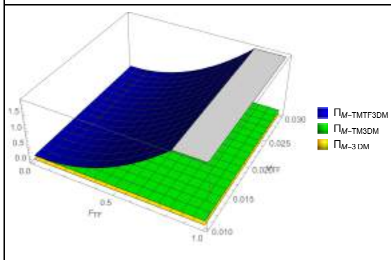
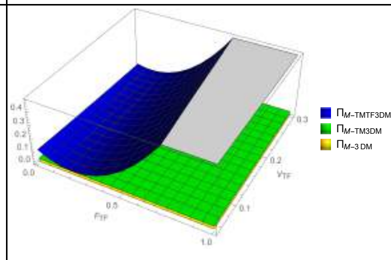
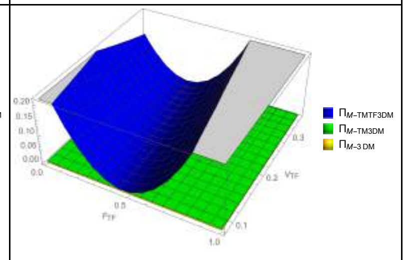
Table 5-19 Traditional Manufacturer's Maximized Profit: Comparison by TM Product Cost – TMTF3DM, TM34DM and 3DM

Low	Medium	High
		

	TM Product			TF Product			3DP Product		Delivery
	F_M	V_M	α	F_{TF}	V_{TF}	β	F_{3D}	V_{3D}	c_L
Low	-	-	0.1	0.025	0.02	0.2	0.1	0.03	0.01
Medium	-	-	0.2	0.1	0.25	0.4	0.3	0.3	0.01

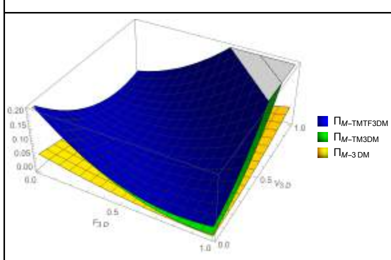
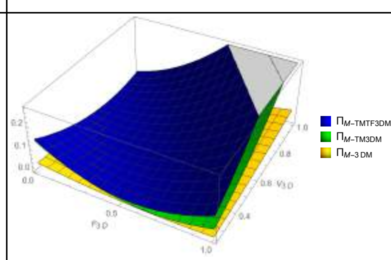
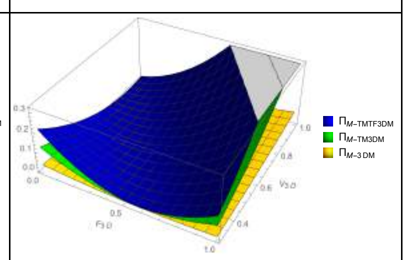
High	-	-	0.3	0.3	0.3	0.6	0.6	0.35	0.01

Table 5-20 Traditional Manufacturer's Maximized Profit: Comparison by TF Product Cost – TMTF3DM, TM34DM and 3DM

Low	Medium	High
		

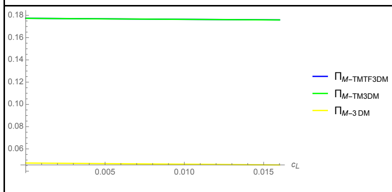
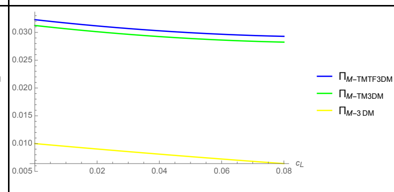
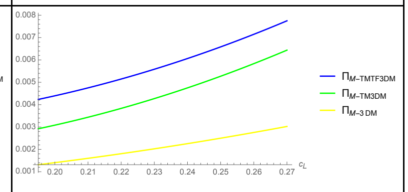
	TM Product			TF Product			3DP Product		Delivery
	F_M	V_M	α	F_{TF}	V_{TF}	β	F_{3D}	V_{3D}	c_L
Low	0.01	0.01	0.1	-	-	0.2	0.1	0.03	0.01
Medium	0.05	0.05	0.2	-	-	0.4	0.3	0.3	0.01
High	0.1	0.08	0.3	-	-	0.6	0.6	0.35	0.01

Table 5-21 Traditional Manufacturer's Maximized Profit: Comparison by 3DP Product Cost – TMTF3DM, TM34DM and 3DM

Low	Medium	High
		

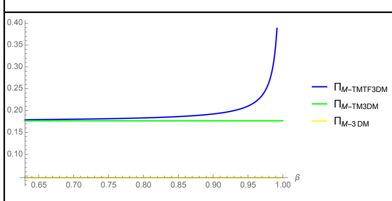
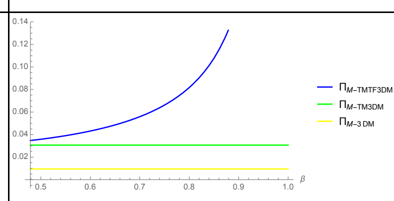
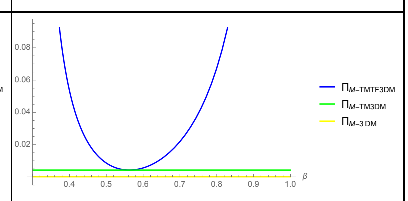
	TM Product			TF Product			3DP Product		Delivery
	F_M	V_M	α	F_{TF}	V_{TF}	β	F_{3D}	V_{3D}	c_L
Low	0.01	0.01	0.1	0.025	0.02	0.2	-	-	0.01
Medium	0.05	0.05	0.2	0.1	0.25	0.4	-	-	0.01
High	0.1	0.08	0.3	0.3	0.3	0.6	-	-	0.01

Table 5-22 Traditional Manufacturer's Maximized Profit: Comparison by Logistics Delivery Cost – TMTF3DM, TM34DM and 3DM

Low	Medium	High
		

	TM Product			TF Product			3DP Product		Delivery
	F_M	V_M	α	F_{TF}	V_{TF}	β	F_{3D}	V_{3D}	c_L
Low	0.01	0.01	0.1	0.025	0.02	0.2	0.1	0.03	-
Medium	0.05	0.05	0.2	0.1	0.25	0.4	0.3	0.3	-
High	0.1	0.08	0.3	0.3	0.3	0.6	0.6	0.35	-

Table 5-23 Traditional Manufacturer's Maximized Supply Chain Profit: Comparison by TF Product Customization Level – TM3DL and TMTF3DM

Low	Medium	High
		

	TM Product			TF Product			3DP Product		Delivery
	F_M	V_M	α	F_{TF}	V_{TF}	β	F_{3D}	V_{3D}	c_L
Low	0.01	0.01	0.1	0.025	0.02	-	0.1	0.03	0.01
Medium	0.05	0.05	0.2	0.1	0.25	-	0.3	0.3	0.01
High	0.1	0.08	0.3	0.3	0.3	-	0.6	0.35	0.01

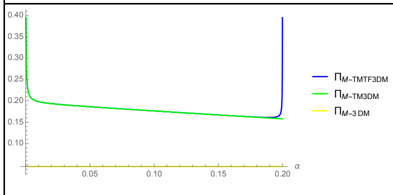
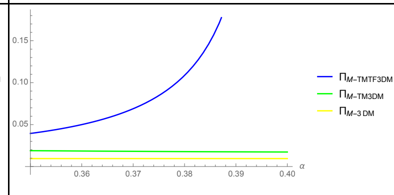
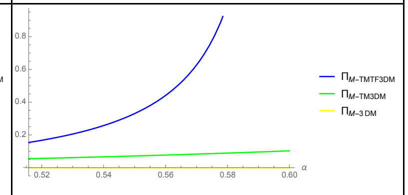
PROPOSITION *5-11*.

(1) Under the low supply chain setting, operating TM, TF and 3DP production is the best manufacturing strategy for the traditional manufacturer if the TM product customization level is comparatively high; otherwise, TM3DM is the best manufacturing strategy.

(2) *Under the medium/high supply chain setting, the traditional manufacturer is always better off operating the TMTF3DM manufacturing strategy.*

This proposition shows that the parameter α plays a crucial role in the traditional manufacturer's manufacturing strategy in the supply chain on the low-cost setting. Recall that α is an indicator of the TF product customization level. A higher α implies that the TM product is much more similar to the TM and the 3DP products. If α is extremely high, the competition between the TM, the TF and the 3DM product is more aggressive, which leads to more profits for the traditional manufacturer. However, if α is in the lower range, then the TM, the TF, and the 3DP product are differentiated by huge gaps in product customization level. The TF product, whose product customization level is located in the middle, cannibalizes the TM product market (by its higher production customization) and the 3DP product market (by low pricing). This outcome indicates that it is not profitable to the traditional manufacturer to operate the 3 differentiated production lines. Therefore, instead of introducing both TF and 3DP production, directly adopting 3DP production is the best strategy for the traditional manufacturer. In practice, for those small but professional studios for racing car component manufacturing, adding 3DP production is a better choice for their high-customization but low volume manufacturing. For example, SR Machining, a manufacturer of aircraft brake inserts, has successfully adopted 3DP production into its manufacturing system and achieved better business performance (3D Systems, 2018d). However, on the medium and high supply chain setting, no matter the TF product customization level, the traditional manufacturer is always better off using the TMTF3DM manufacturing strategy. One example is GE Aircraft (3D Systems, 2018e; Kellner, 2018), which simultaneously operates TM, TF and 3DP production lines for aircraft bracket production, depending on the different consumer requirements and production line availability.

Table 5-24 Traditional Manufacturer's Maximized Supply Chain Profit: Comparison by TM Product Customization – TMTF3DM, TM34DM and 3DM

Low	Medium	High
		

	TM Product			TF Product			3DP Product		Delivery
	F_M	V_M	α	F_{TF}	V_{TF}	β	F_{3D}	V_{3D}	c_L
Low	0.01	0.01	-	0.025	0.02	0.2	0.1	0.03	0.01
Medium	0.05	0.05	-	0.1	0.25	0.4	0.3	0.3	0.01
High	0.1	0.08	-	0.3	0.3	0.6	0.6	0.35	0.01

PROPOSITION *5-12.* *For the logistics vendor, compared to the 3DP product cost, 1) if the TM product customization level is low and the TM product costs are comparatively high, or 2) if the TM product customization level is high but the TM product costs are comparatively low, the logistics vendor can glean more profits in the TMTF3DM or the TM3DM model. Otherwise, the logistics vendor can gain more profits in the 3DM model.*

Intuitively, we expect that the logistics vendor can attain better profitability under the TMTF3DM model, because a larger product range represents more product delivery revenue for the logistics vendor. But this proposition indicates that 1) the logistics vendor's profitability under the TMTF3DM and the TM3DM model is the same and his/her financial performance only depends on the TM product costs, the logistics delivery cost and the TM product customization level under equilibriums. The explanation is that, under both models, the competition among products depends on the TM product costs and the TM product customization level. In Dong et al. (2017)'s study, they also point out that if there is traditional manufacturing line, adopting the traditional flexible technology may reduce product variety.. For example, if the costs of the TM product are low and the TM product customization level is low, the traditional manufacturer uses low pricing for the TM product in order to achieve more product sales but uses a high price on the TF and the 3DP product to obtain a higher margin. 2) If the TM product customization level is high but the relevant costs are low, the traditional manufacturer can gain more profits on the TM product, and therefore the logistics vendor can make more profits on the TM product delivery. If the TM product customization level is low but the cost is high, the traditional manufacturer can gain more business from the TF product. Thus, under these two conditions, the wider product range can help the logistics vendor make more profits from the extended market range than from the 3DM model alone.

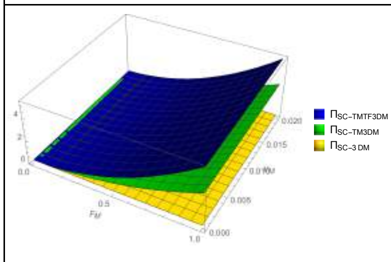
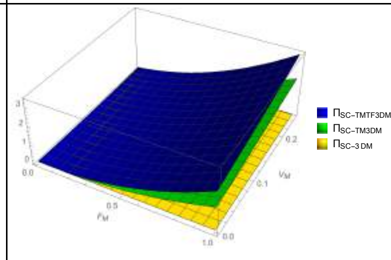
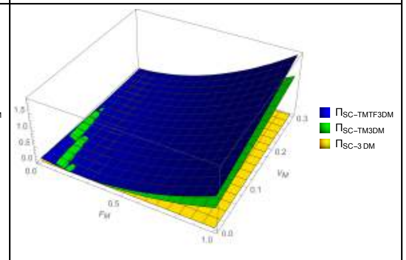
PROPOSITION *5-13*.

(1) Under the low/high supply chain setting, if the TM product costs are sufficiently low, the integrated supply chain can make more profit under the traditional manufacturer's TM3DM strategy; otherwise, TMTF3DM is the best manufacturing strategy for the integrated supply chain.

(2) Under the medium supply chain setting, the TMTF3DM manufacturing strategy is the best choice for the integrated supply chain.

Remarkably, we found that there exist two types of scenario where TM3DM is better than the TMTF3DM strategy for the integrated supply chain. 1) Under the low supply chain setting, if the TM product costs are low, the TM product has the pricing advantage; therefore, it is not necessary to operate an extra TF product. The implication of this finding is that for those durable product industries, it is better to encourage the traditional manufacturer to adopt 3DP rather than traditional manufacturing technologies. 2) With the high supply chain setting, for example in the Prosthesis industry, although the costs of TM production are low, adding a 3DP production line is better than setting up additional flexible production. For instance, Emerging Implant Technologies has introduced a 3DP prosthesis into its current product line (Emerging Implant Technologies, 2018). Besides these two scenarios, even under the medium supply chain setting, the wider product coverage can bring more profits to the integrated supply chain through the positive impact of the expanded consumer base and the mediated market share.

Table 5-25 Integrated Supply Chain's Maximized Profit: Comparison by TM Product Cost – TMTF3DM, TM34DM and 3DM

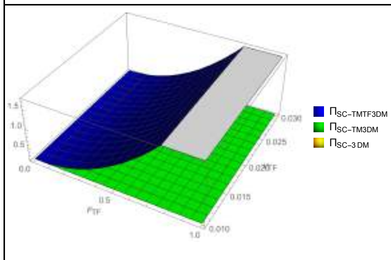
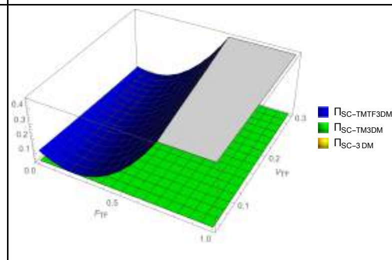
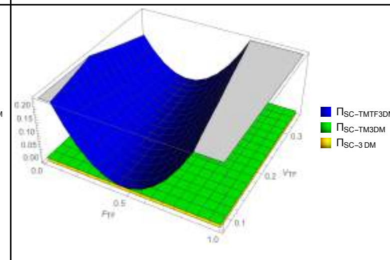
Low	Medium	High
		

	TM Product			TF Product			3DP Product		Delivery
	F_M	V_M	α	F_{TF}	V_{TF}	β	F_{3D}	V_{3D}	c_L
Low	-	-	0.1	0.025	0.02	0.2	0.1	0.03	0.01
Medium	-	-	0.2	0.1	0.25	0.4	0.3	0.3	0.01
High	-	-	0.3	0.3	0.3	0.6	0.6	0.35	0.01

PROPOSITION 5-14. *The integrated supply chain can gain more profits if the traditional manufacturer chooses the TMTF3DM manufacturing strategy, no matter the costs of the TF/3DP product, the cost of logistics delivery, or the customization level of the TM and the TF product.*

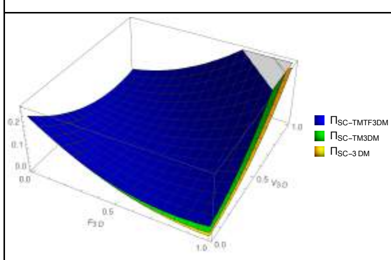
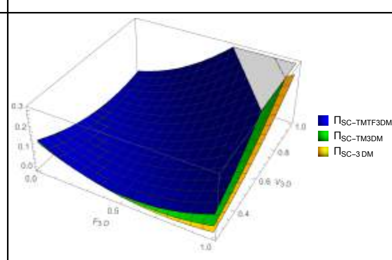
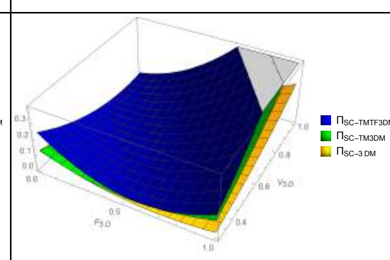
This proposition endorses one of our expectations that the wider product range helps the integrated supply chain's development. Taking the above proposition into consideration as well, interestingly, we expect that the cost of the TM product, other costs and even the product customization level cannot influence the overall supply chain performance (Table 5-26 to Table 5-30). Therefore, during the supply chain's evolution from a traditional manufacturing system to high customization 3DP production, the only consideration is the cost of TM production.

Table 5-26 Integrated Supply Chain's Maximized Profit: Comparison by TF Product Cost – TMTF3DM, TM34DM and 3DM

Low	Medium	High
		

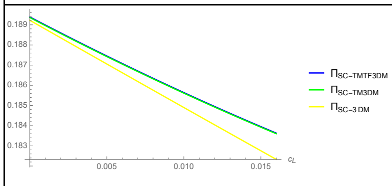
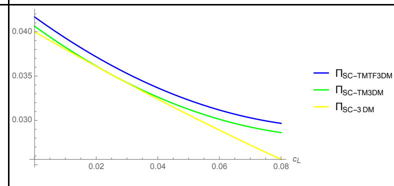
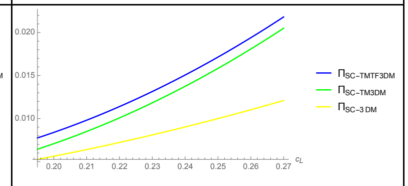
	TM Product			TF Product			3DP Product		Delivery
	F_M	V_M	α	F_{TF}	V_{TF}	β	F_{3D}	V_{3D}	c_L
Low	0.01	0.01	0.1	-	-	0.2	0.1	0.03	0.01
Medium	0.05	0.05	0.2	-	-	0.4	0.3	0.3	0.01
High	0.1	0.08	0.3	-	-	0.6	0.6	0.35	0.01

Table 5-27 Integrated Supply Chain's Maximized Profit: Comparison by 3DP Product Cost – TMTF3DM, TM34DM and 3DM

Low	Medium	High
		

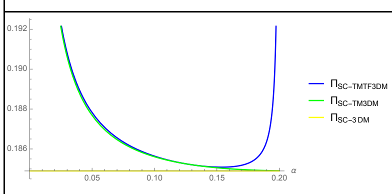
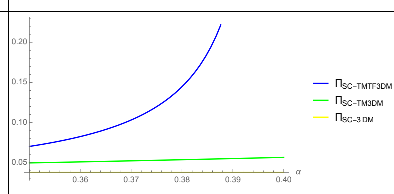
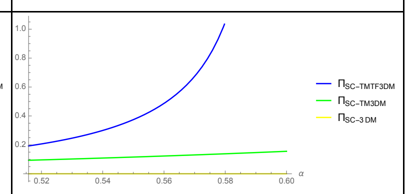
	TM Product			TF Product			3DP Product		Delivery
	F_M	V_M	α	F_{TF}	V_{TF}	β	F_{3D}	V_{3D}	c_L
Low	0.01	0.01	0.1	0.025	0.02	0.2	-	-	0.01
Medium	0.05	0.05	0.2	0.1	0.25	0.4	-	-	0.01
High	0.1	0.08	0.3	0.3	0.3	0.6	-	-	0.01

Table 5-28 Integrated Supply Chain's Maximized Profit: Comparison by Logistics Delivery Cost – TMTF3DM, TM34DM and 3DM

Low	Medium	High
		

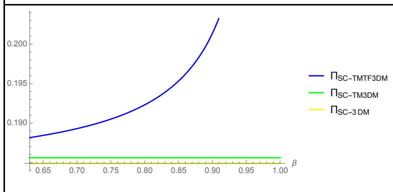
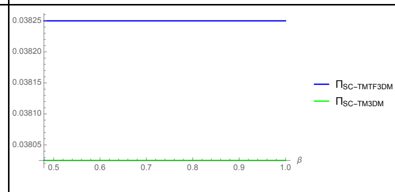
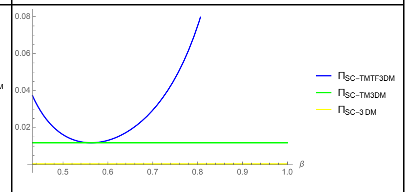
	TM Product			TF Product			3DP Product		Delivery
	F_M	V_M	α	F_{TF}	V_{TF}	β	F_{3D}	V_{3D}	c_L
Low	0.01	0.01	0.1	0.025	0.02	0.2	0.1	0.03	-
Medium	0.05	0.05	0.2	0.1	0.25	0.4	0.3	0.3	-
High	0.1	0.08	0.3	0.3	0.3	0.6	0.6	0.35	-

Table 5-29 Integrated Supply Chain's Maximized Profit: Comparison by TM Product Customization Level – TMTF3DM, TM34DM and 3DM

Low	Medium	High
		

	TM Product			TF Product			3DP Product		Delivery
	F_M	V_M	α	F_{TF}	V_{TF}	β	F_{3D}	V_{3D}	c_L
Low	0.01	0.01	-	0.025	0.02	0.2	0.1	0.03	0.01
Medium	0.05	0.05	-	0.1	0.25	0.4	0.3	0.3	0.01
High	0.1	0.08	-	0.3	0.3	0.6	0.6	0.35	0.01

Table 5-30 Integrated Supply Chain's Maximized Profit: Comparison by TF Product Customization Level – TM3DL and TMTF3DM

Low	Medium	High
		

	TM Product			TF Product			3DP Product		Delivery
	F_M	V_M	α	F_{TF}	V_{TF}	β	F_{3D}	V_{3D}	c_L
Low	0.01	0.01	0.1	0.025	0.02	-	0.1	0.03	0.01
Medium	0.05	0.05	0.2	0.1	0.25	-	0.3	0.3	0.01
High	0.1	0.08	0.3	0.3	0.3	-	0.6	0.35	0.01

5.6 Comparison between the TMTF3DL and TMTF3DM Model

Under this subsection, we compare the TMTF3DL and TMTF3DL model and try to answer the questions: 1) Should the traditional manufacturer operate the 3DP product on his/her own, and if so, then under what conditions? 2) What is the impact on the logistics vendor's profitability? 3) What are the impacts on the integrated supply chain's overall performance?

PROPOSITION *5-15.* *It is not always beneficial to the traditional manufacturer to operate the 3DM product by himself/herself.*

(1) Under the low supply chain setting, no matter the product costs and the product customization level, the traditional manufacturer can glean more profits in the TMTF3DM model.

(2) Under the medium supply chain setting, in most cases, the traditional manufacturer can generate more profits under the self-operated 3DP model. However, the only exception is that if the TM product costs are high, letting the logistics vendor handle the 3DP product is more profitable to the traditional manufacturer in the decentralized Bertrand supply chain.

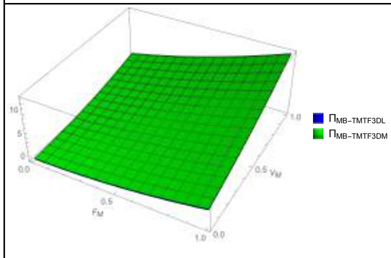
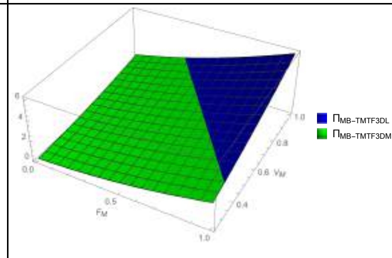
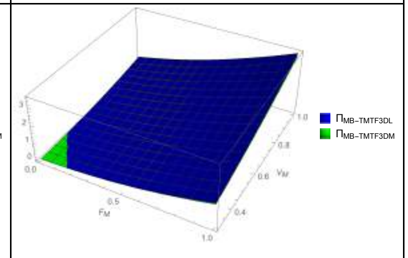
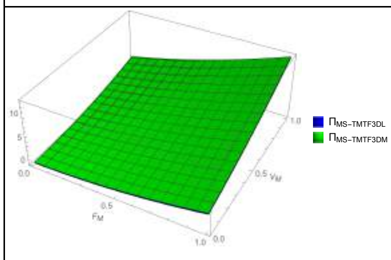
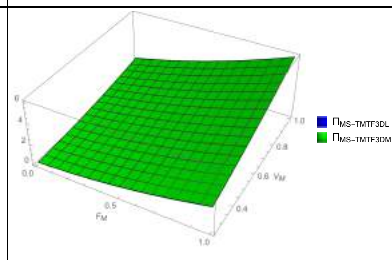
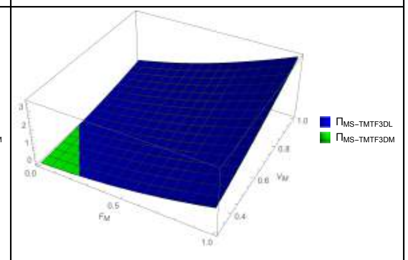
(3) Under the high supply chain setting, it is profitable for the traditional manufacturer to offer a 3DP product 1) if the TM product costs are low; 2) if the fixed TF product cost is sufficiently low or high; or 3) if the logistics delivery cost is high.

We have identified several scenarios under which the traditional manufacturer could let the logistics vendor handle the 3DP product market (Table 13 to Table 18).

Firstly, we find that in the Bertrand supply chain on the medium setting, if the TM product costs are high, it is profitable to the traditional manufacturer to let the logistics vendor operate the 3DP product business. In the Bertrand supply chain, the traditional manufacturer gives the prices to his/her product first and then the logistics vendor sets the 3DP product price, and therefore if the traditional manufacturer operates the 3DM product, s/he increases the price of the TF and the 3DP product to offer price advantages to the TM product. But this results in shrunken product sales overall. Therefore, the traditional manufacturer cannot generate more profits under this scenario. An example to this would be the knee arthroplasty case, one of the knee arthroplasty company Courtesy of Aesculap AG outsourcing the high customized customer order to the third-party 3DP professional Stratasys (Thompson et al., 2016).

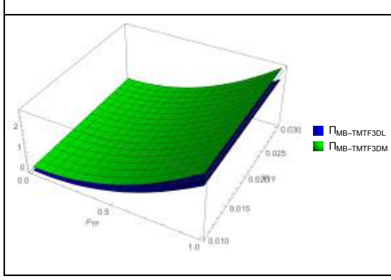
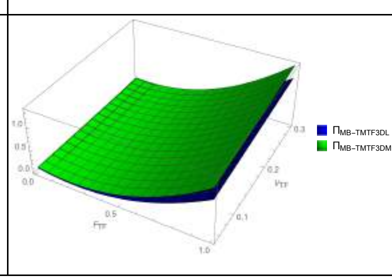
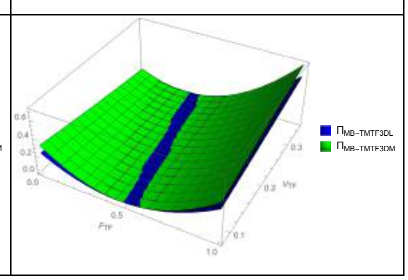
Secondly, under the high supply chain setting, 1) if the TM product cost is low, besides the new revenue stream from the 3DP product, the traditional manufacturer can also make more profits on the low-price TM product. 2) If the fixed cost of the TF product is extremely low (e.g. nut) or extremely high (e.g. aerospaceplane), the TF product has customization advantages over the TM or the TF product has price advantages over the 3DM product. No matter under which scenario, the traditional manufacturer can benefit from the aggressive product competition. 3) If the logistics delivery cost is high, it is better to let the logistics vendor offer the 3DP product because the traditional manufacturer needs to pay the delivery service fee to the logistics vendor for all product sales.

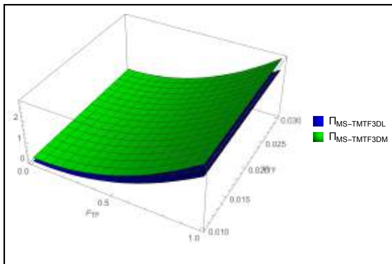
Table 5-31 Traditional Manufacturer's Maximized Profit: Comparison by TM Product Cost – TMTF3DL and TF3DL

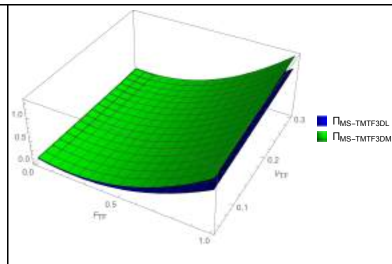
Low	Medium	High
		
		

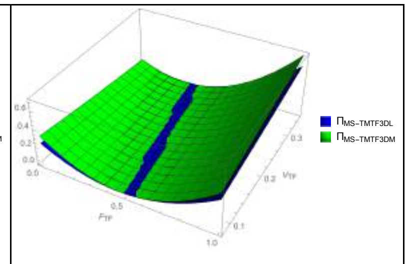
	TM Product			TF Product			3DP Product		Delivery
	F_M	V_M	α	F_{TF}	V_{TF}	β	F_{3D}	V_{3D}	c_L
Low	-	-	0.1	0.025	0.02	0.2	0.1	0.03	0.01
Medium	-	-	0.2	0.1	0.25	0.4	0.3	0.3	0.01
High	-	-	0.3	0.3	0.3	0.6	0.6	0.35	0.01

Table 5-32 Traditional Manufacturer's Maximized Profit: Comparison by TF Product Cost – TM3DL and TMTF3DM

Low	Medium	High
		



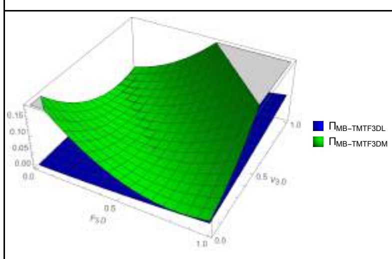


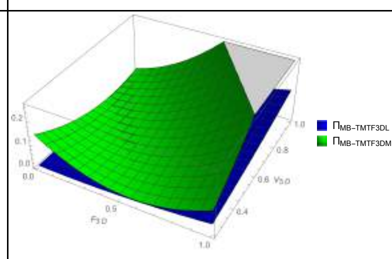


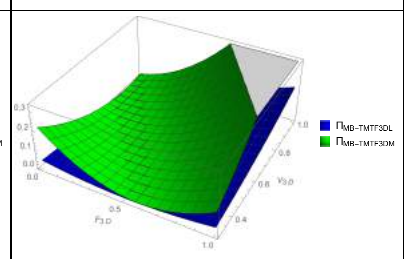
	TM Product			TF Product			3DP Product		Delivery
	F_M	V_M	α	F_{TF}	V_{TF}	β	F_{3D}	V_{3D}	c_L
Low	0.01	0.01	0.1	-	-	0.2	0.1	0.03	0.01
Medium	0.05	0.05	0.2	-	-	0.4	0.3	0.3	0.01
High	0.1	0.08	0.3	-	-	0.6	0.6	0.35	0.01

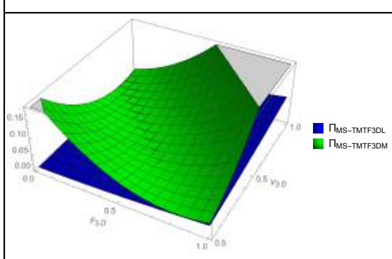
Table 5-33 Traditional Manufacturer's Maximized Profit: Comparison by 3DP Product Cost – TM3DL and TMTF3DM

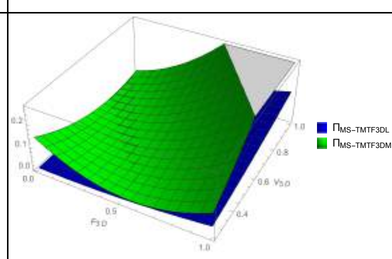
Low	Medium	High

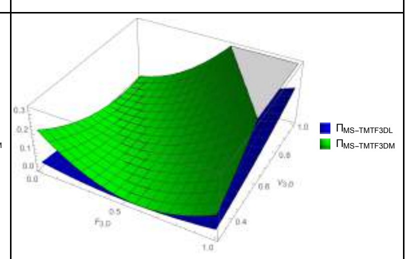






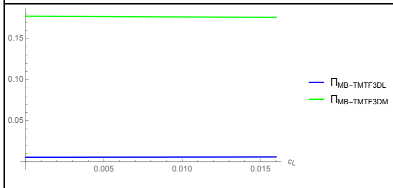
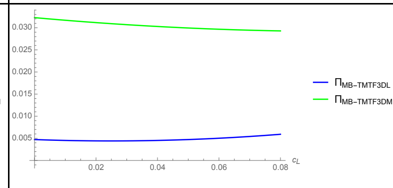
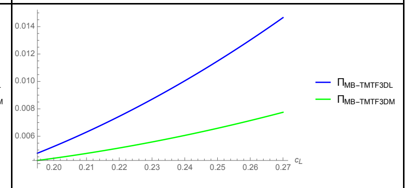
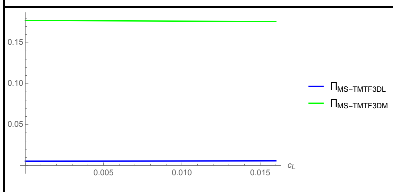
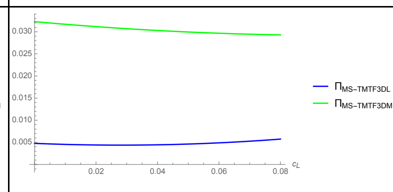
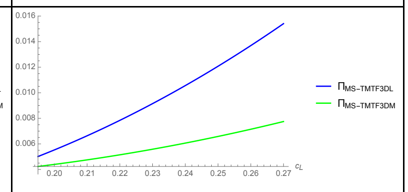






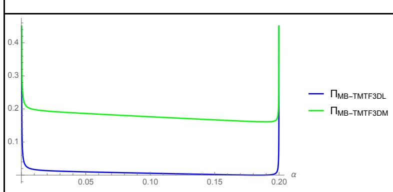
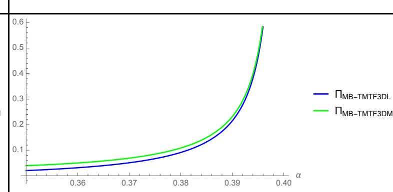
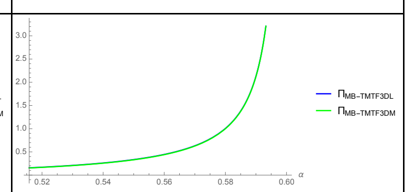
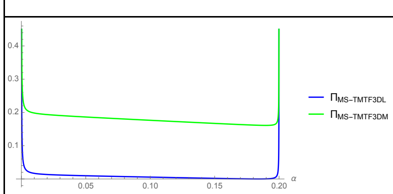
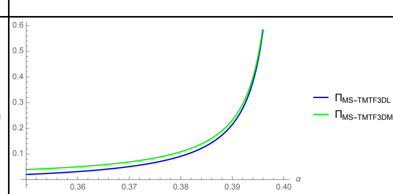
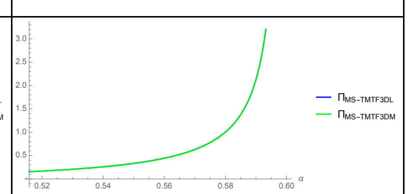
	TM Product			TF Product			3DP Product		Delivery
	F_M	V_M	α	F_{TF}	V_{TF}	β	F_{3D}	V_{3D}	c_L
Low	0.01	0.01	0.1	0.025	0.02	0.2	-	-	0.01
Medium	0.05	0.05	0.2	0.1	0.25	0.4	-	-	0.01
High	0.1	0.08	0.3	0.3	0.3	0.6	-	-	0.01

Table 5-34 Traditional Manufacturer’s Maximized Profit: Comparison by Logistics Delivery Cost – TM3DL and TMTF3DM

Low	Medium	High
		
		

	TM Product			TF Product			3DP Product		Delivery
	F_M	V_M	α	F_{TF}	V_{TF}	β	F_{3D}	V_{3D}	c_L
Low	0.01	0.01	0.1	0.025	0.02	0.2	0.1	0.03	-
Medium	0.05	0.05	0.2	0.1	0.25	0.4	0.3	0.3	-
High	0.1	0.08	0.3	0.3	0.3	0.6	0.6	0.35	-

Table 5-35 Traditional Manufacturer’s Maximized Supply Chain Profit: Comparison by TM Product Customization Level – TM3DL and TMTF3DM

Low	Medium	High
		
		

	TM Product	TF Product	3DP Product	Delivery

	F_M	V_M	α	F_{TF}	V_{TF}	β	F_{3D}	V_{3D}	c_L
Low	0.01	0.01	0.1	0.025	0.02	-	0.1	0.03	0.01
Medium	0.05	0.05	0.2	0.1	0.25	-	0.3	0.3	0.01
High	0.1	0.08	0.3	0.3	0.3	-	0.6	0.35	0.01

Table 5-36 Traditional Manufacturer's Maximized Supply Chain Profit: Comparison by TF Product Customization Level – TM3DL and TMTF3DM

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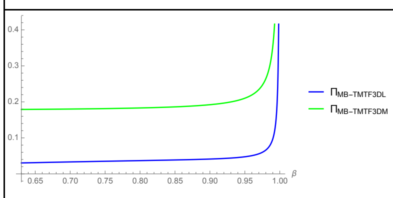
<td>
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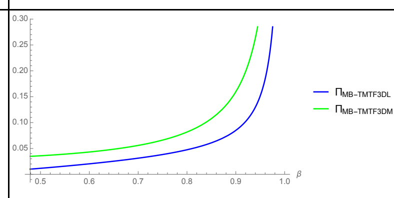
<td>
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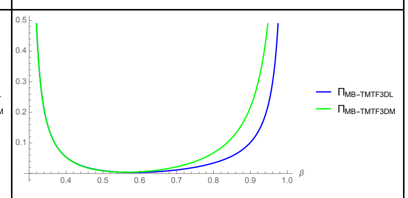
<td>
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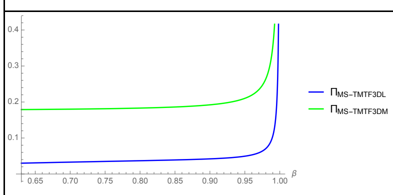
<td>
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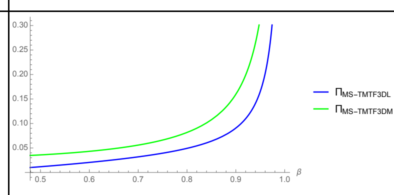
<td>
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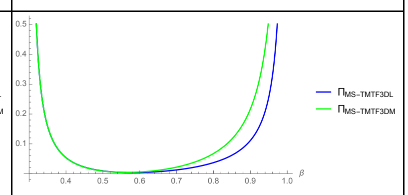
<td>
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	TM Product			TF Product			3DP Product		Delivery
	F_M	V_M	α	F_{TF}	V_{TF}	β	F_{3D}	V_{3D}	c_L
Low	0.01	0.01	0.1	0.025	0.02	-	0.1	0.03	0.01
Medium	0.05	0.05	0.2	0.1	0.25	-	0.3	0.3	0.01
High	0.1	0.08	0.3	0.3	0.3	-	0.6	0.35	0.01

PROPOSITION *5-16.* *It is not always beneficial to the logistics vendor to operate the 3DP product by himself/herself.*

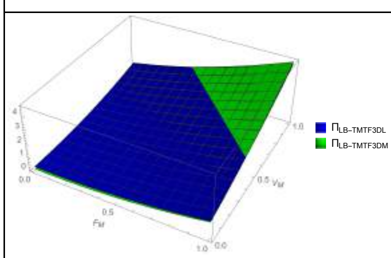
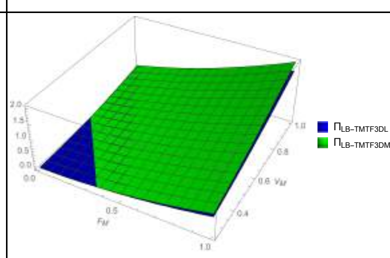
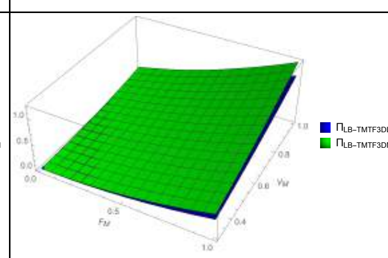
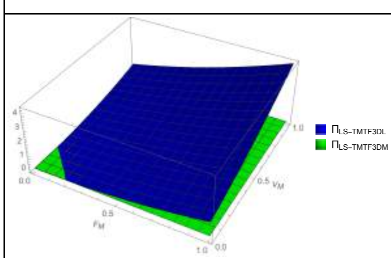
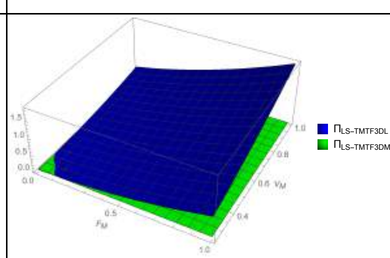
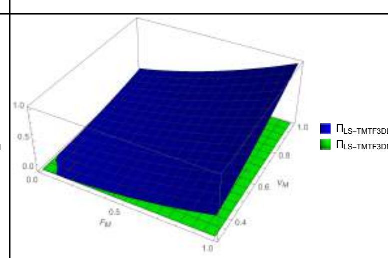
By comparing the logistics vendor's profitability under the TMTF3DL model and the TMTF3DM model (

Table **19** to Table 24), we identified the following scenarios where the logistics vendor can also share the benefits of the traditional manufacturer's TMTF3DM manufacturing strategy through two effects: the increased need for product delivery or the expanded 3DP product sales.

1) In the Bertrand supply chain, it is profitable to the logistics vendor to offer the 3DP product if a) the TM product costs are low; b) the fixed TF product cost is located at medium level; c) 3DP product costs are at an average level; d) the logistics delivery cost is high; or e) the TM product customization level is high.

2) In the Stackelberg supply chain, the logistics vendor can make more profits through the self-operated 3DP model except when: a) the TM product costs are low; b) the TF cost is at a low or high level; c) 3DP product costs are low; or d) the TM product customization level is high.

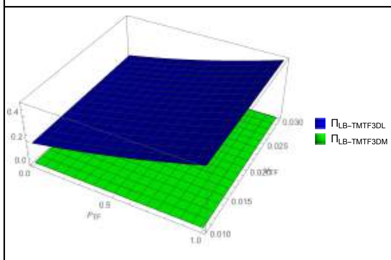
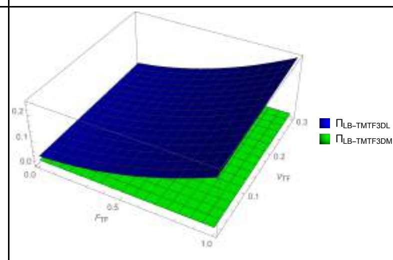
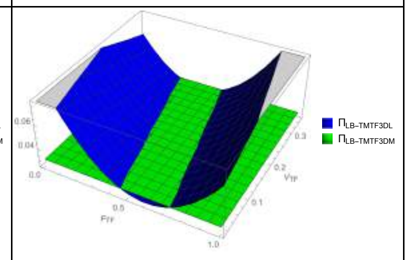
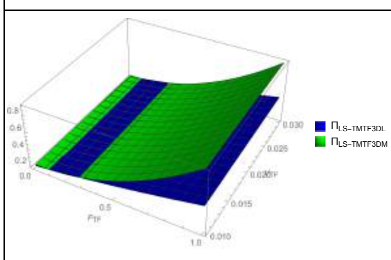
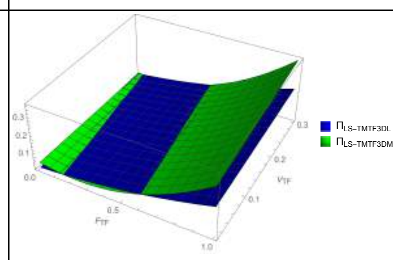
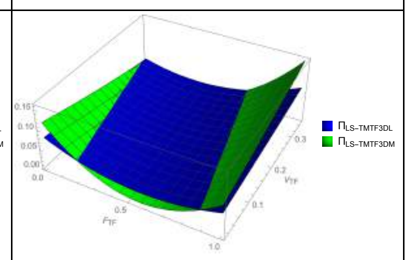
Table 5-37 Logistics Vendor's Maximized Profit: Comparison by TM Product Cost – TMTF3DL and TF3DL

Low	Medium	High
		
		

	TM Product			TF Product			3DP Product		Delivery
	F_M	V_M	α	F_{TF}	V_{TF}	β	F_{3D}	V_{3D}	c_L

Low	-	-	0.1	0.025	0.02	0.2	0.1	0.03	0.01
Medium	-	-	0.2	0.1	0.25	0.4	0.3	0.3	0.01
High	-	-	0.3	0.3	0.3	0.6	0.6	0.35	0.01

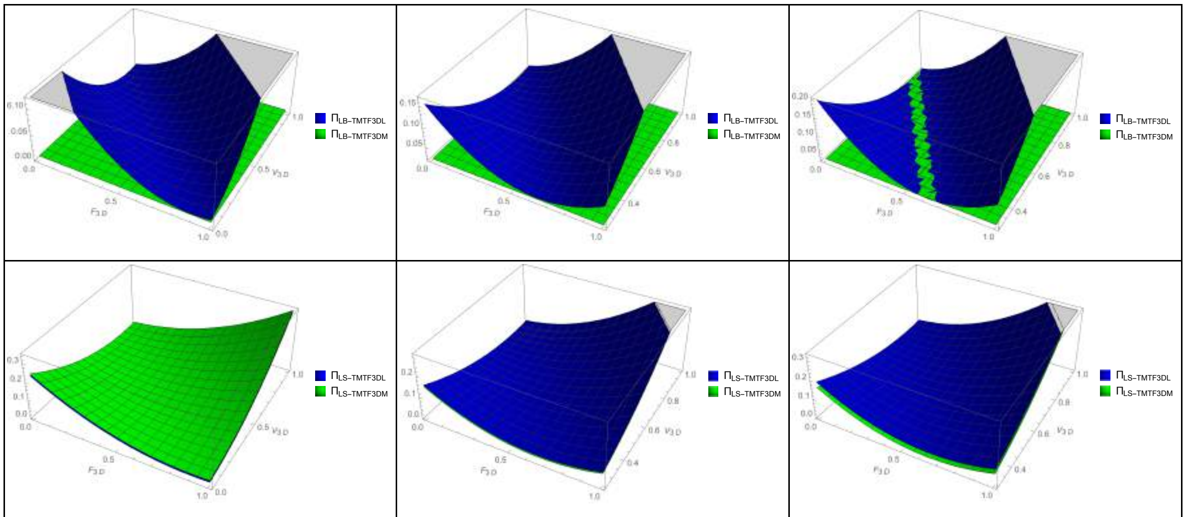
Table 5-38 Logistics Vendor's Maximized Profit: Comparison by TF Product Cost – TM3DL and TMTF3DM

Low	Medium	High
		
		

	TM Product			TF Product			3DP Product		Delivery
	F_M	V_M	α	F_{TF}	V_{TF}	β	F_{3D}	V_{3D}	c_L
Low	0.01	0.01	0.1	-	-	0.2	0.1	0.03	0.01
Medium	0.05	0.05	0.2	-	-	0.4	0.3	0.3	0.01
High	0.1	0.08	0.3	-	-	0.6	0.6	0.35	0.01

Table 5-39 Logistics Vendor's Maximized Profit: Comparison by 3DP Product Cost – TM3DL and TMTF3DM

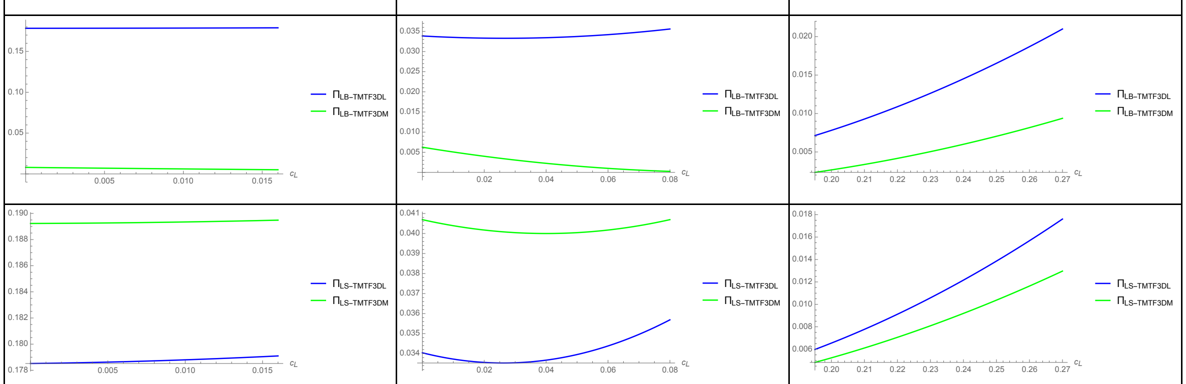
Low	Medium	High



	TM Product			TF Product			3DP Product		Delivery
	F_M	V_M	α	F_{TF}	V_{TF}	β	F_{3D}	V_{3D}	c_L
Low	0.01	0.01	0.1	0.025	0.02	0.2	-	-	0.01
Medium	0.05	0.05	0.2	0.1	0.25	0.4	-	-	0.01
High	0.1	0.08	0.3	0.3	0.3	0.6	-	-	0.01

Table 5-40 Logistics Vendor's Maximized Profit: Comparison by Logistics Delivery Cost –TM3DL and TMTF3DM

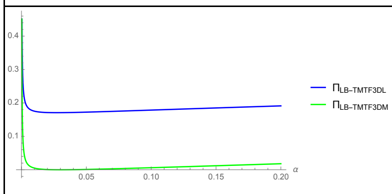
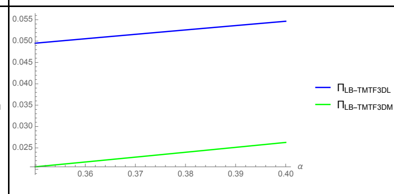
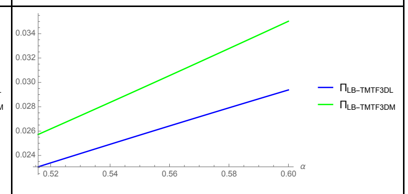
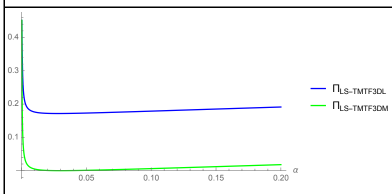
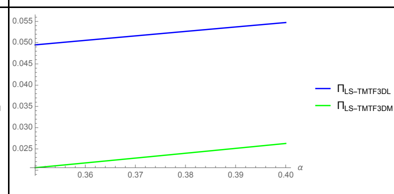
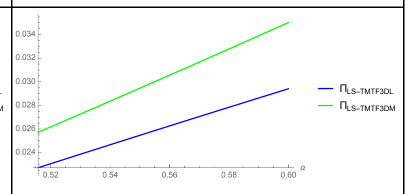
Low	Medium	High



	TM Product			TF Product			3DP Product		Delivery
	F_M	V_M	α	F_{TF}	V_{TF}	β	F_{3D}	V_{3D}	c_L
Low	0.01	0.01	0.1	0.025	0.02	0.2	0.1	0.03	-

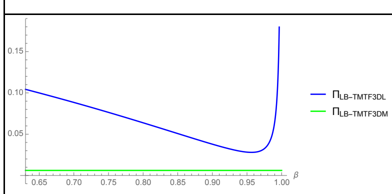
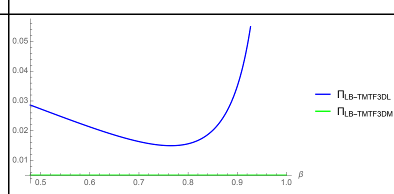
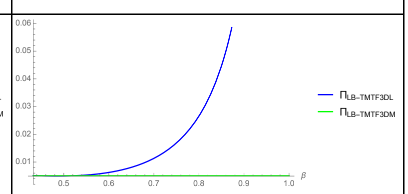
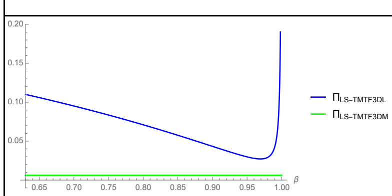
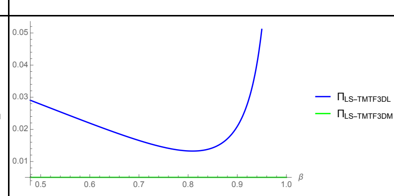
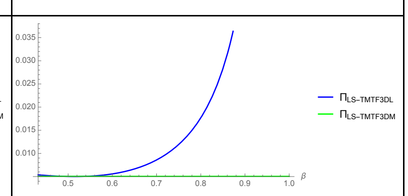
Medium	0.05	0.05	0.2	0.1	0.25	0.4	0.3	0.3	-
High	0.1	0.08	0.3	0.3	0.3	0.6	0.6	0.35	-

Table 5-41 Logistics Vendor's Maximized Supply Chain Profit: Comparison by TM Product Customization Level – TM3DL and TMTF3DM

Low	Medium	High
		
		

	TM Product			TF Product			3DP Product		Delivery
	F_M	V_M	α	F_{TF}	V_{TF}	β	F_{3D}	V_{3D}	c_L
Low	0.01	0.01	-	0.025	0.02	0.2	0.1	0.03	0.01
Medium	0.05	0.05	-	0.1	0.25	0.4	0.3	0.3	0.01
High	0.1	0.08	-	0.3	0.3	0.5	0.6	0.35	0.01

Table 5-42 Logistics Vendor's Maximized Supply Chain Profit: Comparison by TF Product Customization Level – TM3DL and TMTF3DM

Low	Medium	High
		
		

	TM Product			TF Product			3DP Product		Delivery
	F_M	V_M	α	F_{TF}	V_{TF}	β	F_{3D}	V_{3D}	c_L

Low	0.01	0.01	0.1	0.025	0.02	-	0.1	0.03	0.01
Medium	0.05	0.05	0.2	0.1	0.25	-	0.3	0.3	0.01
High	0.1	0.08	0.3	0.3	0.3	-	0.6	0.35	0.01

PROPOSITION *5-17.*

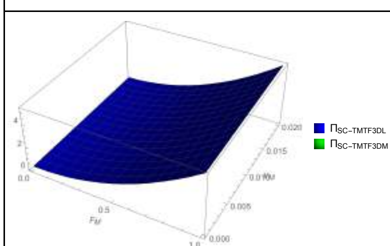
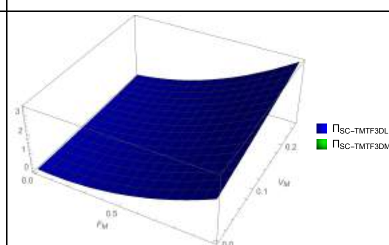
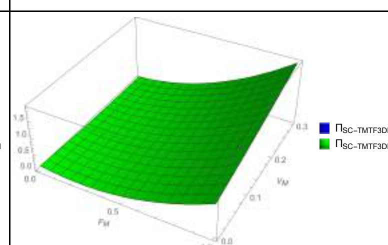
(1) Under the low/medium supply chain setting, in most cases, the integrated supply chain can attain better performance under the TMTF3DL model. However, if the 3DP product costs are high or the TF product customization level is high, the integrated supply chain can gain more profits under the TMTF3DM model.

(2) Under the high supply chain setting, the integrated supply chain can gain more profits by the traditional manufacturer's TMTF3MD strategy if a) the TM product costs are high; or b) the TF product costs are low; or c) the 3DP product costs are high.

This proposition gives the conditions under which the integrated supply chain can make more profits. Therefore, as Table 5-43 to

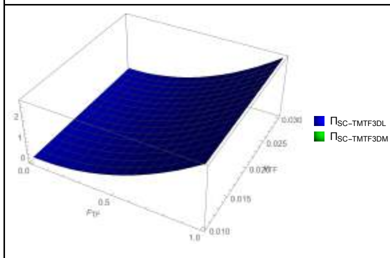
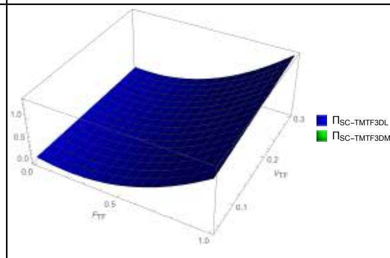
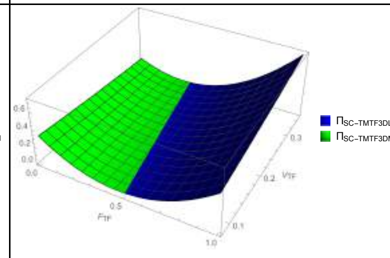
Table 5-48 show, the different approaches to 3DP adoption have different impacts on the integrated supply chain, and the product costs and the product customization level play crucial roles here.

Table 5-43 Integrated Supply Chain's Maximized Profit: Comparison by TM Product Cost – TMTF3DL and TF3DL

<table>
<tr><td>Low</td><td>Medium</td><td>High</td></tr>
<tr><td>
</td><td>
</td><td>
</td></tr>
</table>

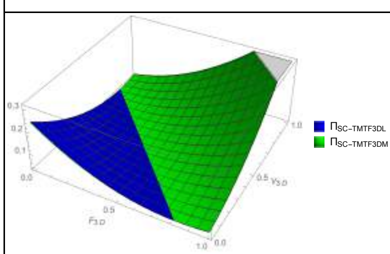
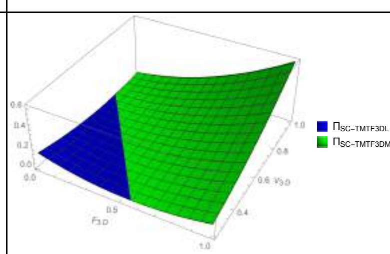
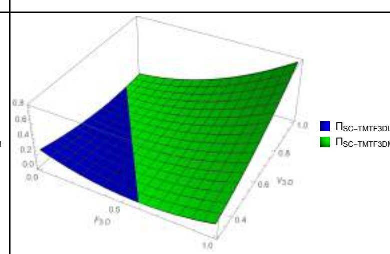
	TM Product			TF Product			3DP Product		Delivery
	F_M	V_M	α	F_{TF}	V_{TF}	β	F_{3D}	V_{3D}	c_L
Low	-	-	0.1	0.025	0.02	0.2	0.1	0.03	0.01
Medium	-	-	0.2	0.1	0.25	0.4	0.3	0.3	0.01
High	-	-	0.3	0.3	0.3	0.6	0.6	0.35	0.01

Table 5-44 Integrated Supply Chain's Maximized Profit: Comparison by TF Product Cost –TM3DL and TMTF3DM

Low	Medium	High
		

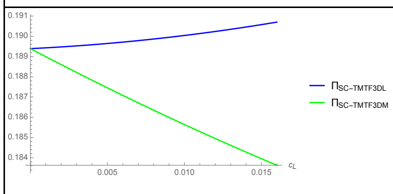
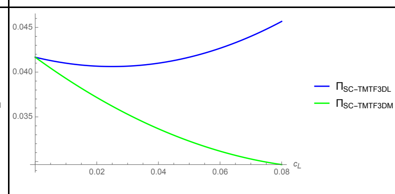
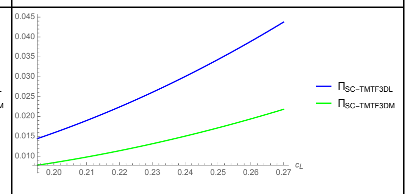
	TM Product			TF Product			3DP Product		Delivery
	F_M	V_M	α	F_{TF}	V_{TF}	β	F_{3D}	V_{3D}	c_L
Low	0.01	0.01	0.1	-	-	0.2	0.1	0.03	0.01
Medium	0.05	0.05	0.2	-	-	0.4	0.3	0.3	0.01
High	0.1	0.08	0.3	-	-	0.6	0.6	0.35	0.01

Table 5-45 Integrated Supply Chain's Maximized Profit: Comparison by 3DP Product Cost – TM3DL and TMTF3DM

Low	Medium	High
		

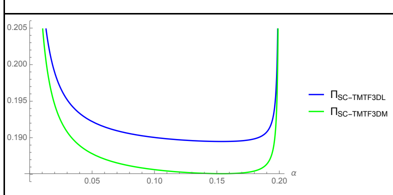
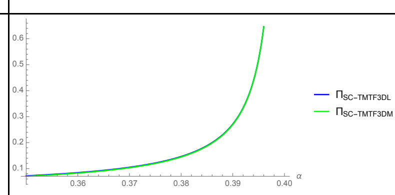
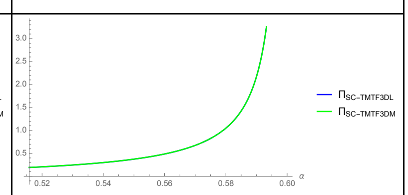
	TM Product			TF Product			3DP Product		Delivery
	F_M	V_M	α	F_{TF}	V_{TF}	β	F_{3D}	V_{3D}	c_L
Low	0.01	0.01	0.1	0.025	0.02	0.2	-	-	0.01
Medium	0.05	0.05	0.2	0.1	0.25	0.4	-	-	0.01
High	0.1	0.08	0.3	0.3	0.3	0.6	-	-	0.01

Table 5-46 Integrated Supply Chain's Maximized Profit: Comparison by Logistics Delivery Cost – TM3DL and TMTF3DM

Low	Medium	High
		

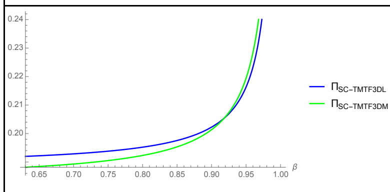
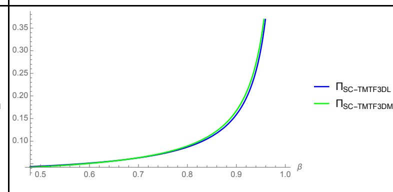
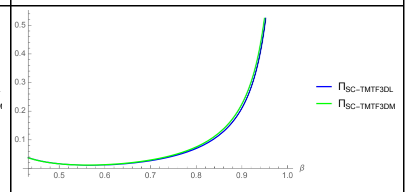
	TM Product			TF Product			3DP Product		Delivery
	F_M	V_M	α	F_{TF}	V_{TF}	β	F_{3D}	V_{3D}	c_L
Low	0.01	0.01	0.1	0.025	0.02	0.2	0.1	0.03	-
Medium	0.05	0.05	0.2	0.1	0.25	0.4	0.3	0.3	-
High	0.1	0.08	0.3	0.3	0.3	0.6	0.6	0.35	-

Table 5-47 Integrated Supply Chain's Maximized Profit: Comparison by TM Product Customization Level – TM3DL and TMTF3DM

Low	Medium	High
		

	TM Product			TF Product			3DP Product		Delivery
	F_M	V_M	α	F_{TF}	V_{TF}	β	F_{3D}	V_{3D}	c_L
Low	0.01	0.01	0.1	0.025	0.02	-	0.1	0.03	0.01
Medium	0.05	0.05	0.2	0.1	0.25	-	0.3	0.3	0.01
High	0.1	0.08	0.3	0.3	0.3	-	0.6	0.35	0.01

Table 5-48 Integrated Supply Chain's Maximized Profit: Comparison by TF Product Customization Level – TM3DL and TMTF3DM

Low	Medium	High
		

	TM Product			TF Product			3DP Product		Delivery
	F_M	V_M	α	F_{TF}	V_{TF}	β	F_{3D}	V_{3D}	c_L
Low	0.01	0.01	0.1	0.025	0.02	-	0.1	0.03	0.01
Medium	0.05	0.05	0.2	0.1	0.25	-	0.3	0.3	0.01
High	0.1	0.08	0.3	0.3	0.3	-	0.6	0.35	0.01

5.7 Chapter Summary

Motivated by the new development in flexible manufacturing technology and the revolutionary 3DP manufacturing technology, this model investigates the impact of different manufacturing technologies on a traditional manufacturer's manufacturing strategy. In this model, we have tested five different manufacturing technology combinations which the traditional manufacturer could use to cope with the logistics vendor's 3DP adoption. The following sections outlines some important managerial insights and theoretical contributions of this model analysis.

Managerial Insights

The key message we have obtained from this model is that, in light of first-mover advantages, one might expect the logistics vendor to prefer offering the 3DP product for the sake of a new revenue stream, just like UPS (UPS, 2016, 2017). Interestingly, our results show that this intuition does not always hold true. In most of the cases, the logistics vendor can make more profits if s/he only provides the logistics delivery service than if s/he starts to offer the 3DP product (Figure 5-15 and Figure 5-16). These results also indicate that the value of 3DP is not only limited to technological value but also the business value (Wohlers Associates, 2018). This finding is supported by the case of DHL and Panalpina. Both companies are leading logistics vendors but they do not themselves operate 3DP product businesses but only provide professional 3DP related delivery services to the traditional manufacturer (MINI, 2018; Panalpina, 2018; Pooley, 2013).

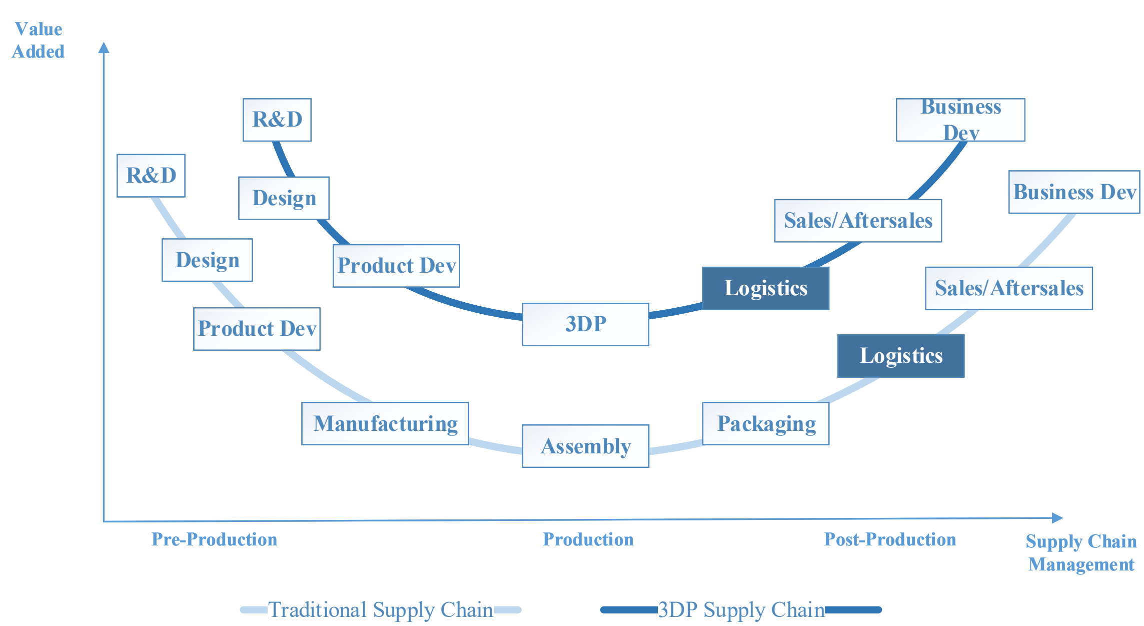


Figure 5-15 Logistics Vendor Offer 3DP Product - UPS Model

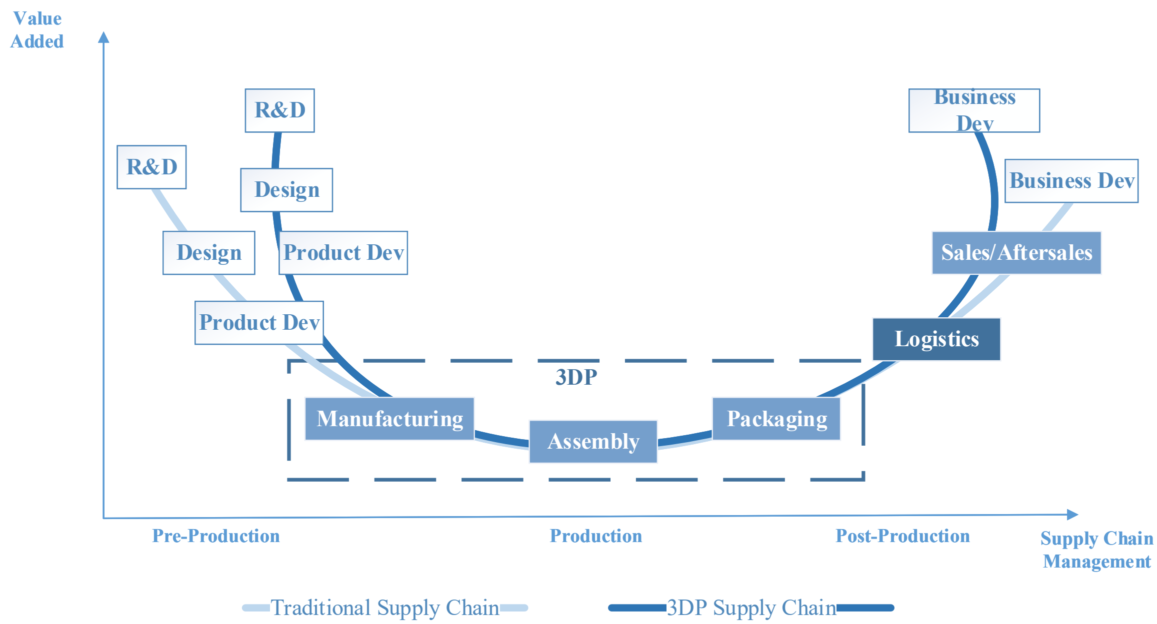


Figure 5-16 Traditional Manufacturer Offers 3DP Product - DHL and Panalpina Model

Secondly, when it comes to the investment cost and improving the product customization level, the traditional manufacturer had better not use both the traditional flexible manufacturing technology and the 3DP manufacturing technology together for high value products. For example, some diesel producers (e.g. Rezmin Tool & Die, Ernst Keller) are now fully using 3DP printing for their product manufacturing and product design (3D Systems, 2018a, 2018c). However, for low-cost items, the traditional manufacturer is better off adopting the 3DP technology together with the flexible traditional manufacturing technology for a wider coverage of consumer base. For example, Gira uses TM, TF and 3DP production technology for electrical components production (3D Systems, 2018b).

Thirdly, full 3DP product adoption is still not yet a beneficial strategy for the integrated supply chain. This explains why the progress of adopting 3DP manufacturing technology has slowed down. Lowering the cost of 3DP production is a solution to the problem, as shown 3DP technology of different costs can help to cover a wider range of products. Therefore, in terms of further development of the 3DP technology industry, additional support from the local government or research institutions is needed.

Moreover, the results have important implications for both decision makers and policymakers. Understanding the adoption of 3DP, manufacturers can better focus their R&D efforts on projects that ideally perform both in their economic and environmental aspects. These results highlight the fact that, at this stage, encouraging 3DP adoption through legislation ultimately aimed at improving manufacturing technology may in fact still have the inverse effect on traditional manufacturing. Therefore, it is a big challenge for the policymakers to find a way to not only improve the manufacturing industry overall performance but also further help the further 3DP technology's adoption.

Theoretical Contributions

Firstly, this model endogenizes the 3DP adoption decision under the 3DP enabled supply chain and develops a stylized model to study the interaction between traditional manufacturing, traditional flexible manufacturing technology and 3DP technology. The quantitative research analysis on how and when the both the traditional manufacturer and the logistics vendor should adopt 3DP manufacturing technology enriches the existing literature on the 3DP supply chain research. Thus, this research has extended the existing 3DP research with a new comparison on the traditional flexible manufacturing technology and the 3DP technology. The results support the traditional manufacturer in deciding which manufacturing technology strategy is profitable, and for which products it may be worth using 3DP technology.

Therefore, this model contributes to the knowledge about the new technology disruption on how to deal with the competition from the new 3DP technology and how to involve the flexible manufacturing technology under the threat of 3DP. The results provide further understanding of how to cope with the technology disruption: (1) self-adopt and (2) outsourcing.

Lastly, this model analyzes the consumer surplus of different manufacturing decisions made by the traditional manufacturer. The results can help to inform the traditional manufacturer and the logistics vendor with regard to the adoption of new manufacturing technology and consumer behaviour research.

Chapter 6 Logistics Vendor's 3DP Engagement Strategy

This chapter attempts to build a model for studying the logistics vendor's optimal approach to collaboration with the third-party 3DP professionals and the traditional manufacturer, obtaining optimal pricing strategies for both the traditional manufacturer and the logistics vendor, and the maximum profits available under different scenarios. We seek to answer the following questions: What are the best 3DP engagement models for the logistics vendor? How does the cost of outsourcing 3DP design and the cost of obtaining the 3DP design from the traditional manufacturer affect optimal pricing and the collaboration relationship in different supply chain structures? To investigate these questions, we develop a game-theoretical model, which integrates the different channels of power and demand uncertainty to characterize the impact of varying collaboration models on different decentralized and centralized supply chains.

The rest of this chapter is organized as follows: Section 6.1 gives the necessary background information; Section 6.2 presents the problem and develops the model; then the optimal decisions and related sensitive analysis under different 3DP engagement models is explored in Section 6.3. Section 6.4 to Section 6.8 conduct comparative analysis across all these models. Section 9 summarizes the model with a discussion of the practical implications of the findings. All the proofs are listed in the Appendix C.

6.1 Introduction

3DP technology is recognized as one of the solutions of transfer the supply chain, especially the 3DP technology adds new possibilities into the logistics services industry. 'We believe that deepening our capabilities in this area could further strengthen the logistics industry through business model innovation and the creation of new solutions.' said Lee Eng Keat, director of logistics, Singapore Economic Development Board (Liao et al., 2014).

However, due to considerations related to investment in new 3D printers, the asset management of current manufacturing machines, and the technical requirements associated with product design, logistics vendors do not currently offer 3DP manufacturing. The ways in which logistics vendors engage with 3DP services could be summarized into the following three approaches.

The first approach (Figure 6-1) (denoted by 'Model X') is that the logistics vendor only provides the 3DP delivery service. The specific examples for this business model are the DHL and Mini collaboration model and the UPS and Materialise collaboration model. The DHL and Mini collaboration model is a typical model of how the logistics vendor could be engaged in the traditional manufacturer's 3DP manufacturing service. At the current stage, DHL is playing a goods delivery service role (MINI, 2018). In the UPS and Materialise collaboration model, UPS is working with one of the best 3DP companies and so far has also provided the delivery service (UPS, 2018). In addition, Panalpina, one of the world's leading logistics vendors, also provides a 3DP goods delivery service to Shapeways (a 3DP community) (Shapeways, 2016).

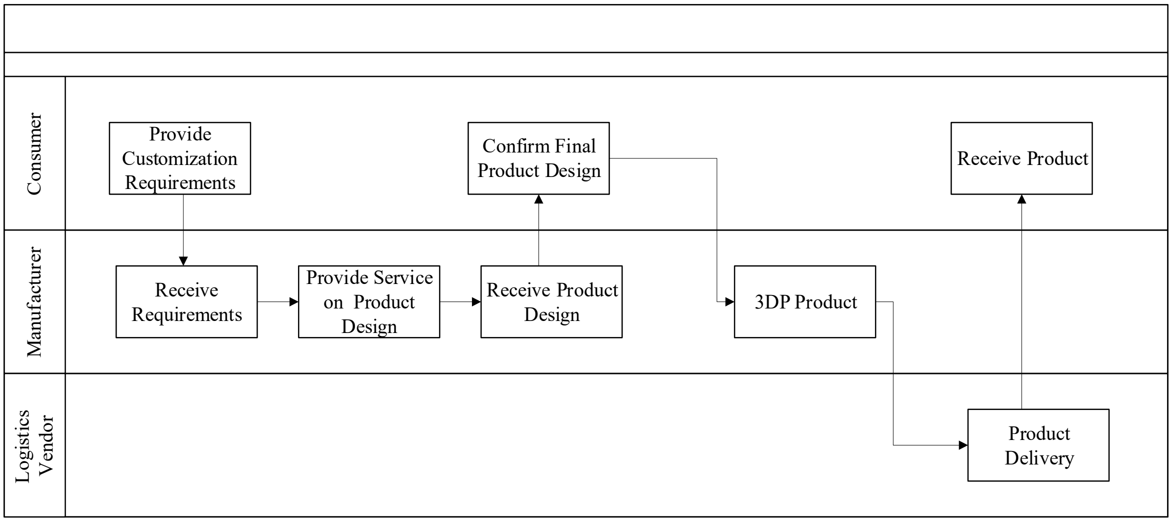


Figure 6-1 The First 3DP Engagement Approach: Model X

The second approach (Figure 6-2) (denoted by 'Model Y') is that the logistics vendor provides both the delivery service and the product design service. One typical example here is the UPS and Fast Radius collaboration model. UPS outsources the 3DP design and development work to Fast Radius and UPS provides the print and delivery service itself (B. Zhang, 2016).

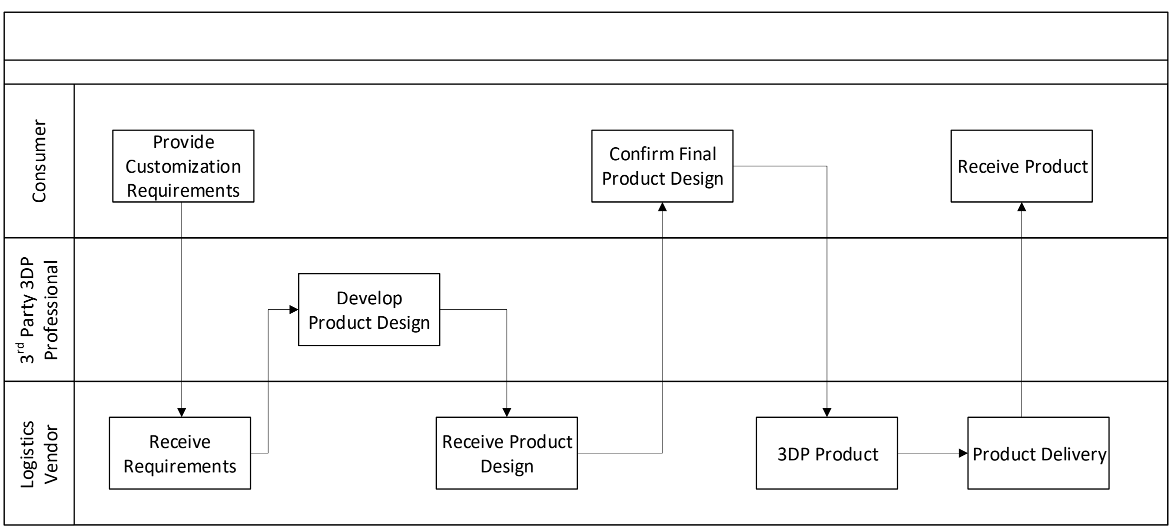


Figure 6-2 The Second 3DP Engagement Approach: Model Y

The third approach (Figure 6-3) (denoted by 'Model Z') is that the traditional manufacturer authorizes the logistics vendor to use the product design and the logistics vendor provides

3DP printing and goods delivery services. For instance, Panalpina's partner (e.g. Shapeways, one of biggest 3D printing marketplace) authorizes use of a 3DP solution and Panalpina provides the service of 'printing' and delivery (Panalpina, 2018).

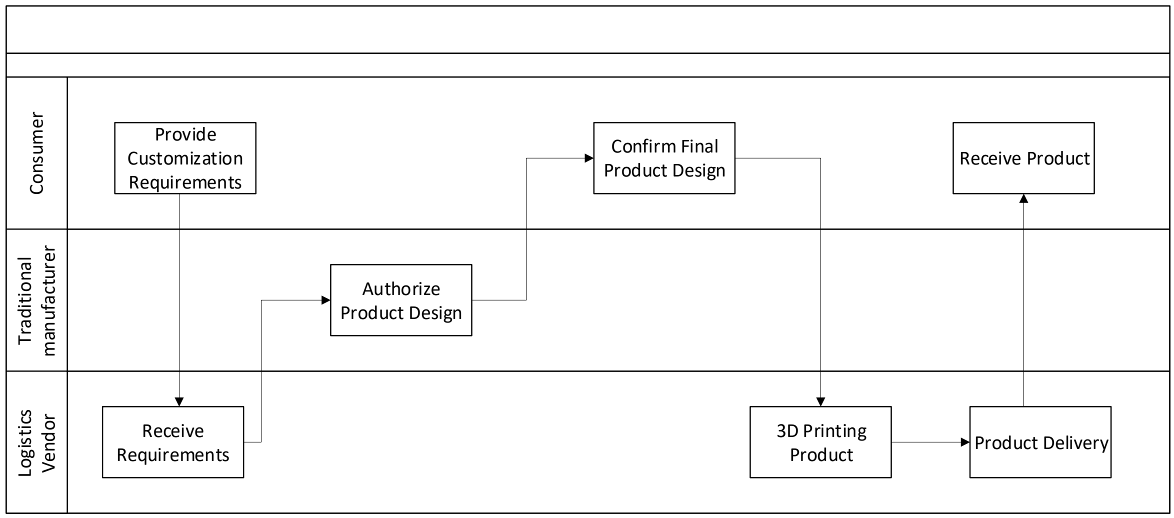


Figure 6-3 The Third 3DP Engagement Approach: Model Z

The future of the logistics vendor's 3DP service is exciting but also uncertain. Therefore, in this chapter we build up a theoretical model of a supply chain to explore which type of engagement is the best approach. We discuss and compare the three engagement approaches above. After that, we also introduce a new engagement approach into the discussion and comparison where the logistics vendor offers all of the services: product design, 3DP, and the goods delivery service.

Specifically, our research question for this chapter is '*what is the best 3DP adoption plan for the logistics vendor?*' The detailed sub-questions are as follows.

Q3.1. Under what conditions will a logistics vendor choose to outsource the product design to a third-party 3DP design company?

Q3.2. Under what conditions will a logistics vendor choose to purchase the product design from the original traditional manufacturer?

Q3.3. What are the impacts of different logistics vendor's 3DP adoption strategies on the relationship between the logistics vendor and traditional manufacturer?

6.2 Problem Description

We consider a supply chain where the consumer can choose to buy a TM product at price p_M, buy an authorized 3DP product or an unauthorized 3DP product ('grey goods') at price p_{3D}. Using the same mould setups as in the previous chapters, we assume that each consumer has an intrinsic valuation v of the authorized 3DP product (where v is assumed to be a uniform distribution from 0 to 1). In addition, it is generally agreed that the traditional manufacturer has a better understanding of product design. Therefore, the traditional manufacturer can provide a higher quality of product design than the third-party 3DP professional (González-Maestre & Granero, 2018; Lumsakul, Sheldrick, & Rahimifard, 2018). Accordingly, we assume all the consumers have a higher net expected utility for the authorized 3DP product (v) than the unauthorized 3DP product (δv, $0 < \delta < 1$, δ is the discount rate for the product design quality). This assumption is widely used in the operational literature, for example by Ru, Shi, & Zhang (2015) and Huang, He, & Chen (2018). At the same time, as we discussed in the previous chapters, the customization level of the 3DP product is higher than the TM product, and so we assume for all the consumers that their net expected utility of buying a 3DP product is higher than buying a TM product. Therefore, the consumer's willingness-to-pay for the TM product is $\alpha\delta v$ (where the value of parameter α is the discount rate on the consumer's willingness-to-pay for the TM product's customization level, $0 < \alpha < 1$). In summary, the net expected utilities of consumers buying the authorized 3DP product, the unauthorized 3DP product and the TM product are $U_{3DA} = v - p_{3D}$, $U_{3DU} = \delta v - p_{3D}$, and $U_M = \alpha\delta v - p_M$. We assume the consumers are strategic: they only buy the product which provides the highest non-negative utility to maximize utility.

By considering the investment in new 3DP engagement, we assume that the customers in one model cannot purchase a product from the other models (for example, the product in Model X and Model Y are in two different industries). This assumption is in line with previous modelling techniques used in studies in the supply chain and operations management literature (Bergen, Heide, & Dutta, 1998; Rachel Yang, Ahmadi, & Monroe, 1998). Therefore, depending on the traditional manufacturer's channel decision, the game sequence can be stated in three or four steps as follows (Figure 6-4).

Under Model X, the traditional manufacturer self-manufactures the 3DP product:

Step 1: The logistics vendor releases the logistics delivery service fee.

Step 2: The traditional manufacturer sets the prices for the TM product and the 3DP product simultaneously.

Step 3: The consumer determines his/her purchasing decision.

Under Model Y and Model Z, the traditional manufacturer sells the TM product and the logistics vendor offers the 3DP product:

Step 1: The logistics vendor releases the logistics delivery service fee.

Step 2: The traditional manufacturer sets the prices for the TM product.

Step 3: The logistics vendor announces the 3DP product price.

Step 4: The consumer determines his/her purchasing decision.

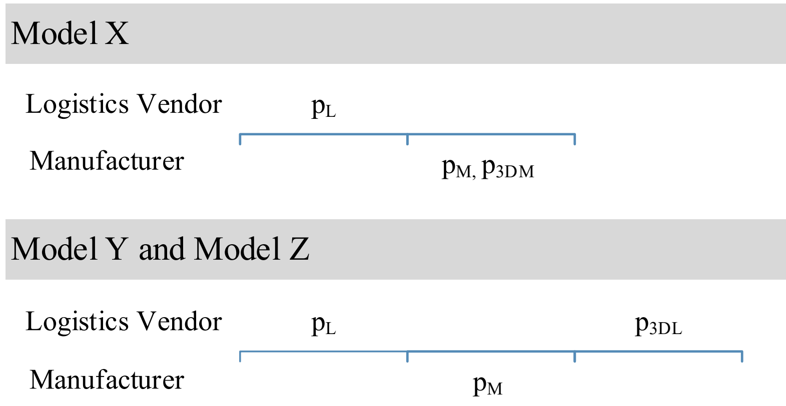


Figure 6-4 Pricing Sequence for Model X, Model Y, and Model Z in a Decentralized Supply Chain

All notions are summarized in the table below.

Table 6-1 Definitions of Parameters

Indexes	**Definition**
M	Index of the traditional manufacturer
L	Index of the logistics vendor or logistics delivery
SC	Index of the supply chain
X	Subscript, index of the Model X
Y	Subscript, index of the Model Y
Z	Subscript, index of the Model Z
I	Subscript, integrated supply chain
D	Subscript, decentralized supply chain
Parameter	Definition
α	Consumer value discount for the TM product customization level, $0 < \alpha < 1$.
δ	The discount rate of the product design quality for the unauthorized 3DP product, $0 < \delta < 1$
β	The unit product design authorization fee of the 3DP product, $0 < \beta < 1$
γ	The product design fee charged by the third-party 3DP professional, $0 < \gamma < 1$
p_i	The unit selling price for a product or service, $0 < p_i < 1$.
c_i	The unit manufacturing cost for a product or service, $0 < c_i < 1$.

q_i	The sales quantity for the product, $0 < q_i < 1$.
$\prod_i^j$	The profit function, $\prod_i \geq 0$.

6.3 Model Analysis

Under this subsection, we investigate the three models with details.

6.3.1 Model X

We consider the first 3DP engagement approach, in which, as demonstrated in Figure 6-5, the traditional manufacturer sells both the 3DP (p_{3D}) and TM (p_M) product into the market and the logistics vendor only provides the product delivery service at price p_L.

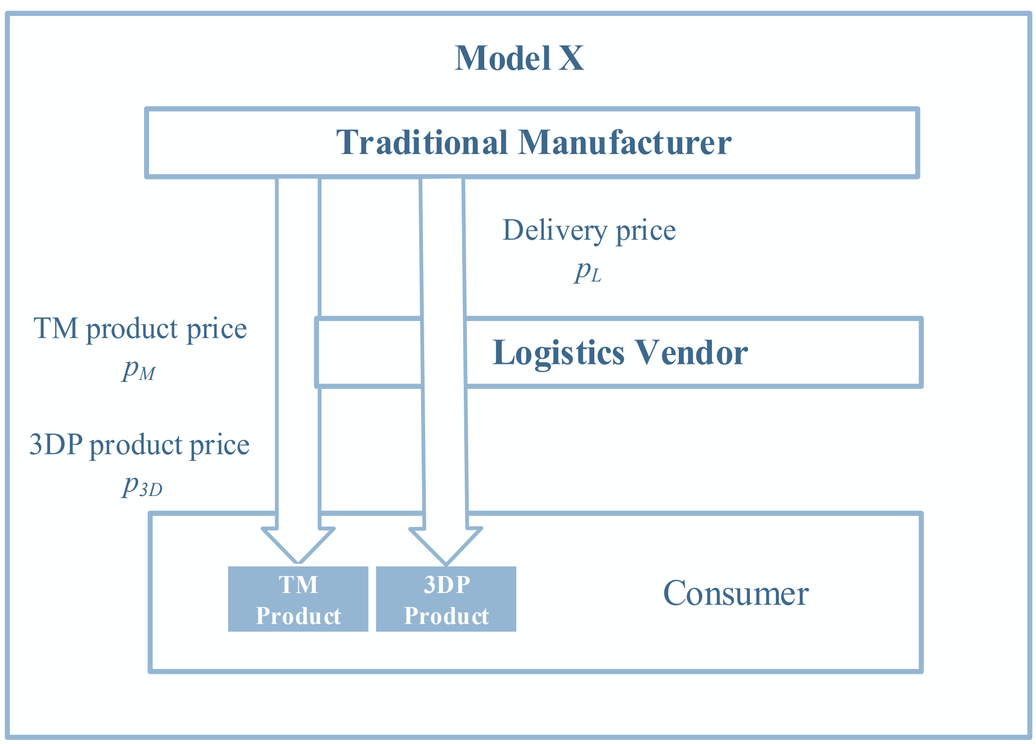


Figure 6-5 Supply Chain Structure of Model X

With the customer's net expected utility, the demand for the TM product and the 3DP product in Model X is $q_M = 1\int_{\frac{p_M}{\alpha\delta}}^{\frac{p_{3D}-p_M}{1-\alpha\delta}} dv = \frac{p_{3D}-p_M}{1-\alpha\delta} - \frac{p_M}{\alpha\delta}$ and $q_{3D} = 1\int_{\frac{p_{3D}-p_M}{1-\alpha\delta}}^{1} dv = 1 - \frac{p_{3D}-p_M}{1-\alpha\delta}$

respectively. Then, only if $\alpha p_{3D} \geq p_M$, will the demand for the TM product be positive. Otherwise, if the traditional manufacturer uses a low-price regime for the 3DP product, such that $\alpha p_{3D} < p_M$, the demand for the TM product becomes 0. However, as we indicated at the beginning of this chapter, this model tries to explore the manufacturing strategy associated with the 3DP engagement strategy. Therefore, we only consider the scenario where the market demand for both the TM and the 3DP product is positive under all the different models therein.

Focusing on our main research issues and for simplicity, we only consider the product cost and the product delivery cost, as all the other costs can be easily included and do not affect the main results in this chapter. Therefore, under the decentralized supply chain, the traditional manufacturer's profit and the logistics vendor's profit are as follows:

$$\prod\nolimits_X M(p_M, p_{3D}) = (p_M - c_M - p_L)q_M + (p_{3D} - c_{3D} - p_L)q_{3D} \tag{6.1}$$

$$\prod\nolimits_X L(p_L) = (p_L - c_L)(q_M + q_{3D}) \tag{6.2}$$

Under the integrated supply chain, the system profit is

$$\prod\nolimits_X SC(p_M, p_{3D}) = (p_M - c_M - c_L)q_M + (p_{3D} - c_{3D} - c_L)q_{3D} \tag{6.3}$$

PROPOSITION *6-1.* *In the decentralized supply chain, there exists the maximum profit for the traditional manufacturer* $\prod_X^* M(p_M, p_{3D}) = \frac{1}{16(-1+\alpha\delta)\alpha\delta}(\alpha\delta(-4 + (7 - 3\alpha\delta)\alpha\delta) - 4\alpha\delta c_{3D}^2 + (-1 + \alpha\delta)c_L(-2\alpha\delta + c_L) + 2(-1 + \alpha\delta)(3\alpha\delta + c_L)c_M - (1 + 3\alpha\delta)c_M^2 + 8\alpha\delta c_{3D}(1 - \alpha\delta + c_M))$ *and the maximum profit for the logistics vendor* $\prod_X^* L(p_L) = \frac{(-\alpha\delta+c_L+c_M)^2}{8\alpha\delta}$*, both of which are maximized by unique optimal price* $p_L^* = \frac{1}{2}(\alpha\delta + c_L - c_M)$, $p_M^* = \frac{1}{4}(3\alpha\delta + c_L + c_M)$, $p_{3D}^* = \frac{1}{4}(2 + \alpha\delta + 2c_{3D} + c_L - c_M)$ *and optimal sales of the TM and 3DP product* $q_M^* = \frac{-2\alpha\delta c_{3D} - (-1+\alpha\delta)(\alpha\delta+c_L)+(1+\alpha\delta)c_M}{4(-1+\alpha\delta)\alpha\delta}$ *and* $q_{3D}^* = \frac{-1+\alpha\delta+c_{3D}-c_M}{2(-1+\alpha\delta)}$.

In the integrated supply chain, there also exists the maximum profit for the integrated supply chain $\prod_X^* SC(p_M, p_{3D}) = -\frac{1}{4(-1+\alpha\delta)\alpha\delta}(\alpha\delta - \alpha\delta^2 + \alpha\delta c_{3D}^2 - (-1 + \alpha\delta)c_L^2 + 2\alpha\delta c_{3D}(-1 + \alpha\delta - c_M) + 2(-1 + \alpha\delta)c_L(\alpha\delta - c_M) + c_M^2)$*, which is maximized by unique optimal price* $p_M^* = \frac{1}{2}(\alpha\delta +$

$c_L + c_M$) *and* $p_{3D}^* = \frac{1}{2}(1 + c_{3D} + c_L)$*; and the optimal product sales of the TM and 3DP product are* $q_M^* = \frac{c_L - \alpha\delta(c_{3D}+c_L)+c_M}{2(-1+\alpha\delta)\alpha\delta}$ *and* $q_{3D}^* = \frac{-1+\alpha\delta+c_{3D}-c_M}{2(-1+\alpha\delta)}$.

Next, we try to analyze the impact of the costs on the optimal decisions and the equilibrium-maximized profits.

PROPOSITION *6-2.* *In decentralized model X,*

(1) The optimal price of the logistics service decreases in the cost of the TM but increases in the cost of the logistics service; the cost of the 3DP product has no direct impact on the optimal price of the logistics service;

(2) The optimal price of the TM product increases in the cost of the TM product and the logistics service; the cost of the 3DP product has no direct impact on the optimal price of the TM product;

(3) The optimal price of the 3DP product decreases in the cost of the TM product but increases in both the cost of the logistics service and the 3DP product;

(4) The optimal sales of the TM product decrease in the cost of the TM product and the logistics service but increase in the cost of the 3DP product;

(5) The optimal sales of the 3DP product increase in the cost of the TM product but decrease in the cost of the TM product; the cost of the logistics service has no direct impact on the optimal price of the 3DP product.

(6) The traditional manufacturer's maximized profit

   a. *decreases in the cost of the TM product if a)* $\frac{3}{4}(-1+\alpha\delta)(-1+c_{3D}) < c_L < 1$ *or b)* $0 < c_L < \frac{3}{4}(-1+\alpha\delta)(-1+c_{3D})$ *and* $0 < c_M < \frac{4\alpha\delta c_{3D}+(-1+\alpha\delta)(3\alpha\delta+c_L)}{1+3\alpha\delta}$*; otherwise, it increases in the cost of the TM product.*

   b. *decreases in the cost of the logistics service.*

   c. *increases in the cost of the 3DP product if a)* $\frac{c_M}{\delta} < \alpha < 1$ *and* $-(-1+\alpha\delta)(\alpha\delta - c_M) < c_L < \alpha\delta - c_M$ *; or b)* $0 < c_L < -(-1+\alpha\delta)(\alpha\delta - c_M)$ *and* $1 - \alpha\delta + c_M < c_{3D} < 1$*; otherwise, it decreases in the cost of the 3DP product.*

(7) The logistics vendor's maximized profit decreases in both the cost of the TM product and the logistics service; there is no direct relationship between the logistics vendor's maximized profit and the 3DP product cost.

The findings of properties (1)-(5) of PROPOSITION 4-5 could be summarized into the following four points. Firstly, the higher the relevant costs are, the higher the product/service price is (for example, the higher the TM product cost and/or the higher the logistics service cost is, the higher the TM product price is). Secondly, the TM product cost has a negative impact on both the logistics service price and the 3DP product price. This indicates that if the cost of the TM product is low, then i) the logistics vendor uses a high-price regime for the logistics service to maximize his/her profit; ii) the traditional manufacturer sets the price of the 3DP product high to a) maximize the unit margin for the 3DP product and b) keep the TM product's pricing advantage. Thirdly, surprisingly, the cost of the 3DP product cannot directly influence the price of the logistics service or the cost of the 3DP product. Lastly, the lower the relevant costs are, the higher optimal product quantity is. This finding is quite straightforward. The relationship between the cost and the product sales is negative. However, the impact of the cost of the logistics service on the optimal price of the 3DP product is slight.

Intuitively, we assume that the cost reduction on the product contributes to the traditional manufacturer's profitability. However, this Proposition implies that this assumption holds only when the costs of the logistics delivery service and the TM/3DP product are below a certain threshold, or else when TM product customization and the TM product design quality are below a certain threshold. Further details are given below.

Firstly, a cost reduction on TM results in a lower TM product price and a higher 3DP product price. Therefore, more price-sensitive consumers choose to buy the cheaper TM product instead of the 3DP product. Notice that when the logistics delivery service is costly, it forces the logistics vendor to use a higher price for the logistics delivery. Therefore, generally, the price of the TM product is still in the high region; if the cost of the TM reduces, the new profits generated from the TM product cannot cover the loss incurred from the 3DP product. Thus, overall, the traditional manufacturer's profits decrease. In addition, if the logistics delivery service demand is low, and if the TM product cost is low as well, then the cost reduction can help the traditional manufacturer gain more price-sensitive consumers for the TM product – but the TM product unit margin is low. Thus, the traditional manufacturer still cannot generate more profit. However, if the logistics delivery cost is low but the TM product cost is high, the TM product cost reduction can help the traditional manufacturer derive more profits from the TM product sales than the profit lost on the 3DP product. Thus, in practice, for those manufacturers who operate certain low value-add TM and 3DP products, but for whom the delivery cost is comparatively high (e.g. office accessories), it is not a profitable strategy to put effort into TM product cost reduction. For those items with high production cost and a low delivery service cost (e.g. automotive engines, aeroplane parts), cost reduction on the TM product part is still beneficial to the traditional manufacturer.

Secondly, property (2) suggests that cost reduction on the logistics delivery service brings more profits to the traditional manufacturer through more TM product sales. However, it has no direct impact on the 3DP product's equilibrium quantity.

Thirdly, if 1) both the customization level of the TM product and the logistics delivery cost are high or 2) the logistics delivery cost is low but the 3DP product cost is high, the cost reduction on the 3DP product results in profit lost to the traditional manufacturer. Because the new profits on the increased 3DP product sales cannot cover the profit lost on the low 3DP product unit margin. Lastly, the cost reduction on the TM product and the logistics service cost contribute to the logistics vendor's profit. More precisely, the cost reduction on the TM product forces the logistics vendor to use a high-price regime for the logistics service. Although sales of the TM product decrease under this scenario, the TM product sales increase. Overall, the logistics vendor gains more profits on a) the increased demand for TM product delivery service and 2) the higher unit price margin of the logistics delivery service. Meanwhile, as demonstrated in the related proof, cost reduction for the delivery service results in price decreases for the logistics service and increases in TM product sales. Thus, thanks to the increased need for a TM product delivery service the logistics vendor can still derive more profit overall. This is a quite straightforward finding. Under model X, the cost reduction on the logistics delivery service is still a strategy for the logistics vendor to use to improve business performance. In addition, although the logistics vendor handles the 3DP product delivery, the cost of the 3DP product has no influence on the logistics vendor's profit.

PROPOSITION *6-3*. *In integrated model X,*

1. *The optimal price of the TM product increases in the cost of the TM product and the logistics service; the cost of the 3DP product has no direct impact on the optimal price of the TM product;*
2. *The optimal price of the 3DP product increases in both the cost of the logistics service and the 3DP product; the cost of the TM product has no direct impact on the price of the 3DP product;*
3. *The optimal number of sales of the TM product decreases in the cost of the TM product and the logistics service but increases in the cost of the 3DP product;*
4. *The optimal number of sales of the 3DP product increases in the cost of the TM product but decreases in the cost of the TM product; the cost of the logistics service has no direct impact on the optimal price of the 3DP product.*
5. *The maximized profit of the integrated supply chain decreases in the cost of the TM product and the logistics delivery service; but it increases in the cost of the 3DP product only if a)* $\frac{c_M}{\delta} < \alpha < 1$ *and* $-(-1 + \alpha\delta)(\alpha\delta - c_M) < c_L < \alpha\delta - c_M$ *or b)* $0 < c_L < -(-1 + \alpha\delta)(\alpha\delta - c_M)$ *and* $1 - \alpha\delta + c_M < c_{3D} < 1$ *; otherwise, it decreases in the cost of the 3DP product.*

Most of the findings of PROPOSITION 6-3 are the same as the findings in PROPOSITION 4-5; the only difference is that the cost of the TM product has no direct impact on the price of the 3DP product because the price of the logistics delivery service is not a consideration for the traditional manufacturer's pricing strategy under the integrated supply chain. Additionally, the cost of both the TM and the 3DP product is not considered in his/her pricing strategy. In addition, this proposition also implies that the system performance could be enhanced by cost reductions on the TM product and the logistics service, because the system can achieve more TM product sales. However, a cost reduction on the 3DP product cannot always help the integrated supply chain gain more profits. Specifically, if 1) both the customization level of the TM product and the delivery cost are high or 2) the delivery cost is low but the 3DP product cost is high, then any cost reduction on the 3DP product leads to an increase in 3DP product sales but the supply chain loses more on the low 3DP product unit margin.

Unfortunately, because of the complex nature of the optimal product quantity decisions and the maximized profit functions, it is difficult to obtain direct insight into the impact of customization level and product design quality discount rate on these optimal decisions. Therefore, the following sections use numerical tests to determine the relative performance of customers' customization sensitivity and sensitivity to product design quality with regard to the optimal decisions under different 3DP engagement models. To ensure consistency, we employ two full factorial designs (as Table 6-2 and Table 6-3 show) based on the one we used in Chapter 4, followed by a depiction of the optimal prices and quantities for each parameter for different scenarios.

Table 6-2 Parameter Values in the Numerical Testing for the Impacts of Customization Level on the Optimal Decisions

	c_{3D}	c_L	c_M	δ
Low	0.3	0.01	0.01	0.1
Medium	0.6	0.01	0.01	0.4
High	0.9	0.01	0.01	0.7

Table 6-3 Parameter Values in the Numerical Testing for the Impacts of Product Design Quality Level on the Optimal Decisions

	c_{3D}	c_L	c_M	α
Low	0.3	0.01	0.01	0.2
Medium	0.6	0.01	0.01	0.5
High	0.9	0.01	0.01	0.8

PROPOSITION *6-4*. *In decentralized model X,*

(1) The optimal price of the logistics service, the TM product price, and the 3DP product price increases in the TM customization level and/or the design quality of the TM product.

(2) The optimal number of sales of the TM product increases in the TM customization level and/or the design quality of the TM product, but the optimal number of 3DP product sales decreases in it.

(3) The traditional manufacturer benefits from the improvement of the TM customization level and/or the design quality of the TM product only under the supply chain with the high-setting. Under the supply chain with the medium-setting, the traditional manufacturer's profitability is concave in the TM customization level and/or the

design quality of the TM product. Under the supply chain with the low-setting, the higher the TM product customization level and/or the design quality, the lower the traditional manufacturer's profitability.

(4) The logistics vendor can always achieve better profitability by the improvement of the TM product customization level and/or the design quality.

Under the integrated supply chain,

(1) The optimal price of the TM product increases in the TM customization level and/or the design quality of the TM product; the TM customization level and/or the design quality of the TM product has no direct impact on the 3DP product price.

(2) The optimal number of sales of the TM product increases in the TM customization level and/or the design quality of the TM product, but the optimal number of 3DP product sales decreases in it.

(3) The improvement of the TM product customization level contributes to better financial performance of the integrated supply chain.

We can obtain the following results from the above proposition:

(1) As illustrated in Figure 6-6, improvement in either the TM product customization level or the design quality always contributes to more TM product sales and results in cannibalization of the 3DP product sales. With the higher TM product customization level or design quality, the traditional manufacturer uses a high-price regime for both products for the purpose of maximizing profits. However, if the supply chain is under the low-setting, although the strategy of high pricing helps the traditional manufacturer gain more profits from TM product sales, s/he loses more from the dropping 3DP product sales. Overall, the traditional manufacturer cannot gain a better financial result. Under the supply chain with a medium-setting, if either α or δ is relatively low, the traditional manufacturer cannot achieve better profitability by improving them. The reason behind this is obvious: the better the TM product is, the more profit is lost on the 3DP product sales. Therefore, the traditional manufacturer's profitability decreases in the improvement of α or δ. If either α or δ is sufficiently high, a further improvement helps the traditional manufacturer generate

more profits on the TM product and can cover the loss due to the effect of cannibalization. Thus, the improvement of α or δ brings benefits to the traditional manufacturer. Lastly, under the supply chain with a high setting, the traditional manufacturer benefits from the improvement of either α or δ because s/he can enjoy more sales of the better TM product.

(2) Figure 6-6 also demonstrates that improvement in either the TM product customization level or the design quality helps the logistics vendor gain more profits from either the high logistics service unit price margin or the increased TM product sales. More precisely, with the improvement in either α or δ, the logistics vendor raises the delivery price to maximize the profit. Therefore, the logistics vendor can generate a portion of the profit by the high unit logistics service price. Meanwhile, although 3DP product sales decrease, the logistics vendor can still generate more profits on the increased TM product sales. Generally, the logistics vendor can always achieve better profitability.

(3) The findings about the impact of α or δ on the optimal decisions under the integrated supply chain are similar to the findings we discussed for property (1) above. The only difference is that α and δ have no direct impact on the 3DP product equilibrium price because of the visibility of the information on all the products/services. At supply chain level (Figure 6-7), the improvement of α or δ always helps the system enjoy more benefits from increased TM product sales or the high-pricing strategy for the TM product.

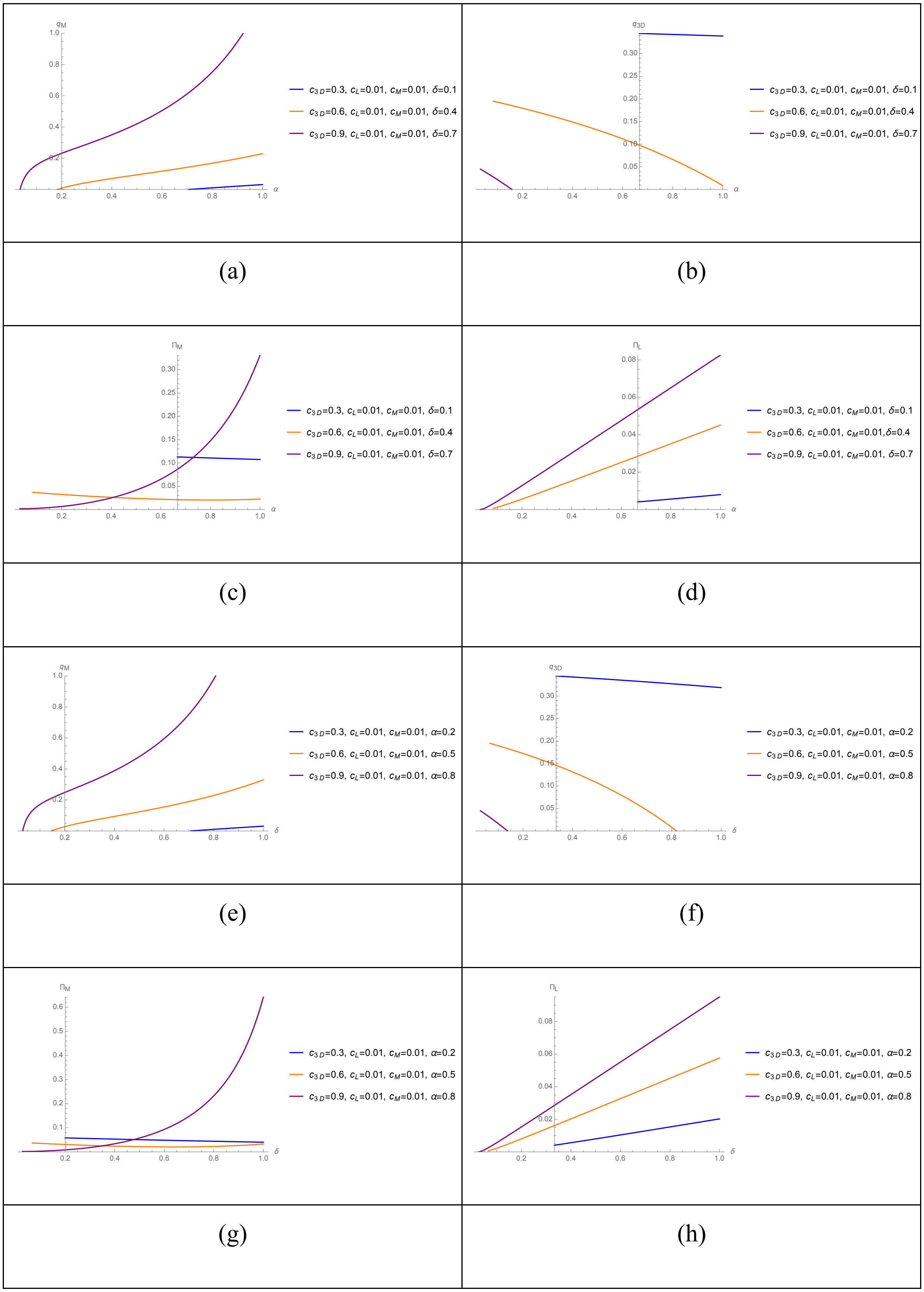


Figure 6-6 Impact of Customization Level and Product Design Level in a Decentralized Supply Chain – Model X

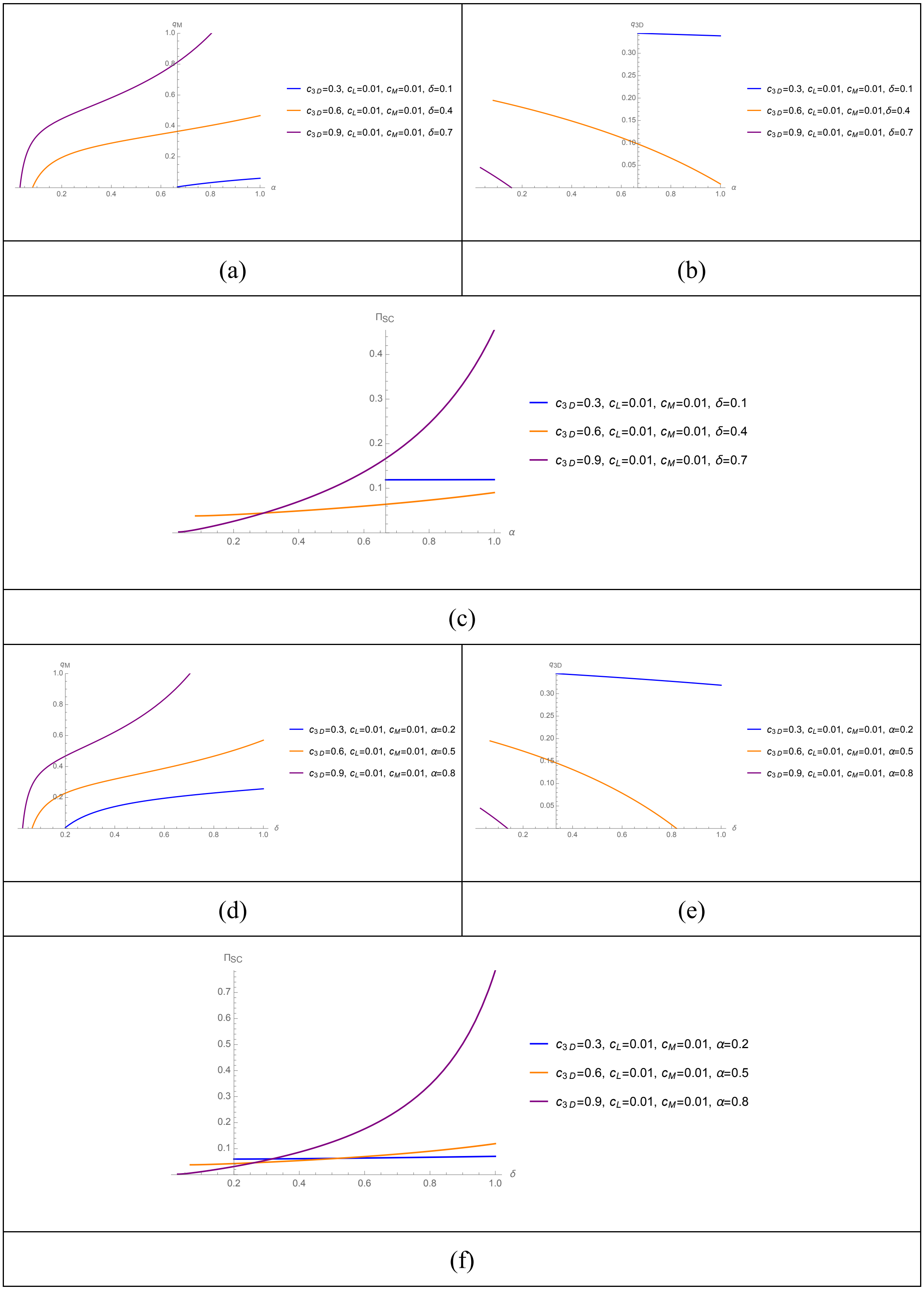


Figure 6-7 Impact of Customization Level and Product Design Level in an Integrated Supply Chain – Model X

6.3.2 Model Y

Under the second 3DP engagement scenario (also called system 'Y', Figure 6-8), the logistics vendor provides a 3DP product (p_{3D}) designed by the third-party 3DP professional at a cost of γ ($0 < \gamma < 1$).

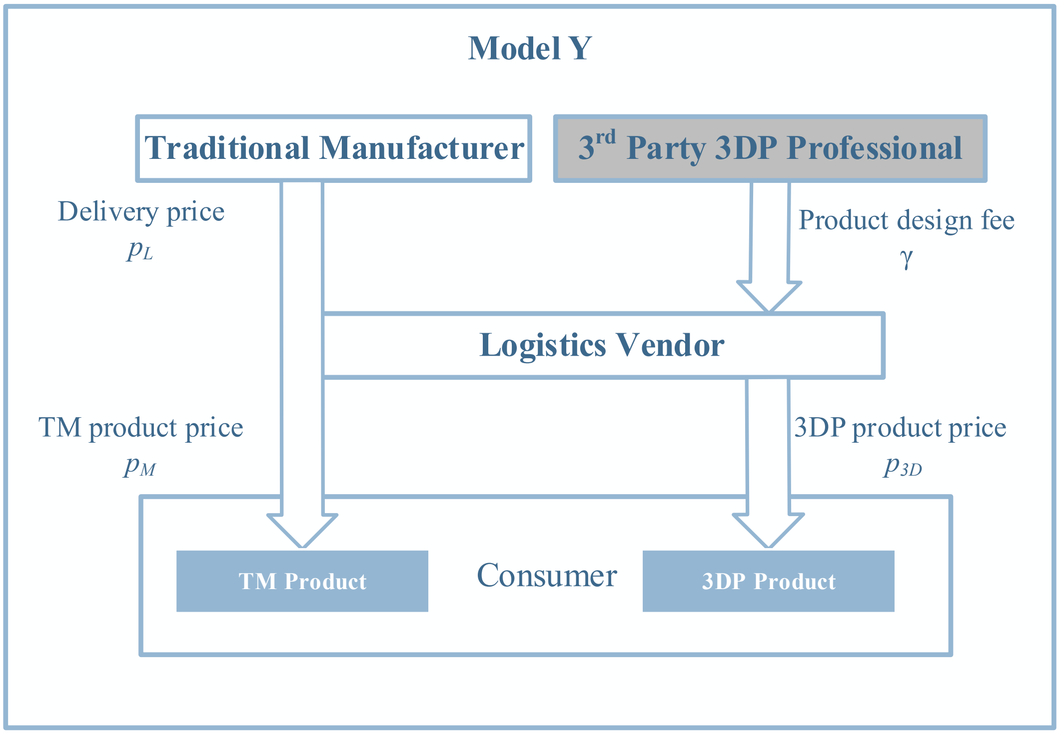


Figure 6-8 Supply Chain Structure for Model Y

Under the decentralized supply chain, the profits of the traditional manufacturer and the logistics vendor are shown in equation (6.4) and (6.5), respectively.

$$\prod\nolimits_Y M(p_M) = (p_M - c_M - p_L)q_M \tag{6.4}$$

$$\prod\nolimits_Y L(p_L, p_{3D}) = (p_L - c_L)q_M + (p_{3D} - c_{3D} - \gamma)q_{3D} \tag{6.5}$$

The profit of the integrated supply chain is

$$\prod\nolimits_Y SC(p_M, p_{3D}) = (p_M - c_M - c_L)q_M + (p_{3D} - c_{3D})q_{3D} \tag{6.6}$$

PROPOSITION 6-5. *In the decentralized supply chain, the maximum profit for the traditional manufacturer is shown in Equation (6.27) and the maximum profit for the logistics vendor is as shown in Equation (6.28), both of which are maximized by the optimal price given in Equation (6.22), (6.23) and (6.24). Meanwhile, the optimal market demand for the TM and 3DP product is given in Equation (6.25) and (6.26).*

In the integrated supply chain, the maximum profit for the supply chain is $\prod_Y^* SC(p_M, p_{3D}) = -\frac{-(-1+\alpha)\alpha\delta^2+\alpha c_{3D}^2+(c_L+c_M)^2-2\alpha c_{3D}(\delta-\alpha\delta+c_L+c_M)}{4(-1+\alpha)\alpha\delta}$*, which is maximized by* $p_M^* = \frac{1}{2}(\alpha\delta + c_L + c_M)$ *and* $p_{3D}^* = \frac{1}{2}(\delta + c_{3D})$*; the optimal market demand for the TM and 3DP product is* $q_M^* = \frac{-\alpha c_{3D}+c_L+c_M}{2(-1+\alpha)\alpha\delta}$ *and* $q_{3D}^* = \frac{\delta-\alpha\delta-c_{3D}+c_L+c_M}{2\delta-2\alpha\delta}$.

PROPOSITION 6-6. *In decentralized model Y,*

(1) The optimal price of the logistics service decreases in the cost of TM but increases in the cost of the TM product, the cost of the 3DP product and the cost of outsourcing 3DP design, but it increases in the cost of the logistics service.
(2) The optimal price of the TM product increases in all the costs involved for the products/service.
(3) The optimal price of the 3DP product decreases in the cost of the TM product and the cost of the logistics service but increases in the cost of the 3DP product and the cost of third-party 3DP design.
(4) The optimal number of sales of the TM product decreases in the cost of the TM product and the logistics service but increases in the cost of the 3DP product and the third-party 3DP design fee.
(5) The optimal number of sales of the 3DP product increases in the cost of the TM product and the cost of the logistics service but decreases in the cost of the 3DP product and the third-party 3DP design fee.
(6) The traditional manufacturer's maximized profit decreases in both the cost of the TM product and the logistics delivery service, but it increases in the cost of the 3DP product and the cost of outsourcing 3DP product design.
(7) The logistics vendor's maximized profit decreases in the both the cost of the TM product and the logistics delivery service. However, the logistics vendor's profit decreases in the cost of the 3DP product or the third-party 3DP design fee only if $0 < c_M + c_L < \frac{(-1+\alpha)\alpha(8+(-5+\alpha)\alpha)\delta^2}{-8+\alpha(9-2\alpha+(-2+\alpha)^2\delta)}$ *and* $\frac{(-8+(9-2\alpha)\alpha)\gamma-(-1+\alpha)(8+(-5+\alpha)\alpha)\delta+(-2+\alpha)^2c_L+(-2+\alpha)^2c_M}{8+\alpha(-9+2\alpha)} < c_{3D} < 1$*; otherwise, it increases in the direct costs of the 3DP product.*

This proposition presents the relationships between all the costs and the optimal decisions and maximized profits. The findings here can be summarized into the following points:

Firstly, reducing the cost of the TM product and the logistics delivery service is a win-win strategy for both the traditional manufacturer and the logistics vendor (D. R. Eyers & Potter, 2015; Liu et al., 2014). Specifically, cost reduction on the TM product contributes to the traditional manufacturer's low pricing strategy, which aims to increase the market share of the TM product. Because of the cost reduction on the TM product, it is hard for the logistics vendor to use a high-pricing strategy for the logistics delivery service to i) mitigate the low pricing advantage of the TM product and ii) generate more profits from increased TM product sales. As a result, the traditional manufacturer can gain more profits by the TM product cost reduction. Meanwhile, the traditional manufacturer's low TM pricing also forces the logistics vendor to use higher pricing for the 3DP product to allow a larger price margin on the 3DP product. Although the 3DP product loses some price-sensitive consumers, the logistics vendor can still gain more profits from the TM product delivery service. Meanwhile, the cost reduction on the logistics service actually helps the traditional manufacturer's low-pricing strategy and it also helps the TM product to gain more market share. Conversely, it cannibalizes the 3DP product market share because the logistics vendor had to use a high-price regime on the 3DP product for the purpose of getting a better profitability. Overall, both the traditional manufacturer and the logistics vendor can enjoy the benefits of the cost reduction on the logistics service. However, this also implies that the advantages of the logistics service cost reduction have a rare positive impact on the logistics vendor's 3DP product business.

Secondly, the cost of both the 3DP product and the third-party 3DP design fee results in a cannibalization effect on the TM product sales. It is easy to see that a cost reduction for the 3DP product or the third-party 3DP design fee helps the logistics vendor use a low-price strategy for the 3DP product to increase its market share. As the relevant costs of the 3DP product are low, the traditional manufacturer had to set the price of the TM product low to maintain the TM product's pricing advantage. Consequently, the low-price 3DP product can attract more price-sensitive consumers and consumers sensitive to either customization or product design quality to buy the 3DP product instead of the TM product. Therefore, the traditional manufacturer cannot achieve better profitability due to the cannibalization of the 3DP product.

Thirdly, depending on the different supply chain settings, the impacts of the cost of the 3DP product and the third-party 3DP design fee on the logistics vendor's profits are different. Specifically, 1) if the TM product's direct costs are extremely high (e.g. c_L is located in the high region, or c_M and c_L are costly) the price of the logistics service is high. Therefore, a cost reduction on c_{3D} and/or γ helps the logistics vendor achieve more 3DP product sales but s/he loses business on the delivery of the TM product. Although the logistics vendor uses a larger unit delivery margin, overall it still cannot save the loss incurred from TM product delivery. 2) If the TM product's direct costs are considerably low, when the 3DP product production is costly, although cost reduction on c_{3D} and/or γ can push some consumers to shift and buy the 3DP product, the profits generated from those consumers cannot save the loss due to decreased TM product delivery. However, if the 3DP product cost is sufficiently low, there are more price-sensitive, customization-sensitive, or product-design sensitive consumers who choose to buy the 3DP product. The new profits from this are sufficient to cover the loss made on the delivery service. Thus, the logistics vendor's profitability could be improved by the cost reduction on the 3DP product and the third-party 3DP product design fee. This finding implies that for those low-cost products (e.g., office accessories), reducing the 3DP product cost or finding a low-cost 3DP product design company are sustainable business strategies for 3DP-enabled logistics vendors. For example, Panalpina is now considering how to integrate its 3DP product business with some 3DP design communities who can provide low-cost 3DP design services, such as Shapeways (Shapeways, 2016).

PROPOSITION 6-7. *Under the integrated model Y,*

(1) The optimal price of the TM product increases in the cost of the TM and the cost of the logistics service. The 3DP product's related costs cannot influence the TM product price.

(2) The optimal price of the 3DP product increases in the cost of the 3DP product. All other costs have no direct impact on it.

(3) The optimal number of sales of the TM product decreases in the cost of the TM product and the logistics service but increases in the cost of the 3DP product.

(4) The optimal number of sales of the 3DP product increases in the cost of the TM product and the logistics service but decreases in the cost of the 3DP product.

(5) The cost of outsourced 3DP product design has no impact on any of the optimal decisions.

(6) If $0 < \delta < \frac{1}{1+\gamma}$ *and* $c_{3D} > -\frac{\gamma\delta}{-1+\delta}$, *the supply chain profitability decreases in both the TM product cost and the logistics delivery cost. If* $0 < \delta < \frac{1}{1+\gamma}$ *and* $0 < c_{3D} < -\frac{\gamma\delta}{-1+\delta}$ *or 2)* $\frac{1}{1+\gamma} \leq \delta < 1$, *the supply chain's maximized profit is concave in the TM cost/delivery service cost.*

(7) The impact of the 3DP product cost on the supply chain profitability differs by the supply chain cost structure:

a. If 1) $\frac{\alpha^2\delta^2+c_L+c_M}{\alpha\delta} - \gamma - \delta > c_L + c_M$, $c_L < \frac{(-1+\alpha)\alpha\delta^2}{-1+\alpha\delta}$ *and* $\frac{(-1+\alpha)\alpha\delta^2}{-1+\alpha\delta} < c_L + c_M$ *or* $\frac{\alpha^2\delta^2+c_L+c_M}{\alpha\delta} - \gamma - \delta > c_L + c_M$ *and* $\frac{(-1+\alpha)\alpha\delta^2}{-1+\alpha\delta} \leq c_L < \alpha\delta$, *the supply chain profit increases in the 3DP product cost;*

b. If the supply chain satisfies 1) $c_L < \frac{(-1+\alpha)\alpha\delta^2}{-1+\alpha\delta}$ *and* $c_L + c_M \leq \frac{(-1+\alpha)\alpha\delta^2}{-1+\alpha\delta}$, *or 2)* $\frac{(-1+\alpha)\alpha\delta^2}{-1+\alpha\delta} < c_L + c_M$ *and* $\frac{\alpha^2\delta^2+c_L+c_M}{\alpha\delta} - \gamma - \delta < c_L + c_M$, *or 3)* $\frac{\alpha^2\delta^2+c_L+c_M}{\alpha\delta} - \gamma - \delta < c_L + c_M$ *and* $\frac{(-1+\alpha)\alpha\delta^2}{-1+\alpha\delta} \leq c_L$, *the supply chain profit is concave in the 3DP cost.*

Initially, we assumed that the cost reductions on the product or service contribute to a better supply chain financial performance. However, the above proposition implies that under certain supply chain structures the cost reduction might hurt the supply chain's overall performance.

The TM/3DP product-related costs contribute to the increase sales of the TM/3DP product by a low-price strategy and cannibalize the rival's product sales. The impacts of the TM product and the delivery cost on supply chain profitability could be summarized into three different scenarios. Firstly, when the third-party 3DP product design quality is low, the consumer's valuation of the 3DP product is low. Therefore, if the cost of the 3DP product is high, the cost reduction on the TM product or the logistics service helps the supply chain generate more profits on the TM product to cover the loss on the 3DP product. Secondly, if both the 3DP product design quality and the cost of the 3DP product are low, the supply chain also benefits from the reduction of the TM product costs when those costs are also relatively low. However, if the TM product's related costs are high, the cost reduction on the TM results in more supply chain profits losses due to 1) low TM product unit price margin and/or 2) decreased 3DP product quantity. Lastly, if the third-party 3DP product design quality is high, but the TM product costs are low, the supply chain can generate more profits on the increased TM product sales and/or the high 3DP product price through reductions in the TM product's related costs. However, in this case, if the TM product's related costs are high, the supply chain loses more benefits from the reduced 3DP product sales.

This proposition also shows that the impacts of the 3DP product cost on the supply chain's overall performance are more complex (Y. Li, Jia, Cheng, & Hu, 2017; Zeltmann et al., 2016). Firstly, if 1) the TM product's related costs are sufficiently low, and the logistics cost is at the medium level or 2) the TM product costs are at the medium level, but the logistics cost is extremely low, then a cost reduction for the 3DP product results in the supply chain gaining more profits from the increase in 3DP product sales and this covers its loss from the TM product sales. Secondly, if 1) the TM product's related costs are sufficiently low, and especially if the logistics cost is low and 2) the TM product costs are extremely high (no matter whether or not the TM product cost or the logistics cost is considerably high), then the 3DP product cost reduction contributes more profits to the supply chain if the 3DP product is not costly (i.e. a low or medium cost structure product). Otherwise, the supply chain loses profits by the 3DP product cost reduction (either on declined TM product sales or the 3DP product's low unit margin).

Compared to Model X, Model Y has one more variable γ. Thus, we simulate the value of γ in our two full factorial designs, as Table 4-3 and Table 6-5 shows. We use these numerical examples to illustrate the impact of the TM customization level and the product design quality on the optimal decisions and the equilibrium profitability.

Table 6-4 Parameter Values in the Numerical Testing for the Impacts of Customization Level on the Optimal Decisions – Model Y

	c_{3D}	c_L	c_M	δ	γ
Low	0.3	0.01	0.01	0.1	0.2
Medium	0.6	0.01	0.01	0.4	0.4
High	0.9	0.01	0.01	0.7	0.6

Table 6-5 Parameter Values in the Numerical Testing for the Impacts of Product Design Quality Level on the Optimal Decisions – Model Y

	c_{3D}	c_L	c_M	α	γ
Low	0.3	0.01	0.01	0.2	0.2
Medium	0.6	0.01	0.01	0.5	0.4
High	0.9	0.01	0.01	0.8	0.6

PROPOSITION *6-8.* *In decentralized model Y,*

(1) The optimal price of the logistics service is convex in the TM product customization level. Both the optimal price of the TM product and the 3DP product increase in the TM product customization level. The optimal number of product sales of the TM product increases in the TM product customization level. The TM product customization level has no direct impact on the optimal number of 3DP product sales.

(2) The optimal price of the logistics delivery service, the TM product, the 3DP product and the optimal number of TM product sales increases in the third-party 3DP product design quality. The optimal number of 3DP product sales decreases in it.

(3) Both the traditional manufacturer's and the logistics vendor's maximized profit increase in the TM product customization level but decrease in the third-party 3DP product design quality.

Under the integrated supply chain,

(1) The optimal TM product price increases in both the TM product customization level and the third-party 3DP design quality. The optimal 3DP product price and the optimal number of sales increases in the third-party 3DP design quality but the TM product customization level has no direct impact on the optimal 3DP product price or the optimal number of sales. The optimal number of TM product sales increases in the TM product customization level but decreases in the third-party 3DP product design quality.

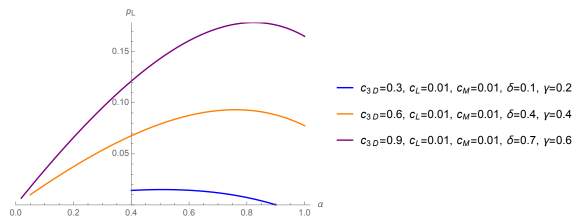
(2) *The maximized supply chain profit increases in the TM product customization level but decreases in the third-party 3DP product design quality.*

As in Figure 6-9, first of all, the improvement of the TM product customization level not only contributes to the TM product's high-price strategy and the improvement of the third-party 3DP product design, but it also has positive impacts on the optimal price of both the TM product and the 3DP product. This finding also supports by the research conducted by (Liao et al., 2014). Their study suggests the improving on the product service can help the manufacturer get the advantages on product pricing.

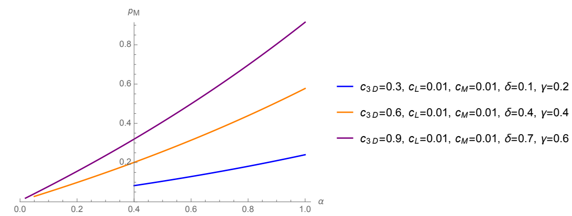
In addition, we can also show that improved TM product customization cannot always help the traditional manufacturer achieve more product sales. If the TM product customization level is in the low region, the improvement of the TM product forces the logistics vendor to use a high-price strategy for the delivery service for the purpose of maximizing his/her profitability and mitigating the TM product's pricing advantage. Meanwhile, a higher customization TM product yields higher TM product sales. Accordingly, the logistics vendor also uses a high-price strategy in order to increase his/her profit. As a result, the traditional manufacturer can gain more profits on the increased TM product sales and the high TM product price. Meanwhile, the logistics vendor can also enjoy more profits on the increased TM product delivery and the high delivery service price. If the TM product customization level is in the high region, any improvement to TM product customization pushes the logistics vendor to use a low-price regime for the delivery service. The logistics vendor can help the traditional manufacturer's low pricing strategy for the TM product and then gain more profits on the increased TM product sales. In this situation, both the traditional manufacturer and the logistics vendor can benefit from the increased TM product sales.

Next, Figure 6-9 also illustrates that the optimal price of the logistics service, the TM product and the 3DP product increases in the quality of the third-party product design. With high product design quality, both the traditional manufacturer and the logistics vendor use a high price strategy for the TM and the 3DP product. At the same time, it also pushes the logistics vendor to price the service higher for the purpose of maximizing profits. Thus, more consumers choose to buy the TM product instead of the 3DP product because of its pricing advantage. Consequently, the traditional manufacturer loses profit due to having to pay high delivery fees. Meanwhile, the logistics vendor's profitability is also hurt by the improvement of the quality of the third-party product design, which leads to the decline of 3DP product sales.

Under the integrated supply chain (Figure 6-10), the impact of the TM product customization level on the supply chain performance is positive but the third-party 3DP product design quality has a negative impact on the supply chain's overall performance. Firstly, due to the supply chain integration and the model settings, the third-party 3DP product design quality has no direct impact on the optimal price or on the sales of the 3DP product. In addition, improved TM product customization helps the TM with a high-price strategy and also helps the TM product achieve more sales. Thus, the improvement of the TM product customization level helps the supply chain attain more sales of the TM product. However, the improvement of the third-party 3DP product design quality brings more product sales to the logistics vendor's 3DP product. This is because more consumers sensitive to high product design quality choose to buy the 3DP product instead of the TM product. Consequently, the improvement of the third-party 3DP product leads to the integrated supply chain losing more profits on the TM product sales.


p_L
α
c3D=0.3, cL=0.01, cM=0.01, δ=0.1, γ=0.2
c3D=0.6, cL=0.01, cM=0.01, δ=0.4, γ=0.4
c3D=0.9, cL=0.01, cM=0.01, δ=0.7, γ=0.6

(a)


p_M
α
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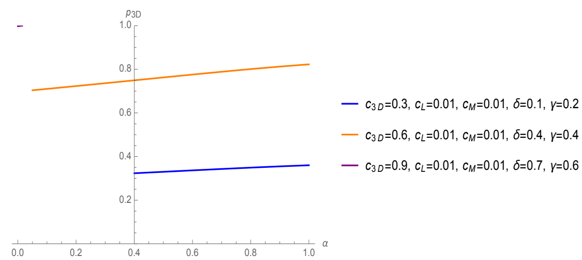
c3D=0.6, cL=0.01, cM=0.01, δ=0.4, γ=0.4
c3D=0.9, cL=0.01, cM=0.01, δ=0.7, γ=0.6

(b)


p_3D
α
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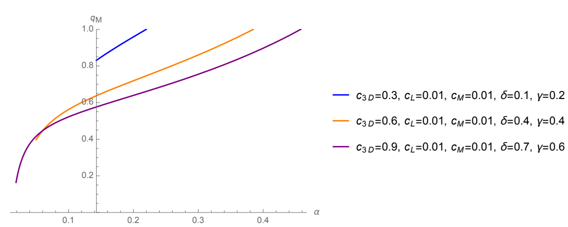
c3D=0.9, cL=0.01, cM=0.01, δ=0.7, γ=0.6

(c)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α
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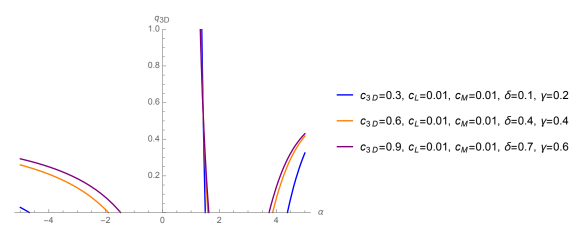
c3D=0.9, cL=0.01, cM=0.01, δ=0.7, γ=0.6

(d)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α
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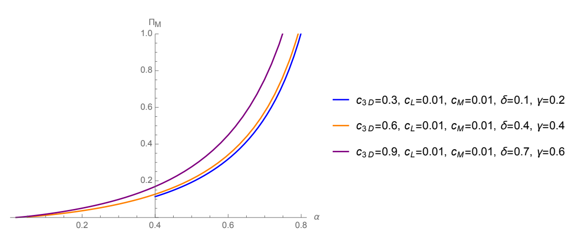
c3D=0.9, cL=0.01, cM=0.01, δ=0.7, γ=0.6

(e)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α
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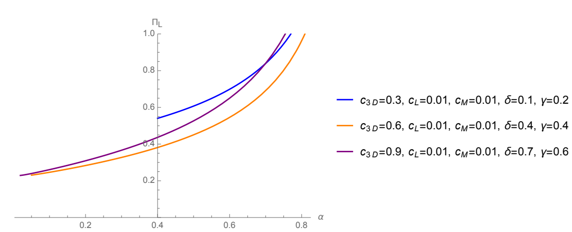
c3D=0.9, cL=0.01, cM=0.01, δ=0.7, γ=0.6

(f)


Π_L
α
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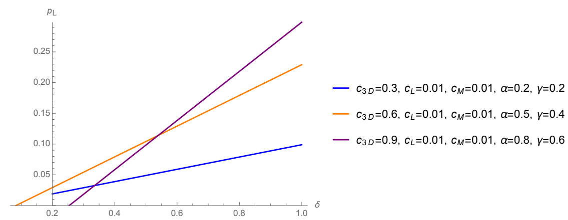
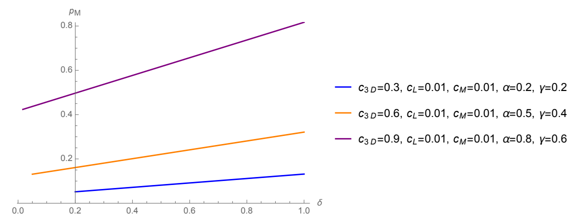
c3D=0.9, cL=0.01, cM=0.01, δ=0.7, γ=0.6

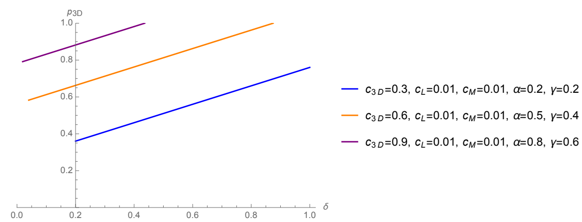
(g)



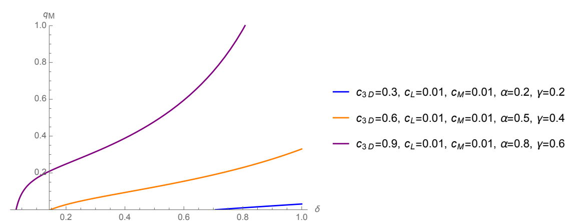
(h)



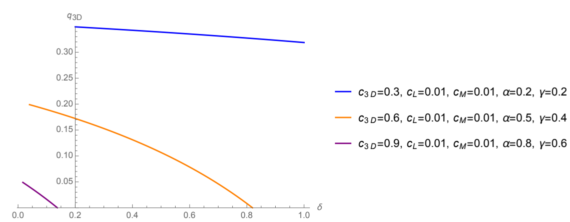
(i)



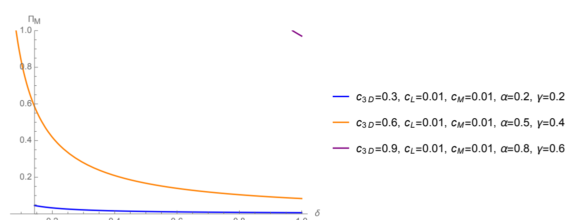
(j)



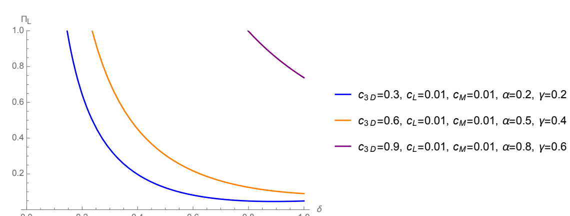
(k)



(l)



(m)



(n)

Figure 6-9 Impact of Customization Level and Product Design Level in the Decentralized Supply Chain – Model Y

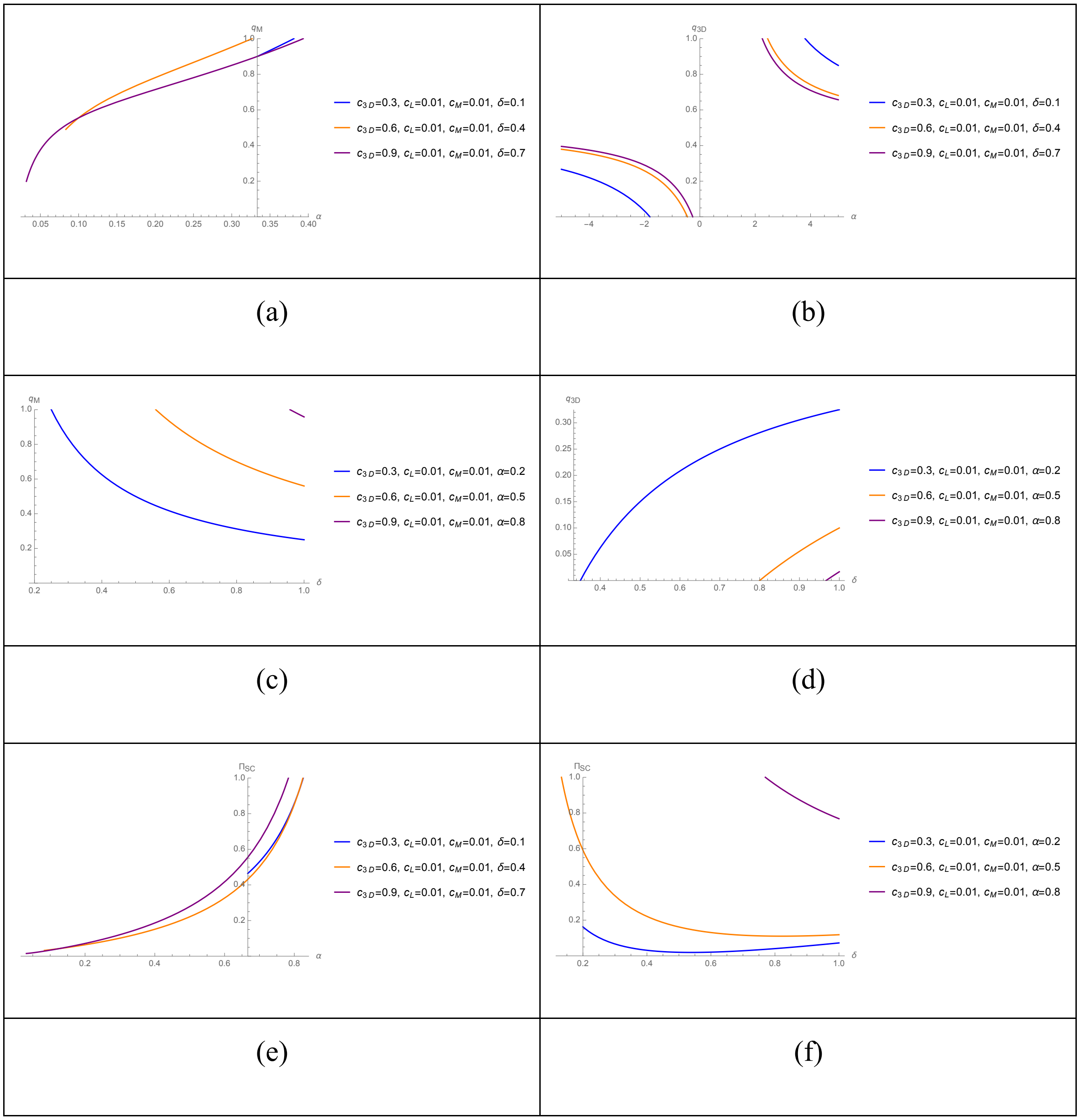


Figure 6-10 Impact of Customization Level and Product Design Level in the Integrated Supply Chain – Model Y

6.3.3 Model Z

In the third 3DP engagement model (here termed Model Y), the traditional manufacturer authorizes the product design for the logistics vendor's 3DP product, under the condition that the traditional manufacturer collects an authorization fee β $(0 < \beta < 1)$ (Figure 6-11).

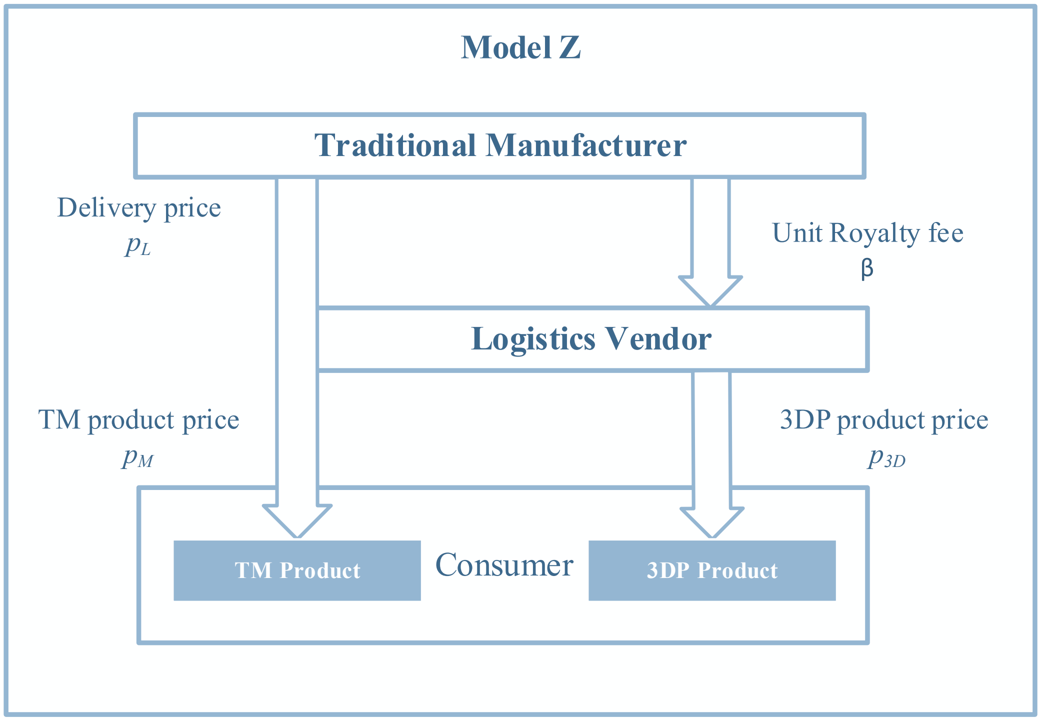


Figure 6-11 Supply Chain Structure of Model Z

In the decentralized supply chain, both the traditional manufacturer's and the logistics vendor's profit functions can be rewritten as

$$\prod\nolimits_{Z} M(p_M) = (p_M - c_M - p_L)q_M + \beta q_{3D} \tag{6.7}$$

$$\prod\nolimits_{Z} L(p_L, p_{3D}) = (p_L - c_L)q_M + (p_{3D} - c_{3D} - \beta)q_{3D} \tag{6.8}$$

The profit of the integrated supply chain is

$$\prod\nolimits_{Z} SC(p_M, p_{3D}) = (p_M - c_M - c_L)q_M + (p_{3D} - c_{3D})q_{3D} \tag{6.9}$$

PROPOSITION 6-9. *In the decentralized supply chain, the maximum profit for the traditional manufacturer is Equation (6.39) and the maximum profit for the logistics vendor is Equation (6.40), both of which are maximized by the optimal price in Equation (6.34), (6.35) and (6.36).*
The optimal market demand for the TM and 3DP product is Equation (6.37) and (6.38).
In the integrated supply chain, the maximum profit for the supply chain is $\prod_Y^* SC(p_M, p_{3D}) = -\frac{\alpha\delta(1-\alpha\delta)+\alpha\delta c_{3D}^2+(c_L+c_M)^2-2\alpha\delta c_{3D}(1-\alpha\delta+c_L+c_M)}{4\alpha\delta(-1+\alpha\delta)}$, *which is maximized by* $p_M^* = \frac{1}{2}(\alpha\delta +$

$c_L + c_M)$ *and* $p_{3D}^* = \frac{1}{2}(1 + c_{3D})$. *The optimal market demand for the TM and 3DP product is* $q_M^* = \frac{-\alpha\delta c_{3D} + c_L + c_M}{2\alpha\delta(-1+\alpha\delta)}$ *and* $q_{3D}^* = \frac{1-\alpha\delta - c_{3D} + c_L + c_M}{2-2\alpha\delta}$.

PROPOSITION *6-10.* *In decentralized model Z,*

(1) *The optimal price of the logistics service decreases in the cost of the TM, the cost of the 3DP product and the unit product design authorization fee, but it increases in the cost of the logistics service.*
(2) *The optimal price of the TM product increases in all the involved costs for the products/service.*
(3) *The optimal price of the 3DP product decreases in the cost of the TM product and the cost of the logistics service but increases in the cost of the 3DP product and the unit product design authorization fee.*
(4) *The optimal sales of the TM product decrease in the cost of the TM product and the logistics service but increase in the cost of the 3DP product and the unit product design fee.*
(5) *The optimal sales of the 3DP product increase in the cost of the TM product and the cost of the logistics service but decrease in the cost of the 3DP product and the unit product design fee.*
(6) *The traditional manufacturer's maximized profit is concave in the cost of the TM product, the logistics delivery service and the 3DP product while it decreases in the authorization cost for the product design.*
(7) *The logistics vendor's profit is concave in all of the different costs.*

We obtain some interesting findings from the above proposition.

Firstly, it is straightforward that the cost reduction on the TM product helps the traditional manufacturer's low pricing strategy for the TM product. However, the low-priced TM product pushes the logistics vendor to raise the cost of the delivery service to 1) generate more profits on the delivery service and 2) mitigate the TM product's pricing advantage. Meanwhile, the logistics vendor also selects a high-price regime on the 3DP product to increase the product's unit margin. However, if the TM product's cost is low, the traditional manufacturer cannot generate more profits because s/he had to pay the high delivery fee. At the same time, due to the loss from the decreased 3DP product sales, the logistics vendor cannot generate more profits either.

However, if the TM product cost is high, the cost reduction on the TM product helps the traditional manufacturer attract more price-sensitive consumers to buy the TM product. Thus, both the supply chain agents can achieve better financial performance from the dramatically increased TM product sales. In general, the impacts of the cost reduction on the logistics service are the same as the impacts of the cost reduction on the TM product, but the only difference is that the logistics price increases in the cost of the logistics delivery service.

Secondly, both reduction of the 3DP product cost and the unit product design fee have the same impact on the optimal decisions in this supply chain structure. The cost reduction on c_{3D} or β forces the logistics vendor to use a high price for the logistics service to mitigate the TM product's pricing advantage. Interestingly, the cost reduction on c_{3D} or β can enhance the pricing advantages of both the 3DP product and the TM product. This is simply because after the traditional manufacturer notices the cost reduction on the 3DP product, s/he has to use a low-price strategy on the TM product to maintain its pricing advantage. Consequently, more consumers choose to buy the 3DP product and this induces a cannibalization effect on the TM product's sales.

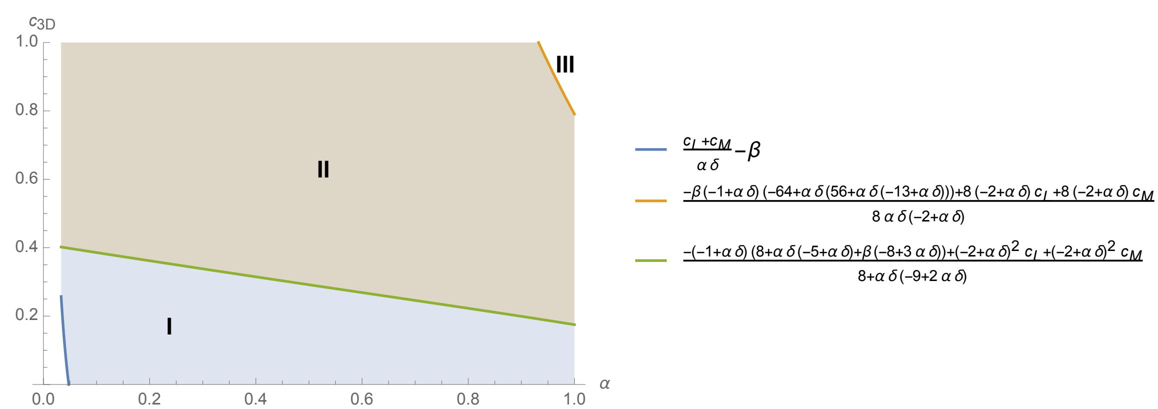


Figure 6-12 The Impact of 3DP Product Cost on the Maximized Profits – Decentralized Model Z (given $c_L = 0.01$, $c_M = 0.01$, $\delta = 0.7$, and $\beta = 0.6$)

Thirdly, the impacts of the 3DP product's cost and the unit product design fee on both agents' profitability are different. In view of PROPOSITION 6-10, Figure 6-12 illustrates three different scenarios. As we explained in the above proposition, the cost reduction on the 3DP product results in a low price for both the TM and the 3DP product. Meanwhile, the cost reduction also helps the 3DP product to increase its market share but cannibalizes the TM product. Under model Z, the traditional manufacturer can generate profit from two streams: one is the TM product sales and the other is the design service for the 3DP product. The logistics vendor can also generate profit in two ways: from the delivery service for the TM product and from the 3DP product sales. Firstly, if the cost of the 3DP product is low (located in Region I), both the traditional manufacturer's and the logistics vendor's profits decrease in the cost of the 3DP product. 3DP product cost reduction is a win-win strategy. It allows the traditional manufacturer to make more profit on the 3DP product design service to cover its loss from TM product sales. Meanwhile, the logistics vendor can make more profit on the 3DP product, although s/he loses profits on the TM product delivery service. Secondly, if the 3DP cost is slightly higher (Region II), the traditional manufacturer's profit decreases in the cost of the 3DP product but the logistics vendor's profit increases in it. In this case, the traditional manufacturer can still benefit from the increased demand for the 3DP product design service, but the logistics vendor cannot generate more profit overall due to the increasing loss made on TM product delivery. Therefore, under this supply chain structure, it is neither beneficial nor strategical for the logistics vendor to put effort into 3DP product cost reduction. Lastly, if the 3DP cost is high, both member's maximized profit increases in the cost of the 3DP product; it is a lose-lose strategy. Under this scenario, the 3DP product's cost reduction hurts both supply chain players' maximized profit. The traditional manufacturer loses more on TM product sales and the logistics vendor also cannot generate more profits either from 3DP product sales or the TM product delivery service.

Lastly, the traditional manufacturer's maximized profit decreases in the product design authorization fee but the logistics vendor's maximized profit is concave in it. When the design authorization fee is low (i.e., $\frac{c_L+c_M}{\alpha\delta} - c_{3D} <$

$\beta\frac{-8+\alpha\delta(5-\alpha\delta)+(8-3\alpha\delta)c_{3D}+(-2+\alpha\delta)c_L+(-2+\alpha\delta)c_M}{-8+4\alpha\delta}$), if the traditional manufacturer raises the product design authorization fee, it results in a high 3DP product price. Therefore, the 3DP product loses some price-sensitive consumers. Accordingly, the traditional manufacturer loses profit from providing 3DP product design and the logistics vendor loses profit on 3DP product sales. Although both supply chain agents can attain more profit on the increased TM product sales, they cannot achieve better business performance. When the design authorization fee is higher than the threshold ($\beta\frac{-8+\alpha\delta(5-\alpha\delta)+(8-3\alpha\delta)c_{3D}+(-2+\alpha\delta)c_L+(-2+\alpha\delta)c_M}{-8+4\alpha\delta}$), if the fee increases, more price-sensitive consumers switch and buy the TM product. However, the profit the traditional manufacturer generates from this increase in TM product sales cannot cover his/her loss from the decreased demand for 3DP product design authorization. The logistics vendor can benefit from the dramatically increased use of the TM product delivery service, although his/her profit from 3DP product sales drops. The studies about 3DP intellectual (Esmond & Phero, 2014; Piller et al., 2004) indicate that the industry should notice and have actions on the 3DP intellectual issue. This finding implies that although charge the 3DP design fee is a method to protecting the intellectual, but the increasing the 3DP product design authorization fee is not at all a strategical action for the traditional manufacturer,

***PROPOSITION* 6-11.** In integrated supply chain of model Z,

(1) The optimal price of the TM product increases in the cost of the TM product and the logistics service. The optimal price of the 3DP product only increases in the cost of the 3DP product. The optimal TM product sales decrease in the cost of the TM product but increase in the cost of the 3DP product. Meanwhile, the optimal 3DP product sales increase in the cost of the TM product and the logistics service but decrease in the cost of the 3DP product.
(2) The supply chain's overall profitability is concave in the cost of the TM product, the logistics service and the 3DP product.

In the integrated supply chain, the unit product design fee is not a consideration with regard to the optimal decisions. In the following discussion, we analyze the impact of different costs under integrated Model Z one by one.

Firstly, the impacts of the cost of the TM product and the logistics service are the same. A cost reduction on the TM product and on the logistics delivery service helps the TM product gain more market share through a low TM price strategy and also cannibalizes the 3DP product market share. When the cost of the TM product and the logistics service is low ($c_M < \alpha\delta c_{3D} - c_L$ or $c_L < \alpha\delta c_{3D} - c_M$), the cost reduction helps the supply chain achieve more profits on the increased TM product sales than the lost on the 3DP product sales. However, if the TM product and logistics service are costly (($\alpha\delta(c_{3D} + \beta) - c_L > c_M > \alpha\delta c_{3D} - c_L$ or $\alpha\delta(c_{3D} + \beta) - c_M > c_L > \alpha\delta c_{3D} - c_M$)), the cost reduction on the TM product and logistics service cannot help the supply chain generate more profits on the TM product than the loss made on 3DP product sales. Therefore, it cannot help the improvement of the integrated supply chain.

Secondly, a cost reduction can help the 3DP product expand its market share through a low-price strategy. But, surprisingly, under this supply chain setting, the cost of the 3DP product has no direct impact on the optimal TM product price. Depending on the different 3DP product cost levels, the impacts of the 3DP product cost on the integrated supply chain are different. When the 3DP product cost is low ($\frac{c_L + c_M}{\alpha\delta} - \beta < c_{3D} < 1 - \alpha\delta + c_L + c_M$), the cost reduction helps the supply chain generate more profits on 3DP product sales. However, when the 3DP product cost is high ($1 - \alpha\delta + c_L + c_M < c_{3D} < 1$), a cost reduction on the 3DP product results in the system losing profit from either 1) the decreased TM product sales or 2) the low unit price margin for the 3DP product. This finding implies that 3DP product cost reduction is a beneficial strategy for the integrated supply chain only if the 3DP product is not costly. Therefore, in practice, reducing the 3DP production cost is one of the key future directions that should be taken to improve low-cost 3DP product manufacturing.

Compared to Model X, Model Z includes one more parameter β. Using the same methodology, we assigned the value of β in our two full factorial designs for numerical tests (Table 6-6 and Table 6-7).

Table 6-6 Parameter Values in the Numerical Testing of the Impacts of Customization Level on the Optimal Decisions – Model Z

	c_{3D}	c_L	c_M	δ	β
Low	0.3	0.01	0.01	0.1	0.2
Medium	0.6	0.01	0.01	0.4	0.4
High	0.9	0.01	0.01	0.7	0.6

Table 6-7 Parameter Values in the Numerical Testing of the Impacts of Product Design Quality Level on the Optimal Decisions – Model Z

	c_{3D}	c_L	c_M	α	β
Low	0.3	0.01	0.01	0.2	0.2
Medium	0.6	0.01	0.01	0.5	0.4
High	0.9	0.01	0.01	0.8	0.6

PROPOSITION *6-12*. *In decentralized model Z,*

(1) *The optimal price of the logistics vendor increases in the TM product customization level and product design quality in the supply chain with the low- and medium-setting; it is convex in the TM product customization level and product design quality in the supply chain with the high-setting. The optimal price of both the TM product and the 3DP product increases in the TM product customization level and product design quality;*

(2) *The optimal market demand for the TM product increases in the TM product customization level and product design quality. Only in the supply chain with the low-setting do the 3DP product sales decrease in the TM product customization level and product design quality, otherwise, the TM product customization level and the product design quality have no direct impact on 3DP product sales.*

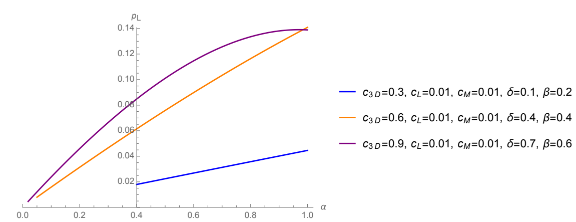
(3) *The optimal market demand for the 3DP product increases in the cost of the TM product and the logistics service; however, it decreases in the cost of the TM product.*

(4) *The traditional manufacturer's maximized profit decreases in the TM product customization level but the logistics vendor's maximized profit increases in it.*

(5) Both the traditional manufacturer's and the logistics vendor's maximized profit increases in the product design quality under the supply chain with the medium and high setting. However, under the low setting, the improvement in the product design quality benefits the logistics vendor, but the traditional manufacturer cannot achieve better profitability.

The findings of this proposition (shown in Figure 6-13) can be summarized as follows:

Firstly, under the supply chain with the low setting, improvement of the TM product's customization level or the design quality pushes the traditional manufacturer to set the TM product price high. And the logistics vendor uses a high price regime for the delivery service to 1) mitigate the TM product's pricing advantage and 2) increase the profits made on the delivery service. In addition, a high TM product price also offers room to the logistics vendor to increase the 3DP product's unit margin. As a result, more consumers choose the TM product because of the improved customization level and design quality. Therefore, the 3DP product loses market share. However, under the supply chain with the medium setting, the improvement in α or δ cannot directly influence the 3DP product sales, because the product pricing still determines the consumer's shopping behavior (Chiang et al., 2003; Vorst & Beulens, 2002). For the traditional manufacturer, improvement in the product design enables generation of more profits from either the higher TM product price or the increased TM product sales. But the logistics vendor loses more profits from the decline in expensive 3DP product sales, although the profits from the logistics service increase. However, there is one exception. In the supply chain with the low-cost setting, the improvement in the TM product design quality pushes the logistics vendor to use a high price strategy for the logistics service. Therefore, the delivery cost accounts for a large portion of the low-cost TM product's cost structure. In this case, the traditional manufacturer cannot achieve better financial performance due to the huge cost of TM product delivery.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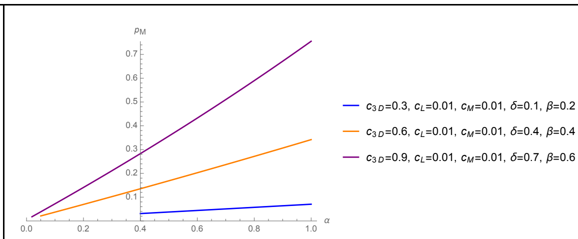
0.12
0.10
0.08
0.06
0.04
0.02
0.0
0.2
0.4
0.6
0.8
1.0
α
c3D=0.3, cL=0.01, cM=0.01, δ=0.1, β=0.2
c3D=0.6, cL=0.01, cM=0.01, δ=0.4, β=0.4
c3D=0.9, cL=0.01, cM=0.01, δ=0.7, β=0.6

(a)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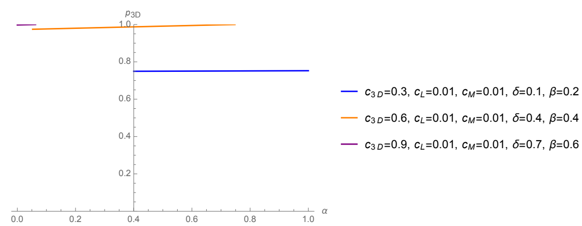
0.2
0.1
0.0
0.2
0.4
0.6
0.8
1.0
α
c3D=0.3, cL=0.01, cM=0.01, δ=0.1, β=0.2
c3D=0.6, cL=0.01, cM=0.01, δ=0.4, β=0.4
c3D=0.9, cL=0.01, cM=0.01, δ=0.7, β=0.6

(b)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0.2
0.0
0.2
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0.6
0.8
1.0
α
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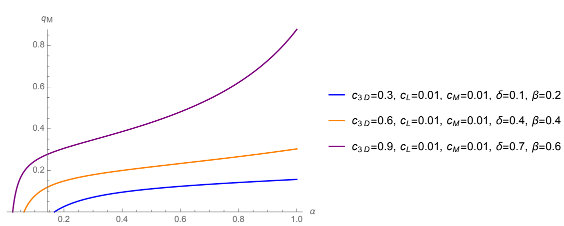
c3D=0.6, cL=0.01, cM=0.01, δ=0.4, β=0.4
c3D=0.9, cL=0.01, cM=0.01, δ=0.7, β=0.6

(c)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0.2
0.4
0.6
0.8
1.0
α
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c3D=0.6, cL=0.01, cM=0.01, δ=0.4, β=0.4
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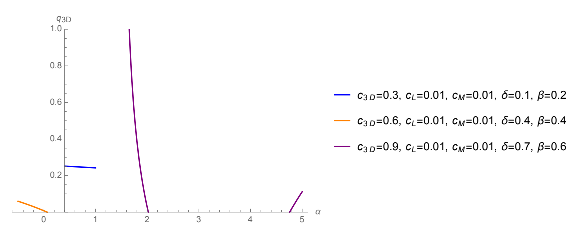
(d)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0
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2
3
4
5
α
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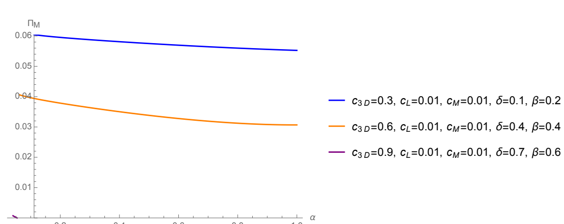
c3D=0.6, cL=0.01, cM=0.01, δ=0.4, β=0.4
c3D=0.9, cL=0.01, cM=0.01, δ=0.7, β=0.6

(e)


Π_M
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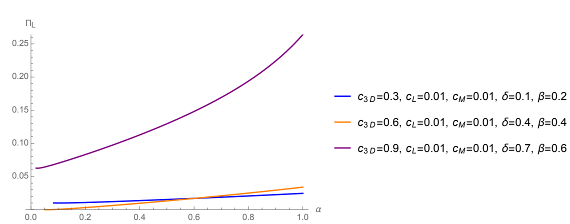
0.04
0.03
0.02
0.01
0.2
0.4
0.6
0.8
1.0
α
c3D=0.3, cL=0.01, cM=0.01, δ=0.1, β=0.2
c3D=0.6, cL=0.01, cM=0.01, δ=0.4, β=0.4
c3D=0.9, cL=0.01, cM=0.01, δ=0.7, β=0.6

(f)


Π_L
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0.20
0.15
0.10
0.05
0.0
0.2
0.4
0.6
0.8
1.0
α
c3D=0.3, cL=0.01, cM=0.01, δ=0.1, β=0.2
c3D=0.6, cL=0.01, cM=0.01, δ=0.4, β=0.4
c3D=0.9, cL=0.01, cM=0.01, δ=0.7, β=0.6

(g)

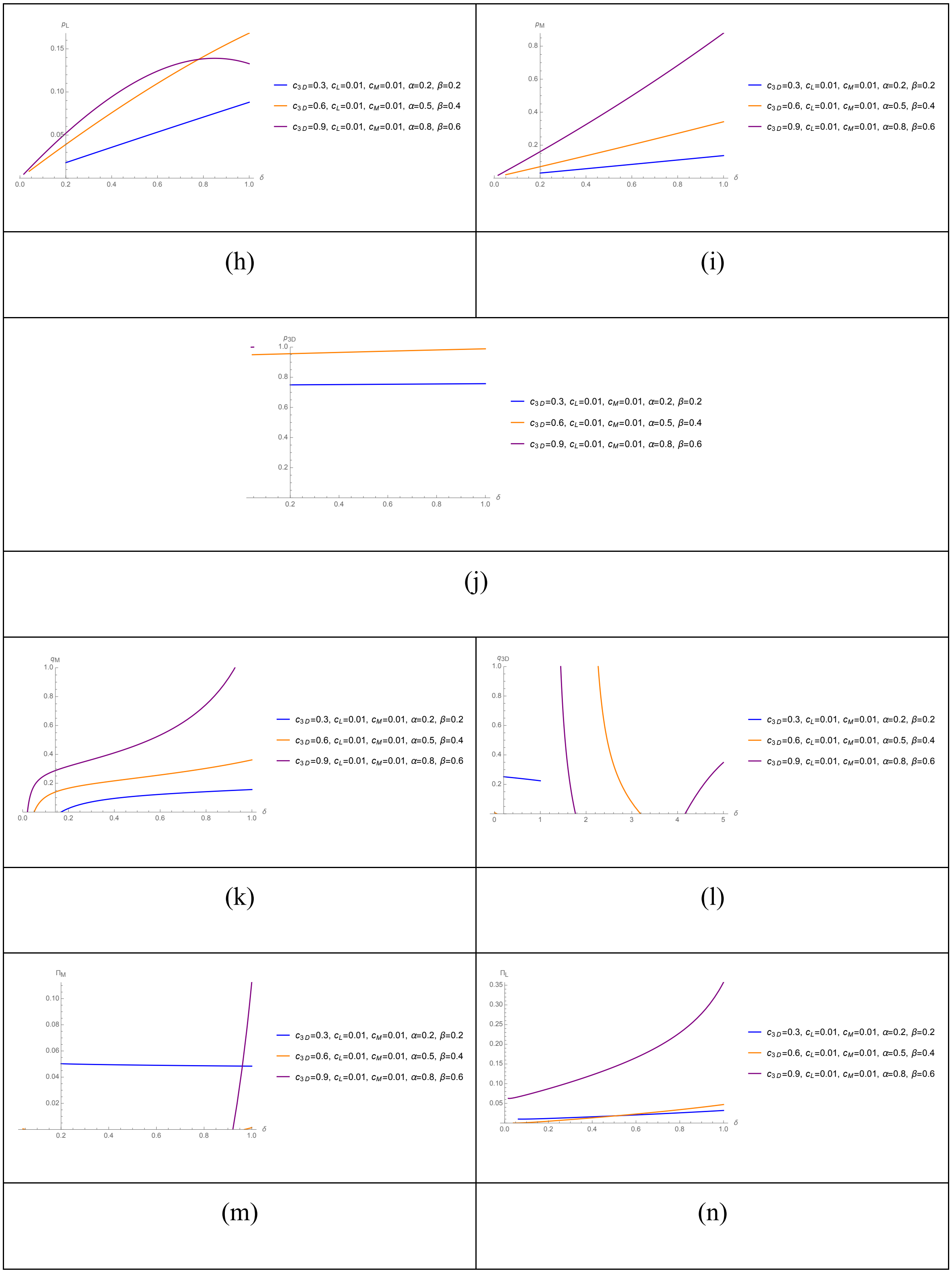


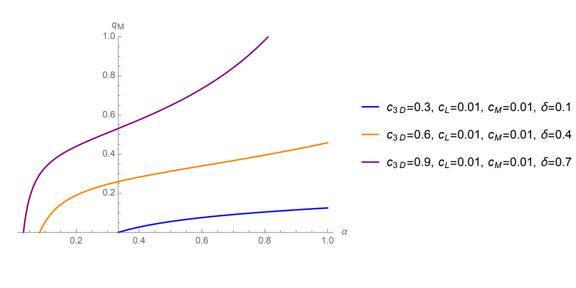
Figure 6-13 Impact of Customization Level and Product Design Level in the Decentralized Supply Chain – Model Z

PROPOSITION *6-13.* *Under the integrated model Z,*

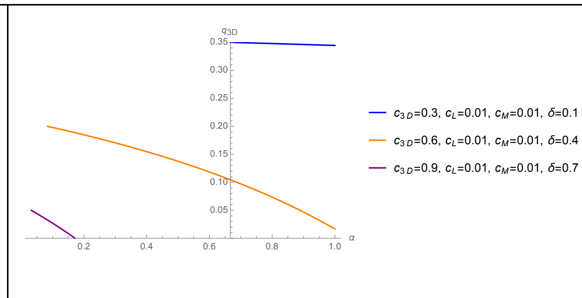
(1) Both the optimal price and quantity of the TM product increase in the TM product customization level and the product design quality. The TM product customization level and product design level have no direct impact on the 3DP product price but both of them negatively impact the 3DP product's optimal sales.

(2) The supply chain's performance improves in either the TM product customization level or product design quality.

As Figure 6-14 shows, the improvement of α or δ can help the system gain more profits from the TM product business (increased TM product price and larger TM product sales), although sales of the 3DP product drop.



(a)



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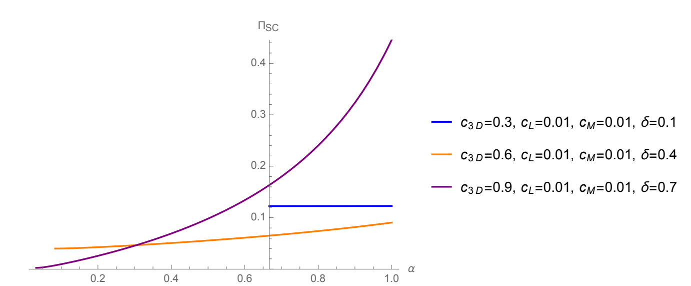

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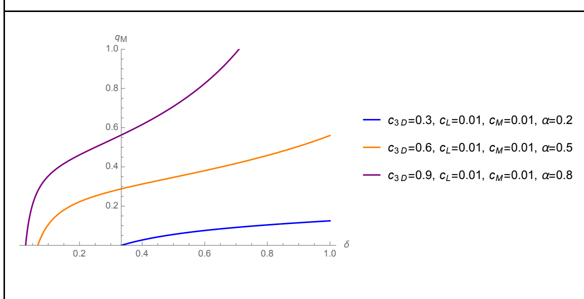
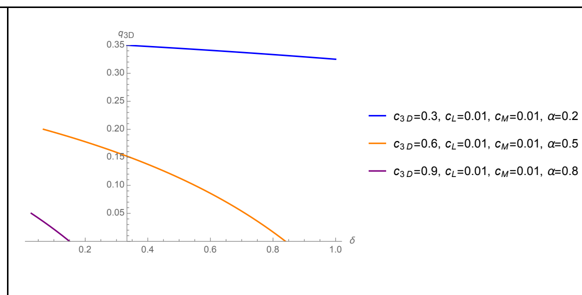
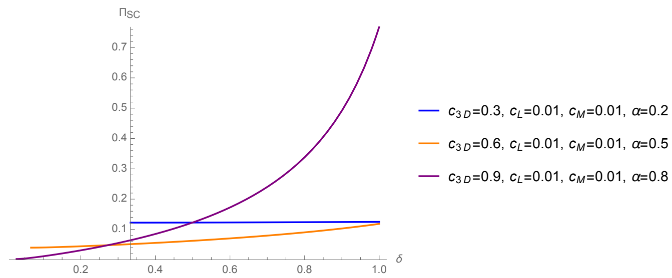


(d)



(e)



(f)

Figure 6-14 Impact of Customization Level and Product Design Level in the Integrated Supply Chain – Model Z

6.4 The Logistics Vendor's 3DP Adoption Strategy

In following subsections, for the purpose of find out the best 3DP engagement strategy, we try to put Model X, Model Y, and Model Z into comparisons.

6.4.1 The Logistics Vendor's 3DP Adoption Strategy

To understand should the Logistics Vendor only provide the 3DP product delivery service or sell the self-produced 3DP product by the third-party 3DP professional's product design, we will compare Model X and Model Y. Firstly, and we test under which conditions the traditional manufacturer should leave the whole 3DP product market to the logistics vendor. Then we attempt to analyze the impact on the logistics vendor's profitability. Lastly, we also compare the profitability of the whole supply chain under model X and model Y.

PROPOSITION *6-14.* *In the decentralized supply chain, if the traditional manufacturer leaves the 3DP market and authorizes its 3DP product design to the logistics vendor,*

(1) When the product quality is high, the traditional manufacturer can make more profit only if the cost of the 3DP product is low; when the product quality is low, it is beneficial to the traditional manufacturer only if the 3DP product production is costly.
(2) The logistics vendor incurs a profit loss.

(3) The logistics vendor reduces the logistics service fee. If the cost of the 3DP product is low, the traditional manufacturer reduces the TM product price; if the cost of the 3DP product is high, the traditional manufacturer raises the TM product price; if the cost of the 3DP product is low, the logistics vendor uses a low 3DP product price. If the cost of the 3DP product is high, the logistics vendor uses a high 3DP product price.

(4) The traditional manufacturer sells more TM products in Model Y. If the product design quality is low, the 3DP product sells more in Model Y; if the product design quality is high, the 3DP product sells less in Model Y.

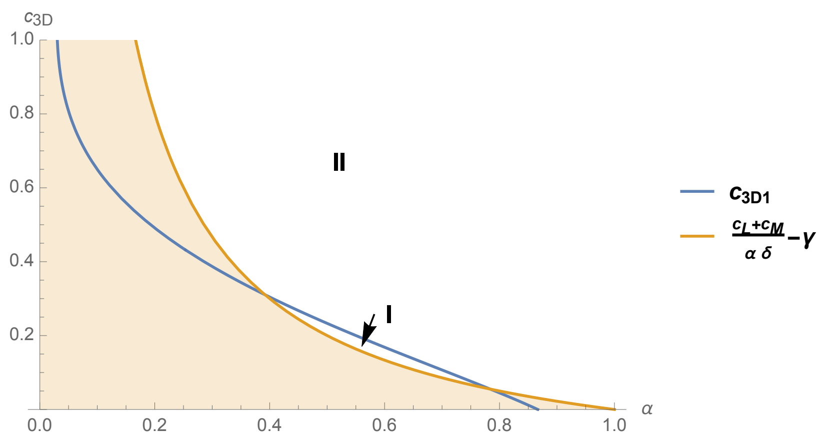
(5) 

Figure 6-15 Traditional Manufacturer's Profit: Comparison between Model X and Y (given $c_{3D} = 0.5, c_L = 0.01, c_M = 0.01, \delta = 0.1, \gamma = 0.2$)

PROPOSITION 6-14 shows that operating the entire 3DP product service is not always profitable for the traditional manufacturer, but it always results in profit loss for the logistics vendor.

After the logistics vendor starts to do the 3DP product business, s/he lowers the price of the delivery service for the purpose of increasing his/her profit on TM product delivery. If the cost of 3DP is low ($\frac{c_L+c_M}{\alpha\delta} - \gamma < c_{3D} < \frac{-2(-4+\alpha)\gamma-(8+(-5+\alpha)\alpha)\delta+(-3+\alpha)c_L+(-3+\alpha)c_M}{2(-4+\alpha)}$), the traditional manufacturer uses low pricing on the TM product to keep its pricing advantage. However, if the 3DP product is costly ($\frac{-2(-4+\alpha)\gamma-(8+(-5+\alpha)\alpha)\delta+(-3+\alpha)c_L+(-3+\alpha)c_M}{2(-4+\alpha)} < c_{3D} < 1$), it offers more room to the traditional manufacturer to raise the price of the TM product for the purpose of maximizing the unit margin on the TM product. By the same logic, if the 3DP product is not costly ($\frac{c_L+c_M}{\alpha\delta} - \gamma < c_{3D} <$

$-\frac{2(8-8\gamma+\alpha(-5+\alpha+3\gamma))+(-2+\alpha)(8+(-5+\alpha)\alpha)\delta+(-4+\alpha)(-3+\alpha)c_L-(4+(-3+\alpha)\alpha)c_M}{2(-2+\alpha)\alpha}$), the logistics vendor uses a low 3DP product price; otherwise, the logistics vendor uses a high 3DP product price to cover the costs and to maximize the profits on the 3DP product. Consequently, the traditional manufacturer can always sell more TM products. The reason behind this is that the TM product always has a price advantage regardless of the 3DP product price. However, only if the product design quality is low (0< $\delta < \frac{-8+7\alpha-\alpha^2}{-8+5\alpha+\alpha^2}$), can the 3DP product actually sell more. Therefore, the traditional manufacturer can discourage 3DP product sales by lowering the product design quality. This finding shows that both the design quality and the 3DP product cost are key considerations for the traditional manufacturer's 3DP strategy.

Specifically, when the product design quality is high ($\frac{-16\alpha+8\alpha^2}{-64+144\alpha-137\alpha^2+59\alpha^3-11\alpha^4+\alpha^5} < \delta < 1$), only if the 3DP product is not costly (Region II, Figure 6-15) is it profitable to the traditional manufacturer to conduct the 3DP business on his/her own. The traditional manufacturer can have more control over the pricing strategy for the TM and 3DP product, which helps the traditional manufacturer to achieve better profitability, especially on the product price. However, if 3DP is costly (Region I, Figure 6-15), it is not profitable for the traditional manufacturer because in this case, the traditional manufacturer uses a low pricing strategy on the TM product and the 3DP product's unit price margin is comparatively low. Therefore, the traditional manufacturer cannot make more profit. However, if the product design quality is low ($0 < \delta < \frac{-16\alpha+8\alpha^2}{-64+144\alpha-137\alpha^2+59\alpha^3-11\alpha^4+\alpha^5}$), the effect of this strategy on the traditional manufacturer's profitability is the opposite. When the 3DP product is not costly (Region II, Figure 6-15), the traditional manufacturer can obtain more profit on the 3DP product. This is because the traditional manufacturer can use a low-price strategy for the 3DP product and then increase the market demand for the 3DP product. However, if the cost of the 3DP product is high (Region II, Figure 6-15), the traditional manufacturer cannot sufficiently increase profit from 3DP product sales to cover its loss from the reduced TM product sales. However, the impact of the logistics vendor's 3DP strategy on his/her profit is more straightforward: because of the reduced price for the logistics service and the TM product market demand, the logistics vendor always loses profit on TM product delivery, although s/he can make new profits on 3DP product sales. But, overall, the profit loss for this part outweighs the new profit generated from the new 3DP product business.

In summary, this proposition implies that 1) it is not profitable to the logistics vendor to 3DP those products for which the traditional manufacturer already has 3DP production and for which the product price is comparatively low. For example, currently French toymaker Smoby Toys is using FDM to produce indoor and outdoor plastic toys for infants and young children (Stratasys, 2018). Although UPS also has the capability to produce these kinds of toys, considering the profitability of this strategy, these products are not a beneficial focus for the logistics vendor's 3DP business. 2) As we discussed in the introduction chapter, the logistics vendor's 3DP adoption is one of the most efficient approaches to 'production-on-scale' for the 3DP production. For the development of 3DP adoption, the government should establish some regulations or policies to support the logistics vendor's 3DP product business. For example, the government could reduce the tax rate for 3DP product businesses or set up some funding streams to support initial investment in 3DP adoption.

PROPOSITION *6-15.* *In the integrated supply chain, if the traditional manufacturer leaves the 3DP market and authorizes the use of its 3DP product design to the logistics vendor,*

(1) There is no impact on the optimal price for the TM product. The logistics vendor reduces the 3DP product price; the traditional manufacturer sells more TM products, but the market demand for the 3DP product reduces.

(2) As for supply chain profitability,

  a. When the product design quality is high, but the TM product customization level is low, this strategy is not profitable.

b. *When the product design quality is low, but the TM product customization level is high, this strategy is only not profitable to the supply chain if the cost of the 3DP product is located at the medium level. If 3DP production is extremely costly or extremely cheap, this strategy is profitable to the supply chain.*

This proposition demonstrates that after the logistics vendor fully takes over 3DP production and design, the logistics vendor uses a low price for the 3DP product in order to gain more profits from 1) the new 3DP product and/or 2) the logistics delivery service. As a result, under Model Y, the supply chain can sell more TM products but the 3DP market demand reduces. Under the following two scenarios, the supply chain cannot achieve better performance. First, if the product design quality is high ($\frac{-1+c_L-c_L^2+c_M-c_Lc_M}{-1+c_M} < \delta < 1$) but the customization level is low ($\frac{c_L+c_M}{\gamma\delta} < \alpha < \frac{-1+\delta+c_L+c_M-\delta c_M}{\delta c_L}$), the 3DP product loses its advantages with regard to product design. Second, better performance is also not obtainable if the cost of the 3DP product is located at the medium level ($\frac{(-1+\alpha\delta)c_L+\frac{(-1+\delta+c_L)^2}{\sqrt{K}}+(-1+\delta)c_M}{-1+\delta} < c_{3D} < \frac{(-1+\alpha\delta)c_L-\frac{(-1+\delta+c_L)^2}{\sqrt{K}}+(-1+\delta)c_M}{-1+\delta}$, where $K = \frac{(-1+\delta+c_L)^2}{(-1+\alpha)\delta(-1+\alpha\delta)}$). In these two cases, the newly generated profits from the increased TM sales cannot cover the losses incurred from the 3DP product sales. For the other situations, the supply chain can obtain more profit from the increased TM product sales to cover its loss from the 3DP product sales. Therefore, this proposition also shows that it is not beneficial to 3DP adoption if the logistics vendor operates the 3DP product market. Therefore, the manufacturing industry should still encourage more traditional manufacturers to look into 3DP products (Holmström et al., 2016). In addition, it also implies that the logistics vendor's 3DP adoption still needs more government or industry support (Ernst & Young, 2016; Wohlers Associates, 2018).

6.4.2 The Traditional Manufacturer's 3DP Product Design Strategy

We now extend the comparison by considering the impact of the traditional manufacturer's control of product design. In recent years, more and more traditional manufacturers have clamoured for greater protection of product design and intellectual property (IP), especially in the 3DP product industry (Esmond & Phero, 2014; Gao et al., 2015; Manners-Bell & Lyon, 2012; Wilkof, 2016). For the purpose of protecting IP related issues, some 3DP enabled logistics vendors choose to collaborate with traditional manufacturers on product design; for example, Panalpina collaborates with Shapeways (Shapeways, 2016). In this case, intuitionally, both parties can benefit from this business model. Specifically, although the traditional manufacturer often suffers from intense competition with the 3DP product provider (the logistics vendor), s/he can gain some sales by providing the product design service. At the same time, the logistics vendor can offer a better product design service for his/her 3DP product business. Therefore, in this subsection we compare model X and model Y to test whether it is a beneficial strategy for the traditional manufacturer to authorize its 3DP product design to the logistics vendor. Then we also examine the impact of this strategy on the logistics vendor's profitability and on the integrated supply chain.

PROPOSITION *6-16.* *Under the decentralized supply chain, if the traditional manufacturer leaves the 3DP market and authorizes its 3DP product design to the logistics vendor, but controls the product design,*

(1) *When the 3DP product design authorization fee is high, or the product design authorization fee is low but the 3DP product is cheap, this strategy is not profitable to the traditional manufacturer. When the 3DP product design authorization fee is low but 3DP production is costly, the traditional manufacturer can gain more profits by this strategy.*
(2) *When the product design authorization fee is high, or the product design authorization fee is low but the 3DP product cost is extremely high or sufficiently low, the logistics vendor can obtain more profit under model Z. When the product design authorization fee is low and the 3DP production cost is located at the middle level, the logistics vendor cannot gain more profits by this strategy.*
(3) *Depending on different product design authorization fees, the impact of this strategy on the optimal decisions is different.*

We now use a numerical example to illustrate the equilibrium optimal decisions under different values of β (product design authorization fee). We first use $c_L = 0.2$, $c_M = 0.3$, $c_{3D} = 0.6$ and $\delta = 0.8$ to examine the impact of controlling the 3DP product design strategy (from Model X to Model Y) on the optimal decisions (Figure 6-16, Table 6-8). We also set $c_L = 0.03$, $c_M = 0.03$, $c_{3D} = 0.15$, $\delta = 0.5$ and $\alpha = 0.6$ to examine the impact of β on the traditional manufacturer's equilibrium business model strategy (Figure 6-17). In addition, we use another set of numbers ($c_L = 0.04$, $c_M = 0.04$, $c_{3D} = 0.3$, $\delta = 0.2$, $\alpha = 0.5$) to demonstrate the decision regions of the impact on the logistics vendor's profitability.

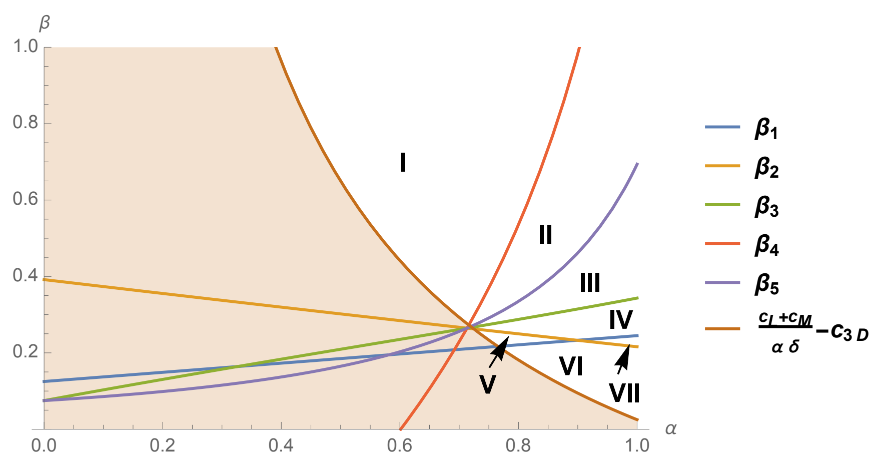


Figure 6-16 The Decision Regions of β on the Optimal Decisions (given $c_L = 0.2$, $c_M = 0.3$, $c_{3D} = 0.6$, $\delta = 0.8$)

Table 6-8 The Decision Regions of β on the Optimal Decisions – Model X vs Model Z

	$p^*_{LX} - p^*_{LZ}$	$p^*_{MX} - p^*_{MZ}$	$p^*_{3DX} - p^*_{3DZ}$	$q^*_{MX} - q^*_{MZ}$	$q^*_{3DX} - q^*_{3DZ}$
Region I	> 0	> 0	> 0	< 0	< 0
Region II	> 0	> 0	> 0	> 0	< 0
Region III	> 0	> 0	> 0	> 0	> 0
Region IV	> 0	> 0	< 0	> 0	> 0
Region V	> 0	< 0	< 0	> 0	> 0
Region VI	< 0	< 0	< 0	> 0	> 0
Region VII	< 0	> 0	< 0	> 0	> 0

Figure 6-16 and Table 6-8 show that there are 7 different decision regions for the impact of β on the optimal decisions. Specifically, under region I, where β is extremely high, the logistics vendor uses a low price regime for the logistics delivery for the purpose of increasing the profit of the goods delivery service. Because of the high β, the traditional manufacturer sets the TM product price low to keep the TM product's price advantage and this forces the logistics vendor to use a lower 3DP product price to maintain the market share. Therefore, this results in an increase of the TM product and 3DP product sales. However, if β is slightly lower, in Region II, the 3DP product price is lower than Region I, and so some more customization-sensitive consumers start to buy the 3DP product and the sales of the TM product reduce. Then, if the value of β falls to Region III or lower (Regions IV-VII), the price of the TM and the 3DP product are much more similar, which results in more competition between the TM and the 3DP product. Therefore, both the sales of the TM and the 3DP product reduce. Next, if the value of β is located in Region IV, both the traditional manufacturer and the logistics vendor use a high-price regime on the TM and the 3DP product to increase the unit price margin of the product to maximize their profits. Then, in Region VI and VII, the logistics vendor shifts to using a high-price strategy for the logistics delivery service to compensate for the loss from decreased TM product sales. Lastly, in Region VII, the traditional manufacturer returns to using a low-price strategy on the TM product to attract more price-sensitive consumers. However, both the product sales for the TM and the 3DP product still show a declining trend.

The findings above help us to understand the impact of this strategy on the traditional manufacturer's and the logistics vendor's profitability. Intuitionally, we assumed that a higher authorization fee would help the traditional manufacturer to generate more profits and that the 3DP product business could also improve the logistics vendor's financial performance. Surprisingly, our findings from this proposition imply that our assumption only holds under certain conditions.

For the traditional manufacturer, if the authorization fee is high ($\beta > \beta^*$, Region II, Figure 6-17), s/he cannot achieve better profitability. Because of the high authorization fee, the traditional manufacturer loses profitability on 1) the decreased TM product unit margin or 2) the 3DP product business. However, if the authorization fee is low ($\beta < \beta^*$, Region I, Figure 6-17), then if the 3DP product cost is high, the traditional manufacturer loses more profit on both the 3DP and TM product business than the new profits generated from the product design authorization fee. However, in this case, if the 3DP product cost is high, the TM product has the absolute advantage of price over the 3DP product. Therefore, the traditional manufacturer can achieve better financial performance.

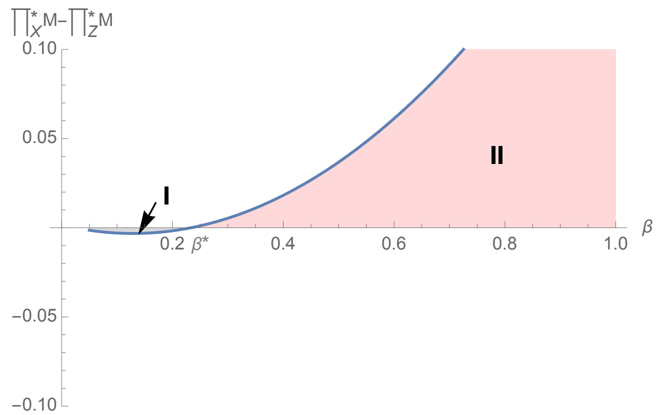


Figure 6-17 The Decision Regions of β on the Traditional Manufacturer's Profits (given $c_L = 0.03$, $c_M = 0.03$, $c_{3D} = 0.15$, $\delta = 0.5$, $\alpha = 0.6$)

Note: $\beta^* = \frac{1}{2(-1+\alpha\delta)(-64+\alpha\delta(68+\alpha\delta(-23+3\alpha\delta)))}\left(-8\alpha\delta(-3+\alpha\delta)(-2+\alpha\delta)(-1+\alpha\delta)+2(-1+\alpha\delta)(-40+\alpha\delta(36+\alpha\delta(-9+\alpha\delta)))c_L+8(-3+\alpha\delta)(-2+\alpha\delta)(-1+\alpha\delta)c_M+\sqrt{((-1+\alpha\delta)(64+\alpha\delta(-96+\alpha\delta(49+\alpha\delta(-10+\alpha\delta))))((-228+\alpha\delta(219+\alpha\delta(-62+7\alpha\delta)))c_L^2-2(-1+\alpha\delta)^2(-4+3\alpha\delta)c_L(\alpha\delta-c_M)+(-1+\alpha\delta)(36+\alpha\delta(-23+3\alpha\delta))(-\alpha\delta+c_M)^2))}\right)$

The impacts of controlling product design on the logistics vendor's optimal business model could be summarized into two categories, as illustrated in Figure 6-18. Firstly, if the product design authorization fee is high (Region II, $\beta^* < \beta$), the logistics vendor can obtain more profits either from 1) the new 3DP business, 2) increased TM product sales, or 3) the increased unit price margin on the logistics delivery service. Secondly, if the product design authorization fee is low (Region II, $\beta < \beta^*$), there are two different scenarios. 1) If 3DP production is cheap, the logistics vendor can make more profit because s/he can profit from 1) the new 3DP product business and/or 2) the increased unit margin on the logistics delivery price. Secondly, if the 3DP product is costly, the logistics vendor cannot achieve better performance because the profit gain from the new 3DP product business and the increased unit margin on the logistics delivery price cannot cover that which is lost on the decreased TM product delivery service.

The results in this proposition suggest that raising the product design authorization fee to a high level cannot benefit the traditional manufacturer. This may explain why some large companies are not directly authorizing product designs to their logistics vendors who have 3DP capabilities. For example, GE is currently using the logistics delivery service provided by UPS, but GE does not outsource any part of its 3DP business to UPS yet (Kellner, 2018; B. Zhang, 2016).

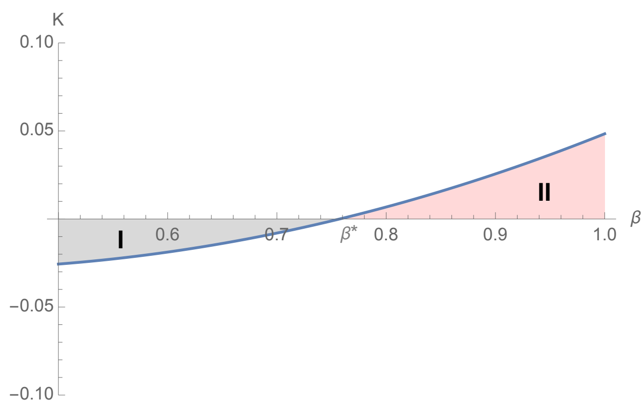


Figure 6-18 The Decision Regions of β on the Logistics Vendor's Profits (given $c_L = 0.04$, $c_M = 0.04$, $c_{3D} = 0.3$, $\delta = 0.2$, $\alpha = 0.5$)

Note: $K = \alpha\delta(\alpha\delta + 2\beta(-4 + \beta + 2\alpha\delta)) - (-8\beta + 2\alpha\delta + 4\alpha\beta\delta - c_L - c_M)(c_L + c_M)$,
$\beta^* = -\frac{1}{2\alpha\delta}\big(2\alpha^2\delta^2 + 4(c_L + c_M) - 2\alpha\delta(2 + c_L + c_M) + \sqrt{2}\sqrt{(8 + \alpha\delta(-9 + 2\alpha\delta))(-\alpha\delta + c_L + c_M)^2}\big)$

PROPOSITION *6-17.* *In the integrated supply chain, if the traditional manufacturer leaves the 3DP market and authorizes the 3DP product design to the logistics vendor, it is not* *beneficial to the supply chain's development. Specifically, there is no impact on the TM product price, and the logistics vendor uses a low 3DP product price. In addition, TM product sales decrease but 3DP product sales increase.*

This proposition implies that for the consideration of developing the supply chain, it is better to encourage the traditional manufacturer to operate the 3DP product. However, if the logistics vendor can sell the 3DP product with authorized product design, the logistics vendor uses a low 3DP product price for the purpose of attracting more price- and customization-sensitive consumers. Consequently, more consumers switch from the TM product market to the 3DP product market. However, at the supply chain level, profit is lost due to 1) decreased TM product sales and/or 2) the low unit margin for the 3DP product. This finding echoes our findings in *PROPOSITION* 6-15 and other related literature (Despeisse et al., 2017; Gebler et al., 2014; Rehnberg & Ponte, 2018; Wohlers Associates, 2016). Accordingly, encouraging more traditional manufacturers to adopt 3DP is a long-term strategy not only for the industry's development but also for the 3DP industry's development.

6.4.3 The Logistics Vendor's 3DP Product Design Strategy

Under this subsection, we seek to explore which business model the 3DP capable logistics vendor should adopt for 3DP product design by comparing the logistics vendor's profitability under model Y and Model Z. Should they purchase the product design from the traditional manufacturer (Model X) or from the third-party 3DP product design professional (Model Y)? Right now, more logistics vendors have a passion for the 3DP product business, but they are still seeking to determine which approach to 3DP adoption is the best one for them. Therefore, this subsection tries to answer the question: which 3DP engagement model is the best one for the logistics vendor's business and the supply chain's sustainable development.

However, due to the complexity of the structured model, in this section, we use a numerical example to illustrate the impact of different product design strategies on the logistics vendor and on the traditional manufacturer's 3DP adoption strategy. Specifically, we use a factored design (Table 6-9) to examine the impact of the costs of product design by the traditional manufacturer β and the cost of design by the third-party 3DP design professional γ on both the traditional manufacturer's and the logistics vendor's business performance in supply chain structures at low, medium, and high settings. In addition, we also compare the integrated supply chain's performance under different models as well.

Table 6-9 Parameter Values in the Numerical Testing for the 3DP Design Strategy

	c_{3D}	c_L	c_M	δ	α
Low	0.3	0.01	0.01	0.1	0.2
Medium	0.6	0.01	0.01	0.4	0.5
High	0.9	0.01	0.01	0.7	0.8

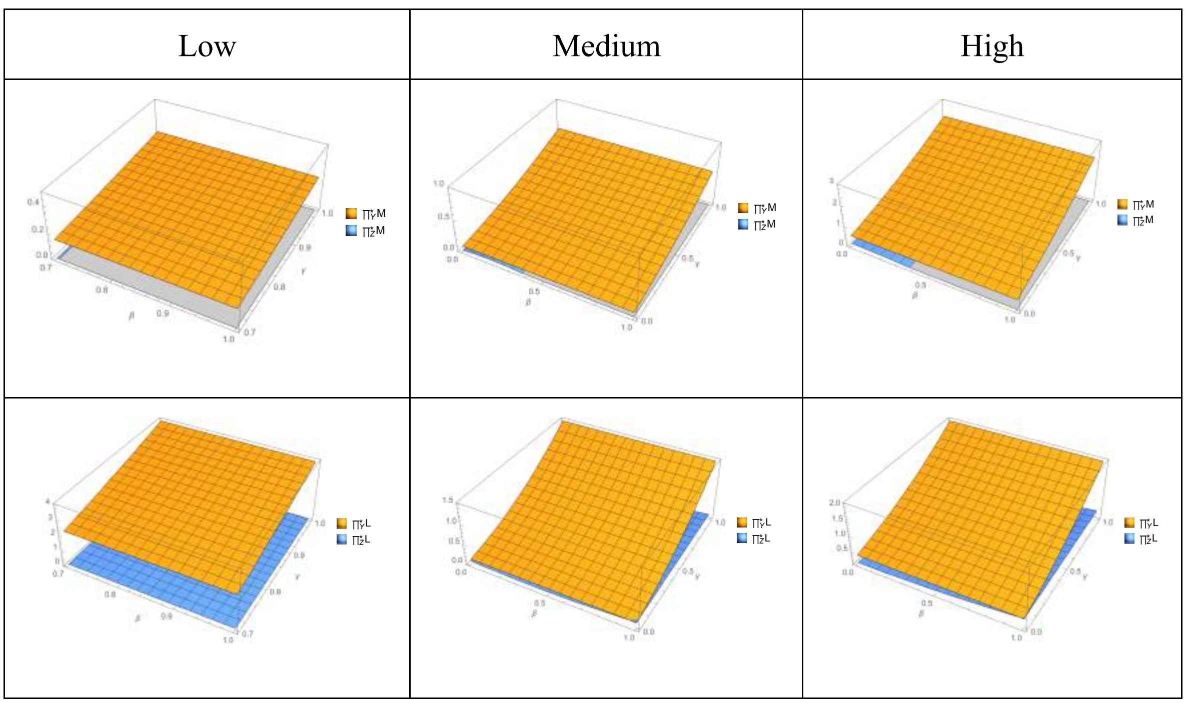
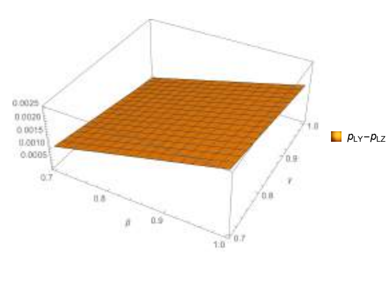
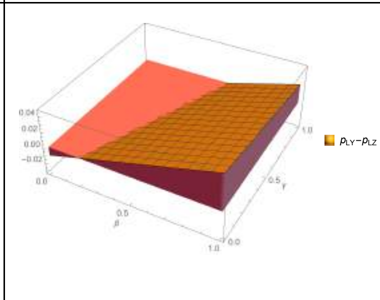
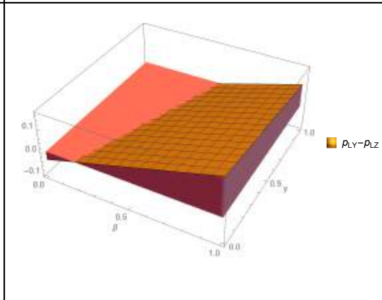
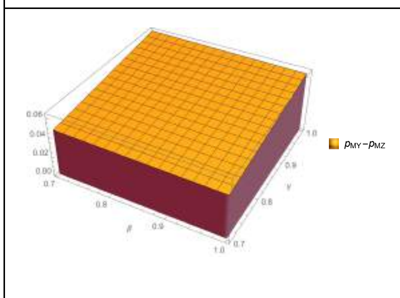
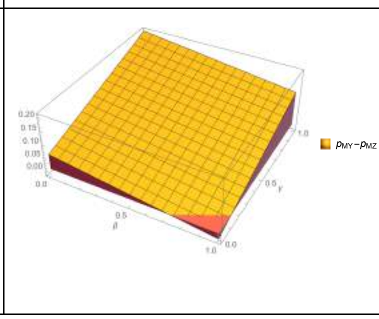
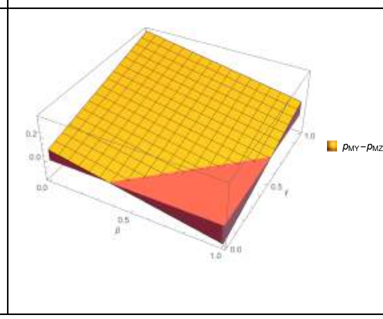


Figure 6-19 Comparisons of the Traditional Manufacturer's and the Logistics Vendor's Profitability – Model Y and Model Z

From Figure 6-19 and Figure 6-20, several observations can be made. Firstly, under the supply chain with the low-setting, because the logistics vendor needs to pay the product design authorization fee to the traditional manufacturer under Model Z, s/he uses a low-price regime on the TM product delivery service. This low-price strategy also helps the traditional manufacturer to set the TM product's price low to maintain the price advantage. Therefore, the logistics vendor has to use a low-price strategy on the 3DP product for the purpose of gaining more price-sensitive consumers. Therefore, sales of the TM and the 3DP product are larger in Model Y than in Model Z. Both the traditional manufacturer and the logistics vendor can obtain more profits under model Y. This may explain why some logistics vendors are focusing on the 3DP business for low-cost items and the traditional manufacturers under this product category are not striving to eliminate logistics vendors' 3DP production (Ciampa & Meo, 2011; Wohlers Associates, 2018).

Next, we analyze the supply chain performance under the medium-setting and high-setting. i) The lower the product design authorization fee (β) is, the lower the logistics delivery fee that is charged by the logistics vendor. ii) If β is high but the third-party product design fee (γ) is low, the TM product price under Model Y is lower than the TM product price under model Z. The reason is that the 3DP product has more price advantages under Model Z. Therefore, the logistics vendor can use the low-price strategy under Model Z. If β is comparatively low but γ is high, the traditional manufacturer uses a low-price strategy on the TM product under Model Z to keep the TM product's price advantage. Meanwhile, the low β helps the logistics vendor use a low-price strategy on the 3DP product as well. If the value of β and γ is located at the rest regions, the traditional manufacturer uses a low-price strategy on TM under Model Z, in view of new profits from product design authorization. And the logistics vendor uses a low price on the 3DP product for the purpose of maximizing profits on the 3DP product business. However, in all of these scenarios, the cannibalization effect becomes much fiercer under model Z. Thus, both products' sales perform better under Model Y than Model Z. In general, the traditional manufacturer and the logistics vendor can enjoy more profits under Model Y. However, there is one exception: under the supply chain with the medium setting, if β is extremely high but γ is sufficiently low (Figure 6-19), the logistics vendor surprisingly can achieve better profitability under Model Z, because in this case, the logistics vendor can use a high unit margin on the logistics delivery price and/or the 3DP product price. This finding reflects the fact that some 3DP enabled logistics vendors now also target high value added automotive parts production as their new 3DP business direction (Baumers et al., 2016; Laplume, Anzalone, & Pearce, 2016; Liu et al., 2014; Wohlers Associates, 2018).

Low	Medium	High
		
		

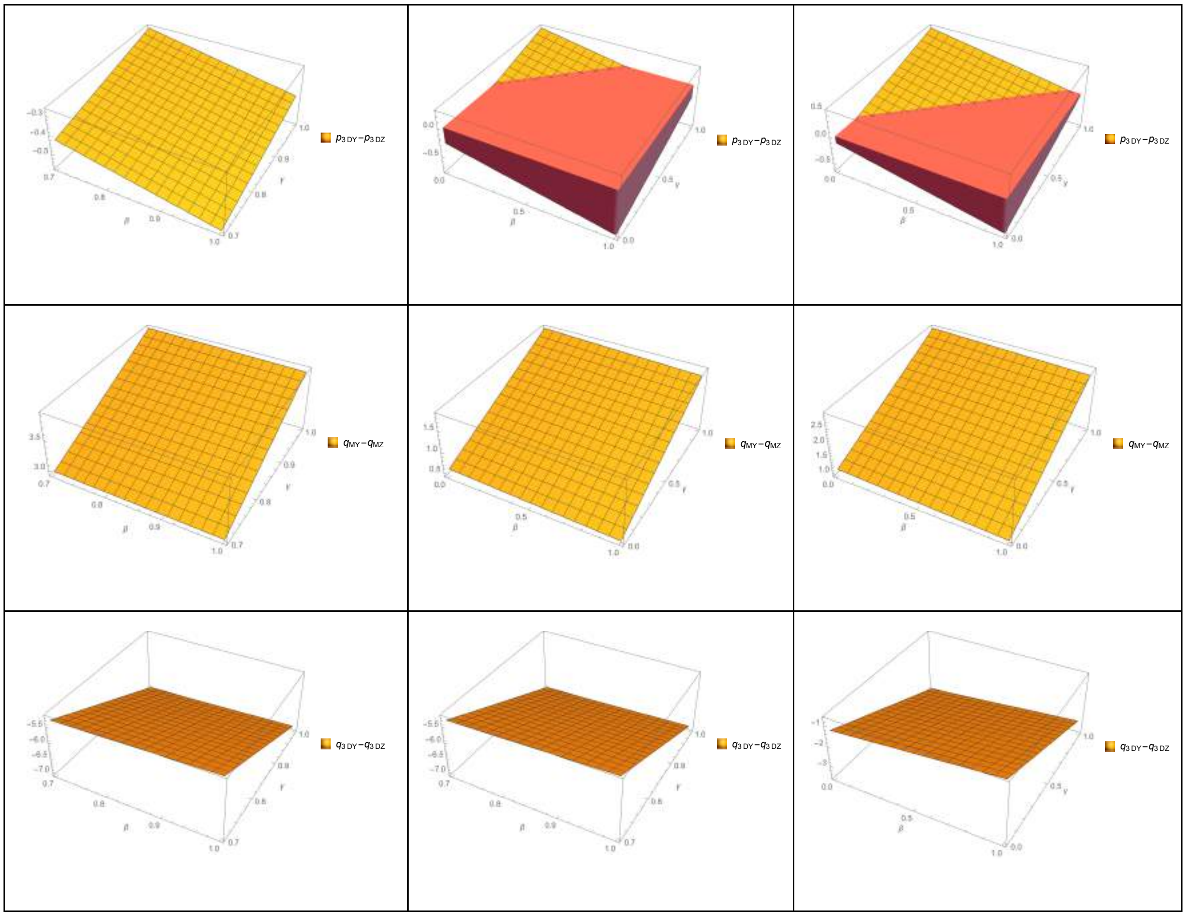


Figure 6-20 Comparisons of the Optimal Decisions – Model Y and Model Z

PROPOSITION *6-18.* *Compared to model Y, if the traditional manufacturer chooses to control the product design (Model Z), the system can achieve better profitability. Specifically, there is no difference in the TM product price, but the 3DP product price increases. If the 3DP product is costly, the TM product sales drop but the 3DP product sales rise. Otherwise, the TM product sales rise but the 3DP product sales decline.*

This proposition indicates that at the integrated supply chain level, it is good for the industry's development if the traditional manufacturer can help with the product design because the supply chain can benefit from i) the increased 3DP product price if the 3DP product is costly or ii) increased TM product sales if 3DP production is cheap. Interestingly, this finding is in conflict with the findings for the decentralized supply chain. Under the decentralized supply chain, individual entities can obtain more profits in Model Y, but Model Z contributes to the integrated supply chain's development. Therefore, Model Y is still a short-term strategy for the 3DP industry's development. But encouraging the traditional manufacturer to participate in the adoption of 3DP can benefit the supply chain's development and the 3DP industry's development in the long term (Despeisse et al., 2017; Wohlers Associates, 2018).

6.5 Chapter Summary

This chapter has explored the 3DP engagement model, considering product design quality, product customization level, and the cost of product design from two different sources (a third-party 3DP company or the traditional manufacturer). Three different logistics vendor's 3DP engagement models were analyzed. Firstly, the traditional manufacturer offers the TM and 3DP product and the logistics vendor only offers a goods delivery service (Model X). Secondly, the traditional manufacturer only offers the TM product and the service of goods delivery, the logistics vendor also produces a 3DP product designed by third-party 3DP design professionals (Model Y). Thirdly, the traditional manufacturer sells the TM product and also provides the product design for the logistics vendor's 3DP product; the logistics vendor can thus profit from the TM product delivery and the sales of the 3DP product (Model Z). We have also identified both the traditional manufacturer's and the logistics vendor's collaboration strategies and discussed the impacts of the involved critical system parameters on both players' optimal decisions under different 3DP engagement models to obtain several managerial insights.

Managerial Insights

We have showen that the traditional manufacturer's 3DP engagement strategy depends strongly on the 3DP product's cost, product design quality, and the product design authorization fee. Firstly, the traditional manufacturer cannot always gain more profits under the self-3DP production model. For example, if the product design quality is low and 3DP production is costly, the manufacturer can make more profit from the TM product sales if the traditional manufacturer leaves the whole 3DP product market to the logistics vendor. If the 3DP product authorization fee is low but the 3DP production cost is high, the traditional manufacturer can benefit from providing the 3DP product design.

As compared to Model X, the logistics vendor cannot gain more profits by choosing to produce the 3DP product with a third-party 3DP product design. This finding implicates that for those 3DP-enabled logistics vendors (for example, UPS), it is not profitable to participate in the market competition where the traditional manufacturer already has TM and 3DP production (like GE). Meanwhile, if the logistics vendor chooses to use the traditional manufacturer's product design and only operates the actual 3DP production, it is a strategical move only for products for which the design authorization fee is extremely high (e.g. limited-edition products, products with a requirement for a high level of design skills (Ernst & Young, 2016; Newcastle University, 2018) or if the 3DP authorization fee is low but 3DP production is costly (e.g. some specific aerospace equipment or F1 race car parts (3D systems, 2013; 3D Systems, 2018e). In addition, if the logistics vendor chooses to adopt 3DP production, using third-party 3DP product design professionals is in general better than cooperating with the traditional manufacturer. However, if the product design authorization fee is extremely high, the logistics vendor can use a high 3DP product price to increase his/her profits on the TM product delivery service.

Lastly, our findings in this chapter suggest that 3DP promises a revolution to supply chain development in the long-term, and we should encourage more traditional manufacturers to start transferring their products to the 3DP production line for the supply chain's long-term development. Although some research points out that 3DP is the future of some industries, our findings here indicate that compared to the hard-revolution, adding 3DP products into the manufacturing system is a more profitable soft-landing plan for both the traditional manufacturer and the integrated supply chain's development (Ernst & Young, 2016; S. Ford & Despeisse, 2016; Wohlers Associates, 2018). Furthermore, at the current stage, 3DP adoption by the logistics vendor is a strategy for the evolution of the supply chain, which means it cannot always contribute to the integrated supply chain's development, but it helps the traditional manufacturer to start thinking about 3DP adoption. Therefore, the 3DP industry is keen for additional help with market expansion, such as policy and regulatory support. The latter can help to reduce the fixed costs of 3DP production and encourage 3DP usage.

Theoretical Contributions

In particular, this model is probably the first to study the current logistics vendor's 3DP adoption strategies. In detail, this model reviews three different 3DP engagement approach by the logistics vendor first, and then quantitively analyzes the performance of those three different 3DP engagements. It contributes to the body of knowledge of managing the new technology disruption in the logistics industry. The results support the logistics vendor in deciding how to engage the 3DP technology into their traditional logistic delivery business.

In addition, this model also contributes to the literature on the 3DP intellectual research. Most of exisiting under the 3DP intellectual research are limited to discuss the importance of protecting intellectual in a legal perspective (Gao et al., 2015; Wilkof, 2016), Different from that, this chapter uses game theories to analytically analyze what are the impact of intellectual protection (through design fee and royalty fee) on the supply chain performance from the operational and management perspectives.

Chapter 7 Conclusions

This chapter summarizes the thesis, presents the research findings, and identifies areas for further study. The following section, Section 7.1, provides a summary of the research, Section 7.2 summarizes the research findings, and Section 7.3 presents the limitations of this research and finally also suggests areas for future study.

7.1 Research Summary

With the rapid growth of the disruptive 3DP technology, it continues to offer tremendous untapped potential for the improvement of manufacturing technology, especially about product customization. Therefore, it is important and timely to explore the question: 'What is the impact of 3DP adoption on the supply chain?' The prime motivation of this research is the need to deeply understand the current 3DP adoption situation, to find insights and analysis tools that will assist in maximizing the potential of this 3DP market. What is immediately derived from the prime motivation is the secondary motivations relating to the factors that influence 3DP adoption by the logistics vendor and the traditional manufacturer, including cost, price, market demand, and the level of customization of the 3DP products.

This PhD thesis has focused on investigating this question and has developed three models to assess the impact of 3DP adoption. The respective models have 1) explored the possibility of the logistics vendor's 3DP adoption; 2) sought to help the manufacturer to evaluate different manufacturing strategies to improve product customization; and 3) investigated and compared the logistics vendor's different 3DP adoption strategies and, in turn, produced some insights into the future development of manufacturing strategy and 3DP adoption. More specifically, we have studied various new technology adoption issues in supply chain management connected to the impact of the new 3DP technology. As a result, we have proposed three different game theoretical models to determine (i) if the logistics vendor starts to provide a 3DP service, how the competition and collaboration between the logistics vendor and traditional manufacturer may change the interactions among supply chain systems; (ii) what the most effective 3DP adoption strategies are for the traditional manufacturer, and (iii) what the implications are for the logistics vendors in terms of 3DP adoption efficiency. We have diagnosed the problems of pricing, production cost, individual supply chain member's profitability and the overall supply chain profitability, especially when the consumers exhibit different purchasing behaviour with regard to different product customization.

7.2 Research Findings and Discussion

The research findings from this PhD thesis are considered to be of interest to practitioners contemplating 3DP adoption and to 3DP companies wishing to promote 3DP adoption. This research raises awareness of the possible 3DP adoption strategies and the related impact on the supply chain through three different studies.

Our first study in Chapter 4 has considered the impact of the logistics vendor's 3DP adoption on the supply chain. We have investigated the competition and/or collaboration relationship between the traditional manufacturer and the logistics vendor before and after the logistics vendor starts to offer high customization 3DP products in a single supply chain (one traditional manufacturer, one logistics vendor and one consumer). Consumers' evaluation of the TM and 3DP product can mainly be influenced by two key factors: the product price and the product customization level. This is supported with the findings of Schröder et al. (2015) and Dong et al. (2017) indicating that product price and the product customization level are two key success factors on 3DP adoption. Nowadays, product customization is a robust cognitive bias that influences consumers' shopping behaviour and consumers evaluate production customization as increasingly important (Attaran, 2017; Macchion et al., 2017).

We have considered the consumers to have uncertainty and heterogeneous preferences about product customization level, but the customization level of the 3DP product was greater than the TM product. Followed the literature on product competition, we have introduced the product customization level as a factor that affects consumers' product choice to analyze the product competition strategy and the logistics vendor's 3DP adoption decisions. We have found that the logistics vendor can be better off if s/he starts to provide a 3DP service in addition to the traditional TM product delivery service (Wohlers Associates, 2018). While the logistics vendor's 3DP adoption might aggravate the competition between the 3DP and the TM product, there exists a scenario in which the logistics vendor's 3DP adoption strategy might mitigate product competition, benefiting both the traditional manufacturer and the logistics vendor and even improving the overall supply chain performance. This finding is somewhat consistent with the findings of Song & Zhang (2018), indicating that 3DP could improve the overall supply chain system performance as it has no requirements on product delivery.

Our second study in Chapter 5 has explored the traditional manufacturer's 3DP adoption strategy. We have considered the traditional manufacturer's production strategy in the face of the logistics vendor's 3DP product competition. In a supply chain consisting of a traditional manufacturer and a logistics vendor, the traditional manufacturer could use either traditional flexible manufacturing technology or the new 3DP technology to produce vertically differentiated products: low customization TM products and high customization traditional flexibly manufactured products or the 3DP product. If the manufacturer now traditionally sells the TM product through the logistics vendor's delivery service, then to cope with the logistics vendor's high customization 3DP product, s/he might establish a traditional flexible manufactured product or a 3DP product. In a recent study conducted by Dong et al. (2017), they have found that using the multi-product technologies (dedicated technology, flexible technology and 3DP technology) might reduce the product variety and only 3DP printing can always enhance the product variety. However, our model has indicated that if the traditional manufacturer sells high customization products through traditional flexible manufacturing technology, after the logistics vendor adopts the 3DP technology, (i) multi-product manufacturing does not always bring more profits to the logistics vendor ; (ii) product differentiation can help the traditional manufacturer achieve better financial performance; (iii) the integrated supply chain can achieve better performance in most cases. But, if the production volume is low and the TF product costs are located within a certain low range, then the integrated supply chain can achieve better performance than traditional manufacturing which fully uses TF manufacturing technology.

Moreover, if the traditional manufacturer decides to add a traditionally manufactured product, the supply chain profits from it. This finding is consistent with the research results in (Holmström et al., 2010; Wohlers Associates, 2018). By using case studies on the 3DP adoption, both of the papers have suggested that the current supply chain could be benefited by operating both the advanced 3DP and the traditional manufacturing technology.

If the traditional manufacturer decides to replace traditional manufacturing production with traditional flexible manufacturing production, the supply chain can only gain more profits if product production is cheap overall and the cost of the traditionally manufactured product is low. Besides, we have demonstrated that if traditional manufacturing starts to adopt 3DP technology, (i) the traditional manufacturer is always better off using traditional manufacturing, traditional flexible manufacturing and 3DP manufacturing together. This finding is different from the research results in (Dong et al., 2017)'s study, which showed that adding the traditional flexible technology in addition to other technologies may reduce product variety chosen by the firm and only 3DP technology can improve the product variety. (ii) The logistics vendor can also gain more profits when the traditional manufacturer sells

TM, TF and 3DP products if the TM product cost is high but the TM product customization level is low, or the TM product cost is low, but the TM product customization level is high. Otherwise, the logistics vendor can gain more profits only if the traditional manufacturer fully moves to 3DP manufacturing. (iii) If the 3DP production is extremely cheap (e.g. nut) or expensive (e.g. aerospace plane) overall, then adding 3DP technology but no flexible manufacturing technology contributes to the overall supply chain performance; otherwise, operating all three different manufacturing technologies is the best strategy for the integrated supply chain.

In summary, firstly, under the Bertrand supply chain with the medium setting, if the TM product costs are high, it is profitable to the traditional manufacturer to let the logistics vendor operate the 3DP product business. Secondly, with the high setting, if the TM product costs are low, the traditional manufacturer can also gain more profits on the low-price TM product. If the fixed cost of the TF product is extremely low or extremely high, the TF product has product customization advantages over the TM or the TF product and has price advantages over the 3DP product, whilst the traditional manufacturer can benefit from the aggressive product competition. Thirdly, if the logistics delivery cost is high, it is better to let the logistics vendor offer the 3DP product because the traditional manufacturer needs to pay the delivery service fee to the logistics vendor for all product sales. Fourthly, it is not always beneficial to the logistics vendor to handle 3DP products. Lastly, multi-product competition cannot contribute to supply chain performance improvement. In a supply chain where production is too low, the supply chain can show better performance if the logistics vendor offers the 3DP product, but if the level of 3DP product customization is distinguishingly high or the TF product customization level is high, the supply chain can achieve better performance if the traditional manufacturer offers the 3DP product himself/herself. In the high product production supply chain, the supply chain can benefit from the traditional manufacturer's three production line strategy if the TM product costs are high, the TF product costs are low, or the 3DP product costs are high.

Our third study in Chapter 5 considered the logistics vendor's 3DP engagement strategy. It has been suggested that the traditional manufacturer would be the best user of the 3DP technology and it is not easy for the logistics vendor to provide a professional product design service for the 3DP product, (D. R. Eyers & Potter, 2015; Holmström et al., 2010; Ryan et al., 2017). Thus, starting to offer the 3DP product and how to operate the 3DP product design service are important business strategy issues for the logistics vendor. We built up theoretical models for a supply chain consisting of a traditional manufacturer, a logistics vendor and a third-party 3DP product design professional to discuss three different 3DP engagement strategies for the logistics vendor: (i) the traditional manufacturer sells both the 3DP product and TM product into the market and the logistics vendor only provides the product delivery service; (ii) the logistics vendor provides the 3DP product but it is designed by a third-party 3DP design professional; and (iii) the logistics vendor provides the 3DP product but the product design is authorized by the traditional manufacturer. We derived the equilibrium product costs, the logistics vendor's 3DP engagement strategy and efforts, and the product price to provide managerial insights.

We obtained some interesting findings. Firstly, if the logistics vendor provides the 3DP product with a third-party 3DP professional's design, it is still beneficial to the traditional manufacturer under certain conditions (e.g. if the third-party 3DP product design professional's product design quality is high but the 3DP product cost is low, or the third-party 3DP product design professional's product design quality is low but the 3DP product cost is high); but it is always profitable to the logistics vendor to offer the 3DP product. This finding echos to the similar research results in (Pooley, 2013), the 3DP offers advantages in less delivery cost and the logistics vendor might be the best adopter of the 3DP manufacturing technology.

However, the integrated supply chain shows different performance depending on the third-party professional's product design quality, TM product customization level, and 3DP product cost. For instance, if the third-party professional's design quality is high, but the TM product customization level is low, it is not profitable to the integrated supply chain if the logistics vendor starts to offer a 3DP product. Conversely, if the third-party professional's design quality is low but the 3DP product cost is extremely high, the integrated supply chain can show better performance if the 3DP product is offered by the logistics vendor instead of the traditional manufacturer.

Secondly, the traditional manufacturer can choose to provide a 3DP product design service to the logistics vendor instead of offering a 3DP product if the 3DP product design authorization fee and the 3DP product cost meet certain conditions. When the 3DP product design authorization fee is high, or the product design authorization fee is low but the 3DP product is cheap, the traditional manufacturer can generate more profit by controlling the 3DP product design if and only if 3DP production is cheap. Conversely, when the 3DP product design authorization fee is low but 3DP production is costly, the traditional manufacturer can gain more profits by controlling and providing 3DP product design only. As for the logistics vendor, when the product design authorization fee is high, or the product design authorization fee is low but the 3DP product cost is extremely high or sufficiently low, the logistics vendor can gain more profits by offering the 3DP product with the traditional manufacturer's 3DP product design. Conversely, when the product design authorization fee is low and the 3DP production cost is at the middle level, the logistics vendor can obtain more benefits by providing 3DP with the third-party professional's 3DP product design. At the integrated supply chain level, it is not beneficial if the traditional manufacturer leaves the entire 3DP product market to the logistics vendor and the third-party 3DP professional, and it is always beneficial to the supply chain if the logistics vendor chooses to purchase the 3DP product design from the traditional manufacturer.

We summarize the managerial implications from key stakeholder perspectives as follows.

Insights for the logistics vendor

The managers of logistics vendors should be encouraged to engage in 3DP adoption because 3DP service can grant logistics vendors a new business opportunity to enhance their value in the supply chain. They should work with 3DP developers to accelerate the development and commercialization of 3DP technology. However, it is worth noting that a capable logistics vendor should not always use 3DP as the game-changer to reshape the supply chain structure, under certain conditions the logistics vendor can obtain a higher profit by not using 3DP. Therefore, it is critical for managers of logistics vendors to examine the market condition and the cost structure to strategically use 3DP as a game-changer or as a potential threat. Most importantly, this research also gives suggestions on the 3DP adoption of the different product under the different market structure which could be used as an important reference for the logistics vendor who is really considering 3DP as his/her new business.

Insights for the traditional manufacturer

When logistics vendors are going to adopt 3DP, traditional manufacturers certainly face new competition pressure. The conventional wisdom usually suggests that managers of traditional manufacturers should attempt to deter the adoption of 3DP by logistics vendors, which perhaps leads to new channel conflict. Our analysis demonstrates that it is not always necessary to do so. Actually, the adoption of 3DP by the logistics vendor can benefit the traditional manufacturer in the same supply chain if the traditional manufacturing product still has cost advantages. In other words, traditional manufacturers should embrace rather than boycott 3DP by logistics vendors under certain conditions. Meanwhile, there exist scenarios that beneficial to the traditional manufacturer to combine the 3DP manufacturing technology into his/her manufacturing system. Besides, this research also can be used for the improvement of his/her business and R&D strategy for the different 3DP product (e.g. how to extend the current 3DP adoption market, how to explore the new 3DP adoption market, which part of the 3DP technology should be improved).

Insights for the policymaker

Although 3DP technology has more than 50 years of development history, it is still in infancy (Ryan et al., 2017; Wohlers Associates, 2018). The research results also help the policymaker to have a further understanding of the impact of 3DP adoption on the supply chain. This research points out that for different 3DP technology/product, the impact on traditional manufacturing and the supply chain are different. Our research findings above highlights three important issues for the policymaker of 3DP industry: (1) It is still not always beneficial to adopt the 3DP manufacturing technology either by the traditional manufacturer or the logistics vendor, therefore, the policymaker should help the expansion of the 3DP technology adoption by government support; (2) Protecting the intellectual of 3DP by charge the design fee cannot help the long-term development of the 3DP industry; (3) Although the manufacturing industry should encourage the 3DP adoption for the long-term development, how to protect or upgrade the traditional manufacturing technology is also important. Thus, the policymaker should help the manufacturing industry to softly transfer and upgrade some out-of-date traditional manufacturing technology step by step and get the balance between the new disruptive 3DP manufacturing technology and the traditional manufacturing or the flexible manufacturing technology to improve the supply chain sustainability.

7.3 Research Limitations and Future Research Directions

This work is by no means an exhaustive study of the research questions we addressed. There are several methods which could be used to extend and enrich our models and the analysis in this research. The PhD research work presented in this thesis is limited by several factors.

Firstly, it is obvious that not all of the related variables and their causal relationships were considered. The factors considered here which might influence the consumer's shopping behaviour were limited to the product cost and product customization. Some other key factors which might relate to the consumer's actual shopping behaviour were not included, such as different product delivery lead times (Song & Zhang, 2018; UPS, 2016) and the consumer's hassle cost for getting the TM product or the 3DP product (Chiang et al., 2003). To increase the generalizability of the research findings, this limitation might be mitigated by exploring new factors which will also influence the consumer's shopping decisions, such as by:

- adding more variables related to consumer shopping behaviour into the models developed in this research
- comparing and contrasting the results of the different variables in the research results
- using empirical testing for our analytical results

Secondly, different types of 3DP technology need different amounts of investment and the production costs are different, but for the generalizability of the research, we have not specified the 3DP technology in this thesis. Therefore, the research findings are limited by the diverse cost elements to different 3DP technologies/products. Over the years, a large body of research has case studied the implication of a specific 3DP technology (Bamford, Karjalainen, & Jenavs, 2012; Oettmeier & Hofmann, 2016; Wohlers Associates, 2018). Therefore, it might be easier to focus on one specific 3DP technology and extend the 3DP supply chain research by considering:

- developing a better profit model for the traditional manufacturer, the logistics vendor, and the integrated supply chain (by considering more cost elements)
- comparing and contrasting the results for the different 3DP technologies in the research results

Thirdly, the three models discussed were built on the logistics vendor's 3DP adoption. However, in practice, other supply chain members might be the 3DP provider as well – for example, the retailer or the distributor. Therefore, a richer model of contracts among supply chain members with the adoption of more general models of 3DP adoption could provide a more nuanced understanding of the strategic impact of the presence of 3DP adoption. A future research direction would be to study the other supply chain member's 3DP adoption strategy by:

- investigating the other supply chain member's 3DP adoption possibilities (e.g. retailer, channel distributer)
- comparing and contrasting the results of different supply chain member's 3DP adoption and identifying the best 3DP adoption strategy for different types of product

In the end, as 3DP has not been widely adopted, the relevant research data is lacking; as a quantitative analytical model, the results could be more robust and accurate if additional work was conducted to increase the generalisability of the study and extend the research to a wider area. In addition, the research results still need to be tested by actual future business cases, if at all possible.

Yet it is clear that 3DP technology is on an improvement trajectory that eventually will compete with traditional manufacturing and even replace it. As such we conclude that 3DP manufacturing will bring more research questions about how to adopt it in supply chain management research domain, such as the product scheduling issue, inventory and distribution management, product variety problems, etc. In the following section, we summarize the new ideas and ground the future research agenda for the 3DP supply chain research field.

Production Scheduling Issue

3DP technology has fewer requirements about the workforce and even the workplace (Pooley, 2013; Sculpteo, 2018). For example, by using 3DP technology, the assembly process would be eliminated from the supply chain processes. However, currently, 3DP still cannot fully replace traditional manufacturing technologies. As mentioned in Abstract, 3DP technology has advantages on economic-of-one while traditional manufacturing is good at economic-of-scale. Therefore, how to combine 3DP manufacturing technology with other traditional manufacturing technology would be one of the key research questions. In detail, when the manufacturer gets a consumer order with some product variants, s/he needs to plan the production schedule by selecting the right manufacturing methodology according to requirements on product variants, product cost, production time, and even the delivery lead time.

Inventory and Distribution Management

As discussed in the Literature Review chapter, 3DP technology is a tool to fulfil the consumer order with high customization requirements in product design and product delivery (Conner et al., 2014; Novshek & Thoman, 2006). Therefore, to improve the product customization level, the traditional manufacturer would consider adopting the 3DP technology into his/her current manufacturing system, However, the new 3DP technology has different requirements on the inventory and distribution. For example, some 3D printed product does not need inventory and distribution, while, for some large or complex product which only could be partially 3D printed, they still need inventory and distribution support. Thus, how to change the current inventory and distribution system for the new 3DP enabled supply chain would be another interesting research question in the research agenda.

Intellectual Property Problem

Section 2.1.4 highlights the importance of protecting the intellectual property for the 3DP product design (Esmond & Phero, 2014; Wilkof, 2016). What would be the best strategy to manage the 3DP product design in the supply chain is an urgent question need to be fully assessed. Although this research question has been assessed in Chapter 6, this research has not considered other IP management strategies, such as open-source. Therefore, it would be noteworthy to put this research question into the research agenda.

Appendix A: List of 3DP Supply Chain Studies

	Research Topic	Method	Key Findings	Source
1	Production Cost	Axiomatic	This paper proposed a new cost model for laser sintering based on the Hopkinson-Dickens model. It also points out that it is essential to evolve the current cost models by considering more new factors, and indirect cost play a critical role in the new modern cost model.	(Ruffo et al., 2006)
2	Production Cost	Axiomatic	Based on the Hopkinson-Dickens model, this paper proposed a new cost model which considered the simultaneous production of different parts through a case study.	(Ruffo & Hague, 2007)
3	Supply Chain Management: Sourcing	Interpritve	The status of bureaus in the factory and the sequential use of rapid prototyping costing are two key considerations for rapid manufacturing.	(Ruffo et al., 2007)
4	Supply Chain Management	Empiricial	This paper demonstrates the use of Rapid Manufacturing (RM) as the enabling technology for flexible manufacturing in a number of industrial sectors. The use of RM will have particular impact on supply chain management paradigms such as lean and agile and has particular strategic fit with mass customisation.	(Tuck et al., 2007)
5	Production Cost	Axiomatic	This study used a thermodynamic framework to characterize and analyze the material and energy resources used in 20 different manufacturing processes. The results confirmed that exergy analysis can be used to identify where resources are lost in these processes, which is the first step in proposing and/or redesigning new more efficient processes.	(Gutowski et al., 2009)

6	Intellectual Property	Interpretive	This paper investigates existing IP legislation and case law about 3DP with regard to copyright design protection, patents, trademarks, and passing off. The outcome of this paper reports that in the UK 3D printer owners use 3DP to produce items for personal use and not for marketing.	(Bradshaw et al., 2010)
7	Supply Chain Management	Interpretive	The rapid manufacturing can simultaneously improve service and reduce the inventory for the spare parts supply chain. The two most feasible adoption strategies are centralized development by the original equipment manufacturer or setting the rapid manufacturing close to the point of the market.	(Holmström et al., 2010)
8	Product Technology	Interpretive	This paper compares the characteristics and applications of 3DP with mass customization and other manufacturing technology. It concludes that 3DP brings changes in production time, costs, and materials.	(Berman, 2012)
9	Supply Chain Management	Interpretive	This paper outlines a literature review on the societal impact of additive manufacturing from a technical perspective, including customized healthcare products, the environmental impact on sustainability, and simplified supply chains.	(S. H. Huang et al., 2013)
10	Supply Chain Management	Interpretive	3DP has advantages in terms of production costs and logistics costs, and it also has the potential to reduce the time required for design and production. Also, it helps product design innovation.	(Petrick & Simpson, 2014)
11	Product Technology	Empirical	This paper uses a geometrical benchmarking model (GBM) to test and evaluate the geometrical accuracy of open source	(Sanchez et al., 2014)

			FDM (Fused Deposition Modelling) 3D printers.	
12	Production Cost	Axiomatic	3DP has the potential for cost reduction and to decouple energy and CO_2 emissions.	(Gebler et al., 2014)
13	Product Technology	Empirical	This research presents new practical applications for developing gradient alloys with low-coefficients of thermal expansion and multifunctional properties.	(Hofmann et al., 2014)
14	Supply Chain Management	Empirical	Using empirical research, this paper develops a multiple hybrid criteria decision-making framework for evaluating and enhancing appropriate 3DP providers' service performance. This study also uses Decision-Making Trial and Network Process based Evaluation Laboratory, as well as VIKOR (VIseKriterijumska Optimizacijia I Kompromisno Resenje).	(Liao et al., 2014)
15	Supply Chain Management	Empirical	This paper evaluates the impact of additive manufacturing in the aircraft spare parts industry by comparing three different structured supply chain: a conventional supply chain, a centralized AM supply chain and a distributed AM supply chain. The study finally concludes that AM has the potential to reduce the safety inventory level.	(Liu et al., 2014)
16	Supply Chain Management	Empirical	This paper develops an implementation framework as a guide for AM adoption from the perspective of AM technology, the supply chain, organization, operation and strategy.	(Mellor et al., 2014)
17	Supply Chain Management	Interpretive	In this paper, the authors analyze the potential of 3DP in practice, research and teaching with regard to supply chain management and identify impacts of 3DP on these areas.	(Waller & Fawcett, 2014)

18	Intellectual Property	Interpretive	This paper summarises the status of the additive manufacturing revolution and corresponding legal developments and then points out the necessity of protecting innovation.	(Esmond & Phero, 2014)
19	Product Technology	Interpretive	This paper uses mathematical analyzes to investigate the correlation between the energy consumption and geometry of parts manufactured by Binder-Jetting. It then proposes a process model to improve the design of part geometry with regard to energy consumption.	(Xu et al., 2015)
20	Business Model	Interpretive	This study points out that in a monopoly market structure, by using AM the barriers to market entry are fewer and AM also enables the ability to serve multiple markets at the same time. In addition, AM can help the manufacturer to reduce the price of products.	(Weller et al., 2015)
21	Industry Review	Interpretive	This report provides various 3DP industry insights, including in terms of technology development, adoption, the advantages of 3DP, and future challenges.	(Ernst & Young, 2016)
22	Supply Chain Management	Empirical	This paper compares direct digital manufacturing with traditional tool-based manufacturing and finds that that digital manufacturing has advantages for the unit production cost but it cannot have a better performance on several orders of magnitude. Therefore, it brings more challenges for operations management. In addition, this paper also summarizes these challenges for operations and supply chain management.	(Holmström et al., 2016)
23	Business Model	Interpretive	3DP has the potential to change business model innovation by enabling	(Rayna & Striukova, 2016)

			adaptive business models and by adding rapid prototyping.	
24	Production Cost	Interpretive	By comparing the cost models of two different AM technologies, this paper shows that economies of scale are achievable with AM.	(Baumers et al., 2016)
25	Supply Chain Management	Interpretive	This study summarizes the state of AM development and studies about how AM can influence business model development and operations in consumer goods manufacturing.	(Bogers et al., 2016)
26	Supply Chain Management	Empirical	Based on the analysis of two case studies, this paper concludes that the whole supply chain and internal processes are affected by AM with regard to the production of industrial parts.	(Oettmeier & Hofmann, 2016)
27	Intellectual Property	Interpretive	This paper reviews the creation of patent rights and the enforcement of registered patents. It finds that patent considerations may be more crucial than copyrights and trademarks.	(Wilkof, 2016)
28	Supply Chain Management	Interpretive	This paper identifies the challenges, highlights, impacts, trends, and transformative potential of AM technology. It also summarizes the advantages and disadvantages of traditional manufacturing.	(Attaran, 2017)
29	Supply Chain Management: Manufacturing	Axiomatic	This research compares 3DP and traditional flexible technology with regard to assortment and capacity decisions. Its results suggest that 3DP can always contribute to product variety and that it has influence on company's product assortment and production strategy.	(Dong et al., 2017)
30	Supply Chain Management	Interpretive	This paper uses multidimensional scaling to investigate and study the	(Niaki & Nonino, 2017a)

			current researches about AM in management, business and economics domain and then proposes future research directions.	
31	Supply Chain Management	Interpretive	This paper explores the current state of affairs and main problems for Chinese manufacturing and the 3DP industry and analyzes the potential impacts of 3DP on Chinese manufacturing.	(Long et al., 2017)
32	Supply Chain Management	Interpretive	This study identifies and conceptualizes a frame for the global factory concept. And then it further investigates the potential impact of AM on the global production. At last, it concludes that AM will changes the industries and production activity with managerial and practical implications.	(Hannibal & Knight, 2018)
33	Supply Chain Management	Interpretive	This paper summarizes current 3DP technology adoption in oral drug production and by consulting with experts identifies that mass production might still be too ambitious for the oral drug industry.	(Hsiao et al., 2018)
34	Product Technology	Empirical	This paper selects a patient who once use a handmade prosthesis as research objective and then use 3DP technology to re-create the patient's uncompromised anatomy from CT scan data to explore the possibilities of medical imaging and 3D modelling for prosthesis production.	(Mohammed et al., 2018)
35	Supply Chain Management	Interpretive	This paper examines the impacts of 3DP adoption on global value chains and finds that in a complementarity scenario of where 3DP and traditional manufacturing are overlapping, 3DP can increase the total value add for the value chain. However, in a substitution	(Rehnberg & Ponte, 2018)

			scenario of 3DP partly or entirely replacing traditional manufacturing, 3DP reduces the overall value-add.	
36	Product Technology	Empirical	This paper reviews current treatments including the use of prosthetic ears or surgical methods such as auto-grafting rib cartilage and finds that although they are highly dependent on the surgeon's skill, the quality is quite poor. Meanwhile, 3DP technology can provide higher quality, lower costs and more customization options to patients and parents alike.	(Ross et al., 2018)
37	Supply Chain Management: Logistics	Axiomatic	This paper presents a model to analyze the impact of 3DP on spare parts logistics and finds that 3DP has advantages in terms of cost saving and also increases the variety of parts.	(Song & Zhang, 2018)
38	Production Cost	Axiomatic	This paper proposes a decision-making model based on the lifecycle costs of two components from two different companies and finds that component reliability is essential, whilst short production lead times can aid the reduction of logistical costs and help overcome design and production costs.	(Westerweel et al., 2018)
39	Industry Review	Interpretive	This report offers a general review of the current state of the 3DP industry and its future development.	(Wohlers Associates, 2018)

Appendix B: Proofs of Chapter 4

Proof of *PROPOSITION 4-1.* By using the backward induction, the first-order-conditions of $\prod_{3DN} M$ from Equation (4.1) is

$$\frac{\partial \prod_{3DN} M(p_M)}{\partial p_M} = \frac{\alpha + c_M + p_L - 2p_M}{\alpha}$$

Here, it is easy to verify that $\prod_{3DN} M$ strictly convex in p_M. Therefore, the solution to the first order conditions gives the maximizer.

$$\frac{\partial \prod_{3DN} M(p_M)}{\partial p_M} = \frac{\alpha + c_M + p_L - 2p_M}{\alpha} = 0$$

Then, the optimal price for the TM product is $p_M^* = \frac{1}{2}(\alpha + c_M + p_L)$

Accordingly, the logistics vendor's profit function is

$$\prod_{3DN} L(p_L) = (p_L - c_L)q_M = (p_L - c_L)\left(1 - \frac{p_M}{\alpha}\right)$$
$$= \frac{(c_L - p_L)(-\alpha + c_M + p_L)}{2\alpha}$$

Which is convex in p_L. So, the first-order-conditions of $\prod_{3DN} L$ gives the maximizer.

$$\frac{\partial \prod_{3DN} L(p_L)}{\partial p_L} = \frac{\alpha + c_L - c_M - 2p_L}{2\alpha} = 0$$

the optimal price of the logistics vendor's goods delivery service is $p_L^* = \frac{1}{2}(\alpha + c_L - c_M)$.

Because $p_L^* = \frac{1}{2}(\alpha + c_L - c_M)$, so $p_M^* = \frac{1}{4}(3\alpha + c_L + c_M)$.

Besides, the optimal demand of the TM product is $q_M^* = \frac{\alpha - c_L - c_M}{4\alpha}$ and the maximum profits for the manufacturer and the logistics vendor are as follows

$$\prod_{3DN}^* M(p_M) = \frac{(-\alpha + c_L + c_M)^2}{16\alpha} \quad (4.19)$$

$$\prod_{3DN}^* L(p_L) = \frac{(-\alpha + c_L + c_M)^2}{8\alpha} \quad (4.20)$$

Proof of *PROPOSITION* 4-2. $\prod_{3DN} TMS$ is concave in p_M, so the first-order-conditions of $\prod_{3DN} TMS$ in Equation (4.3) gives the maximum value.

$$\frac{\partial \prod_{3DN} TMS(p_M)}{\partial p_M} = \frac{\alpha + c_L + c_M - 2p_M}{\alpha} = 0$$

Therefore, when $p_M^* = \frac{1}{2}(\alpha + c_L + c_M)$ and $q_M^* = \frac{\alpha - c_L - c_M}{2\alpha}$, the supply chain system achieves the maximum profit as

$$\prod\nolimits_{3DN}^{*} TMS = \frac{(-\alpha + c_L + c_M)^2}{4\alpha} \tag{4.21}$$

where $\alpha - c_L - c_M > 0$.

Proof of *PROPOSITION* 4-3. According to Equation (4.4) and Equation (4.5), the first-order-conditions and the second-order-conditions of $\prod_{3D} M(p_M)$ and $\prod_{3D} L(p_{3D}, p_L)$ in Equation (4.6) and Equation (4.7),

$$\begin{cases} \dfrac{\partial \prod_{3D} M(p_M)}{\partial p_M} = \dfrac{c_M + \alpha p_{3D} + p_L - 2p_M}{\alpha - \alpha^2} \\ \dfrac{\partial \prod_{3D} L(p_{3D}, p_L)}{\partial p_{3D}} = \dfrac{1 - \alpha + c_{3D} - c_L - 2p_{3D} + p_L + p_M}{1 - \alpha} \end{cases}$$

$$\begin{cases} \dfrac{\partial \prod_{3D}^2 M(p_M)}{\partial p_M^2} = \dfrac{2}{(-1 + \alpha)\alpha} < 0 \\ \dfrac{\partial \prod_{3D}^2 L(p_{3D}, p_L)}{\partial p_{3D}^2} = \dfrac{2}{-1 + \alpha} < 0 \end{cases}$$

So, the solution to the first-order-conditions gives the unique maximizer.

$$\begin{cases} \dfrac{\partial \prod_{3D} M(p_M)}{\partial p_M} = \dfrac{c_M + \alpha p_{3D} + p_L - 2p_M}{\alpha - \alpha^2} = 0 \\ \dfrac{\partial \prod_{3D} L(p_{3D}, p_L)}{\partial p_{3D}} = \dfrac{1 - \alpha + c_{3D} - c_L - 2p_{3D} + p_L + p_M}{1 - \alpha} = 0 \end{cases}$$

$$\begin{cases} p_M^* = \dfrac{(-1 + \alpha)\alpha - \alpha c_{3D} + \alpha c_L - 2c_M - (2 + \alpha)p_L}{-4 + \alpha} \\ p_{3D}^* = \dfrac{2 - 2\alpha + 2c_{3D} - 2c_L + c_M + 3p_L}{4 - \alpha} \end{cases}$$

Then, the logistics vendor's profit function (4.7) can be updated as

$$
\begin{aligned}
&\prod\nolimits_{3D} L(p_{3D}, p_L) \\
&= \frac{(1-\alpha)(8+\alpha)p_L^2}{(-4+\alpha)^2(-1+\alpha)\alpha} \\
&+ \frac{((1-\alpha)\alpha^2 c_{3D} - 2(1-\alpha)(4+\alpha)c_L + (-1+\alpha)(\alpha(8+\alpha) - 8c_M))p_L}{(-4+\alpha)^2(-1+\alpha)\alpha} \\
&+ \frac{1}{(-4+\alpha)^2(-1+\alpha)\alpha}(8(1-\alpha)\alpha c_{3D} - 4(1-\alpha)\alpha^2 c_{3D} \\
&- (-2+\alpha)^2\alpha c_{3D}^2 + (1-\alpha)\alpha(4+\alpha)c_L + \alpha(4+(-3+\alpha)\alpha)c_{3D}c_L \\
&- \alpha^2 c_L^2 - 2(-2+\alpha)\alpha c_{3D}c_M + (-8+6\alpha)c_L c_M - \alpha(2-2\alpha+c_M)^2)
\end{aligned} \tag{4.22}
$$

which is convex in p_L, so the first-order-conditions gives the maximum profit.

$$
\frac{\partial \prod_{3D} L(p_{3D}, p_L)}{\partial p_L} = \frac{-\alpha^2 c_{3D} + 2(4+\alpha)c_L - 8c_M + (8+\alpha)(\alpha - 2p_L)}{(-4+\alpha)^2\alpha} = 0
$$

$$
p_L^* = \frac{\alpha(8+\alpha) - \alpha^2 c_{3D} + 2(4+\alpha)c_L - 8c_M}{2(8+\alpha)}
$$

The final optimal decisions are

$$
p_L^* = \frac{\alpha(8+\alpha) - \alpha^2 c_{3D} + 2(4+\alpha)c_L - 8c_M}{2(8+\alpha)} \tag{4.23}
$$

$$
p_M^* = \frac{\alpha(8+\alpha) + \alpha(4+\alpha)c_{3D} + 4c_L + 4c_M}{2(8+\alpha)} \tag{4.24}
$$

$$
p_{3D}^* = \frac{8+\alpha+(8+3\alpha)c_{3D} - 2c_L - 2c_M}{2(8+\alpha)} \tag{4.25}
$$

$$
q_M^* = -\frac{(2+\alpha)(\alpha c_{3D} - c_L - c_M)}{(-1+\alpha)\alpha(8+\alpha)} \tag{4.26}
$$

$$
q_{3D}^* = \frac{-8+7\alpha+\alpha^2 - (-8+\alpha+\alpha^2)c_{3D} - 6c_L - 6c_M}{2(-1+\alpha)(8+\alpha)} \tag{4.27}
$$

The maximized profits are

$$
\prod\nolimits_{3DB}^{*} M(p_M) = -\frac{(2+\alpha)^2(-\alpha c_{3D} + c_L + c_M)^2}{(-1+\alpha)\alpha(8+\alpha)^2} \tag{4.28}
$$

$$\prod\nolimits_{3DB}^{*} L\,(p_{3D}, p_L)$$

$$= \frac{1}{4(\alpha-1)\alpha(8+\alpha)}((-1+\alpha)\alpha(8+\alpha) + \alpha(-8+\alpha(3+\alpha))c_{3D}^2 - 2\alpha c_{3D}(-8+7\alpha+\alpha^2-4c_L-4c_M) - 4(c_L+c_M)^2) \tag{4.29}$$

where $\alpha c_{3D} - c_M - c_L > 0$ ($c_{3D} > \frac{c_L+c_M}{\alpha}$) and $0 < c_L + c_M < \alpha < 1$.

The first-order-conditions and the second-order-conditions of $\prod_{3DB} SC(p_M, p_{3D}, p_L)$ in Equation (4.8) are

$$\begin{cases} \dfrac{\partial \prod_{3DB} SC(p_M, p_{3D})}{\partial p_M} = -\dfrac{-\alpha c_{3D} + c_L + c_M + 2\alpha p_{3D} - 2p_M}{(-1+\alpha)\alpha} \\ \dfrac{\partial \prod_{3DB} SC(p_M, p_{3D})}{\partial p_{3D}} = \dfrac{-1+\alpha - c_{3D} + c_L + c_M + 2p_{3D} - 2p_M}{-1+\alpha} \end{cases}$$

$$\begin{cases} \dfrac{\partial \prod_{3DB}^2 SC(p_M, p_{3D})}{\partial p_M^2} = \dfrac{2}{(-1+\alpha)\alpha} < 0 \\ \dfrac{\partial \prod_{3DB}^2 SC(p_M, p_{3D})}{\partial p_{3D}^2} = \dfrac{2}{-1+\alpha} < 0 \\ \dfrac{\partial \prod_{3DB}^2 SC(p_M, p_{3D})}{\partial p_M \partial p_{3D}} = -\dfrac{2}{-1+\alpha} > 0 \\ \dfrac{\partial \prod_{3DB}^2 SC(p_M, p_{3D})}{\partial p_{3D} \partial p_M} = -\dfrac{2}{-1+\alpha} > 0 \end{cases}$$

So, the determinant of the Hessian Matrix can be written as

$$H = \begin{vmatrix} \dfrac{2}{(-1+\alpha)\alpha} & -\dfrac{2}{-1+\alpha} \\ -\dfrac{2}{-1+\alpha} & \dfrac{2}{-1+\alpha} \end{vmatrix} = \frac{2}{(-1+\alpha)\alpha} \times \left(\frac{2}{-1+\alpha}\right) - \left(-\frac{2}{-1+\alpha}\right)^2 = \frac{4}{(1-\alpha)\alpha} > 0$$

Therefore, this Hessian Matrix is a negative-definite matrix, the solution to the first-order-conditions gives the unique maximizer of $\prod_{3DB} SC(p_M, p_{3D})$.

$$\begin{cases} \dfrac{\partial \prod_{3DB} SC(p_M, p_{3D})}{\partial p_M} = -\dfrac{-\alpha c_{3D} + c_L + c_M + 2\alpha p_{3D} - 2p_M}{(-1+\alpha)\alpha} = 0 \\ \dfrac{\partial \prod_{3DB} SC(p_M, p_{3D})}{\partial p_{3D}} = \dfrac{-1+\alpha - c_{3D} + c_L + c_M + 2p_{3D} - 2p_M}{-1+\alpha} = 0 \end{cases}$$

$$p_M^* = \frac{1}{2}(\alpha + c_L + c_M) \tag{4.30}$$

$$p_{3D}^* = \frac{1}{2}(1 + c_{3D}) \tag{4.31}$$

So,

$$q_M^* = \frac{-\alpha c_{3D} + c_L + c_M}{2(-1+\alpha)\alpha} \tag{4.32}$$

$$q_{3D}^* = \frac{1 - \alpha - c_{3D} + c_L + c_M}{2 - 2\alpha} \tag{4.33}$$

$$\prod\nolimits_{3DB}^{*} SC(p_M, p_{3D}) = -\frac{-(-1+\alpha)\alpha + \alpha c_{3D}^2 + (c_L + c_M)^2 - 2\alpha c_{3D}(1 - \alpha + c_L + c_M)}{4(-1+\alpha)\alpha} \tag{4.34}$$

Proof of *PROPOSITION* 4-4. Use the same methodology as in Bertrand, this model uses the backward induction to find out the Nash equilibrium of $\prod_{3D} L(p_{3D}, p_L)$ and $\prod_{3D} M(p_M)$.

To do so, first, it is easily to find out that $\prod_{3D} L(p_{3D}, p_L)$ is convex in p_{3D}. So, the first-order-conditions of $\prod_{3D} L(p_{3D}, p_L)$ in Equation (4.7) gives the maximizer,

$$\frac{\partial \prod_{3D} L(p_{3D}, p_L)}{\partial p_{3D}} = \frac{1 - \alpha + c_{3D} - c_L - 2p_{3D} + p_L + p_M}{1 - \alpha} = 0$$

$$p_{3D}^* = \frac{1}{2}(1 - \alpha + c_{3D} - c_L + p_L + p_M)$$

Then, the $\prod_{3D} M(p_M)$ can be updated as

$$\prod\nolimits_{3D} M(p_M) = \frac{(c_M + p_L - p_M)(\alpha(1 - \alpha + c_{3D} - c_L + p_L) + (-2+\alpha)p_M)}{2(-1+\alpha)\alpha}$$

which is also convex in p_M, so the first-order-condition of $\prod_{3D} M(p_M)$ archives the maximized value.

$$\frac{\partial \prod_{3D} M(p_M)}{\partial p_M} = \frac{(c_M + p_L - p_M)(\alpha(1 - \alpha + c_{3D} - c_L + p_L) + (-2+\alpha)p_M)}{2(-1+\alpha)\alpha} = 0$$

$$p_{\mathrm{M}}^* = \frac{(-1+\alpha)\alpha - \alpha c_{3D} + \alpha c_L + (-2+\alpha)c_M - 2p_L}{2(-2+\alpha)}$$

p_{3D}^* updates as

$$p_{3D}^{*} = \frac{-4 + 5\alpha - \alpha^2 + (-4 + \alpha)c_{3D} - (-4 + \alpha)c_L - 2c_M + \alpha c_M + 2(-3 + \alpha)p_L}{4(-2 + \alpha)}$$

The $\prod_{3D} L(p_{3D}, p_L)$ can be rewritten as

$$\begin{aligned}
&\prod\nolimits_{3D} L(p_{3D}, p_L) \\
&\quad = -\frac{1}{16(-2 + \alpha)^2(-1 + \alpha)\alpha}((4 - 3\alpha)^2\alpha c_{3D}^2 + \alpha^3 c_L^2 \\
&\quad + \alpha(4 - 5\alpha + \alpha^2 - (-2 + \alpha)c_M)^2 + 2c_L(-(-2 + \alpha)(8 + (-8 + \alpha)\alpha)c_M \\
&\quad + (-1 + \alpha)(8 + (-4 + \alpha)\alpha)(\alpha - 2p_L)) - 4(-1 + \alpha)(\alpha(8 + (-5 + \alpha)\alpha) \\
&\quad - (-4 + \alpha)(-2 + \alpha)c_M)p_L + 4(-1 + \alpha)(8 + (-5 + \alpha)\alpha)p_L^2 \\
&\quad + 2\alpha c_{3D}((-8 + (12 - 5\alpha)\alpha)c_L + (-4 + 3\alpha)(4 - 5\alpha + \alpha^2 - (-2 \\
&\quad + \alpha)c_M) + 2(-1 + \alpha)\alpha p_L))
\end{aligned}$$

and it is convex in p_L, so the first-order-conditions gives the maximizer

$$\begin{aligned}
&\frac{\partial \prod_{3D} L(p_{3D}, p_L)}{\partial p_L} \\
&\quad = -\frac{1}{4(-2 + \alpha)^2\alpha}(-\alpha(8 + (-5 + \alpha)\alpha) + \alpha^2 c_{3D} - (8 + (-4 + \alpha)\alpha)c_L \\
&\quad + (-4 + \alpha)(-2 + \alpha)c_M + 16p_L + 2(-5 + \alpha)\alpha p_L) = 0
\end{aligned}$$

$$p_L^{*} = \frac{\alpha(8 + (-5 + \alpha)\alpha) - \alpha^2 c_{3D} + (8 + (-4 + \alpha)\alpha)c_L - (-4 + \alpha)(-2 + \alpha)c_M}{2(8 + (-5 + \alpha)\alpha)}$$

Therefore, the final optimal decisions are

$$p_L^{*} = \frac{\alpha(8 + (-5 + \alpha)\alpha) - \alpha^2 c_{3D} + (8 + (-4 + \alpha)\alpha)c_L - (-4 + \alpha)(-2 + \alpha)c_M}{2(8 + (-5 + \alpha)\alpha)} \tag{4.35}$$

$$p_M^{*} = \frac{\alpha(8 + (-5 + \alpha)\alpha) - (-4 + \alpha)\alpha c_{3D} + (-2 + \alpha)^2 c_L + (-2 + \alpha)^2 c_M}{2(8 + (-5 + \alpha)\alpha)} \tag{4.36}$$

$$p_{3D}^{*} = \frac{8 + (-5 + \alpha)\alpha + (8 - 3\alpha)c_{3D} + (-2 + \alpha)c_L + (-2 + \alpha)c_M}{2(8 + (-5 + \alpha)\alpha)} \tag{4.37}$$

$$q_M^{*} = \frac{(-2 + \alpha)(\alpha c_{3D} - c_L - c_M)}{(-1 + \alpha)\alpha(8 + (-5 + \alpha)\alpha)} \tag{4.38}$$

$$q_{3D}^{*} = \frac{1}{2(-1+\alpha)(8+(-5+\alpha)\alpha)}((-1+\alpha)(8+(-5+\alpha)\alpha)+(8+(-7+\alpha)\alpha)c_{3D}-6c_L-6c_M-(-5+\alpha)\alpha(c_L+c_M)) \tag{4.39}$$

The maximized profits are

$$\prod_{3DS}^{*} M(p_M) = \frac{2(-2+\alpha)(-\alpha c_{3D}+c_L+c_M)^2}{(-1+\alpha)\alpha(8+(-5+\alpha)\alpha)^2} \tag{4.40}$$

$$\prod_{3DS}^{*} L(p_{3D}, p_L) = \frac{1}{4(-1+\alpha)\alpha(8+(-5+\alpha)\alpha)}((-1+\alpha)\alpha(8+(-5+\alpha)\alpha)+\alpha(-8+(9-2\alpha)\alpha)c_{3D}^2-(-2+\alpha)^2(c_L+c_M)^2+2\alpha c_{3D}(-(-1+\alpha)(8+(-5+\alpha)\alpha)+(-2+\alpha)^2c_L+(-2+\alpha)^2c_M)) \tag{4.41}$$

where $\alpha c_{3D} - c_M - c_L > 0$ ($c_{3D} > \frac{c_L+c_M}{\alpha}$) and $0 < c_L + c_M < \alpha < 1$.

It is easily to find out that $\prod_{3DS} SC(p_M, p_{3D})$ is convex in p_{3D}. So, the first-order-conditions of $\prod_{3DS} SC(p_M, p_{3D})$ in (3.8) gives the maximizer,

$$\frac{\partial \prod_{3DS} SC(p_M, p_{3D})}{\partial p_{3D}} = \frac{-1+\alpha-c_{3D}+c_L+c_M+2p_{3D}-2p_M}{-1+\alpha} = 0$$

$$p_{3D}^{*} = \frac{1}{2}(1-\alpha+c_{3D}-c_L-c_M)+p_M$$

Then, the $\prod_{3DS} SC(p_M, p_{3D}, p_L)$ can be rewritten as

$$\prod_{3DS} SC(p_M, p_{3D}) = -\frac{1}{4(-1+\alpha)\alpha}(\alpha c_{3D}^2-2\alpha c_{3D}(1-\alpha+c_L+c_M)+\alpha(-1+\alpha+c_L+c_M)^2-4(-1+\alpha)(\alpha+c_L+c_M)p_M+4(-1+\alpha)p_M^2)$$

And it is convex in p_M, so the first-order-conditions gives the maximized value.

$$\frac{\partial \prod_{3DS} SC(p_M, p_{3D})}{\partial p_M} = \frac{-1+\alpha-c_{3D}+c_L+c_M+2p_{3D}-2p_M}{-1+\alpha} = 0$$

$$p_M^{*} = \frac{1}{2}(\alpha+c_L+c_M)$$

There, the optimal decisions are

$$p_M^* = \frac{1}{2}(\alpha + c_L + c_M) \tag{4.42}$$

$$p_{3D}^* = \frac{1}{2}(1 + c_{3D}) \tag{4.43}$$

So,

$$q_M^* = \frac{-\alpha c_{3D} + c_L + c_M}{2(-1+\alpha)\alpha} \tag{4.44}$$

$$q_{3D}^* = \frac{1 - \alpha - c_{3D} + c_L + c_M}{2 - 2\alpha} \tag{4.45}$$

$$\prod\nolimits_{3DS}^{*} SC(p_M, p_{3D}) = -\frac{-(-1+\alpha)\alpha + \alpha c_{3D}^2 + (c_L + c_M)^2 - 2\alpha c_{3D}(1 - \alpha + c_L + c_M)}{4(-1+\alpha)\alpha} \tag{4.46}$$

Proof of *PROPOSITION* 4-5. According to Table 4-2, it is easy to find out that for the Bertrand market,

$$\frac{\partial p_L^*}{\partial c_M} = -\frac{4}{8+\alpha} < 0 \qquad \frac{\partial p_L^*}{\partial c_L} = \frac{4+\alpha}{8+\alpha} > 0 \qquad \frac{\partial p_L^*}{\partial c_{3D}} = -\frac{\alpha^2}{2(8+\alpha)} < 0$$

$$\frac{\partial p_M^*}{\partial c_M} = \frac{2}{8+\alpha} > 0 \qquad \frac{\partial p_M^*}{\partial c_L} = \frac{2}{8+\alpha} > 0 \qquad \frac{\partial p_M^*}{\partial c_{3D}} = \frac{\alpha(4+\alpha)}{2(8+\alpha)} > 0$$

$$\frac{\partial p_{3D}^*}{\partial c_M} = -\frac{1}{8+\alpha} < 0 \qquad \frac{\partial p_{3D}^*}{\partial c_L} = -\frac{1}{8+\alpha} < 0 \qquad \frac{\partial p_{3D}^*}{\partial c_{3D}} = \frac{8+3\alpha}{2(8+\alpha)} > 0$$

For the equilibrium market demand,

$$\frac{\partial q_M^*}{\partial c_M} = \frac{2+\alpha}{\alpha(-8+7\alpha+\alpha^2)} < 0 \qquad \frac{\partial q_{3D}^*}{\partial c_M} = -\frac{3}{-8+7\alpha+\alpha^2} > 0$$

$$\frac{\partial q_M^*}{\partial c_L} = \frac{2+\alpha}{\alpha(-8+7\alpha+\alpha^2)} < 0 \qquad \frac{\partial q_{3D}^*}{\partial c_L} = -\frac{3}{-8+7\alpha+\alpha^2} > 0$$

$$\frac{\partial q_M^*}{\partial c_{3D}} = -\frac{2+\alpha}{-8+7\alpha+\alpha^2} > 0 \qquad \frac{\partial q_{3D}^*}{\partial c_{3D}} = -\frac{-8+\alpha+\alpha^2}{2(-1+\alpha)(8+\alpha)} < 0$$

For the traditional manufacturer leading Stackelberg market,

$$\frac{\partial p_L^*}{\partial c_M} = -\frac{(-4+\alpha)(-2+\alpha)}{2(8+(-5+\alpha)\alpha)} < 0 \quad \frac{\partial p_L^*}{\partial c_L} = \frac{8+(-4+\alpha)\alpha}{2(8+(-5+\alpha)\alpha)} > 0 \quad \frac{\partial p_L^*}{\partial c_{3D}} = -\frac{\alpha^2}{2(8+(-5+\alpha)\alpha)} < 0$$

$$\frac{\partial p_M^*}{\partial c_M} = \frac{(-2+\alpha)^2}{2(8+(-5+\alpha)\alpha)} > 0 \quad \frac{\partial p_M^*}{\partial c_L} = \frac{(-2+\alpha)^2}{2(8+(-5+\alpha)\alpha)} > 0 \quad \frac{\partial p_M^*}{\partial c_{3D}} = -\frac{(-4+\alpha)\alpha}{2(8+(-5+\alpha)\alpha)} > 0$$

$$\frac{\partial p_{3D}^*}{\partial c_M} = \frac{-2+\alpha}{2(8+(-5+\alpha)\alpha)} < 0 \quad \frac{\partial p_{3D}^*}{\partial c_L} = \frac{-2+\alpha}{2(8+(-5+\alpha)\alpha)} < 0 \quad \frac{\partial p_{3D}^*}{\partial c_{3D}} = \frac{8-3\alpha}{2(8+(-5+\alpha)\alpha)} > 0$$

For the equilibrium market demand,

$$\frac{\partial q_M^*}{\partial c_M} = -\frac{-2+\alpha}{(-1+\alpha)\alpha(8+(-5+\alpha)\alpha)} < 0 \quad \frac{\partial q_{3D}^*}{\partial c_M} = -\frac{6+(-5+\alpha)\alpha}{2(-1+\alpha)(8+(-5+\alpha)\alpha)} > 0$$

$$\frac{\partial q_M^*}{\partial c_L} = -\frac{-2+\alpha}{(-1+\alpha)\alpha(8+(-5+\alpha)\alpha)} < 0 \quad \frac{\partial q_{3D}^*}{\partial c_L} = -\frac{6+(-5+\alpha)\alpha}{2(-1+\alpha)(8+(-5+\alpha)\alpha)} > 0$$

$$\frac{\partial q_M^*}{\partial c_{3D}} = \frac{-2+\alpha}{(-1+\alpha)(8+(-5+\alpha)\alpha)} > 0 \quad \frac{\partial q_{3D}^*}{\partial c_{3D}} = \frac{8+(-7+\alpha)\alpha}{2(-1+\alpha)(8+(-5+\alpha)\alpha)} < 0$$

Proof of *PROPOSITION* 4-6. The optimal prices and market demand of the Bertrand-market and Stackelberg-market are the same. For the optimal prices,

$$\frac{\partial p_M^*}{\partial c_M} = \frac{1}{2} > 0 \quad \frac{\partial p_M^*}{\partial c_L} = \frac{1}{2} > 0 \quad \frac{\partial p_{3D}^*}{\partial c_{3D}} = \frac{1}{2} > 0$$

For the optimal market demand,

$$\frac{\partial q_M^*}{\partial c_M} = \frac{1}{2(-1+\alpha)\alpha} < 0 \quad \frac{\partial q_{3D}^*}{\partial c_M} = \frac{1}{2-2\alpha} > 0$$

$$\frac{\partial q_M^*}{\partial c_L} = \frac{1}{2(-1+\alpha)\alpha} < 0 \qquad \frac{\partial q_{3D}^*}{\partial c_L} = \frac{1}{2-2\alpha} > 0$$

$$\frac{\partial q_M^*}{\partial c_{3D}} = \frac{1}{2-2\alpha} > 0 \qquad \frac{\partial q_{3D}^*}{\partial c_{3D}} = \frac{1}{2(-1+\alpha)} < 0$$

Proof of *PROPOSITION* 4-7. From Equation (4.28), it is easy to find out that

(1) $\prod_{3DB}^* M(p_M)$ is concave in c_M, therefore, when

$$\frac{\partial \prod_{3DB}^* M(p_M)}{\partial c_M} = -\frac{2(2+\alpha)^2(-\alpha c_{3D} + c_L + c_M)}{(-1+\alpha)\alpha(8+\alpha)^2} = 0$$

$$c_M^* = \alpha c_{3D} - c_L$$

gives the minimum value. However, because $\alpha c_{3D} > c_L + c_M$, therefore, $\prod_{3DB}^* M(p_M)$ is decreasing in c_M;

(2) $\prod_{3DB}^* M(p_M)$ is concave in c_L, therefore, when

$$\frac{\partial \prod_{3DB}^* M(p_M)}{\partial c_L} = -\frac{2(2+\alpha)^2(-\alpha c_{3D} + c_L + c_M)}{(-1+\alpha)\alpha(8+\alpha)^2} = 0$$

$$c_L^* = \alpha c_{3D} - c_M$$

gives the minimum value. However, because $\alpha c_{3D} > c_L + c_M$, therefore, $\prod_{3DB}^* M(p_M)$ is decreasing in c_L;

(3) $\prod_{3DB}^* M(p_M)$ is concave in c_{3D}, therefore, when

$$\frac{\partial \prod_{3DB}^* M(p_M)}{\partial c_{3D}} = \frac{2(2+\alpha)^2(-\alpha c_{3D} + c_L + c_M)}{(-1+\alpha)(8+\alpha)^2} = 0$$

$$c_{3D}^* = \frac{c_L + c_M}{\alpha}$$

gives the minimum value. However, because $\alpha c_{3D} > c_L + c_M$, therefore, $\prod_{3DB}^* M(p_M)$ is increasing in c_{3D}.

According to Equation (4.29), we can have,

(1) $\prod_{3DB}^{*} L\,(p_{3D}, p_L)$ is concave in c_M, so, if

$$\frac{\partial \prod_{3DB}^{*} L\,(p_{3D}, p_L)}{\partial c_M} = \frac{2\alpha c_{3D} - 2(c_L + c_M)}{(-1+\alpha)\alpha(8+\alpha)} = 0$$

$$c_M^{*} = \alpha c_{3D} - c_L$$

gives the minimum value. However, because $\alpha c_{3D} > c_L + c_M$, therefore, $\prod_{3DB}^{*} M(p_M)$ is decreasing in c_M;

(2) $\prod_{3DB}^{*} L\,(p_{3D}, p_L)$ is concave in c_L, so, if

$$\frac{\partial \prod_{3DB}^{*} L\,(p_{3D}, p_L)}{\partial c_L} = \frac{2\alpha c_{3D} - 2(c_L + c_M)}{(-1+\alpha)\alpha(8+\alpha)} = 0$$

$$c_L^{*} = \alpha c_{3D} - c_M$$

gives the minimum value. However, because $\alpha c_{3D} > c_L + c_M$, therefore, $\prod_{3DB}^{*} M(p_M)$ is decreasing in c_L;

(3) $\prod_{3DB}^{*} L\,(p_{3D}, p_L)$ is concave in c_{3D}, so, if

$$\frac{\partial \prod_{3DB}^{*} L\,(p_{3D}, p_L)}{\partial c_{3D}} = \frac{-(-1+\alpha)(8+\alpha) + (-8+\alpha(3+\alpha))c_{3D} + 4c_L + 4c_M}{2(-1+\alpha)(8+\alpha)} = 0$$

$$c_{3D}^{*} = \frac{(-1+\alpha)(8+\alpha) - 4(c_L + c_M)}{-8+\alpha(3+\alpha)} > \frac{c_L + c_M}{\alpha}$$

gives the minimum value. However, because $\alpha c_{3D} > c_L + c_M$, therefore,

If $\frac{c_L+c_M}{\alpha} < c_{3D} < \frac{(-1+\alpha)(8+\alpha)-4(c_L+c_M)}{-8+\alpha(3+\alpha)}$, $\prod_{3DB}^{*} L\,(p_{3D}, p_L)$ decreases in c_{3D};

If $\frac{(-1+\alpha)(8+\alpha)-4(c_L+c_M)}{-8+\alpha(3+\alpha)} < c_{3D} < 1$, $\prod_{3DB}^{*} L\,(p_{3D}, p_L)$ increases in c_{3D}.

Use the similar approach, based on Equation (4.40), it is easy to derive that

(1) $\prod_{3DS}^{*} M(p_M)$ is concave in c_M, therefore, when

$$\frac{\partial \prod_{3DS}^{*} M(p_M)}{\partial c_M} = \frac{4(-2+\alpha)(-\alpha c_{3D} + c_L + c_M)}{(-1+\alpha)\alpha(8+(-5+\alpha)\alpha)^2} = 0$$

$$c_M^{*} = \alpha c_{3D} - c_L$$

gives the minimum value. However, because $\alpha c_{3D} > c_L + c_M$, therefore, $\prod_{3DS}^{*} M(p_M)$ is decreasing in c_M;

(2) $\prod_{3DS}^{*} M(p_M)$ is concave in c_L, therefore, when

$$\frac{\partial \prod_{3DS}^{*} M(p_M)}{\partial c_L} = \frac{4(-2+\alpha)(-\alpha c_{3D} + c_L + c_M)}{(-1+\alpha)\alpha(8+(-5+\alpha)\alpha)^2} = 0$$

$$c_L^{*} = \alpha c_{3D} - c_M$$

gives the minimum value. However, because $\alpha c_{3D} > c_L + c_M$, therefore, $\prod_{3DS}^{*} M(p_M)$ is decreasing in c_L;

(3) $\prod_{3DS}^{*} M(p_M)$ is concave in c_{3D}, therefore, when

$$\frac{\partial \prod_{3DS}^{*} M(p_M)}{\partial c_{3D}} = -\frac{4(-2+\alpha)(-\alpha c_{3D} + c_L + c_M)}{(-1+\alpha)(8+(-5+\alpha)\alpha)^2} = 0$$

$$c_{3D}^{*} = \frac{c_L + c_M}{\alpha}$$

gives the minimum value. However, because $\alpha c_{3D} > c_L + c_M$, therefore, $\prod_{3DS}^{*} M(p_M)$ is increasing in c_{3D}.

According to Equation (4.41), it is easily to find out that,

(1) $\prod_{3DS}^{*} L\,(p_{3D}, p_L)$ is concave in c_M, so, if

$$\frac{\partial \prod_{3DS}^{*} L\,(p_{3D}, p_L)}{\partial c_M} = \frac{(-2+\alpha)^2(\alpha c_{3D} - c_L - c_M)}{2(-1+\alpha)\alpha(8+(-5+\alpha)\alpha)} = 0$$

$$c_M^{*} = \alpha c_{3D} - c_L$$

gives the minimum value. However, because $\alpha c_{3D} > c_L + c_M$, therefore, $\prod_{3DS}^{*} M(p_M)$ is decreasing in c_M;

(2) $\prod_{3DS}^{*} L\,(p_{3D}, p_L)$ is concave in c_L, so, if

$$\frac{\partial \prod_{3DS}^{*} L\,(p_{3D}, p_L)}{\partial c_L} = \frac{(-2+\alpha)^2(\alpha c_{3D} - c_L - c_M)}{2(-1+\alpha)\alpha(8+(-5+\alpha)\alpha)} = 0$$

$$c_L^* = \alpha c_{3D} - c_M$$

gives the minimum value. However, because $\alpha c_{3D} > c_L + c_M$, therefore, $\prod_{3DS}^{*} M(p_M)$ is decreasing in c_L;

(3) $\prod_{3DS}^{*} L\,(p_{3D}, p_L)$ is concave in c_{3D}, so, if

$$\frac{\partial \prod_{3DS}^{*} L\,(p_{3D}, p_L)}{\partial c_{3D}}$$
$$= \frac{-(-1+\alpha)(8+(-5+\alpha)\alpha) + (-8+(9-2\alpha)\alpha)c_{3D} + (-2+\alpha)^2 c_L + (-2+\alpha)^2 c_M}{2(-1+\alpha)(8+(-5+\alpha)\alpha)}$$
$$= 0$$

$$c_{3D}^* = \frac{-(-1+\alpha)(8+(-5+\alpha)\alpha) + (-2+\alpha)^2(c_L + c_M)}{8+\alpha(-9+2\alpha)} > \frac{c_L + c_M}{\alpha}$$

gives the minimum value. However, because $\alpha c_{3D} > c_L + c_M$, therefore,

If $\frac{c_L + c_M}{\alpha} < c_{3D} < \frac{-(-1+\alpha)(8+(-5+\alpha)\alpha)+(-2+\alpha)^2(c_L+c_M)}{8+\alpha(-9+2\alpha)}$, $\prod_{3DS}^{*} L\,(p_{3D}, p_L)$ decreases in c_{3D};

If $\frac{-(-1+\alpha)(8+(-5+\alpha)\alpha)+(-2+\alpha)^2(c_L+c_M)}{8+\alpha(-9+2\alpha)} < c_{3D} < 1$, $\prod_{3DS}^{*} L\,(p_{3D}, p_L)$ increases in c_{3D}.

For the total supply chain maximized profits, Equation (4.34) is the same with Equation (4.46) and which are concave in c_M, c_L, and c_{3D}.

$$\frac{\partial \prod_{3DB}^{*} SC\,(p_{3D}, p_L)}{\partial c_M} = \frac{\partial \prod_{3DS}^{*} SC\,(p_{3D}, p_L)}{\partial c_M} = -\frac{-2\alpha c_{3D} + 2(c_L + c_M)}{4(-1+\alpha)\alpha} = 0$$

$$c_M^* = \alpha c_{3D} - c_L$$

and

$$\frac{\partial \prod_{3DB}^{*} SC\,(p_{3D}, p_L)}{\partial c_L} = \frac{\partial \prod_{3DS}^{*} SC\,(p_{3D}, p_L)}{\partial c_L} = -\frac{-2\alpha c_{3D} + 2(c_L + c_M)}{4(-1+\alpha)\alpha} = 0$$

$$c_M^* = \alpha c_{3D} - c_M$$

Because $\alpha c_{3D} > c_L + c_M$, so $\prod_{3DB}^{*} SC\,(p_{3D}, p_L)$ or $\prod_{3DS}^{*} SC\,(p_{3D}, p_L)$ decrases in c_M and c_L.

Then, set

$$\frac{\partial \prod_{3DB}^{*} SC\,(p_{3D}, p_L)}{\partial c_{3D}} = \frac{\partial \prod_{3DS}^{*} SC\,(p_{3D}, p_L)}{\partial c_{3D}} = -\frac{2\alpha c_{3D} - 2\alpha(1 - \alpha + c_L + c_M)}{4(-1+\alpha)\alpha} = 0$$

$$c_{3D}^* = 1 - \alpha + c_L + c_M > \frac{c_L + c_M}{\alpha}$$

therefore,

If $\frac{c_L+c_M}{\alpha} < c_{3D} < 1 - \alpha + c_L + c_M$, $\prod_{3DB}^{*} SC\,(p_{3D}, p_L)$ or $\prod_{3DS}^{*} SC\,(p_{3D}, p_L)$ decreases in c_{3D};

If $1 - \alpha + c_L + c_M < c_{3D} < 1$, $\prod_{3DB}^{*} SC\,(p_{3D}, p_L)$ or $\prod_{3DS}^{*} SC\,(p_{3D}, p_L)$increases in c_{3D}.

Proof of *PROPOSITION* 4-8.

$$\frac{\partial p_{3D}^*}{\partial c_{3D}} = \frac{1}{2} > 0 \qquad\qquad \frac{\partial q_{3D}^*}{\partial c_{3D}} = -\frac{1}{2} < 0$$

And for the maximized profits, it is convex in c_{3D}. Therefore, the first-order-condition

$$\frac{\partial \prod_{F3D}^{*} L(p_{3D})}{\partial c_{3D}} = \frac{\partial \prod_{F3D}^{*} SC(p_{3D})}{\partial c_{3D}} = \frac{1}{2}(-1 + c_{3D}) = 0$$

$$c_{3D}^* = 1$$

Because $0 < c_{3D} < 1$, therefore, the profit of the logistics vendor and supply chain decrease in c_{3D}.

Proof of *PROPOSITION* 4-11.

(1) For the logistics vendor's maximized profits, compare Equation (4.29) and (4.20),

$$\prod\nolimits_{3DB}^{*} L\,(p_{3D}, p_L) - \prod\nolimits_{3DN}^{*} L(p_L)$$

$$= -\frac{1}{8(-1+\alpha)(8+\alpha)}((-2+\alpha)(-1+\alpha)(8+\alpha) - 2(-8+\alpha(3+\alpha))c_{3D}^2 + 16c_L + 4c_{3D}((-1+\alpha)(8+\alpha) - 4c_L - 4c_M) + 16c_M - (7+\alpha)(2\alpha - c_L - c_M)(c_L + c_M))$$

It is concave in c_{3D}, therefore, when the first-order-condition

$$\frac{\partial(\prod_{3DB}^{*} L\,(p_{3D}, p_L) - \prod_{3DN}^{*} L(p_L))}{\partial c_{3D}} = \frac{-(-1+\alpha)(8+\alpha) + (-8+\alpha(3+\alpha))c_{3D} + 4c_L + 4c_M}{2(-1+\alpha)(8+\alpha)} = 0$$

$$c_{3D} = \frac{(-1+\alpha)(8+\alpha) - 4c_L - 4c_M}{-8+\alpha(3+\alpha)}$$

There is the minimum value of

$$\prod\nolimits_{3DB}^{*} L\,(p_{3D}, p_L) - \prod\nolimits_{3DN}^{*} L(p_L) = -\frac{(3+\alpha)(-\alpha + c_L + c_M)^2}{8\big(-8+\alpha(3+\alpha)\big)} > 0$$

(2) For the traditional manufacturer's maximized profits, compare Equation (4.28) and (4.19)

$$\prod\nolimits_{3DB}^{*} M\,(p_M) - \prod\nolimits_{3DN}^{*} M(p_M)$$

$$= -\frac{1}{16(-1+\alpha)(8+\alpha)^2}((-1+\alpha)\alpha(8+\alpha)^2 + 16\alpha(2+\alpha)^2 c_{3D}^2 + 128c_L + 128c_M - 32(2+\alpha)^2 c_{3D}(c_L + c_M) + (c_L + c_M)(-2\alpha(48+\alpha(15+\alpha)) + (112+\alpha(31+\alpha))c_L + (112+\alpha(31+\alpha))c_M))$$

It is also concave in c_{3D}, therefore, when the first-order-condition

$$\frac{\partial(\prod_{3DB}^{*} M\,(p_M) - \prod_{3DN}^{*} M(p_M))}{\partial c_{3D}} = -\frac{2(2+\alpha)^2(\alpha c_{3D} - c_L - c_M)}{(-1+\alpha)(8+\alpha)^2} = 0$$

$$c_{3D} = \frac{c_L + c_M}{\alpha}$$

There is the minimum value of

$$\prod\nolimits_{3DB}^{*} M\,(p_{3D}, p_L) - \prod\nolimits_{3DN}^{*} M(p_{3D}, p_L) = -\frac{(-\alpha + c_L + c_M)^2}{16\alpha} < 0$$

Then, if $\prod_{3DB}^{*} M\,(p_{3D}, p_L) - \prod_{3DN}^{*} M(p_{3D}, p_L) = 0$,

$$c_{3D1} = \frac{c_L + c_M}{\alpha} - \frac{(\alpha+8)(\alpha - c_L - c_M)\sqrt{1-\alpha}}{4\alpha(2+\alpha)}$$

$$c_{3D2} = \frac{c_L + c_M}{\alpha} + \frac{(\alpha+8)(\alpha - c_L - c_M)\sqrt{1-\alpha}}{4\alpha(2+\alpha)}$$

Here, $c_{3D1} < \frac{c_L+c_M}{\alpha} < c_{3D2} < 1$. Because $c_{3D} > \frac{c_L+c_M}{\alpha}$, therefore,

$$\begin{cases} if\ \dfrac{c_L + c_M}{\alpha} < c_{3D} < c_{3D2}, \prod\nolimits_{3DB}^{*} M\,(p_{3D}, p_L) - \prod\nolimits_{3DN}^{*} M(p_{3D}, p_L) < 0; \\ if\ c_{3D2} < c_{3D} < 1, \prod\nolimits_{3DB}^{*} M\,(p_{3D}, p_L) - \prod\nolimits_{3DN}^{*} M(p_{3D}, p_L) > 0. \end{cases} \tag{4.47}$$

(3) Based on Table 4-2, compare the optimal price and quantity,

p_L^*	$\frac{\alpha(8+\alpha) - \alpha^2 c_{3D} + 2(4+\alpha)c_L - 8c_M}{2(8+\alpha)} - \frac{1}{2}(\alpha + c_L - c_M) = \frac{\alpha(-\alpha c_{3D} + c_L + c_M)}{2(8+\alpha)} < 0$
p_M^*	$\frac{\alpha(8+\alpha) + \alpha(4+\alpha)c_{3D} + 4c_L + 4c_M}{2(8+\alpha)} - \frac{1}{4}(3\alpha + c_L + c_M) = \frac{\alpha(-8-\alpha+2(4+\alpha)c_{3D} - c_L - c_M)}{4(8+\alpha)}$ If $\frac{c_L+c_M}{\alpha} < c_{3D} < \frac{8+\alpha+c_L+c_M}{8+2\alpha}$, $\frac{\alpha(-8-\alpha+2(4+\alpha)c_{3D}-c_L-c_M)}{4(8+\alpha)} < 0$; If $\frac{8+\alpha+c_L+c_M}{8+2\alpha} < c_{3D} < 1$, $\frac{\alpha(8+\alpha-2(4+\alpha)c_{3D}+c_L+c_M)}{4(8+\alpha)} > 0$.

q_M^*	$-\frac{(2+\alpha)(\alpha c_{3D}-c_L-c_M)}{(-1+\alpha)\alpha(8+\alpha)}-\left(-\frac{-\alpha+c_L+c_M}{4\alpha}\right)$ $=\frac{-(-1+\alpha)(8+\alpha)-4(2+\alpha)c_{3D}+(11+\alpha)(c_L+c_M)}{4(-1+\alpha)(8+\alpha)}$ If $\frac{c_L+c_M}{\alpha}<c_{3D}<\frac{-(-1+\alpha)(8+\alpha)+(11+\alpha)(c_L+c_M)}{4(2+\alpha)}$, $\frac{-8+7\alpha+\alpha^2+4(2+\alpha)c_{3D}-(11+\alpha)c_L-(11+\alpha)c_M}{4(-1+\alpha)(8+\alpha)}<0$; If $\frac{-(-1+\alpha)(8+\alpha)+(11+\alpha)(c_L+c_M)}{4(2+\alpha)}<c_{3D}<1$, $\frac{-8+7\alpha+\alpha^2+4(2+\alpha)c_{3D}-(11+\alpha)c_L-(11+\alpha)c_M}{4(-1+\alpha)(8+\alpha)}>0$.

Proof of *PROPOSITION* 4-12.

(1) For the logistics vendor's maximized profits, compare Equation (4.41) and (4.20),

$$\prod\nolimits_{3DS}^{*} L\,(p_{3D},p_L)-\prod\nolimits_{3DN}^{*} L(p_L)$$
$$=\frac{1}{4}+\frac{(-8+(9-2\alpha)\alpha)c_{3D}^2}{4(-1+\alpha)(8+(-5+\alpha)\alpha)}-\frac{(-2+\alpha)^2(c_L+c_M)^2}{4(-1+\alpha)\alpha(8+(-5+\alpha)\alpha)}-\frac{(-\alpha+c_L+c_M)^2}{8\alpha}+\frac{c_{3D}((1-\alpha)(8+(-5+\alpha)\alpha)+(-2+\alpha)^2c_L+(-2+\alpha)^2c_M)}{2(-1+\alpha)(8+(-5+\alpha)\alpha)}$$

It is concave in c_{3D}, therefore, when the first-order-condition

$$\frac{\partial(\prod_{3DB}^{*} L\,(p_{3D},p_L)-\prod_{3DN}^{*} L(p_L))}{\partial c_{3D}}$$
$$=\frac{-(-1+\alpha)(8+(-5+\alpha)\alpha)+(-8+(9-2\alpha)\alpha)c_{3D}+(-2+\alpha)^2c_L+(-2+\alpha)^2c_M}{2(-1+\alpha)(8+(-5+\alpha)\alpha)}$$
$$=0$$

$$c_{3D} = \frac{-(-1+\alpha)(8+(-5+\alpha)\alpha)+(-2+\alpha)^2(c_L+c_M)}{8+\alpha(-9+2\alpha)}$$

There is the minimum value of

$$\prod\nolimits_{3DS}^{*} L\,(p_{3D}, p_L) - \prod\nolimits_{3DN}^{*} L(p_L) = \frac{(-\alpha+c_L+c_M)^2}{8(8+\alpha(-9+2\alpha))} > 0$$

(2) For the traditional manufacturer's maximized profits, compare Equation (4.40) and (4.19)

$$\prod\nolimits_{3DS}^{*} M\,(p_M) - \prod\nolimits_{3DN}^{*} M(p_M)$$
$$= \frac{2(-2+\alpha)\alpha c_{3D}^2}{(-1+\alpha)(8+(-5+\alpha)\alpha)^2} + \frac{2(-2+\alpha)c_L^2}{(-1+\alpha)\alpha(8+(-5+\alpha)\alpha)^2}$$
$$+ \frac{4(-2+\alpha)c_L c_M}{(-1+\alpha)\alpha(8+(-5+\alpha)\alpha)^2} + \frac{2(-2+\alpha)c_M^2}{(-1+\alpha)\alpha(8+(-5+\alpha)\alpha)^2}$$
$$- \frac{(-\alpha+c_L+c_M)^2}{16\alpha} + c_{3D}\Big(-\frac{4(-2+\alpha)c_L}{(-1+\alpha)(8+(-5+\alpha)\alpha)^2}$$
$$- \frac{4(-2+\alpha)c_M}{(-1+\alpha)(8+(-5+\alpha)\alpha)^2}\Big)$$

It is also concave in c_{3D}, therefore, when the first-order-condition

$$\frac{\partial(\prod_{3DS}^{*} M\,(p_M) - \prod_{3DN}^{*} M(p_M))}{\partial c_{3D}} = \frac{4(-2+\alpha)(\alpha c_{3D}-c_L-c_M)}{(-1+\alpha)(8+(-5+\alpha)\alpha)^2} = 0$$

$$c_{3D} = \frac{c_L+c_M}{\alpha}$$

There is the minimum value of

$$\prod\nolimits_{3DS}^{*} M\,(p_{3D}, p_L) - \prod\nolimits_{3DN}^{*} M(p_{3D}, p_L) = -\frac{(-\alpha+c_L+c_M)^2}{16\alpha} < 0$$

Then, if $\prod_{3DS}^{*} M\,(p_{3D}, p_L) - \prod_{3DN}^{*} M(p_{3D}, p_L) = 0$,

$$c_{3D1} = \frac{c_L+c_M}{\alpha} + \frac{\sqrt{2}(8+(-5+\alpha)\alpha)(\alpha-c_L-c_M)\sqrt{(-2+\alpha)(-1+\alpha)}}{8(-2+\alpha)\alpha}$$

$$c_{3D2} = \frac{c_L + c_M}{\alpha} - \frac{\sqrt{2}(8 + (-5 + \alpha)\alpha)(\alpha - c_L - c_M)\sqrt{(-2 + \alpha)(-1 + \alpha)}}{8(-2 + \alpha)\alpha}$$

Here, $c_{3D1} < \frac{c_L+c_M}{\alpha} < c_{3D2} < 1$. Because $c_{3D} > \frac{c_L+c_M}{\alpha}$, therefore,

$$\begin{cases} if\ \frac{c_L + c_M}{\alpha} < c_{3D} < c_{3D2}, \prod_{3DS}^{*} M\,(p_{3D}, p_L) - \prod_{3DN}^{*} M(p_{3D}, p_L) < 0; \\ if\ c_{3D2} < c_{3D} < 1, \prod_{3DB}^{*} M\,(p_{3D}, p_L) - \prod_{3DN}^{*} M(p_{3D}, p_L) > 0. \end{cases} \tag{4.48}$$

(3) Based on Table 4-2, compare the optimal price and quantity under Stackelberg-equilibrium,

p_L^*	$\frac{\alpha(8 + (-5 + \alpha)\alpha) - \alpha^2 c_{3D} + (8 + (-4 + \alpha)\alpha)c_L - (-4 + \alpha)(-2 + \alpha)c_M}{2(8 + (-5 + \alpha)\alpha)} - \frac{1}{2}(\alpha + c_L - c_M) = \frac{\alpha(-\alpha c_{3D} + c_L + c_M)}{2(8 + (-5 + \alpha)\alpha)} < 0$
p_M^*	$\frac{\alpha(8 + (-5 + \alpha)\alpha) - (-4 + \alpha)\alpha c_{3D} + (-2 + \alpha)^2(c_L + c_M)}{2(8 + (-5 + \alpha)\alpha)} - \frac{1}{4}(3\alpha + c_L + c_M) = \frac{\alpha(-8 - (-5 + \alpha)\alpha - 2(-4 + \alpha)c_{3D} + (-3 + \alpha)(c_L + c_M))}{4(8 + (-5 + \alpha)\alpha)}$ If $\frac{c_L+c_M}{\alpha} < c_{3D} < \frac{-8-(-5+\alpha)\alpha+(-3+\alpha)(c_L+c_M)}{2(-4+\alpha)}$, $\frac{\alpha(-8-(-5+\alpha)\alpha-2(-4+\alpha)c_{3D}+(-3+\alpha)(c_L+c_M))}{4(8+(-5+\alpha)\alpha)} < 0$; If $\frac{-8-(-5+\alpha)\alpha+(-3+\alpha)(c_L+c_M)}{2(-4+\alpha)} < c_{3D} < 1$, $\frac{\alpha(-8-(-5+\alpha)\alpha-2(-4+\alpha)c_{3D}+(-3+\alpha)(c_L+c_M))}{4(8+(-5+\alpha)\alpha)} > 0$.
q_M^*	$-\frac{(2 + \alpha)(\alpha c_{3D} - c_L - c_M)}{(-1 + \alpha)\alpha(8 + \alpha)} - \left(-\frac{-\alpha + c_L + c_M}{4\alpha}\right) = \frac{4\alpha(-\alpha + c_L + +c_M) + \frac{4(-2 + \alpha)(\alpha c_{3D} - c_L - c_M)}{(-1 + \alpha)(8 + (-5 + \alpha)\alpha)} + c_M}{4\alpha(-1 + \alpha)(8 + (-5 + \alpha)\alpha)}$ If $\frac{c_L+c_M}{\alpha} < c_{3D} < -\frac{-(-1+\alpha)(8+(-5+\alpha)\alpha)+(-3+\alpha)^2(c_L+c_M)}{4(-2+\alpha)}$, $\frac{4\alpha(-\alpha+c_L++c_M)+\frac{4(-2+\alpha)(\alpha c_{3D}-c_L-c_M)}{(-1+\alpha)(8+(-5+\alpha)\alpha)}+c_M}{4\alpha(-1+\alpha)(8+(-5+\alpha)\alpha)} < 0$;

	If $-\frac{-(-1+\alpha)(8+(-5+\alpha)\alpha)+(-3+\alpha)^2(c_L+c_M)}{4(-2+\alpha)} < c_{3D} < 1$, $\frac{4\alpha(-\alpha+c_L++c_M)+\frac{4(-2+\alpha)(\alpha c_{3D}-c_L-c_M)}{(-1+\alpha)(8+(-5+\alpha)\alpha)}+c_M}{4\alpha(-1+\alpha)(8+(-5+\alpha)\alpha)} > 0$.

***Proof of PROPOSITION* 4-13.**

Compare the optimal decisions and maximized profits between the decentralized Bertrand and Stackelberg 3DP enabled market.

(1) For the logistics vendor's maximized profits, compare Equation (4.29) and (4.41),

$$\prod_{3DB}^{*} L\,(p_{3D}, p_L) - \prod_{3DS}^{*} L\,(p_{3D}, p_L) = \frac{(-8+\alpha^2)(\alpha c_{3D} - c_L - c_M)^2}{4(-1+\alpha)(8+\alpha)(8-5\alpha+\alpha^2)} > 0$$

(2) For the traditional manufacturer's maximized profits, compare Equation (4.28) and (4.40),

$$\prod_{3DB}^{*} M\,(p_M) - \prod_{3DS}^{*} M\,(p_M)$$
$$= -\frac{\alpha\big(-64+\alpha(46+(-5+\alpha)(-1+\alpha)\alpha)\big)(-\alpha c_{3D} + c_L + c_M)^2}{(-1+\alpha)(8+\alpha)^2(8+(-5+\alpha)\alpha)^2} < 0$$

(3) Based on Table 4-2, compare the optimal price and quantity under Stackelberg-equilibrium,

p_L^*	$\frac{\alpha(8+\alpha) - \alpha^2 c_{3D} + 2(4+\alpha)c_L - 8c_M}{2(8+\alpha)}$ $-\frac{\alpha(8+(-5+\alpha)\alpha) - \alpha^2 c_{3D} + (8+(-4+\alpha)\alpha)c_L - (-4+\alpha)(-2+\alpha)c_M}{2(8+(-5+\alpha)\alpha)}$ $= -\frac{(-6+\alpha)\alpha^2(\alpha c_{3D} - c_L - c_M)}{2(8+\alpha)(8+(-5+\alpha)\alpha)} > 0$
p_M^*	$\frac{\alpha(8+\alpha) + \alpha(4+\alpha)c_{3D} + 4c_L + 4c_M}{2(8+\alpha)}$ $-\frac{\alpha(8+(-5+\alpha)\alpha) - (-4+\alpha)\alpha c_{3D} + (-2+\alpha)^2 c_L + (-2+\alpha)^2 c_M}{2(8+(-5+\alpha)\alpha)}$ $= \frac{\alpha(-8+\alpha^2)(\alpha c_{3D} - c_L - c_M)}{2(8+\alpha)(8+(-5+\alpha)\alpha)} < 0$

p^*_{3D}	$\frac{8+\alpha+(8+3\alpha)c_{3D}-2c_L-2c_M}{2(8+\alpha)} - \frac{8+(-5+\alpha)\alpha+(8-3\alpha)c_{3D}+(-2+\alpha)c_L+(-2+\alpha)c_M}{2(8+(-5+\alpha)\alpha)} = \frac{\alpha(-4+3\alpha)(\alpha c_{3D}-c_L-c_M)}{2(8+\alpha)(8+(-5+\alpha)\alpha)} < 0$
q^*_M	$-\frac{(2+\alpha)(\alpha c_{3D}-c_L-c_M)}{(-1+\alpha)\alpha(8+\alpha)} - \frac{(-2+\alpha)(\alpha c_{3D}-c_L-c_M)}{(-1+\alpha)\alpha(8+(-5+\alpha)\alpha)} = -\frac{(4+(-2+\alpha)\alpha)(\alpha c_{3D}-c_L-c_M)}{(-1+\alpha)(8+\alpha)(8+(-5+\alpha)\alpha)} > 0$
q^*_{3D}	$\frac{-8+7\alpha+\alpha^2-(-8+\alpha+\alpha^2)c_{3D}-6c_L-6c_M}{2(-1+\alpha)(8+\alpha)} - \frac{(-1+\alpha)(8+(-5+\alpha)\alpha)+(8+(-7+\alpha)\alpha)c_{3D}-6c_L-6c_M-(-5+\alpha)\alpha(c}{2(-1+\alpha)(8+(-5+\alpha)\alpha)} = -\frac{(-4+\alpha)\alpha(1+\alpha)(\alpha c_{3D}-c_L-c_M)}{2(-1+\alpha)(8+\alpha)(8+(-5+\alpha)\alpha)} < 0$

Proof of *PROPOSITION* 4-14.

(1) Because the optimal decisions in decentralized Bertrand and Stackelberg are the same, thus, to assessing the supply chain profitability, compare Equation (4.34) or (4.46) with (4.21),

$$\prod\nolimits_{3D}^{*} SC\,(p_M,p_{3D},p_L) - \prod\nolimits_{3DN}^{*} SC(p_M,p_{3D},p_L)$$

$$= -\frac{1-\alpha}{4(-1+\alpha)} - \frac{c_{3D}^2}{4(-1+\alpha)} - \frac{(c_L+c_M)^2}{4(-1+\alpha)\alpha} - \frac{3(-\alpha+c_L+c_M)^2}{16\alpha} + \frac{c_{3D}(1-\alpha+c_L+c_M)}{2(-1+\alpha)}$$

which is also concave in c_{3D}, therefore, when the first-order-condition

$$\frac{\partial(\prod_{3D}^{*} SC\,(p_M,p_{3D},p_L) - \prod_{3DN}^{*} SC(p_M,p_{3D},p_L))}{\partial c_{3D}} = \frac{1-\alpha-c_{3D}+c_L+c_M}{2(-1+\alpha)} = 0$$

$$c_{3D} = 1-\alpha+c_L+c_M$$

There is the minimum value of

$$\prod_{3D}^{*} L\,(p_{3D}, p_L) - \prod_{3DN}^{*} L(p_L) = -\frac{3(-32+\alpha+4\alpha^2)(-\alpha+c_L+c_M)^2}{16(8+\alpha)^2} > 0$$

(2) Based on Table 4-2, compare the optimal price and quantity of the supply chain equilibrium scenario,

p_M^*	$\frac{1}{2}(\alpha+c_L+c_M) - \frac{1}{4}(3\alpha+c_L+c_M) = \frac{1}{4}(-\alpha+c_L+c_M) < 0$
q_M^*	$\frac{-\alpha c_{3D}+c_L+c_M}{2(-1+\alpha)\alpha} - \left(-\frac{-\alpha+c_L+c_M}{4\alpha}\right) = \frac{\alpha-\alpha^2+c_L+c_M+\alpha(-2c_{3D}+c_L+c_M)}{4(-1+\alpha)\alpha}$ If $\frac{c_L+c_M}{\alpha} < c_{3D} < \frac{-(-1+\alpha)\alpha+(1+\alpha)(c_L+c_M)}{2\alpha}$, $\frac{\alpha-\alpha^2+c_L+c_M+\alpha(-2c_{3D}+c_L+c_M)}{4(-1+\alpha)\alpha} < 0$; If $\frac{-(-1+\alpha)\alpha+(1+\alpha)(c_L+c_M)}{2\alpha} < c_{3D} < 1$, $\frac{\alpha-\alpha^2+c_L+c_M+\alpha(-2c_{3D}+c_L+c_M)}{4(-1+\alpha)\alpha} > 0$.

Proof of *PROPOSITION* 4-15.

(1) Compare the optimal decisions of the full 3DP system with the decentralized traditional manufacturing system,

$$\prod_{F3D}^{*} L\,(p_{3D}, p_L) - \prod_{3DND}^{*} L(p_L) = \frac{1}{4}(-1+c_{3D})^2 - \frac{(-\alpha+c_L+c_M)^2}{8\alpha}$$

Which is concave in c_{3D}, therefore, the first-order-condition is

$$\frac{\partial(\prod_{F3D}^{*} L\,(p_{3D}, p_L) - \prod_{3DND}^{*} L(p_L))}{\partial c_{3D}} = \frac{1}{2}(-1+c_{3D}) = 0$$

$$c_{3D} = 1$$

So, the minimum value is

$$\prod_{F3D}^{*} L\,(p_{3D}, p_L) - \prod_{3DND}^{*} L(p_L) = -\frac{(-\alpha+c_L+c_M)^2}{8\alpha} < 0$$

Therefore, set $\prod_{F3D}^{*} L\,(p_{3D}, p_L) - \prod_{TMD}^{*} L(p_L) = 0$

$$c_{3D1} = \frac{1}{2}(2 + \frac{\sqrt{2}(-\alpha + c_L + c_M)}{\sqrt{\alpha}})$$

$$c_{3D2} = \frac{1}{2}(2 + \frac{\sqrt{2}(\alpha - c_L - c_M)}{\sqrt{\alpha}})$$

Here, $c_{3D2} < \frac{c_L + c_M}{\alpha} < 1 < c_{3D1}$, therefore,

$$\begin{cases} if\ 0 < c_{3D} < c_{3D2}, \prod_{F3D}^{*} L\,(p_{3D}, p_L) - \prod_{3DND}^{*} L(p_L) > 0; \\ if\ c_{3D2} < c_{3D} < \frac{c_L + c_M}{\alpha}, \prod_{F3D}^{*} L\,(p_{3D}, p_L) - \prod_{3DND}^{*} L(p_L) < 0. \end{cases}$$

(2) Compare the optimal decisions of the full 3DP system with the integrated traditional manufacturing system,

$$\prod_{F3D}^{*} SC\,(p_{3D}, p_L) - \prod_{3DNI}^{*} SC(p_L)$$
$$= \frac{1}{4}((-1 + c_{3D})^2 - \frac{(-\alpha + c_L + c_M)^2}{\alpha})$$

Which is concave in c_{3D}, therefore, the first-order-condition is

$$\frac{\partial(\prod_{F3D}^{*} SC\,(p_{3D}, p_L) - \prod_{3DNI}^{*} SC(p_L))}{\partial c_{3D}} = \frac{1}{2}(-1 + c_{3D}) = 0$$

$$c_{3D} = 1$$

So, the minimum value is

$$\prod_{F3D}^{*} SC\,(p_{3D}, p_L) - \prod_{3DNI}^{*} SC(p_L) = -\frac{(-\alpha + c_L + c_M)^2}{4\alpha} < 0$$

Therefore, set $\prod_{F3D}^{*} L\,(p_{3D}, p_L) - \prod_{3DNI}^{*} L(p_L) = 0$

$$c_{3D1} = 1 + \frac{\alpha - c_L - c_M}{\sqrt{\alpha}}$$

$$c_{3D2} = 1 - \frac{-\alpha + c_L + c_M}{\sqrt{\alpha}}$$

Here, $c_{3D1} < \frac{c_L + c_M}{\alpha} < 1 < c_{3D2}$, therefore,

$$\begin{cases} if\ 0 < c_{3D} < c_{3D1}, \prod_{F3D}^{*} SC\,(p_{3D}, p_L) - \prod_{TMI}^{*} SC(p_L) > 0; \\ if\ c_{3D1} < c_{3D} < \dfrac{c_L + c_M}{\alpha}, \prod_{F3D}^{*} SC\,(p_{3D}, p_L) - \prod_{TMI}^{*} SC(p_L) < 0. \end{cases}$$

Proof of *PROPOSITION* 4-16. In pervious decentralized Bertrand-equilibrium 3DP manufacturing system, set the Equation (4.27) $q_{3D}^{*} = 0$,

$$q_{3D}^{*} = \frac{-8 + 7\alpha + \alpha^2 - (-8 + \alpha + \alpha^2)c_{3D} - 6c_L - 6c_M}{2(-1 + \alpha)(8 + \alpha)} = 0$$

$$c_{3D} = \frac{(-1 + \alpha)(8 + \alpha) - 6c_L - 6c_M}{-8 + \alpha + \alpha^2}$$

Then, the Equation (4.23), (4.24), (4.25) and (4.26) can be rewritten as

$$p_{(q_{3D}^{*}=0,LB)}^{*} = \frac{(-4 + \alpha^2)c_L + (-4 + \alpha)(\alpha - c_M)}{-8 + \alpha + \alpha^2} \tag{4.49}$$

$$p_{(q_{3D}^{*}=0,MB)}^{*} = \frac{\alpha(-6 + \alpha(2 + \alpha)) - (2 + \alpha)(c_L + c_M)}{-8 + \alpha + \alpha^2} \tag{4.50}$$

$$p_{(q_{3D}^{*}=0,3DB)}^{*} = -\frac{8 - \alpha(3 + 2\alpha) + (2 + \alpha)(c_L + c_M)}{-8 + \alpha + \alpha^2} \tag{4.51}$$

$$q_{(q_{3D}^{*}=0,MB)}^{*} = -\frac{(2 + \alpha)(\alpha - c_L - c_M)}{\alpha(-8 + \alpha + \alpha^2)} \tag{4.52}$$

where $0 < c_L + c_M < \alpha < 1$.

The new profit functions for the traditional manufacturer and the logistics vendor are

$$\begin{aligned} \prod_{(q_{3D}^{*}=0,B)}^{*} M(p_M) &= (p_M - c_M - p_L)q_M \\ &= -\frac{(-1 + \alpha)(2 + \alpha)^2(-\alpha + c_L + c_M)^2}{\alpha(-8 + \alpha + \alpha^2)^2} \end{aligned} \tag{4.53}$$

$$\begin{aligned} \prod_{(q_{3D}^{*}=0,B)}^{*} L(p_{3D}, p_L) &= (p_L - c_L)q_M \\ &= -\frac{(-4 + \alpha)(2 + \alpha)(-\alpha + c_L + c_M)^2}{\alpha(-8 + \alpha + \alpha^2)^2} \end{aligned} \tag{4.54}$$

Use the same approach as the proof of ***PROPOSITION* 4-16**, after set $q_{3D}^* = 0$ in Equation (4.39), the optimal decisions for the new Nash-Stackelberg equilibrium are

$$p^*_{(q^*_{3D}=0,LS)} = \frac{(4-3\alpha)c_L + (-2+\alpha)^2(\alpha - c_M)}{8+(-7+\alpha)\alpha} \tag{4.55}$$

$$p^*_{(q^*_{3D}=0,MS)} = \frac{\alpha(6+(-6+\alpha)\alpha) - (-2+\alpha)c_L - (-2+\alpha)c_M}{8+(-7+\alpha)\alpha} \tag{4.56}$$

$$p^*_{(q^*_{3D}=0,3DS)} = \frac{8+\alpha(-9+2\alpha) - (-2+\alpha)c_L - (-2+\alpha)c_M}{8+(-7+\alpha)\alpha} \tag{4.57}$$

$$q^*_{(q^*_{3D}=0,MS)} = -\frac{(-2+\alpha)(\alpha - c_L - c_M)}{\alpha(8+(-7+\alpha)\alpha)} \tag{4.58}$$

where $0 < c_L + c_M < \alpha < 1$.

The maximized profits for both the manufacturer and logistics vendor are

$$\prod\nolimits^*_{(q^*_{3D}=0,B)} M(p_M) = \frac{2(-2+\alpha)(-1+\alpha)(-\alpha + c_L + c_M)^2}{\alpha(8+(-7+\alpha)\alpha)^2} \tag{4.59}$$

$$\prod\nolimits^*_{(q^*_{3D}=0,B)} L(p_{3D}, p_L) = -\frac{(-2+\alpha)^3(-\alpha + c_L + c_M)^2}{\alpha(8+(-7+\alpha)\alpha)^2} \tag{4.60}$$

The optimal decisions for the integrated Bertrand and Stackelberg manufacturing system are the same. Therefore, under the Nash-equilibrium, after set $q_{3D}^* = 0$ in Equation (4.45), the optimal decisions are

$$p^*_{(q^*_{3D}=0,MSC)} = \frac{1}{2}(\alpha + c_L + c_M) \tag{4.61}$$

$$p^*_{(q^*_{3D}=0,3DSC)} = \frac{1}{2}(2 - \alpha + c_L + c_M) \tag{4.62}$$

$$q^*_{(q^*_{3D}=0,MSC)} = -\frac{-\alpha + c_L + c_M}{2\alpha} \tag{4.63}$$

where $0 < c_L + c_M < \alpha < 1$.

The maximized profits for both the manufacturer and logistics vendor are

$$\prod\nolimits^*_{(q^*_{3D}=0)} SC(p_M, p_{3D}) = \frac{(-\alpha + c_L + c_M)^2}{4\alpha} \tag{4.64}$$

Proof of *PROPOSITION* 3-17. Under the Bertrand decentralized system, according to Equation (4.49), (4.50), (4.51), and (4.52),

$$\frac{\partial p^*_{(q^*_{3D}=0,LB)}}{\partial c_M} = \frac{4-\alpha}{-8+\alpha+\alpha^2} < 0 \qquad \frac{\partial p^*_{(q^*_{3D}=0,MB)}}{\partial c_L} = \frac{-4+\alpha^2}{-8+\alpha+\alpha^2} < 0$$

$$\frac{\partial p^*_{(q^*_{3D}=0,MB)}}{\partial c_M} = -\frac{2+\alpha}{-8+\alpha+\alpha^2} > 0 \qquad \frac{\partial p^*_{(q^*_{3D}=0,MB)}}{\partial c_L} = -\frac{2+\alpha}{-8+\alpha+\alpha^2} > 0$$

$$\frac{\partial p^*_{(q^*_{3D}=0,3DB)}}{\partial c_M} = -\frac{2+\alpha}{-8+\alpha+\alpha^2} > 0 \qquad \frac{\partial p^*_{(q^*_{3D}=0,3DB)}}{\partial c_L} = -\frac{2+\alpha}{-8+\alpha+\alpha^2} > 0$$

$$\frac{\partial q^*_{(q^*_{3D}=0,MB)}}{\partial c_M} = \frac{2+\alpha}{\alpha(-8+\alpha+\alpha^2)} < 0 \qquad \frac{\partial q^*_{(q^*_{3D}=0,MB)}}{\partial c_L} = \frac{2+\alpha}{\alpha(-8+\alpha+\alpha^2)} < 0$$

For the Stackelberg decentralized system, based on Equation (4.55), (4.56), (4.57) and (4.58),

$$\frac{\partial p^*_{(q^*_{3D}=0,LS)}}{\partial c_M} = \frac{4-\alpha}{-8+\alpha+\alpha^2} < 0 \qquad \frac{\partial p^*_{(q^*_{3D}=0,LS)}}{\partial c_L} = \frac{4-\alpha}{-8+\alpha+\alpha^2} < 0$$

$$\frac{\partial p^*_{(q^*_{3D}=0,MS)}}{\partial c_M} = \frac{2-\alpha}{8+(-7+\alpha)\alpha} > 0 \qquad \frac{\partial p^*_{(q^*_{3D}=0,MS)}}{\partial c_L} = \frac{2-\alpha}{8+(-7+\alpha)\alpha} > 0$$

$$\frac{\partial p^*_{(q^*_{3D}=0,3DS)}}{\partial c_M} = \frac{2-\alpha}{8+(-7+\alpha)\alpha} > 0 \qquad \frac{\partial p^*_{(q^*_{3D}=0,3DS)}}{\partial c_L} = \frac{2-\alpha}{8+(-7+\alpha)\alpha} > 0$$

$$\frac{\partial q^*_{(q^*_{3D}=0,MS)}}{\partial c_M} = \frac{-2+\alpha}{\alpha(8+(-7+\alpha)\alpha)} < 0 \qquad \frac{\partial q^*_{(q^*_{3D}=0,MS)}}{\partial c_L} = \frac{-2+\alpha}{\alpha(8+(-7+\alpha)\alpha)} < 0$$

For the 3DP enabled integrated supply chain, according to Equation (4.61), (4.62), and (4.63),

$$\frac{\partial p^*_{(q^*_{3D}=0,MSC)}}{\partial c_M} = \frac{1}{2} > 0 \qquad \frac{\partial p^*_{(q^*_{3D}=0,MSC)}}{\partial c_L} = \frac{1}{2} > 0$$

$$\frac{\partial p^*_{(q^*_{3D}=0,3DSC)}}{\partial c_M} = \frac{1}{2} > 0 \qquad \frac{\partial p^*_{(q^*_{3D}=0,3DSC)}}{\partial c_L} = \frac{1}{2} > 0$$

$$\frac{\partial q^*_{(q^*_{3D}=0,MSC)}}{\partial c_M} = -\frac{1}{2\alpha} < 0 \qquad \frac{\partial q^*_{(q^*_{3D}=0,MSC)}}{\partial c_L} = -\frac{1}{2\alpha} < 0$$

Under decentralized Bertrand supply chain, from Equation (4.53) and (4.54), it is easy to find out that

(1) $\prod^*_{(q^*_{3D}=0,B)} M(p_\mathrm{M})$ is concave in c_M, therefore, when

$$\frac{\partial \prod^*_{(q^*_{3D}=0,B)} M(p_\mathrm{M})}{\partial c_M} = -\frac{2(-1+\alpha)(2+\alpha)^2(-\alpha+c_L+c_M)}{\alpha(-8+\alpha+\alpha^2)^2} = 0$$

$$c_M^* = \alpha - c_L$$

gives the minimum value. However, because $\alpha c_{3D} > c_L + c_M$, therefore, $\prod^*_{(q^*_{3D}=0,B)} M(p_\mathrm{M})$ is decreasing in c_M;

(2) $\prod^*_{(q^*_{3D}=0,B)} M(p_\mathrm{M})$ is concave in c_L, therefore, when

$$\frac{\partial \prod^*_{(q^*_{3D}=0,B)} M(p_\mathrm{M})}{\partial c_L} = -\frac{2(-1+\alpha)(2+\alpha)^2(-\alpha+c_L+c_M)}{\alpha(-8+\alpha+\alpha^2)^2} = 0$$

$$c_L^* = \alpha - c_M$$

gives the minimum value. However, because $\alpha c_{3D} > c_L + c_M$, therefore, $\prod^*_{(q^*_{3D}=0,B)} M(p_\mathrm{M})$ is decreasing in c_L;

(3) $\prod^*_{(q^*_{3D}=0,B)} L(p_{3D}, p_L)$ is concave in c_M, therefore, when

$$\frac{\partial \prod^*_{(q^*_{3D}=0,B)} L(p_{3D}, p_L)}{\partial c_M} = -\frac{2(-2+\alpha)^3(-\alpha+c_L+c_M)}{\alpha(8+(-7+\alpha)\alpha)^2} = 0$$

$$c_M^* = \alpha - c_L$$

gives the minimum value. However, because $\alpha c_{3D} > c_L + c_M$, therefore, $\prod^*_{(q^*_{3D}=0,B)} L(p_{3D}, p_L)$ is decreasing in c_M;

(4) $\prod^*_{(q^*_{3D}=0,B)} L(p_{3D}, p_L)$ is concave in c_L, therefore, when

$$\frac{\partial \prod^{*}_{(q^{*}_{3D}=0,B)} L(p_{3D}, p_L)}{\partial c_L} = -\frac{2(-4+\alpha)(2+\alpha)(-\alpha+c_L+c_M)}{\alpha(-8+\alpha+\alpha^2)^2} = 0$$

$$c_L^{*} = \alpha - c_M$$

gives the minimum value. However, because $\alpha c_{3D} > c_L + c_M$, thus, $\prod^{*}_{(q^{*}_{3D}=0,B)} L(p_{3D}, p_L)$ is decreasing in c_L.

Under decentralized Stackelberg supply chain, based on Equation (4.59) and (4.60),

(1) $\prod^{*}_{(q^{*}_{3D}=0,S)} M(p_{\mathrm{M}})$ is concave in c_M, therefore, when

$$\frac{\partial \prod^{*}_{(q^{*}_{3D}=0,S)} M(p_{\mathrm{M}})}{\partial c_M} = -\frac{2(-1+\alpha)(2+\alpha)^2(-\alpha+c_L+c_M)}{\alpha(-8+\alpha+\alpha^2)^2} = 0$$

$$c_M^{*} = \alpha - c_L$$

gives the minimum value. However, because $\alpha c_{3D} > c_L + c_M$, therefore, $\prod^{*}_{(q^{*}_{3D}=0,S)} M(p_{\mathrm{M}})$ is decreasing in c_M;

(2) $\prod^{*}_{(q^{*}_{3D}=0,S)} M(p_{\mathrm{M}})$ is concave in c_L, therefore, when

$$\frac{\partial \prod^{*}_{(q^{*}_{3D}=0,S)} M(p_{\mathrm{M}})}{\partial c_L} = -\frac{2(-1+\alpha)(2+\alpha)^2(-\alpha+c_L+c_M)}{\alpha(-8+\alpha+\alpha^2)^2} = 0$$

$$c_L^{*} = \alpha - c_M$$

gives the minimum value. However, because $\alpha c_{3D} > c_L + c_M$, therefore, $\prod^{*}_{(q^{*}_{3D}=0,S)} M(p_{\mathrm{M}})$ is decreasing in c_L;

(3) $\prod^{*}_{(q^{*}_{3D}=0,S)} L(p_{3D}, p_L)$ is concave in c_M, therefore, when

$$\frac{\partial \prod^{*}_{(q^{*}_{3D}=0,S)} L(p_{3D}, p_L)}{\partial c_M} = \frac{4(-2+\alpha)(-1+\alpha)(-\alpha+c_L+c_M)}{\alpha(8+(-7+\alpha)\alpha)^2} = 0$$

$$c_M^{*} = \alpha - c_L$$

gives the minimum value. However, because $\alpha c_{3D} > c_L + c_M$, therefore, $\prod^*_{(q^*_{3D}=0,S)} L(p_{3D}, p_L)$ is decreasing in c_M;

(4) $\prod^*_{(q^*_{3D}=0,S)} L(p_{3D}, p_L)$ is concave in c_L, therefore, when

$$\frac{\partial \prod^*_{(q^*_{3D}=0,S)} L(p_{3D}, p_L)}{\partial c_L} = \frac{4(-2+\alpha)(-1+\alpha)(-\alpha + c_L + c_M)}{\alpha(8+(-7+\alpha)\alpha)^2} = 0$$

$$c_L^* = \alpha - c_M$$

gives the minimum value. However, because $\alpha c_{3D} > c_L + c_M$, thus, $\prod^*_{(q^*_{3D}=0,S)} L(p_{3D}, p_L)$ is decreasing in c_L.

For the integrated supply chain, based on Equation (4.64),

(1) $\prod^*_{(q^*_{3D}=0)} SC(p_{\mathrm{M}}, p_{3D})$ is concave in c_M, therefore, when

$$\frac{\partial \prod^*_{(q^*_{3D}=0)} SC(p_{\mathrm{M}}, p_{3D})}{\partial c_M} = \frac{-\alpha + c_L + c_M}{2\alpha} = 0$$

$$c_M^* = \alpha - c_L$$

gives the minimum value. However, because $\alpha c_{3D} > c_L + c_M$, therefore, $\prod^*_{(q^*_{3D}=0)} SC(p_{\mathrm{M}}, p_{3D})$ is decreasing in c_M;

(2) $\prod^*_{(q^*_{3D}=0,S)} M(p_{\mathrm{M}})$ is concave in c_L, therefore, when

$$\frac{\partial \prod^*_{(q^*_{3D}=0)} SC(p_{\mathrm{M}}, p_{3D})}{\partial c_L} = \frac{-\alpha + c_L + c_M}{2\alpha} = 0$$

$$c_L^* = \alpha - c_M$$

gives the minimum value. However, because $\alpha c_{3D} > c_L + c_M$, therefore, $\prod^*_{(q^*_{3D}=0)} SC(p_{\mathrm{M}}, p_{3D})$ is decreasing in c_L.

Proof of *PROPOSITION* 4-19. Under the Bertrand decentralized market, by comparing the optimal and maximized profits with the benchmark traditional manufacturing system,

(1) For the logistics vendor's maximized profits,

$$\prod\nolimits_{(q_{3D}^{*}=0,B)}^{*} L(p_{3D}, p_L) - \prod\nolimits_{3DN}^{*} L(p_L)$$

$$= -\frac{\left(-32+\alpha\left(-7+\alpha(2+\alpha)\right)\right)(-\alpha+c_L+c_M)^2}{8(-8+\alpha+\alpha^2)^2} > 0$$

(2) For the traditional manufacturer's maximized profits,

$$\prod\nolimits_{(q_{3D}^{*}=0,B)}^{*} M(p_{\mathrm{M}}) - \prod\nolimits_{3DN}^{*} M(p_M) = -\frac{(-16+\alpha(33+\alpha(18+\alpha)))(-\alpha+c_L+c_M)^2}{16(-8+\alpha+\alpha^2)^2}$$

Therefore,

$$\begin{cases} if\ -\dfrac{(-16+\alpha(33+\alpha(18+\alpha)))}{16(-8+\alpha+\alpha^2)^2} > 0, \prod\nolimits_{(q_{3D}^{*}=0,B)}^{*} M(p_{\mathrm{M}}) - \prod\nolimits_{3DN}^{*} M(p_M) > 0; \\ if\ -\dfrac{(-16+\alpha(33+\alpha(18+\alpha)))}{16(-8+\alpha+\alpha^2)^2} < 0, \prod\nolimits_{(q_{3D}^{*}=0,B)}^{*} M(p_{\mathrm{M}}) - \prod\nolimits_{3DN}^{*} M(p_M) < 0. \end{cases}$$

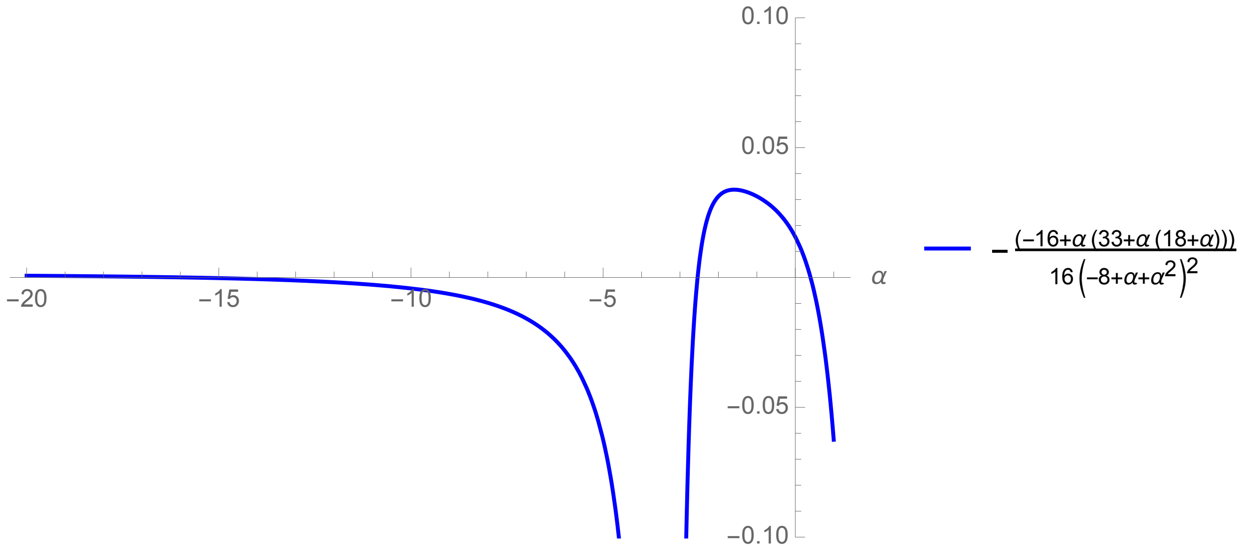
Then, set $-\frac{(-16+\alpha(33+\alpha(18+\alpha)))}{16(-8+\alpha+\alpha^2)^2} = 0$,

$$\alpha = -6 + \frac{25}{\left(-109+12i\sqrt{26}\right)^{1/3}} + \left(-109+12i\sqrt{26}\right)^{1/3} \approx -15.855$$

$$\alpha = -6 - \frac{25\left(1+i\sqrt{3}\right)}{2\left(-109+12i\sqrt{26}\right)^{1/3}} - \frac{1}{2}\left(1-i\sqrt{3}\right)\left(-109+12i\sqrt{26}\right)^{1/3} \approx -2.542$$

$$\alpha = -6 - \frac{25(1-i\sqrt{3})}{2(-109+12i\sqrt{26})^{1/3}} - \frac{1}{2}(1+i\sqrt{3})(-109+12i\sqrt{26})^{1/3} \approx 0.396989$$

Therefore, the value of $-\frac{(-16+\alpha(33+\alpha(18+\alpha)))}{16(-8+\alpha+\alpha^2)^2}$ can be simulated as below



Because $0 < \alpha < 1$,

if $0 < \alpha < -6 - \frac{25(1-i\sqrt{3})}{2(-109+12i\sqrt{26})^{1/3}} - \frac{1}{2}(1+i\sqrt{3})(-109+12i\sqrt{26})^{1/3}$,

$\prod^*_{(q^*_{3D}=0,B)} M(p_{\mathrm{M}}) - \prod^*_{3DN} M(p_M) > 0$;

if $-6 - \frac{25(1-i\sqrt{3})}{2(-109+12i\sqrt{26})^{1/3}} - \frac{1}{2}(1+i\sqrt{3})(-109+12i\sqrt{26})^{1/3} < \alpha < 1$,

$\prod^*_{(q^*_{3D}=0,B)} M(p_{\mathrm{M}}) - \prod^*_{3DN} M(p_M) < 0$.

(3) Based on Table 4-2, compare the optimal price and quantity,

p_L^*	$\frac{(-4+\alpha^2)c_L + (-4+\alpha)(\alpha - c_M)}{-8+\alpha+\alpha^2} - \frac{1}{2}(\alpha + c_L - c_M) = -\frac{(-1+\alpha)\alpha(\alpha - c_L - c_M)}{2(-8+\alpha+\alpha^2)} < 0$
p_M^*	$\frac{\alpha(-6+\alpha(2+\alpha)) - (2+\alpha)c_L - (2+\alpha)c_M}{-8+\alpha+\alpha^2} - \frac{1}{4}(3\alpha + c_L + c_M) = \frac{\alpha(5+\alpha)(\alpha - c_L - c_M)}{4(-8+\alpha+\alpha^2)} < 0$
q_M^*	$-\frac{(2+\alpha)(\alpha - c_L - c_M)}{\alpha(-8+\alpha+\alpha^2)} - \left(-\frac{-\alpha + c_L + c_M}{4\alpha}\right) = -\frac{(5+\alpha)(\alpha - c_L - c_M)}{4(-8+\alpha+\alpha^2)} > 0$

Under the Stackelberg decentralized market, by comparing the optimal and maximized profits with the benchmark traditional manufacturing system,

(1) For the logistics vendor's maximized profits,

$$\prod\nolimits_{(q_{3D}^{*}=0,S)}^{*} L(p_{3D}, p_L) - \prod\nolimits_{3DN}^{*} L(p_L)$$

$$= -\frac{(-16+\alpha(17+(-6+\alpha)\alpha))(-\alpha+c_L+c_M)^2}{8(8+(-7+\alpha)\alpha)^2} > 0$$

(2) For the traditional manufacturer's maximized profits,

$$\prod\nolimits_{(q_{3D}^{*}=0,S)}^{*} M(p_{\mathrm{M}}) - \prod\nolimits_{3DN}^{*} M(p_M)$$

$$= -\frac{(-16+(-11+\alpha)(-3+\alpha)\alpha)(-\alpha+c_L+c_M)^2}{16(8+(-7+\alpha)\alpha)^2}$$

Therefore,

$$\begin{cases} if \ -\frac{(-16+(-11+\alpha)(-3+\alpha)\alpha)}{16(8+(-7+\alpha)\alpha)^2} > 0, \prod\nolimits_{(q_{3D}^{*}=0,S)}^{*} M(p_{\mathrm{M}}) - \prod\nolimits_{3DN}^{*} M(p_M) > 0; \\ if \ -\frac{(-16+(-11+\alpha)(-3+\alpha)\alpha)}{16(8+(-7+\alpha)\alpha)^2} < 0, \prod\nolimits_{(q_{3D}^{*}=0,S)}^{*} M(p_{\mathrm{M}}) - \prod\nolimits_{3DN}^{*} M(p_M) < 0. \end{cases}$$

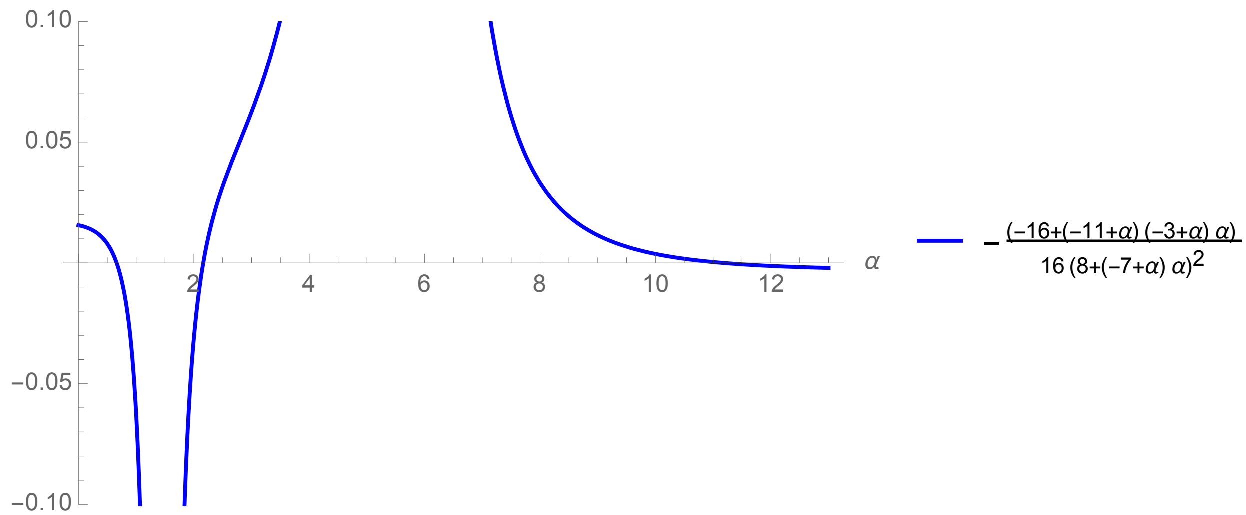
Then, set $-\frac{(-16+(-11+\alpha)(-3+\alpha)\alpha)}{16(8+(-7+\alpha)\alpha)^2} = 0$,

$$\alpha = \frac{1}{3}(14 + \frac{97}{(881+24i\sqrt{237})^{1/3}} + (881+24i\sqrt{237})^{1/3}) \approx 11.1751$$

$$\alpha = \frac{14}{3} - \frac{97(1+i\sqrt{3})}{6(881+24i\sqrt{237})^{1/3}} - \frac{1}{6}(1-i\sqrt{3})(881+24i\sqrt{237})^{1/3} \approx 2.16291$$

$$\alpha = \frac{14}{3} - \frac{97(1-i\sqrt{3})}{6(881+24i\sqrt{237})^{1/3}} - \frac{1}{6}(1+i\sqrt{3})(881+24i\sqrt{237})^{1/3} \approx 0.661956$$

Therefore, the value of $-\frac{(-16+(-11+\alpha)(-3+\alpha)\alpha)}{16(8+(-7+\alpha)\alpha)^2}$ can be simulated as below



Because 0< $\alpha < 1$,

if $0 < \alpha < \frac{14}{3} - \frac{97(1-i\sqrt{3})}{6(881+24i\sqrt{237})^{1/3}} - \frac{1}{6}(1+i\sqrt{3})(881+24i\sqrt{237})^{1/3}$, $\prod^*_{(q^*_{3D}=0,S)} M(p_{\mathrm{M}}) - \prod^*_{3DN} M(p_M) > 0$;

if $\frac{14}{3} - \frac{97(1-i\sqrt{3})}{6(881+24i\sqrt{237})^{1/3}} - \frac{1}{6}(1+i\sqrt{3})(881+24i\sqrt{237})^{1/3} < \alpha < 1$, $\prod^*_{(q^*_{3D}=0,S)} M(p_{\mathrm{M}}) - \prod^*_{3DN} M(p_M) < 0$.

(3) Based on Table 4-2, compare the optimal price and quantity,

p_L^*	$\frac{(-4+\alpha^2)c_L + (-4+\alpha)(\alpha - c_M)}{-8+\alpha+\alpha^2} - \frac{1}{2}(\alpha + c_L - c_M) = -\frac{(-1+\alpha)\alpha(\alpha - c_L - c_M)}{2(-8+\alpha+\alpha^2)} < 0$
p_M^*	$\frac{\alpha(6+(-6+\alpha)\alpha) - (-2+\alpha)c_L - (-2+\alpha)c_M}{8+(-7+\alpha)\alpha} - \frac{1}{4}(3\alpha + c_L + c_M) = \frac{(-3+\alpha)\alpha(\alpha - c_L - c_M)}{4(8+(-7+\alpha)\alpha)} < 0$
q_M^*	$-\frac{(-2+\alpha)(\alpha - c_L - c_M)}{\alpha(8+(-7+\alpha)\alpha)} - \left(-\frac{-\alpha + c_L + c_M}{4\alpha}\right) = -\frac{(-3+\alpha)(\alpha - c_L - c_M)}{4(8+(-7+\alpha)\alpha)} > 0$

Proof of *PROPOSITION* 4-20. Under the Bertrand decentralized market, by comparing the optimal and maximized profits with the decentralized 3DP enabled supply chain,

(1) For the logistics vendor's maximized profits,

$$\prod_{(q_{3D}^*=0,B)}^{*} L(p_{3D}, p_L) - \prod_{3DB}^{*} L(p_{3D}, p_L)$$

$$= \frac{1}{4}(-1 - \frac{(-8+\alpha(3+\alpha))c_{3D}^2}{(-1+\alpha)(8+\alpha)} + \frac{2c_{3D}((-1+\alpha)(8+\alpha) - 4c_L - 4c_M)}{(-1+\alpha)(8+\alpha)}$$

$$+ \frac{4(c_L+c_M)^2}{(-1+\alpha)\alpha(8+\alpha)} - \frac{4(-4+\alpha)(2+\alpha)(-\alpha+c_L+c_M)^2}{\alpha(-8+\alpha+\alpha^2)^2})$$

which is convex in c_{3D}, therefore, when the first-order-condition

$$\frac{\partial \prod_{(q_{3D}^*=0,B)}^{*} L(p_{3D}, p_L) - \prod_{3DB}^{*} L(p_{3D}, p_L)}{\partial c_{3D}}$$

$$= \frac{-8+7\alpha+\alpha^2 - (-8+\alpha(3+\alpha))c_{3D} - 4c_L - 4c_M}{2(-1+\alpha)(8+\alpha)} = 0$$

$$c_{3D}^* = \frac{(-1+\alpha)(8+\alpha) - 4(c_L+c_M)}{-8+\alpha(3+\alpha)}$$

There is the maximum value of

$$\prod_{(q_{3D}^*=0,B)}^{*} L(p_{3D}, p_L) - \prod_{3DB}^{*} L(p_{3D}, p_L) = \frac{(-1+\alpha)(8+\alpha)(-\alpha+c_L+c_M)^2}{(-8+\alpha+\alpha^2)^2(-8+\alpha(3+\alpha))} > 0$$

Set $\prod_{(q_{3D}^*=0,B)}^{*} L(p_{3D}, p_L) - \prod_{3DB}^{*} L(p_{3D}, p_L) = 0$

$$c_{3D1} = \frac{(-1+\alpha)(8+\alpha) - 6(c_L+c_M)}{-8+\alpha+\alpha^2}$$

$$c_{3D2} = \frac{(-1+\alpha)(8+\alpha)(-8+(-1+\alpha)\alpha) - 2(-8+(-5+\alpha)\alpha)(c_L+c_M)}{(-8+\alpha+\alpha^2)(-8+\alpha(3+\alpha))}$$

It is obvious that $\frac{c_L+c_M}{\alpha} < c_{3D1} < c_{3D2} < 1$

If $\frac{c_L+c_M}{\alpha} < c_{3D} < \frac{(-1+\alpha)(8+\alpha)-6(c_L+c_M)}{-8+\alpha+\alpha^2}$, $\prod_{(q_{3D}^*=0,B)}^{*} L(p_{3D}, p_L) - \prod_{3DB}^{*} L(p_{3D}, p_L) < 0$;

If $\frac{(-1+\alpha)(8+\alpha)-6(c_L+c_M)}{-8+\alpha+\alpha^2} < c_{3D} < \frac{(-1+\alpha)(8+\alpha)(-8+(-1+\alpha)\alpha)-2(-8+(-5+\alpha)\alpha)(c_L+c_M)}{(-8+\alpha+\alpha^2)(-8+\alpha(3+\alpha))}$, $\prod^*_{(q^*_{3D}=0,B)} L(p_{3D}, p_L) - \prod^*_{3DB} L(p_{3D}, p_L) > 0$;

If $\frac{(-1+\alpha)(8+\alpha)(-8+(-1+\alpha)\alpha)-2(-8+(-5+\alpha)\alpha)(c_L+c_M)}{(-8+\alpha+\alpha^2)(-8+\alpha(3+\alpha))} < c_{3D} < 1$, $\prod^*_{(q^*_{3D}=0,B)} L(p_{3D}, p_L) - \prod^*_{3DB} L(p_{3D}, p_L) < 0$.

(2) For the traditional manufacturer's maximized profits,

$$\prod\nolimits^*_{(q^*_{3D}=0,B)} M(p_\mathrm{M}) - \prod\nolimits^*_{3DB} M(p_M)$$

$$= \frac{\alpha(2+\alpha)^2 c_{3D}^2}{(-1+\alpha)(8+\alpha)^2} + \frac{(2+\alpha)^2 c_L^2}{(-1+\alpha)\alpha(8+\alpha)^2} + \frac{2(2+\alpha)^2 c_L c_M}{(-1+\alpha)\alpha(8+\alpha)^2}$$
$$+ \frac{(2+\alpha)^2 c_M^2}{(-1+\alpha)\alpha(8+\alpha)^2} - \frac{(-1+\alpha)(2+\alpha)^2(-\alpha+c_L+c_M)^2}{\alpha(-8+\alpha+\alpha^2)^2}$$
$$+ c_{3D}\left(-\frac{2(2+\alpha)^2 c_L}{(-1+\alpha)(8+\alpha)^2} - \frac{2(2+\alpha)^2 c_M}{(-1+\alpha)(8+\alpha)^2}\right)$$

which is convex in c_{3D}, therefore, when the first-order-condition

$$\frac{\partial \prod^*_{(q^*_{3D}=0,B)} M(p_\mathrm{M}) - \prod^*_{3DB} M(p_M)}{\partial c_{3D}} = -\frac{2(2+\alpha)^2(-\alpha c_{3D}+c_L+c_M)}{(-1+\alpha)(8+\alpha)^2} = 0$$

$$c^*_{3D} = \frac{c_L+c_M}{\alpha}$$

There is the maximum value of

$$\prod\nolimits^*_{(q^*_{3D}=0,B)} M(p_\mathrm{M}) - \prod\nolimits^*_{3DB} M(p_M) = -\frac{(-1+\alpha)(2+\alpha)^2(-\alpha+c_L+c_M)^2}{\alpha(-8+\alpha+\alpha^2)^2} > 0$$

Set $\prod^*_{(q^*_{3D}=0,B)} M(p_\mathrm{M}) - \prod^*_{3DB} M(p_M) = 0$

$$c_{3D1} = \frac{(-1+\alpha)(8+\alpha)-6(c_L+c_M)}{-8+\alpha+\alpha^2}$$
$$c_{3D2} = \frac{-(-1+\alpha)\alpha(8+\alpha)+2(-8+\alpha(4+\alpha))(c_L+c_M)}{\alpha(-8+\alpha+\alpha^2)}$$

It is obvious that $c_{3D2} < \frac{c_L+c_M}{\alpha} < c_{3D1} < 1$

If $\frac{c_L+c_M}{\alpha} < c_{3D} < \frac{(-1+\alpha)(8+\alpha)-6(c_L+c_M)}{-8+\alpha+\alpha^2}$, $\prod^*_{(q^*_{3D}=0,B)} M(p_M) - \prod^*_{3DB} M(p_M) > 0$;

If $\frac{(-1+\alpha)(8+\alpha)-6(c_L+c_M)}{-8+\alpha+\alpha^2} < c_{3D} < 1$, $\prod^*_{(q^*_{3D}=0,B)} M(p_M) - \prod^*_{3DB} M(p_M) < 0$.

(3) Compare the optimal price and quantity,

p_L^*	$\frac{(-4+\alpha^2)c_L+(-4+\alpha)(\alpha-c_M)}{-8+\alpha+\alpha^2} - \frac{\alpha(8+\alpha)-\alpha^2 c_{3D}+2(4+\alpha)c_L-8c_M}{2(8+\alpha)}$ $= -\frac{\alpha}{2} + \frac{\alpha^2 c_{3D}}{2(8+\alpha)} - \frac{(4+\alpha)c_L}{8+\alpha} + \frac{(-4+\alpha^2)c_L+(-4+\alpha)(\alpha-c_M)}{-8+\alpha+\alpha^2} + \frac{4c_M}{8+\alpha}$ If $\frac{c_L+c_M}{\alpha} < c_{3D} < \frac{(-1+\alpha)(8+\alpha)-6(c_L+c_M)}{-8+\alpha+\alpha^2}$, $\frac{(-4+\alpha^2)c_L+(-4+\alpha)(\alpha-c_M)}{-8+\alpha+\alpha^2} - \frac{\alpha(8+\alpha)-\alpha^2 c_{3D}+2(4+\alpha)c_L-8c_M}{2(8+\alpha)} < 0$; If $\frac{(-1+\alpha)(8+\alpha)-6(c_L+c_M)}{-8+\alpha+\alpha^2} < c_{3D} < 1$, $\frac{(-4+\alpha^2)c_L+(-4+\alpha)(\alpha-c_M)}{-8+\alpha+\alpha^2} - \frac{\alpha(8+\alpha)-\alpha^2 c_{3D}+2(4+\alpha)c_L-8c_M}{2(8+\alpha)} > 0$.
p_M^*	$\frac{\alpha(-6+\alpha(2+\alpha))-(2+\alpha)c_L-(2+\alpha)c_M}{-8+\alpha+\alpha^2} - \frac{\alpha(8+\alpha)+\alpha(4+\alpha)c_{3D}+4c_L+4c_M}{2(8+\alpha)}$ $= -\frac{\alpha}{2} - \frac{\alpha(4+\alpha)c_{3D}}{2(8+\alpha)} - \frac{2c_L}{8+\alpha} - \frac{2c_M}{8+\alpha} + \frac{\alpha(-6+\alpha(2+\alpha))-(2+\alpha)c_L-(2+\alpha)c_M}{-8+\alpha+\alpha^2}$ If $\frac{c_L+c_M}{\alpha} < c_{3D} < \frac{(-1+\alpha)(8+\alpha)-6(c_L+c_M)}{-8+\alpha+\alpha^2}$, $\frac{\alpha(-6+\alpha(2+\alpha))-(2+\alpha)c_L-(2+\alpha)c_M}{-8+\alpha+\alpha^2} - \frac{\alpha(8+\alpha)+\alpha(4+\alpha)c_{3D}+4c_L+4c_M}{2(8+\alpha)} > 0$; If $\frac{(-1+\alpha)(8+\alpha)-6(c_L+c_M)}{-8+\alpha+\alpha^2} < c_{3D} < 1$, $\frac{\alpha(-6+\alpha(2+\alpha))-(2+\alpha)c_L-(2+\alpha)c_M}{-8+\alpha+\alpha^2} - \frac{\alpha(8+\alpha)+\alpha(4+\alpha)c_{3D}+4c_L+4c_M}{2(8+\alpha)} < 0$.

p_{3D}^*	$-\frac{8-\alpha(3+2\alpha)+(2+\alpha)c_L+(2+\alpha)c_M}{-8+\alpha+\alpha^2}-\frac{8+\alpha+(8+3\alpha)c_{3D}-2c_L-2c_M}{2(8+\alpha)}$ $=-\frac{4}{8+\alpha}-\frac{\alpha}{2(8+\alpha)}-\frac{(8+3\alpha)c_{3D}}{2(8+\alpha)}+\frac{c_L}{8+\alpha}+\frac{c_M}{8+\alpha}-\frac{8-\alpha(3+2\alpha)+(2+\alpha)c_L+(2+\alpha)c_M}{-8+\alpha+\alpha^2}$ If $\frac{c_L+c_M}{\alpha}<c_{3D}<\frac{(-1+\alpha)(8+\alpha)-6(c_L+c_M)}{-8+\alpha+\alpha^2}, -\frac{8-\alpha(3+2\alpha)+(2+\alpha)c_L+(2+\alpha)c_M}{-8+\alpha+\alpha^2}-\frac{8+\alpha+(8+3\alpha)c_{3D}-2c_L-2c_M}{2(8+\alpha)}>0$; If $\frac{(-1+\alpha)(8+\alpha)-6(c_L+c_M)}{-8+\alpha+\alpha^2}<c_{3D}<1, -\frac{8-\alpha(3+2\alpha)+(2+\alpha)c_L+(2+\alpha)c_M}{-8+\alpha+\alpha^2}-\frac{8+\alpha+(8+3\alpha)c_{3D}-2c_L-2c_M}{2(8+\alpha)}<0$.
q_M^*	$-\frac{(2+\alpha)(\alpha-c_L-c_M)}{\alpha(-8+\alpha+\alpha^2)}-\left(-\frac{(2+\alpha)(\alpha c_{3D}-c_L-c_M)}{(-1+\alpha)\alpha(8+\alpha)}\right)$ $=\frac{(2+\alpha)c_{3D}}{(-1+\alpha)(8+\alpha)}-\frac{(2+\alpha)c_L}{(-1+\alpha)\alpha(8+\alpha)}-\frac{(2+\alpha)(\alpha-c_L-c_M)}{\alpha(-8+\alpha+\alpha^2)}-\frac{(2+\alpha)c_M}{(-1+\alpha)\alpha(8+\alpha)}$ If $\frac{c_L+c_M}{\alpha}<c_{3D}<\frac{(-1+\alpha)(8+\alpha)-6(c_L+c_M)}{-8+\alpha+\alpha^2}, -\frac{(2+\alpha)(\alpha-c_L-c_M)}{\alpha(-8+\alpha+\alpha^2)}-\left(-\frac{(2+\alpha)(\alpha c_{3D}-c_L-c_M)}{(-1+\alpha)\alpha(8+\alpha)}\right)>0$; If $\frac{(-1+\alpha)(8+\alpha)-6(c_L+c_M)}{-8+\alpha+\alpha^2}<c_{3D}<1, -\frac{(2+\alpha)(\alpha-c_L-c_M)}{\alpha(-8+\alpha+\alpha^2)}-\left(-\frac{(2+\alpha)(\alpha c_{3D}-c_L-c_M)}{(-1+\alpha)\alpha(8+\alpha)}\right)<0$.

(4) For the integrated Bertrand supply chain's maximized profits,

$$\prod_{(q_{3D}^*=0,B)}^{*}SC(p_{\mathrm{M}},p_{3D})-\prod_{3DB}^{*}SC(p_{\mathrm{M}},p_{3D})=\frac{(1-\alpha-c_{3D}+c_L+c_M)^2}{4(-1+\alpha)}<0$$

(5) Compare the optimal price and quantity,

p_M^*	$\frac{1}{2}(\alpha+c_L+c_M)-\frac{1}{2}(\alpha+c_L+c_M)=0$
p_{3D}^*	$\frac{1}{2}(2-\alpha+c_L+c_M)-\frac{1}{2}(1+c_{3D})=\frac{1}{2}(1-\alpha-c_{3D}+c_L+c_M)$ If $\frac{c_L+c_M}{\alpha}<c_{3D}<1-\alpha+c_L+c_M, \frac{1}{2}(1-\alpha-c_{3D}+c_L+c_M)>0$; If $1-\alpha+c_L+c_M<c_{3D}<1, \frac{1}{2}(1-\alpha-c_{3D}+c_L+c_M)<0$.

q_M^*	$-\frac{-\alpha + c_L + c_M}{2\alpha} - \frac{-\alpha c_{3D} + c_L + c_M}{2(-1+\alpha)\alpha} = \frac{1 - \alpha - c_{3D} + c_L + c_M}{2 - 2\alpha}$ If $\frac{c_L + c_M}{\alpha} < c_{3D} < 1 - \alpha + c_L + c_M, \frac{1-\alpha-c_{3D}+c_L+c_M}{2-2\alpha} > 0$; If $1 - \alpha + c_L + c_M < c_{3D} < 1, \frac{1-\alpha-c_{3D}+c_L+c_M}{2-2\alpha} < 0$.

Under the Stackelberg decentralized market, by comparing the optimal and maximized profits with the decentralized 3DP enabled supply chain,

(1) For the logistics vendor's maximized profits,

$$\prod\nolimits^*_{(q^*_{3D}=0,S)} L(p_{3D}, p_L) - \prod\nolimits^*_{3DS} L(p_{3D}, p_L)$$

$$= -\frac{1}{4} - \frac{(-8 + (9 - 2\alpha)\alpha)c_{3D}^2}{4(-1+\alpha)(8 + (-5+\alpha)\alpha)} + \frac{(-2+\alpha)^2(c_L + c_M)^2}{4(-1+\alpha)\alpha(8 + (-5+\alpha)\alpha)}$$

$$- \frac{(-2+\alpha)^3(-\alpha + c_L + c_M)^2}{\alpha(8 + (-7+\alpha)\alpha)^2}$$

$$- \frac{c_{3D}((1-\alpha)(8 + (-5+\alpha)\alpha) + (-2+\alpha)^2 c_L + (-2+\alpha)^2 c_M)}{2(-1+\alpha)(8 + (-5+\alpha)\alpha)}$$

which is convex in c_{3D}, therefore, when the first-order-condition

$$\frac{\partial \prod^*_{(q^*_{3D}=0,S)} L(p_{3D}, p_L) - \prod^*_{3DS} L(p_{3D}, p_L)}{\partial c_{3D}}$$

$$= -\frac{-(-1+\alpha)(8 + (-5+\alpha)\alpha) + (-8 + (9-2\alpha)\alpha)c_{3D} + (-2+\alpha)^2 c_L + (-2+\alpha)^2 c_M}{2(-1+\alpha)(8 + (-5+\alpha)\alpha)}$$

$$= 0$$

$$c_{3D}^* = \frac{-(-1+\alpha)(8 + (-5+\alpha)\alpha) + (-2+\alpha)^2(c_L + c_M)}{8 + \alpha(-9 + 2\alpha)}$$

There is the maximum value of

$$\prod\nolimits^*_{(q^*_{3D}=0,S)} L(p_{3D}, p_L) - \prod\nolimits^*_{3DS} L(p_{3D}, p_L)$$

$$= -\frac{(-2+\alpha)^2(-1+\alpha)(8 + (-5+\alpha)\alpha)(-\alpha + c_L + c_M)^2}{4(8 + (-7+\alpha)\alpha)^2(8 + \alpha(-9+2\alpha))} > 0$$

Set $\prod^*_{(q^*_{3D}=0,S)} L(p_{3D}, p_L) - \prod^*_{3DS} L(p_{3D}, p_L) = 0$

$$c_{3D1} = \frac{-(-1+\alpha)(8+(-5+\alpha)\alpha)+(-3+\alpha)(-2+\alpha)(c_L+c_M)}{8+(-7+\alpha)\alpha}$$

$$c_{3D2} = \frac{(-1+\alpha)(-8+5\alpha)(8+(-5+\alpha)\alpha)-(-2+\alpha)(8+3(-3+\alpha)\alpha)(c_L+c_M)}{(8+(-7+\alpha)\alpha)(8+\alpha(-9+2\alpha))}$$

It is obvious that $\frac{c_L+c_M}{\alpha} < c_{3D1} < c_{3D2} < 1$

If $\frac{c_L+c_M}{\alpha} < c_{3D} < \frac{-(-1+\alpha)(8+(-5+\alpha)\alpha)+(-3+\alpha)(-2+\alpha)(c_L+c_M)}{8+(-7+\alpha)\alpha}$, $\prod^*_{(q^*_{3D}=0,S)} L(p_{3D},p_L) - \prod^*_{3DS} L(p_{3D},p_L) < 0$;

If $\frac{-(-1+\alpha)(8+(-5+\alpha)\alpha)+(-3+\alpha)(-2+\alpha)(c_L+c_M)}{8+(-7+\alpha)\alpha} < c_{3D} < \frac{(-1+\alpha)(-8+5\alpha)(8+(-5+\alpha)\alpha)-(-2+\alpha)(8+3(-3+\alpha)\alpha)(c_L+c_M)}{(8+(-7+\alpha)\alpha)(8+\alpha(-9+2\alpha))}$, $\prod^*_{(q^*_{3D}=0,S)} L(p_{3D},p_L) - \prod^*_{3DS} L(p_{3D},p_L) > 0$;

If $\frac{(-1+\alpha)(-8+5\alpha)(8+(-5+\alpha)\alpha)-(-2+\alpha)(8+3(-3+\alpha)\alpha)(c_L+c_M)}{(8+(-7+\alpha)\alpha)(8+\alpha(-9+2\alpha))} < c_{3D} < 1$, $\prod^*_{(q^*_{3D}=0,S)} L(p_{3D},p_L) - \prod^*_{3DS} L(p_{3D},p_L) < 0$.

(2) For the traditional manufacturer's maximized profits,

$$\prod\nolimits^*_{(q^*_{3D}=0,S)} M(p_{\mathrm{M}}) - \prod\nolimits^*_{3DS} M(p_M)$$
$$= -\frac{2(-2+\alpha)\alpha c_{3D}^2}{(-1+\alpha)(8+(-5+\alpha)\alpha)^2} - \frac{2(-2+\alpha)c_L^2}{(-1+\alpha)\alpha(8+(-5+\alpha)\alpha)^2}$$
$$- \frac{4(-2+\alpha)c_L c_M}{(-1+\alpha)\alpha(8+(-5+\alpha)\alpha)^2} - \frac{2(-2+\alpha)c_M^2}{(-1+\alpha)\alpha(8+(-5+\alpha)\alpha)^2}$$
$$+ \frac{2(-2+\alpha)(-1+\alpha)(-\alpha+c_L+c_M)^2}{\alpha(8+(-7+\alpha)\alpha)^2}$$
$$+ c_{3D}\left(\frac{4(-2+\alpha)c_L}{(-1+\alpha)(8+(-5+\alpha)\alpha)^2} + \frac{4(-2+\alpha)c_M}{(-1+\alpha)(8+(-5+\alpha)\alpha)^2}\right)$$

which is convex in c_{3D}, therefore, when the first-order-condition

$$\frac{\partial \prod^*_{(q^*_{3D}=0,S)} M(p_{\mathrm{M}}) - \prod^*_{3DS} M(p_M)}{\partial c_{3D}} = \frac{4(-2+\alpha)(-\alpha c_{3D}+c_L+c_M)}{(-1+\alpha)(8+(-5+\alpha)\alpha)^2} = 0$$

$$c^*_{3D} = \frac{c_L+c_M}{\alpha}$$

There is the maximum value of

$$\prod\nolimits_{(q_{3D}^*=0,S)}^{*} M(p_{\mathrm{M}}) - \prod\nolimits_{3DS}^{*} M(p_M) = \frac{2(-2+\alpha)(-1+\alpha)(-\alpha+c_L+c_M)^2}{\alpha(8+(-7+\alpha)\alpha)^2} > 0$$

Set $\prod_{(q_{3D}^*=0,S)}^{*} M(p_{\mathrm{M}}) - \prod_{3DS}^{*} M(p_M) = 0$,

$$c_{3D1} = \frac{-(-1+\alpha)(8+(-5+\alpha)\alpha)+(-3+\alpha)(-2+\alpha)(c_L+c_M)}{8+(-7+\alpha)\alpha}$$

$$c_{3D2} = \frac{(-1+\alpha)\alpha(8+(-5+\alpha)\alpha)-(-16+\alpha(20+(-7+\alpha)\alpha))(c_L+c_M)}{\alpha(8+(-7+\alpha)\alpha)}$$

It is obvious that $c_{3D2} < \frac{c_L+c_M}{\alpha} < c_{3D1} < 1$.

If $\frac{c_L+c_M}{\alpha} < c_{3D} < \frac{-(-1+\alpha)(8+(-5+\alpha)\alpha)+(-3+\alpha)(-2+\alpha)(c_L+c_M)}{8+(-7+\alpha)\alpha}$, $\prod_{(q_{3D}^*=0,S)}^{*} M(p_{\mathrm{M}}) - \prod_{3DS}^{*} M(p_M) > 0$;

If $\frac{-(-1+\alpha)(8+(-5+\alpha)\alpha)+(-3+\alpha)(-2+\alpha)(c_L+c_M)}{8+(-7+\alpha)\alpha} < c_{3D} < 1$, $\prod_{(q_{3D}^*=0,S)}^{*} M(p_{\mathrm{M}}) - \prod_{3DS}^{*} M(p_M) < 0$.

(3) Compare the optimal price and quantity,

<table>
<tr>
<td>p_L^*</td>
<td>$$\frac{(-4+\alpha^2)c_L+(-4+\alpha)(\alpha-c_M)}{-8+\alpha+\alpha^2} - \frac{\alpha(6+(-6+\alpha)\alpha)-(-2+\alpha)c_L-(-2+\alpha)c_M}{8+(-7+\alpha)\alpha}$$
$$= -\frac{\alpha}{2} + \frac{\alpha^2 c_{3D}}{2(8+(-5+\alpha)\alpha)} - \frac{(8+(-4+\alpha)\alpha)c_L}{2(8+(-5+\alpha)\alpha)} + \frac{(-4+\alpha^2)c_L+(-4+\alpha)(\alpha-c_M)}{-8+\alpha+\alpha^2} + \frac{(-4+\alpha)(-2+\alpha)c_M}{2(8+(-5+\alpha)\alpha)}$$
If $\frac{c_L+c_M}{\alpha} < c_{3D} < \frac{(-1+\alpha)(8+(-5+\alpha)\alpha)-(-4+\alpha)(-3+\alpha)(c_L+c_M)}{-8+\alpha+\alpha^2}$, $\frac{(-4+\alpha^2)c_L+(-4+\alpha)(\alpha-c_M)}{-8+\alpha+\alpha^2} - \frac{\alpha(6+(-6+\alpha)\alpha)-(-2+\alpha)c_L-(-2+\alpha)c_M}{8+(-7+\alpha)\alpha} < 0$;
If $\frac{(-1+\alpha)(8+(-5+\alpha)\alpha)-(-4+\alpha)(-3+\alpha)(c_L+c_M)}{-8+\alpha+\alpha^2} < c_{3D} < 1$, $\frac{(-4+\alpha^2)c_L+(-4+\alpha)(\alpha-c_M)}{-8+\alpha+\alpha^2} - \frac{\alpha(6+(-6+\alpha)\alpha)-(-2+\alpha)c_L-(-2+\alpha)c_M}{8+(-7+\alpha)\alpha} > 0$.</td>
</tr>
</table>

p_M^*	$\frac{\alpha(6+(-6+\alpha)\alpha)-(-2+\alpha)c_L-(-2+\alpha)c_M}{8+(-7+\alpha)\alpha} - \frac{\alpha(8+(-5+\alpha)\alpha)-(-4+\alpha)\alpha c_{3D}+(-2+\alpha)^2c_L+(-2+\alpha)^2c_M}{2(8+(-5+\alpha)\alpha)} = -\frac{\alpha}{2}+\frac{(-4+\alpha)\alpha c_{3D}}{2(8+(-5+\alpha)\alpha)}-\frac{(-2+\alpha)^2c_L}{2(8+(-5+\alpha)\alpha)}-\frac{(-2+\alpha)^2c_M}{2(8+(-5+\alpha)\alpha)} + \frac{\alpha(6+(-6+\alpha)\alpha)-(-2+\alpha)c_L-(-2+\alpha)c_M}{8+(-7+\alpha)\alpha}$ If $\frac{c_L+c_M}{\alpha} < c_{3D} < \frac{-(-1+\alpha)(8+(-5+\alpha)\alpha)+(-3+\alpha)(-2+\alpha)(c_L+c_M)}{8+(-7+\alpha)\alpha}$, $\frac{\alpha(6+(-6+\alpha)\alpha)-(-2+\alpha)c_L-(-2+\alpha)c_M}{8+(-7+\alpha)\alpha} - \frac{\alpha(8+(-5+\alpha)\alpha)-(-4+\alpha)\alpha c_{3D}+(-2+\alpha)^2c_L+(-2+\alpha)^2c_M}{2(8+(-5+\alpha)\alpha)} > 0$; If $\frac{-(-1+\alpha)(8+(-5+\alpha)\alpha)+(-3+\alpha)(-2+\alpha)(c_L+c_M)}{8+(-7+\alpha)\alpha} < c_{3D} < 1$, $\frac{\alpha(6+(-6+\alpha)\alpha)-(-2+\alpha)c_L-(-2+\alpha)c_M}{8+(-7+\alpha)\alpha} - \frac{\alpha(8+(-5+\alpha)\alpha)-(-4+\alpha)\alpha c_{3D}+(-2+\alpha)^2c_L+(-2+\alpha)^2c_M}{2(8+(-5+\alpha)\alpha)} < 0$.
p_{3D}^*	$\frac{8+\alpha(-9+2\alpha)-(-2+\alpha)c_L-(-2+\alpha)c_M}{8+(-7+\alpha)\alpha} - \frac{8+(-5+\alpha)\alpha+(8-3\alpha)c_{3D}+(-2+\alpha)c_L+(-2+\alpha)c_M}{2(8+(-5+\alpha)\alpha)} = -\frac{4}{8+(-5+\alpha)\alpha}-\frac{(-5+\alpha)\alpha}{2(8+(-5+\alpha)\alpha)}+\frac{(-8+3\alpha)c_{3D}}{2(8+(-5+\alpha)\alpha)} - \frac{(-2+\alpha)c_L}{2(8+(-5+\alpha)\alpha)}-\frac{(-2+\alpha)c_M}{2(8+(-5+\alpha)\alpha)} + \frac{8+\alpha(-9+2\alpha)-(-2+\alpha)c_L-(-2+\alpha)c_M}{8+(-7+\alpha)\alpha}$ If $\frac{c_L+c_M}{\alpha} < c_{3D} < \frac{-(-1+\alpha)(8+(-5+\alpha)\alpha)+(-3+\alpha)(-2+\alpha)(c_L+c_M)}{8+(-7+\alpha)\alpha}$, $\frac{8+\alpha(-9+2\alpha)-(-2+\alpha)c_L-(-2+\alpha)c_M}{8+(-7+\alpha)\alpha} - \frac{8+(-5+\alpha)\alpha+(8-3\alpha)c_{3D}+(-2+\alpha)c_L+(-2+\alpha)c_M}{2(8+(-5+\alpha)\alpha)} > 0$; If $\frac{-(-1+\alpha)(8+(-5+\alpha)\alpha)+(-3+\alpha)(-2+\alpha)(c_L+c_M)}{8+(-7+\alpha)\alpha} < c_{3D} < 1$, $\frac{8+\alpha(-9+2\alpha)-(-2+\alpha)c_L-(-2+\alpha)c_M}{8+(-7+\alpha)\alpha} - \frac{8+(-5+\alpha)\alpha+(8-3\alpha)c_{3D}+(-2+\alpha)c_L+(-2+\alpha)c_M}{2(8+(-5+\alpha)\alpha)} < 0$.

q_M^*	$$-\frac{(-2+\alpha)(\alpha-c_L-c_M)}{\alpha(8+(-7+\alpha)\alpha)}-\frac{(-2+\alpha)(\alpha c_{3D}-c_L-c_M)}{(-1+\alpha)\alpha(8+(-5+\alpha)\alpha)}$$ $$=\frac{(2-\alpha)c_{3D}}{(-1+\alpha)(8+(-5+\alpha)\alpha)}-\frac{(2-\alpha)c_L}{(-1+\alpha)\alpha(8+(-5+\alpha)\alpha)}$$ $$-\frac{(-2+\alpha)(\alpha-c_L-c_M)}{\alpha(8+(-7+\alpha)\alpha)}-\frac{(2-\alpha)c_M}{(-1+\alpha)\alpha(8+(-5+\alpha)\alpha)}$$ If $\frac{c_L+c_M}{\alpha}<c_{3D}<\frac{-(-1+\alpha)(8+(-5+\alpha)\alpha)+(-3+\alpha)(-2+\alpha)(c_L+c_M)}{8+(-7+\alpha)\alpha}, -\frac{(-2+\alpha)(\alpha-c_L-c_M)}{\alpha(8+(-7+\alpha)\alpha)}-\frac{(-2+\alpha)(\alpha c_{3D}-c_L-c_M)}{(-1+\alpha)\alpha(8+(-5+\alpha)\alpha)}>0$; If $\frac{-(-1+\alpha)(8+(-5+\alpha)\alpha)+(-3+\alpha)(-2+\alpha)(c_L+c_M)}{8+(-7+\alpha)\alpha}<c_{3D}<1, -\frac{(-2+\alpha)(\alpha-c_L-c_M)}{\alpha(8+(-7+\alpha)\alpha)}-\frac{(-2+\alpha)(\alpha c_{3D}-c_L-c_M)}{(-1+\alpha)\alpha(8+(-5+\alpha)\alpha)}<0$.

For the integrated supply chain, there is not difference between Bertrand and Stackelberg, so we take Bertrand as the sample for test. First, for the supply chain's maximized profits,

$$\prod\nolimits_{(q_{3D}^*=0,B)}^{*} SC(p_{\mathrm{M}},p_{3D})-\prod\nolimits_{3DB}^{*} SC(p_{\mathrm{M}},p_{3D})=\frac{(1-\alpha-c_{3D}+c_L+c_M)^2}{4(-1+\alpha)}<0$$

Second, compare the optimal price and quantity,

p_M^*	$$\frac{1}{2}(\alpha+c_L+c_M)-\frac{1}{2}(\alpha+c_L+c_M)=0$$
p_{3D}^*	$$\frac{1}{2}(2-\alpha+c_L+c_M)-\frac{1}{2}(1+c_{3D})=\frac{1}{2}(1-\alpha-c_{3D}+c_L+c_M)$$ If $\frac{c_L+c_M}{\alpha}<c_{3D}<1-\alpha+c_L+c_M, \frac{1}{2}(1-\alpha-c_{3D}+c_L+c_M)>0$; If $1-\alpha+c_L+c_M<c_{3D}<1, \frac{1}{2}(1-\alpha-c_{3D}+c_L+c_M)<0$.
q_M^*	$$-\frac{-\alpha+c_L+c_M}{2\alpha}-\frac{-\alpha c_{3D}+c_L+c_M}{2(-1+\alpha)\alpha}=\frac{1-\alpha-c_{3D}+c_L+c_M}{2-2\alpha}$$ If $\frac{c_L+c_M}{\alpha}<c_{3D}<1-\alpha+c_L+c_M, \frac{1-\alpha-c_{3D}+c_L+c_M}{2-2\alpha}>0$; If $1-\alpha+c_L+c_M<c_{3D}<1, \frac{1-\alpha-c_{3D}+c_L+c_M}{2-2\alpha}<0$.

Proof of *PROPOSITION* 4-21. In a decentralized traditional manufacturing system, according to Equation (4.13),

(1) As CS_{3DND} is concave in c_M. Therefore, the first-order-condition

$$\frac{\partial CS_{3DND}}{\partial c_M} = \frac{1}{16}(-4 - 3(-2+\alpha)\alpha - (-2+\alpha)c_L - (-2+\alpha)c_M) = 0$$

$$c_M^* = -\frac{4}{-2+\alpha} - 3\alpha - c_L > \alpha - c_L$$

Because $c_L + c_M < \alpha < 1$, therefore, CS_{3DND} decreases in c_M.

(2) CS_{3DND} is concave in c_L, the first-order-condition

$$\frac{\partial CS_{3DND}}{\partial c_L} = \frac{1}{16}(-4 - 3(-2+\alpha)\alpha - (-2+\alpha)c_L - (-2+\alpha)c_M) = 0$$

$$c_L^* = -\frac{4}{-2+\alpha} - 3\alpha - c_M > \alpha - c_M$$

Because $c_L + c_M < \alpha < 1$, therefore, CS_{3DND} decreases in c_L.

In an integrated traditional manufacturing system, according to Equation (4.14),

(1) As CS_{3DNI} is concave in c_M. Therefore, the first-order-condition

$$\frac{\partial CS_{3DNI}}{\partial c_M} = \frac{1}{4}(-2 - (-2+\alpha)\alpha - (-2+\alpha)c_L - (-2+\alpha)c_M) = 0$$

$$c_M^* = -\frac{2}{-2+\alpha} - \alpha - c_L > \alpha - c_L$$

Because $c_L + c_M < \alpha < 1$, therefore, CS_{3DNI} decreases in c_M.

(2) CS_{3DNI} is concave in c_L, the first-order-condition

$$\frac{\partial CS_{3DNI}}{\partial c_L} = \frac{1}{4}(-2 - (-2+\alpha)\alpha - (-2+\alpha)c_L - (-2+\alpha)c_M) = 0$$

$$c_L^* = -\frac{2}{-2+\alpha} - \alpha - c_M > \alpha - c_L$$

Because $c_L + c_M < \alpha < 1$, therefore, CS_{3DNI} decreases in c_L.

In a 3DB enabled decentralized Bertrand market, according to Equation (4.15),

(1) CS_{3DB} is concave in c_M. Therefore, the first-order-condition

$$\frac{\partial CS_{3DB}}{\partial c_M} = \frac{1}{2(8+\alpha)^2}(-(8+\alpha)(3+2(-2+\alpha)\alpha) - (8+\alpha(-13+2\alpha(2+\alpha)))c_{3D} + (18-8\alpha)c_L + 2(9-4\alpha)c_M) = 0$$

$$c_M^* = \frac{-(8+\alpha)(3+2(-2+\alpha)\alpha) - (8+\alpha(-13+2\alpha(2+\alpha)))c_{3D} + (18-8\alpha)c_L}{-18+8\alpha}$$

Because $c_L + c_M < \alpha < 1$, therefore,

If $\frac{-(8+\alpha)(3+2(-2+\alpha)\alpha)-(8+\alpha(-13+2\alpha(2+\alpha)))c_{3D}+(18-8\alpha)c_L}{-18+8\alpha} > \alpha - c_L$, that is $c_{3D} > \frac{-24+\alpha(47-2\alpha(10+\alpha))}{8+\alpha(-13+2\alpha(2+\alpha))}$, CS_{3DB} decreases in c_M;

If $\frac{-(8+\alpha)(3+2(-2+\alpha)\alpha)-(8+\alpha(-13+2\alpha(2+\alpha)))c_{3D}+(18-8\alpha)c_L}{-18+8\alpha} < \alpha - c_L$, that is $c_{3D} < \frac{-24+\alpha(47-2\alpha(10+\alpha))}{8+\alpha(-13+2\alpha(2+\alpha))}$,

a) If $c_M < \frac{-(8+\alpha)(3+2(-2+\alpha)\alpha)-(8+\alpha(-13+2\alpha(2+\alpha)))c_{3D}+(18-8\alpha)c_L}{-18+8\alpha}$ CS_{3DB} decreases in c_M;

b) If $\frac{-(8+\alpha)(3+2(-2+\alpha)\alpha)-(8+\alpha(-13+2\alpha(2+\alpha)))c_{3D}+(18-8\alpha)c_L}{-18+8\alpha} < c_M < \alpha - c_L$, CS_{3DB} increases in c_M.

(2) Equation (4.15) CS_{3DB} is concave in c_L. Therefore, the first-order-condition

Therefore, the first-order-condition

$$\frac{\partial CS_{3DB}}{\partial c_L} = \frac{1}{2(8+\alpha)^2}(-(8+\alpha)(3+2(-2+\alpha)\alpha) - (8+\alpha(-13+2\alpha(2+\alpha)))c_{3D} + (18-8\alpha)c_L + 2(9-4\alpha)c_M) = 0$$

$$c_L^* = \frac{-(8+\alpha)(3+2(-2+\alpha)\alpha) - (8+\alpha(-13+2\alpha(2+\alpha)))c_{3D} + (18-8\alpha)c_M}{-18+8\alpha}$$

Because $c_L + c_M < \alpha < 1$, therefore,

If $\frac{-(8+\alpha)(3+2(-2+\alpha)\alpha)-(8+\alpha(-13+2\alpha(2+\alpha)))c_{3D}+(18-8\alpha)c_M}{-18+8\alpha} > \alpha - c_M$, that is $c_{3D} > \frac{-24+\alpha(47-2\alpha(10+\alpha))}{8+\alpha(-13+2\alpha(2+\alpha))}$, CS_{3DB} decreases in c_L;

If $\frac{-(8+\alpha)(3+2(-2+\alpha)\alpha)-(8+\alpha(-13+2\alpha(2+\alpha)))c_{3D}+(18-8\alpha)c_M}{-18+8\alpha} < \alpha - c_M$, that is $c_{3D} <$ $\frac{-24+\alpha(47-2\alpha(10+\alpha))}{8+\alpha(-13+2\alpha(2+\alpha))}$,

a) If $c_L < \frac{-(8+\alpha)(3+2(-2+\alpha)\alpha)-(8+\alpha(-13+2\alpha(2+\alpha)))c_{3D}+(18-8\alpha)c_M}{-18+8\alpha}$, CS_{3DB} decreases in c_L;

b) If $\frac{-(8+\alpha)(3+2(-2+\alpha)\alpha)-(8+\alpha(-13+2\alpha(2+\alpha)))c_{3D}+(18-8\alpha)c_M}{-18+8\alpha} < c_L < \alpha - c_M$, CS_{3DB} increases in c_L.

(3) Equation (4.15) CS_{3DB} is concave in c_{3D}. Therefore, the first-order-condition,

$$\frac{\partial CS_{3DB}}{\partial c_{3D}} = -\frac{1}{4(8+\alpha)^2}((8+\alpha)(8+\alpha(11+\alpha(-6+\alpha(2+\alpha)))) + (-64+\alpha(-48 - 41\alpha + 6\alpha^3 + \alpha^4))c_{3D} + 16c_L + 16c_M + 2\alpha(-13+2\alpha(2+\alpha))(c_L + c_M)) = 0$$

$$c_{3D}^* = -\frac{(8+\alpha)(8+\alpha(11+\alpha(-6+\alpha(2+\alpha)))) + 2(8+\alpha(-13+2\alpha(2+\alpha)))(c_L+c_M)}{-64+\alpha(-48-41\alpha+6\alpha^3+\alpha^4)} > \frac{c_L + c_M}{\alpha}$$

Therefore,

a) If $\frac{c_L+c_M}{\alpha} < c_{3D} < -\frac{(8+\alpha)(8+\alpha(11+\alpha(-6+\alpha(2+\alpha))))+2(8+\alpha(-13+2\alpha(2+\alpha)))(c_L+c_M)}{-64+\alpha(-48-41\alpha+6\alpha^3+\alpha^4)}$, CS_{3DB} decreases in c_{3D};

b) If $-\frac{(8+\alpha)(8+\alpha(11+\alpha(-6+\alpha(2+\alpha))))+2(8+\alpha(-13+2\alpha(2+\alpha)))(c_L+c_M)}{-64+\alpha(-48-41\alpha+6\alpha^3+\alpha^4)} < c_{3D} < 1$, CS_{3DB} increases in c_{3D}.

In a 3DB enabled decentralized Stackelberg market, according to Equation (4.16),

(1) CS_{3DS} is concave in c_M. Therefore, the first-order-condition

$$\frac{\partial CS_{3DS}}{\partial c_M} = \frac{1}{4(8+(-5+\alpha)\alpha)^2}((-2+\alpha)((8+\alpha(-19+\alpha(20+(-8+\alpha)\alpha)))c_{3D} - (3 + (-3+\alpha)\alpha)((-1+\alpha)(8+(-5+\alpha)\alpha) + (-3+\alpha)(-2+\alpha)c_L + (-3 + \alpha)(-2+\alpha)c_M))) = 0$$

$$c_M^* = \frac{1}{(-3+\alpha)(-2+\alpha)(3+(-3+\alpha)\alpha)}((8+\alpha(-19+\alpha(20+(-8+\alpha)\alpha)))c_{3D} - (3+(-3+\alpha)\alpha)((-1+\alpha)(8+(-5+\alpha)\alpha)+(-3+\alpha)(-2+\alpha)c_L))$$

Because $c_L + c_M < \alpha < 1$, therefore,

If $\frac{1}{(-3+\alpha)(-2+\alpha)(3+(-3+\alpha)\alpha)}((8+\alpha(-19+\alpha(20+(-8+\alpha)\alpha)))c_{3D} - (3+(-3+\alpha)\alpha)((-1+\alpha)(8+(-5+\alpha)\alpha)+(-3+\alpha)(-2+\alpha)c_L)) > \alpha - c_L$, that is

$c_{3D} > \frac{(3+(-3+\alpha)\alpha)(-8+\alpha(19+\alpha(-11+2\alpha)))}{8+\alpha(-19+\alpha(20+(-8+\alpha)\alpha))}$, CS_{3DS} decreases in c_M;

If $\frac{1}{(-3+\alpha)(-2+\alpha)(3+(-3+\alpha)\alpha)}((8+\alpha(-19+\alpha(20+(-8+\alpha)\alpha)))c_{3D} - (3+(-3+\alpha)\alpha)((-1+\alpha)(8+(-5+\alpha)\alpha)+(-3+\alpha)(-2+\alpha)c_L)) > \alpha - c_L$, that is

$c_{3D} < \frac{(3+(-3+\alpha)\alpha)(-8+\alpha(19+\alpha(-11+2\alpha)))}{8+\alpha(-19+\alpha(20+(-8+\alpha)\alpha))}$,

a) If $c_M < \frac{1}{(-3+\alpha)(-2+\alpha)(3+(-3+\alpha)\alpha)}((8+\alpha(-19+\alpha(20+(-8+\alpha)\alpha)))c_{3D} - (3+(-3+\alpha)\alpha)((-1+\alpha)(8+(-5+\alpha)\alpha)+(-3+\alpha)(-2+\alpha)c_L))$, CS_{3DS} decreases in c_M;

b) If $\frac{1}{(-3+\alpha)(-2+\alpha)(3+(-3+\alpha)\alpha)}((8+\alpha(-19+\alpha(20+(-8+\alpha)\alpha)))c_{3D} - (3+(-3+\alpha)\alpha)((-1+\alpha)(8+(-5+\alpha)\alpha)+(-3+\alpha)(-2+\alpha)c_L)) < c_M < \alpha - c_L$, CS_{3DS} increases in c_M.

(2) Equation (4.16) CS_{3DS} is concave in c_L. Therefore, the first-order-condition

Therefore, the first-order-condition

$$\frac{\partial CS_{3DS}}{\partial c_L} = \frac{1}{4(8+(-5+\alpha)\alpha)^2}((-2+\alpha)((8+\alpha(-19+\alpha(20+(-8+\alpha)\alpha)))c_{3D} - (3+(-3+\alpha)\alpha)((-1+\alpha)(8+(-5+\alpha)\alpha)+(-3+\alpha)(-2+\alpha)c_L+(-3+\alpha)(-2+\alpha)c_M))) = 0$$

$$c_L^* = \frac{1}{(-3+\alpha)(-2+\alpha)(3+(-3+\alpha)\alpha)}((8+\alpha(-19+\alpha(20+(-8+\alpha)\alpha)))c_{3D} - (3+(-3+\alpha)\alpha)((-1+\alpha)(8+(-5+\alpha)\alpha)+(-3+\alpha)(-2+\alpha)c_M))$$

Because $c_L + c_M < \alpha < 1$, therefore,

If $\frac{1}{(-3+\alpha)(-2+\alpha)(3+(-3+\alpha)\alpha)}((8+\alpha(-19+\alpha(20+(-8+\alpha)\alpha)))c_{3D} - (3+(-3+\alpha)\alpha)((-1+\alpha)(8+(-5+\alpha)\alpha)+(-3+\alpha)(-2+\alpha)c_M)) > \alpha - c_L$, that is

$c_{3D} > \frac{(3+(-3+\alpha)\alpha)(-8+\alpha(19+\alpha(-11+2\alpha)))}{8+\alpha(-19+\alpha(20+(-8+\alpha)\alpha))}$, CS_{3DS} decreases in c_M;

If $\frac{1}{(-3+\alpha)(-2+\alpha)(3+(-3+\alpha)\alpha)}((8+\alpha(-19+\alpha(20+(-8+\alpha)\alpha)))c_{3D} - (3+(-3+\alpha)\alpha)((-1+\alpha)(8+(-5+\alpha)\alpha)+(-3+\alpha)(-2+\alpha)c_M)) > \alpha - c_L$, that is

$c_{3D} < \frac{(3+(-3+\alpha)\alpha)(-8+\alpha(19+\alpha(-11+2\alpha)))}{8+\alpha(-19+\alpha(20+(-8+\alpha)\alpha))}$,

a) If $c_L < \frac{1}{(-3+\alpha)(-2+\alpha)(3+(-3+\alpha)\alpha)}((8+\alpha(-19+\alpha(20+(-8+\alpha)\alpha)))c_{3D} - (3+(-3+\alpha)\alpha)((-1+\alpha)(8+(-5+\alpha)\alpha)+(-3+\alpha)(-2+\alpha)c_M))$, CS_{3DS} decreases in c_M;

b) If $\frac{1}{(-3+\alpha)(-2+\alpha)(3+(-3+\alpha)\alpha)}((8+\alpha(-19+\alpha(20+(-8+\alpha)\alpha)))c_{3D} - (3+(-3+\alpha)\alpha)((-1+\alpha)(8+(-5+\alpha)\alpha)+(-3+\alpha)(-2+\alpha)c_M)) < c_L < \alpha - c_L$, CS_{3DS} increases in c_M.

(3) Equation (4.16) CS_{3DS} is concave in c_{3D}. Therefore, the first-order-condition,

$$\frac{\partial CS_{3DS}}{\partial c_{3D}} = \frac{1}{4(8+(-5+\alpha)\alpha)^2}((8+(-5+\alpha)\alpha)(-8+(-1+\alpha)\alpha(5+(-5+\alpha)\alpha)) - (-64+\alpha(48+\alpha(-41+\alpha(32+(-10+\alpha)\alpha))))c_{3D} - 16c_L - 16c_M + \alpha(46+\alpha(-59+\alpha(36+(-10+\alpha)\alpha)))(c_L+c_M)) = 0$$

$$c_{3D}^{*} = \frac{1}{-64+\alpha(48+\alpha(-41+\alpha(32+(-10+\alpha)\alpha)))}((8+(-5+\alpha)\alpha)(-8+(-1+\alpha)\alpha(5+(-5+\alpha)\alpha))+(-2+\alpha)(8+\alpha(-19+\alpha(20+(-8+\alpha)\alpha)))(c_L+c_M)) > \frac{c_L+c_M}{\alpha}$$

Therefore,

a) If $\frac{c_L+c_M}{\alpha} < c_{3D} < \frac{1}{-64+\alpha(48+\alpha(-41+\alpha(32+(-10+\alpha)\alpha)))}((8+(-5+\alpha)\alpha)(-8+(-1+\alpha)\alpha(5+(-5+\alpha)\alpha))+(-2+\alpha)(8+\alpha(-19+\alpha(20+(-8+\alpha)\alpha)))(c_L+c_M))$, CS_{3DS} decreases in c_{3D};

b) If $\frac{1}{-64+\alpha(48+\alpha(-41+\alpha(32+(-10+\alpha)\alpha)))}((8+(-5+\alpha)\alpha)(-8+(-1+\alpha)\alpha(5+(-5+\alpha)\alpha))+(-2+\alpha)(8+\alpha(-19+\alpha(20+(-8+\alpha)\alpha)))(c_L+c_M)) < c_{3D} < 1$, CS_{3DS} increases in c_{3D}.

In a 3DB enabled integrated market, according to Equation (4.17),

(1) CS_{3D} is concave in c_M. Therefore, the first-order-condition

$$\frac{\partial CS_{3D}}{\partial c_M} = \frac{1}{4}(-2-(-2+\alpha)\alpha-(-2+\alpha)c_L-(-2+\alpha)c_M) = 0$$

$$c_M^{*} = -\frac{2}{-2+\alpha} - \alpha - c_L > \alpha - c_L$$

Because $c_L + c_M < \alpha < 1$, therefore, CS_{3D} decrases in c_M.

(2) CS_{3D} is concave in c_L. Therefore, the first-order-condition

Therefore, the first-order-condition

$$\frac{\partial CS_{3D}}{\partial c_L} = \frac{1}{4}(-2-(-2+\alpha)\alpha-(-2+\alpha)c_L-(-2+\alpha)c_M) = 0$$

$$c_L^{*} = -\frac{2}{-2+\alpha} - \alpha - c_M > \alpha - c_M$$

Because $c_L + c_M < \alpha < 1$, therefore, CS_{3D} decrases in c_L.

(3) CS_{3D} is concave in c_{3D}. Therefore, the first-order-condition,

$$\frac{\partial CS_{3D}}{\partial c_{3D}} = \frac{1}{4}(-1 + c_{3D}) = 0$$

$$c_{3D}^{*} = 1$$

$c_{3D} < 1$, therefore, CS_{3D} decrases in c_{3D}.

Proof of *PROPOSITION* 4-24.

In the decentralized Bertrand market,

$$CS_{3DB} - CS_{3DND} = \frac{1}{32(8+\alpha)^2}((8+\alpha)^2(4+\alpha(8+5(-2+\alpha)\alpha)) - 4(-64+\alpha(-48 - 41\alpha + 6\alpha^3 + \alpha^4))c_{3D}^2 + 128c_L + 128c_M + (c_L + c_M)(2\alpha(-88+\alpha(4 + \alpha(26+3\alpha))) + (16 + (-2+\alpha)\alpha(16+\alpha))c_L + (16 + (-2+\alpha)\alpha(16 + \alpha))c_M) - 8c_{3D}((8+\alpha)(8+\alpha(11+\alpha(-6+\alpha(2+\alpha)))) + 2(8 + \alpha(-13+2\alpha(2+\alpha)))c_L + 2(8+\alpha(-13+2\alpha(2+\alpha)))c_M))$$

which is concave in c_{3D}, therefore, when the first-order-condition

$$\frac{\partial(CS_{3DB} - CS_{3DND})}{\partial c_{3D}} = -\frac{1}{4(8+\alpha)^2}((8+\alpha)(8+\alpha(11+\alpha(-6+\alpha(2+\alpha)))) + (-64 + \alpha(-48 - 41\alpha + 6\alpha^3 + \alpha^4))c_{3D} + 16c_L + 16c_M + 2\alpha(-13+2\alpha(2 + \alpha))(c_L + c_M)) = 0$$

$$c_{3D} = \frac{(8+\alpha)(8+\alpha(11+\alpha(-6+\alpha(2+\alpha)))) + 2(8+\alpha(-13+2\alpha(2+\alpha)))(c_L + c_M)}{-64+\alpha(-48-41\alpha+6\alpha^3+\alpha^4)}$$

There is the minimum value of

$$CS_{3DB} - CS_{3DND} = \frac{1}{32(-64 + \alpha(-48 - 41\alpha + 6\alpha^3 + \alpha^4))}(\alpha(\alpha(192 + \alpha(-568 + \alpha(578 + \alpha(-161 + 3\alpha(-28 + 3\alpha(4 + \alpha)))))) + (-2 + \alpha)(16 + \alpha(5 + \alpha)(-5 + \alpha + \alpha^2))c_L^2 + 2c_L(32 + \alpha(-148 + \alpha(198 + \alpha(-67 + \alpha(-32 + 3\alpha(4 + \alpha))))) + (-2 + \alpha)(16 + \alpha(5 + \alpha)(-5 + \alpha + \alpha^2))c_M) + c_M(64 + 2\alpha(-148 + \alpha(198 + \alpha(-67 + \alpha(-32 + 3\alpha(4 + \alpha))))) + (-2 + \alpha)(16 + \alpha(5 + \alpha)(-5 + \alpha + \alpha^2))c_M))) < 0$$

Then, if $CS_{3DB} - CS_{3DND} = 0$,

$$c_{3DB} = \frac{1}{2(-64 + \alpha(-48 - 41\alpha + 6\alpha^3 + \alpha^4))}\Big(-4(8 + \alpha(-13 + 2\alpha(2 + \alpha)))c_L - 4(8 + \alpha(-13 + 2\alpha(2 + \alpha)))c_M + (8 + \alpha)(8(-2 + \sqrt(\frac{1}{(8 + \alpha)^2}\alpha(\alpha(192 + \alpha(-568 + \alpha(578 + \alpha(-161 + 3\alpha(-28 + 3\alpha(4 + \alpha)))))) + (-2 + \alpha)(16 + \alpha(5 + \alpha)(-5 + \alpha + \alpha^2))c_L^2 + 2c_L(32 + \alpha(-148 + \alpha(198 + \alpha(-67 + \alpha(-32 + 3\alpha(4 + \alpha))))) + (-2 + \alpha)(16 + \alpha(5 + \alpha)(-5 + \alpha + \alpha^2))c_M) + c_M(64 + 2\alpha(-148 + \alpha(198 + \alpha(-67 + \alpha(-32 + 3\alpha(4 + \alpha))))) + (-2 + \alpha)(16 + \alpha(5 + \alpha)(-5 + \alpha + \alpha^2))c_M)))) + \alpha(-22 - 2\alpha(-6 + \alpha(2 + \alpha)) + \sqrt(\frac{1}{(8 + \alpha)^2}\alpha(\alpha(192 + \alpha(-568 + \alpha(578 + \alpha(-161 + 3\alpha(-28 + 3\alpha(4 + \alpha)))))) + (-2 + \alpha)(16 + \alpha(5 + \alpha)(-5 + \alpha + \alpha^2))c_L^2 + 2c_L(32 + \alpha(-148 + \alpha(198 + \alpha(-67 + \alpha(-32 + 3\alpha(4 + \alpha))))) + (-2 + \alpha)(16 + \alpha(5 + \alpha)(-5 + \alpha + \alpha^2))c_M) + c_M(64 + 2\alpha(-148 + \alpha(198 + \alpha(-67 + \alpha(-32 + 3\alpha(4 + \alpha))))) + (-2 + \alpha)(16 + \alpha(5 + \alpha)(-5 + \alpha + \alpha^2))c_M)))))\Big)$$

$$c_{3DB2} = \frac{1}{2(-64+\alpha(-48-41\alpha+6\alpha^3+\alpha^4))}\Big((4(8+\alpha(-13+2\alpha(2+\alpha)))c_L+4(8+\alpha(-13+2\alpha(2+\alpha)))c_M+(8$$

$$+\alpha)(8(2+\sqrt{(}\frac{1}{(8+\alpha)^2}\alpha(\alpha(192+\alpha(-568+\alpha(578+\alpha(-161+3\alpha(-28+3\alpha(4+\alpha))))))+(-2+\alpha)(16$$

$$+\alpha(5+\alpha)(-5+\alpha+\alpha^2))c_L^2+2c_L(32+\alpha(-148+\alpha(198+\alpha(-67+\alpha(-32+3\alpha(4+\alpha)))))+(-2+\alpha)(16$$

$$+\alpha(5+\alpha)(-5+\alpha+\alpha^2))c_M)+c_M(64+2\alpha(-148+\alpha(198+\alpha(-67+\alpha(-32+3\alpha(4+\alpha)))))+(-2$$

$$+\alpha)(16+\alpha(5+\alpha)(-5+\alpha+\alpha^2))c_M))))+\alpha(22+2\alpha(-6+\alpha(2+\alpha))+\sqrt{(}\frac{1}{(8+\alpha)^2}\alpha(\alpha(192+\alpha(-568$$

$$+\alpha(578+\alpha(-161+3\alpha(-28+3\alpha(4+\alpha))))))+(-2+\alpha)(16+\alpha(5+\alpha)(-5+\alpha+\alpha^2))c_L^2+2c_L(32$$

$$+\alpha(-148+\alpha(198+\alpha(-67+\alpha(-32+3\alpha(4+\alpha)))))+(-2+\alpha)(16+\alpha(5+\alpha)(-5+\alpha+\alpha^2))c_M)+c_M(64$$

$$+2\alpha(-148+\alpha(198+\alpha(-67+\alpha(-32+3\alpha(4+\alpha)))))+(-2+\alpha)(16+\alpha(5+\alpha)(-5+\alpha+\alpha^2))c_M)))))\Big)$$

Here, $c_{3DB2} < \frac{c_L+c_M}{\alpha} < c_{3DB} < 1$, therefore,

$$\begin{cases} if\ \dfrac{c_L+c_M}{\alpha} < c_{3D} < c_{3DB}, CS_{3DB} - CS_{3DND} < 0; \\ if\ c_{3DB} < c_{3D} < 1, CS_{3DB} - CS_{3DND} > 0. \end{cases}$$

In the decentralized Stackelberg market,

$$CS_{3DS} - CS_{3DND}$$
$$= \frac{1}{32}((-4 + 3\alpha + c_L + c_M)(\alpha(-2 + 3\alpha) + (-2 + \alpha)c_L + (-2 + \alpha)c_M)$$
$$+ \frac{1}{(8 + (-5 + \alpha)\alpha)^2} 4((8 + (-5 + \alpha)\alpha + (-8 + 3\alpha)c_{3D} - (-2 + \alpha)c_L$$
$$- (-2 + \alpha)c_M)^2 - 2(\alpha(8 + (-5 + \alpha)\alpha) - (-4 + \alpha)\alpha c_{3D} + (-2 + \alpha)^2 c_L$$
$$+ (-2 + \alpha)^2 c_M)((-4 + \alpha)\alpha c_{3D} - (-2 + \alpha)(8 + (-5 + \alpha)\alpha + (-2$$
$$+ \alpha)c_L + (-2 + \alpha)c_M)) + \alpha(4(8 + (-5 + \alpha)\alpha)^2$$
$$- (\alpha(8 + (-5 + \alpha)\alpha) - (-4 + \alpha)\alpha c_{3D} + (-2 + \alpha)^2 c_L$$
$$+ (-2 + \alpha)^2 c_M)^2)))$$

which is concave in c_{3D}, therefore, when the first-order-condition

$$\frac{\partial(CS_{3DS} - CS_{3DND})}{\partial c_{3D}}$$
$$= \frac{1}{4(8 + (-5 + \alpha)\alpha)^2}((8 + (-5 + \alpha)\alpha)(-8 + (-1 + \alpha)\alpha(5 + (-5$$
$$+ \alpha)\alpha)) - (-64 + \alpha(48 + \alpha(-41 + \alpha(32 + (-10 + \alpha)\alpha))))c_{3D} - 16c_L$$
$$- 16c_M + \alpha(46 + \alpha(-59 + \alpha(36 + (-10 + \alpha)\alpha)))(c_L + c_M)) = 0$$
$$c_{3D} = \frac{1}{-64 + \alpha(48 + \alpha(-41 + \alpha(32 + (-10 + \alpha)\alpha)))}((8 + (-5 + \alpha)\alpha)(-8 + (-1$$
$$+ \alpha)\alpha(5 + (-5 + \alpha)\alpha)) + (-2 + \alpha)(8 + \alpha(-19 + \alpha(20 + (-8$$
$$+ \alpha)\alpha)))c_L + (-2 + \alpha)(8 + \alpha(-19 + \alpha(20 + (-8 + \alpha)\alpha)))c_M)$$

There is the minimum value of

$$CS_{3DS} - CS_{3DND} = \frac{1}{32(-64 + \alpha(-48 - 41\alpha + 6\alpha^3 + \alpha^4))}(\alpha(\alpha(192 + \alpha(-568 + \alpha(578 + \alpha(-161 + 3\alpha(-28 + 3\alpha(4 + \alpha)))))) + (-2 + \alpha)(16 + \alpha(5 + \alpha)(-5 + \alpha + \alpha^2))c_L^2 + 2c_L(32 + \alpha(-148 + \alpha(198 + \alpha(-67 + \alpha(-32 + 3\alpha(4 + \alpha))))) + (-2 + \alpha)(16 + \alpha(5 + \alpha)(-5 + \alpha + \alpha^2))c_M) + c_M(64 + 2\alpha(-148 + \alpha(198 + \alpha(-67 + \alpha(-32 + 3\alpha(4 + \alpha))))) + (-2 + \alpha)(16 + \alpha(5 + \alpha)(-5 + \alpha + \alpha^2))c_M))) < 0$$

Then, if $CS_{3DS} - CS_{3DND} = 0$,

$$c_{3DS} = \frac{1}{2(-64+\alpha(48+\alpha(-41+\alpha(32+(-10+\alpha)\alpha))))}\Big(2(-2+\alpha)(8+\alpha(-19+\alpha(20+(-8+\alpha)\alpha)))c_L + 2(-2+\alpha)(8 + \alpha(-19+\alpha(20+(-8+\alpha)\alpha)))c_M + (-5+\alpha)\alpha(16+(-5+\alpha)\alpha)\sqrt{(}\frac{1}{(8+(-5+\alpha)\alpha)^2}\alpha(\alpha(320+\alpha(-1016 + \alpha(1442+\alpha(-1121+3\alpha(164+3(-12+\alpha)\alpha))))) + (-2+\alpha)(-16+\alpha(-25+\alpha(32+(-10+\alpha)\alpha)))c_L^2 + 2c_L(-32+\alpha(-84+\alpha(294+\alpha(-323+\alpha(160+3(-12+\alpha)\alpha)))) + (-2+\alpha)(-16+\alpha(-25+\alpha(32 + (-10+\alpha)\alpha)))c_M) + c_M(-64+2\alpha(-84+\alpha(294+\alpha(-323+\alpha(160+3(-12+\alpha)\alpha)))) + (-2+\alpha)(-16 + \alpha(-25+\alpha(32+(-10+\alpha)\alpha)))c_M))) + 2(\alpha^2(97+\alpha(-103+\alpha(48+(-11+\alpha)\alpha))) + 32(-2 + \sqrt{(}\frac{1}{(8+(-5+\alpha)\alpha)^2}\alpha(\alpha(320+\alpha(-1016+\alpha(1442+\alpha(-1121+3\alpha(164+3(-12+\alpha)\alpha))))) + (-2 + \alpha)(-16+\alpha(-25+\alpha(32+(-10+\alpha)\alpha)))c_L^2 + 2c_L(-32+\alpha(-84+\alpha(294+\alpha(-323+\alpha(160+3(-12 + \alpha)\alpha)))) + (-2+\alpha)(-16+\alpha(-25+\alpha(32+(-10+\alpha)\alpha)))c_M) + c_M(-64+2\alpha(-84+\alpha(294+\alpha(-323 + \alpha(160+3(-12+\alpha)\alpha)))) + (-2+\alpha)(-16+\alpha(-25+\alpha(32+(-10+\alpha)\alpha)))c_M)))))\Big)$$

$$c_{3DS2} = \frac{1}{2(-64+\alpha(48+\alpha(-41+\alpha(32+(-10+\alpha)\alpha))))}\Big(2(-2+\alpha)(8+\alpha(-19+\alpha(20+(-8+\alpha)\alpha)))c_L + 2(-2+\alpha)(8 + \alpha(-19+\alpha(20+(-8+\alpha)\alpha)))c_M - (-5+\alpha)\alpha(16+(-5+\alpha)\alpha)\sqrt{(}\frac{1}{(8+(-5+\alpha)\alpha)^2}\alpha(\alpha(320+\alpha(-1016 + \alpha(1442+\alpha(-1121+3\alpha(164+3(-12+\alpha)\alpha))))) + (-2+\alpha)(-16+\alpha(-25+\alpha(32+(-10+\alpha)\alpha)))c_L^2 + 2c_L(-32+\alpha(-84+\alpha(294+\alpha(-323+\alpha(160+3(-12+\alpha)\alpha)))) + (-2+\alpha)(-16+\alpha(-25+\alpha(32 + (-10+\alpha)\alpha)))c_M) + c_M(-64+2\alpha(-84+\alpha(294+\alpha(-323+\alpha(160+3(-12+\alpha)\alpha)))) + (-2+\alpha)(-16 + \alpha(-25+\alpha(32+(-10+\alpha)\alpha)))c_M))) + 2(\alpha^2(97+\alpha(-103+\alpha(48+(-11+\alpha)\alpha))) - 32(2 + \sqrt{(}\frac{1}{(8+(-5+\alpha)\alpha)^2}\alpha(\alpha(320+\alpha(-1016+\alpha(1442+\alpha(-1121+3\alpha(164+3(-12+\alpha)\alpha))))) + (-2 + \alpha)(-16+\alpha(-25+\alpha(32+(-10+\alpha)\alpha)))c_L^2 + 2c_L(-32+\alpha(-84+\alpha(294+\alpha(-323+\alpha(160+3(-12 + \alpha)\alpha)))) + (-2+\alpha)(-16+\alpha(-25+\alpha(32+(-10+\alpha)\alpha)))c_M) + c_M(-64+2\alpha(-84+\alpha(294+\alpha(-323 + \alpha(160+3(-12+\alpha)\alpha)))) + (-2+\alpha)(-16+\alpha(-25+\alpha(32+(-10+\alpha)\alpha)))c_M)))))\Big)$$

Here, $\frac{c_L+c_M}{\alpha} < c_{3DS} < 1 < c_{3DS2}$, therefore, $if\ \frac{c_L+c_M}{\alpha} < c_{3D} < c_{3DS}, CS_{3DS} - CS_{3DND} > 0;\ if\ c_{3DS} < c_{3D} < 1, CS_{3DS} - CS_{3DND} < 0$.

In the decentralized 3DP enabled market,

$$CS_{3DB} - CS_{3DS} = -\frac{1}{8(8+\alpha)^2(8+(-5+\alpha)\alpha)^2}\alpha(\alpha c_{3D} - c_L - c_M)((512+\alpha(512 + \alpha(-712+\alpha(10+\alpha(119+\alpha(-20+(-4+\alpha)\alpha))))))c_{3D} + (-4 + \alpha)\alpha(280+\alpha(-13+\alpha(-32+\alpha(10+\alpha))))(c_L + c_M) + 2((8+\alpha)(8 + (-5+\alpha)\alpha)(-20+\alpha(19+\alpha(-6+(-2+\alpha)\alpha))) + 448c_L + 448c_M))$$

which is convex in c_{3D}, therefore, when the first-order-condition

$$\frac{\partial(CS_{3DS} - CS_{3DND})}{\partial c_{3D}} = \frac{1}{4(8+\alpha)^2(8+(-5+\alpha)\alpha)^2}\alpha(-\alpha(8+\alpha)(8+(-5+\alpha)\alpha)(-20 + \alpha(19+\alpha(-6+(-2+\alpha)\alpha))) + 256c_L + 256c_M + \alpha(-(512+\alpha(512 + \alpha(-712+\alpha(10+\alpha(119+\alpha(-20+(-4+\alpha)\alpha))))))c_{3D} - (192 + \alpha(-204+\alpha(161+\alpha(-2+\alpha(-26+5\alpha)))))(c_L + c_M))) = 0$$

$$c_{3D} = \frac{1}{\alpha(512+\alpha(512+\alpha(-712+\alpha(10+\alpha(119+\alpha(-20+(-4+\alpha)\alpha))))))}(-\alpha(8 + \alpha)(8+(-5+\alpha)\alpha)(-20+\alpha(19+\alpha(-6+(-2+\alpha)\alpha))) + (256 + \alpha(-192+\alpha(204+\alpha(-161+\alpha(2+(26-5\alpha)\alpha)))))c_L + (256 + \alpha(-192+\alpha(204+\alpha(-161+\alpha(2+(26-5\alpha)\alpha)))))c_M)$$

There is the maximum value of

$$CS_{3DB} - CS_{3DNS} = \frac{1}{8(512+\alpha(512+\alpha(-712+\alpha(10+\alpha(119+\alpha(-20+(-4+\alpha)\alpha))))))}(\alpha(-20 + \alpha(19+\alpha(-6+(-2+\alpha)\alpha))) + (4+\alpha(13+(-4+\alpha)\alpha(2+\alpha)))c_L + (4+\alpha(13 + (-4+\alpha)\alpha(2+\alpha)))c_M)^2 > 0$$

Therefore, set $CS_{3DB} - CS_{3DNS} = 0$,

$$c_{3D1} = \frac{c_L + c_M}{\alpha}$$

$$c_{3D2} = \frac{1}{512 + \alpha(512 + \alpha(-712 + \alpha(10 + \alpha(119 + \alpha(-20 + (-4 + \alpha)\alpha)))))}(2(8 + \alpha)(8 + (-5 + \alpha)\alpha)(-20 + \alpha(19 + \alpha(-6 + (-2 + \alpha)\alpha))) + (896 + (-4 + \alpha)\alpha(280 + \alpha(-13 + \alpha(-32 + \alpha(10 + \alpha)))))c_L + (896 + (-4 + \alpha)\alpha(280 + \alpha(-13 + \alpha(-32 + \alpha(10 + \alpha)))))c_M)$$

Here, $\frac{c_L+c_M}{\alpha} = c_{3D1} < 1 < c_{3D2}$, so when $\frac{c_L+c_M}{\alpha} < c_{3D1} < 1$, $CS_{3DB} - CS_{3DNS} > 0$.

In the Integrated market,

$$CS_{3D} - CS_{3DNI} = \frac{1}{8}(-1 + c_{3D})^2 > 0$$

Proof of *PROPOSITION* 4-25.

In the decentralized market,

$$CS_{F3D} - CS_{3DND} = \frac{1}{32}(4(-1 + c_{3D})^2 + (-4 + 3\alpha + c_L + c_M)(\alpha(-2 + 3\alpha) + (-2 + \alpha)c_L + (-2 + \alpha)c_M))$$

which is concave in c_{3D}, therefore, when the first-order-condition

$$\frac{\partial(CS_{F3D} - CS_{3DND})}{\partial c_{3D}} = \frac{1}{4}(-1 + c_{3D}) = 0$$

$$c_{3D} = 1$$

There is the minimum value of

$$CS_{F3D} - CS_{3DND} = \frac{1}{32}(-4 + 3\alpha + c_L + c_M)(\alpha(-2 + 3\alpha) + (-2 + \alpha)c_L + (-2 + \alpha)c_M)$$

Set $CS_{F3D} - CS_{3DND} = 0$,

$$c_{3D1} = 1 - \frac{1}{2}\sqrt{-(-4+3\alpha+c_L+c_M)(\alpha(-2+3\alpha)+(-2+\alpha)c_L+(-2+\alpha)c_M)}$$

$$c_{3D2} = \frac{1}{2}(2+\sqrt{-(-4+3\alpha+c_L+c_M)(\alpha(-2+3\alpha)+(-2+\alpha)c_L+(-2+\alpha)c_M)})$$

To ensure $-(-4+3\alpha+c_L+c_M)(\alpha(-2+3\alpha)+(-2+\alpha)c_L+(-2+\alpha)c_M) > 0$, then the minimum value of $CS_{F3D} - CS_{3DND} < 0$. Because $c_{3D1} < \frac{c_L+c_M}{\alpha} < 1 < c_{3D2}$,

$$\begin{cases} if\ 0 < c_{3D} < c_{3DB1}, CS_{F3D} - CS_{3DND} > 0; \\ if\ c_{3DB1} < c_{3D} < \dfrac{c_L+c_M}{\alpha}, CS_{F3D} - CS_{3DND} < 0. \end{cases}$$

In the integrated market,

$$CS_{F3D} - CS_{3DNI} = \frac{1}{8}((-1+c_{3D})^2 + (-2+\alpha+c_L+c_M)(\alpha^2+(-2+\alpha)c_L+(-2+\alpha)c_M))$$

which is concave in c_{3D}, therefore, when the first-order-condition

$$\frac{\partial(CS_{F3D} - CS_{3DNI})}{\partial c_{3D}} = \frac{1}{4}(-1+c_{3D}) = 0$$

$$c_{3D} = 1$$

There is the minimum value of

$$CS_{F3D} - CS_{3DNI} = \frac{1}{8}(-2+\alpha+c_L+c_M)(\alpha^2+(-2+\alpha)c_L+(-2+\alpha)c_M)$$

Set $CS_{F3D} - CS_{3DNI} = 0$,

$$c_{3D1} = 1 - \sqrt{-(-2+\alpha+c_L+c_M)(\alpha^2+(-2+\alpha)c_L+(-2+\alpha)c_M)}$$

$$c_{3D2} = 1 + \sqrt{-(-2+\alpha+c_L+c_M)(\alpha^2+(-2+\alpha)c_L+(-2+\alpha)c_M)}$$

To ensure $-(-2+\alpha+c_L+c_M)(\alpha^2+(-2+\alpha)c_L+(-2+\alpha)c_M) > 0$, then the minimum value of $CS_{F3D} - CS_{3DNI} > 0$, therefore, $CS_{F3D} - CS_{3DNI}$.

Appendix C-1: Proofs of Chapter 5

Proof of *PROPOSITION 5-1.*

(1) According to Equation (5.1) and Equation (5.2), the first-order-conditions and the second-order-conditions of $\prod_{3D} M(p_M)$ and $\prod_{3D} L(p_{3DL}, p_L)$ in Equation (5.3) and Equation (5.4),

$$\begin{cases} \dfrac{\partial \prod_{3DL} M(p_M)}{\partial p_M} = \dfrac{F_M + \alpha p_{3\mathrm{DL}} + p_L - 2p_M + V_M}{\alpha - \alpha^2} \\ \dfrac{\partial \prod_{3DL} L(p_{3DL}, p_L)}{\partial p_{3DL}} = \dfrac{1 - \alpha - c_L + F_{3D} - 2p_{3\mathrm{DL}} + p_L + p_M + V_{3D}}{1 - \alpha} \end{cases}$$

$$\begin{cases} \dfrac{\partial \prod_{3DL}^2 M(p_M)}{\partial p_M^2} = \dfrac{2}{(-1+\alpha)\alpha} < 0 \\ \dfrac{\partial \prod_{3DL}^2 L(p_{3D}, p_L)}{\partial p_{3D}^2} = \dfrac{2}{-1+\alpha} < 0 \end{cases}$$

So, the solution to the first-order-conditions gives the unique maximizer.

$$\begin{cases} \dfrac{\partial \prod_{3DL} M(p_M)}{\partial p_M} = \dfrac{F_M + \alpha p_{3DL} + p_L - 2p_M + V_M}{\alpha - \alpha^2} = 0 \\ \dfrac{\partial \prod_{3DL} L(p_{3D}, p_L)}{\partial p_{3D}} = \dfrac{1 - \alpha - c_L + F_{3D} - 2p_{3\mathrm{DL}} + p_L + p_M + V_{3D}}{1 - \alpha} = 0 \end{cases}$$

$$\begin{cases} p_M^* = \dfrac{(-1+\alpha)\alpha + \alpha c_L - 2F_M - 2p_L - \alpha(F_{3D} + p_L + V_{3D}) - 2V_M}{-4+\alpha} \\ p_{3D}^* = \dfrac{2 - 2\alpha - 2c_L + 2F_{3D} + F_M + 3p_L + 2V_{3D} + V_M}{4 - \alpha} \end{cases}$$

Then, the logistics vendor's profit function (5.4) can be updated as

$$\begin{aligned} \prod\nolimits_{3DL} L(p_{3DL}, p_L) \\ = \frac{1}{(-4+\alpha)^2(-1+\alpha)\alpha} (\alpha((-2+\alpha)c_L - (-2+\alpha)F_{3D} - F_M + p_L \\ + 2(-1+\alpha+V_{3D}) - \alpha(p_L + V_{3D}) - V_M)(2 - 2\alpha - 2c_L + (-2 \\ + \alpha)F_{3D} + F_M + 3p_L + (-2+\alpha)V_{3D} + V_M) + (-4+\alpha)(c_L \\ - p_L)((-1+\alpha)\alpha + \alpha c_L + 2F_M + 2p_L + 2V_M - \alpha(F_{3D} + F_M + 2p_L \\ + V_{3D} + V_M))) \end{aligned} \quad (5.26)$$

which is convex in p_L, so the first-order-conditions of Equation (5.26) gives the maximum profit.

$$\frac{\partial \prod_{3DL} L(p_{3DL}, p_L)}{\partial p_L} = \frac{\alpha(8+\alpha) + 2(4+\alpha)c_L - 8F_M - 16p_L - \alpha(2p_L + \alpha(F_{3D} + V_{3D})) - 8V_M}{(-4+\alpha)^2\alpha} = 0$$

$$p_L^* = \frac{\alpha(8+\alpha) + 2(4+\alpha)c_L - 8F_M - \alpha^2(F_{3D} + V_{3D}) - 8V_M}{2(8+\alpha)}$$

The final optimal decisions are

$$p_L^* = \frac{\alpha(8+\alpha) + 2(4+\alpha)c_L - 8F_M - \alpha^2(F_{3D} + V_{3D}) - 8V_M}{2(8+\alpha)} \quad (5.27)$$

$$p_M^* = \frac{\alpha(8+\alpha) + 4c_L + 4F_M + \alpha(4+\alpha)(F_{3D} + V_{3D}) + 4V_M}{2(8+\alpha)} \quad (5.28)$$

$$p_{3DL}^* = \frac{8 + \alpha - 2c_L + (8+3\alpha)F_{3D} - 2F_M + (8+3\alpha)V_{3D} - 2V_M}{2(8+\alpha)} \quad (5.29)$$

$$q_M^* = \frac{(2+\alpha)(c_L + F_M - \alpha(F_{3D} + V_{3D}) + V_M)}{(-1+\alpha)\alpha(8+\alpha)} \quad (5.30)$$

$$q_{3DL}^* = -\frac{-(-1+\alpha)(8+\alpha) + 6c_L + (-8+\alpha+\alpha^2)F_{3D} + 6F_M + (-8+\alpha+\alpha^2)V_{3D} +}{2(-1+\alpha)(8+\alpha)} \quad (5.31)$$

The maximized profits are

$$\prod\nolimits_{3DLB}^{*} M(p_M) = -\frac{(2+\alpha)^2(c_L + F_M - \alpha(F_{3D} + V_{3D}) + V_M)^2}{(-1+\alpha)\alpha(8+\alpha)^2} \quad (5.32)$$

$$\begin{aligned}\prod\nolimits_{3DLB}^{*} L\,(p_{3DL}, p_L) &= \frac{1}{4(-1+\alpha)(8+\alpha)^2}(-(8 + \alpha - 2c_L + (-8+\alpha)F_{3D} - 2F_M \\ &+ (-8+\alpha)V_{3D} - 2V_M)(-(-1+\alpha)(8+\alpha) + 6c_L + (-8+\alpha \\ &+ \alpha^2)F_{3D} + 6F_M + (-8+\alpha+\alpha^2)V_{3D} + 6V_M) \\ &+ \frac{1}{\alpha}(2(2+\alpha)(-c_L - F_M + \alpha(F_{3D} + V_{3D}) - V_M)(-\alpha(8+\alpha) + 8c_L \\ &+ 8F_M + \alpha^2(F_{3D} + V_{3D}) + 8V_M)))\end{aligned} \quad (5.33)$$

(2) Using the same methodology as in Bertrand, this model uses the backward induction to find out the Nash equilibrium of $\prod_{3DL} L(p_{3DL}, p_L)$ and $\prod_{3DL} M(p_M)$.

To do so, first, it is easy to find out that $\prod_{3DL} L(p_{3DL}, p_L)$ is convex in p_{3DL}. So, the first-order-conditions of $\prod_{3DL} L(p_{3DL}, p_L)$ in Equation (5.4) gives the maximizer,

$$\frac{\partial \prod_{3DL} L(p_{3DL}, p_L)}{\partial p_{3DL}} = \frac{1 - \alpha - c_L + F_{3D} - 2p_{3\mathrm{DL}} + p_L + p_M + V_{3D}}{1 - \alpha} = 0$$

$$p_{3D}^* = \frac{1}{2}(1 - \alpha - c_L + F_{3D} + p_L + p_M + V_{3D})$$

Then, the $\prod_{3DL} M(p_M)$ can be updated as

$$\prod\nolimits_{3DL} M(p_M) = \frac{(-p_M + \frac{1}{2}\alpha(1 - \alpha - c_L + F_{3D} + p_L + p_M + V_{3D}))(F_M + p_L - p_M + V_M)}{(-1 + \alpha)\alpha}$$

which is also convex in p_M, so the first-order-condition of $\prod_{3DL} M(p_M)$ archives the maximized value.

$$\frac{\partial \prod_{3DL} M(p_M)}{\partial p_M} = \frac{(-1 + \alpha)\alpha - 2F_M - 2p_L + 4p_M - 2V_M + \alpha(c_L - F_{3D} + F_M - 2p_M - V_{3D} + V_M)}{2(-1 + \alpha)\alpha} = 0$$

$$p_{\mathrm{M}}^* = \frac{(-1 + \alpha)\alpha - 2F_M - 2p_L - 2V_M + \alpha(c_L - F_{3D} + F_M - V_{3D} + V_M)}{2(-2 + \alpha)}$$

p_{3DL}^* updates as

$$p_{3DL}^* = -\frac{1}{4(-2 + \alpha)}(4 - 5\alpha + \alpha^2 + (-4 + \alpha)c_L - (-4 + \alpha)F_{3D} + 2F_M + 6p_L + 2V_M - \alpha(F_M + 2p_L + (-5 + 2\alpha)V_{3D} + V_M))$$

The $\prod_{3DL} L(p_{3DL}, p_L)$ can be rewritten as

$$\prod\nolimits_{3DL} L(p_{3DL}, p_L)$$
$$= \frac{1}{1-\alpha}(-\frac{1}{16(-2+\alpha)^2}(4-5\alpha+\alpha^2+(4-3\alpha)c_L+(-4+3\alpha)F_{3D} + 2F_M - 2p_L + \alpha(-F_M + 2p_L + (-3+2\alpha)V_{3D} - V_M) + 2V_M)(-4+5\alpha - \alpha^2 - (-4+\alpha)c_L + (4-3\alpha)F_{3D} - 2F_M - 6p_L + 8V_{3D} - 2V_M + \alpha(F_M + 2p_L + (-9+2\alpha)V_{3D} + V_M)) + \frac{1}{4\alpha}((c_L - p_L)((-1+\alpha)\alpha + \alpha c_L + 2F_M + 2p_L + 2V_M - \alpha(F_{3D} + F_M + 2p_L + (-1+2\alpha)V_{3D} + V_M))))$$

and it is convex in p_L, so the first-order-conditions gives the maximizer

$$\frac{\partial \prod_{3DL} L(p_{3DL}, p_L)}{\partial p_L} = \frac{1}{4(-2+\alpha)^2\alpha}(\alpha(8+(-5+\alpha)\alpha) + (8+(-4+\alpha)\alpha)c_L - 8F_M - 16p_L - 8V_M - \alpha(\alpha(F_{3D} + F_M + 2p_L + V_{3D} + V_M) - 2(3F_M + 5p_L + 3V_M))) = 0$$

$$p_L^* = \frac{1}{2(8+(-5+\alpha)\alpha)}(\alpha(8+(-5+\alpha)\alpha) + (8+(-4+\alpha)\alpha)c_L - 8F_M - 8V_M - \alpha(-6(F_M+V_M) + \alpha(F_{3D} + F_M + V_{3D} + V_M)))$$

Therefore, the final optimal decisions are

$$p_L^* = \frac{1}{2(8+(-5+\alpha)\alpha)}(\alpha(8+(-5+\alpha)\alpha) + (8+(-4+\alpha)\alpha)c_L - 8F_M - 8V_M - \alpha(-6(F_M+V_M) + \alpha(F_{3D} + F_M + V_{3D} + V_M))) \tag{5.34}$$

$$p_M^* = \frac{1}{2(8+(-5+\alpha)\alpha)}(\alpha(8+(-5+\alpha)\alpha) + (-2+\alpha)^2 c_L + 4F_M - (-4+\alpha)\alpha(F_{3D} - F_M + V_{3D} - V_M) + 4V_M) \tag{5.35}$$

$$p_{3DL}^* = \frac{1}{2(8+(-5+\alpha)\alpha)}(8+(-5+\alpha)\alpha + (-2+\alpha)c_L + (8-3\alpha)F_{3D} - 2F_M - 2V_M + \alpha(F_M + (10+(-6+\alpha)\alpha)V_{3D} + V_M)) \tag{5.36}$$

$$q_M^* = -\frac{1}{2(-1+\alpha)\alpha(8+(-5+\alpha)\alpha)}(2(-2+\alpha)c_L - 4(F_M+V_M) + \alpha(-2(-2+\alpha)F_{3D} + 2F_M + (-4+\alpha(11+(-6+\alpha)\alpha))V_{3D} + 2V_M)) \tag{5.37}$$

$$q_{3DL}^{*}=\frac{1}{2(-1+\alpha)(8+(-5+\alpha)\alpha)}((-1+\alpha)(8+(-5+\alpha)\alpha)-(-3+\alpha)(-2+\alpha)c_L+(8+(-7+\alpha)\alpha)F_{3D}+(-3+\alpha)(-2+\alpha)(-F_M+\alpha V_{3D})-6V_M-(-5+\alpha)\alpha V_M) \tag{5.38}$$

The maximized profits are

$$\prod\nolimits_{3DLS}^{*}M(p_M)=\frac{1}{(-1+\alpha)\alpha(8+(-5+\alpha)\alpha)^2}((c_L+F_M-\alpha(F_{3D}+V_{3D})+V_M)(2(-2+\alpha)c_L-4(F_M+V_M)+\alpha(-2(-2+\alpha)F_{3D}+2F_M+(-4+\alpha(11+(-6+\alpha)\alpha))V_{3D}+2V_M))) \tag{5.39}$$

$$\prod\nolimits_{3DLS}^{*}L(p_{3DL},p_L)=\frac{1}{4(-1+\alpha)(8+(-5+\alpha)\alpha)^2}(((-1+\alpha)(8+(-5+\alpha)\alpha)-(-3+\alpha)(-2+\alpha)c_L+(8+(-7+\alpha)\alpha)F_{3D}+(-3+\alpha)(-2+\alpha)(-F_M+\alpha V_{3D})-6V_M-(-5+\alpha)\alpha V_M)(8+(-5+\alpha)\alpha+(-2+\alpha)c_L+(-8+(7-2\alpha)\alpha)F_{3D}-2F_M-16V_{3D}-2V_M+\alpha(F_M+(20+(-8+\alpha)\alpha)V_{3D}+V_M))+\frac{1}{\alpha}(2(-2+\alpha)c_L-4(F_M+V_M)+\alpha(-2(-2+\alpha)F_{3D}+2F_M+(-4+\alpha(11+(-6+\alpha)\alpha))V_{3D}+2V_M))(-\alpha(8+(-5+\alpha)\alpha)+(-4+\alpha)(-2+\alpha)c_L+8F_M+8V_M+\alpha(-6(F_M+V_M)+\alpha(F_{3D}+F_M+V_{3D}+V_M)))) \tag{5.40}$$

(3) The first-order-conditions and the second-order-conditions of $\prod_{3DB}SC(p_M,p_{3D},p_L)$ in Equation (5.5) are

$$\begin{cases}\dfrac{\partial\prod_{3DLB}SC(p_M,p_{3DL})}{\partial p_M}=-\dfrac{c_L+F_M-2p_M-\alpha(F_{3D}-2p_{3\mathrm{DL}}+V_{3D})+V_M}{(-1+\alpha)\alpha}\\ \dfrac{\partial\prod_{3DLB}SC(p_M,p_{3DL})}{\partial p_{3DL}}=\dfrac{-1+\alpha+c_L-F_{3D}+F_M+2p_{3\mathrm{DL}}-2p_M-V_{3D}+V_M}{-1+\alpha}\end{cases}$$

$$\begin{cases} \frac{\partial \prod_{3DB}^{2} SC(p_M, p_{3D})}{\partial p_M^2} = \frac{2}{(-1+\alpha)\alpha} < 0 \\ \frac{\partial \prod_{3DB}^{2} SC(p_M, p_{3D})}{\partial p_{3D}^2} = \frac{2}{-1+\alpha} < 0 \\ \frac{\partial \prod_{3DB}^{2} SC(p_M, p_{3D})}{\partial p_M \partial p_{3D}} = -\frac{2}{-1+\alpha} > 0 \\ \frac{\partial \prod_{3DB}^{2} SC(p_M, p_{3D})}{\partial p_{3D} \partial p_M} = -\frac{2}{-1+\alpha} > 0 \end{cases}$$

So, the determinant of the Hessian Matrix can be written as

$$H = \begin{vmatrix} \frac{2}{(-1+\alpha)\alpha} & -\frac{2}{-1+\alpha} \\ -\frac{2}{-1+\alpha} & \frac{2}{-1+\alpha} \end{vmatrix} = \frac{2}{(-1+\alpha)\alpha} \times \left(\frac{2}{-1+\alpha}\right) - \left(-\frac{2}{-1+\alpha}\right)^2 = \frac{4}{(1-\alpha)\alpha} > 0$$

Therefore, this Hessian Matrix is a negative-definite matrix, the solution to the first-order-conditions gives the unique maximizer of $\prod_{3DLB} SC(p_M, p_{3DL})$.

$$\begin{cases} \frac{\partial \prod_{3DLB} SC(p_M, p_{3DL})}{\partial p_M} = -\frac{c_L + F_M - 2p_M - \alpha(F_{3D} - 2p_{3\mathrm{DL}} + V_{3D}) + V_M}{(-1+\alpha)\alpha} = 0 \\ \frac{\partial \prod_{3DLB} SC(p_M, p_{3DL})}{\partial p_{3DL}} = \frac{-1 + \alpha + c_L - F_{3D} + F_M + 2p_{3\mathrm{DL}} - 2p_M - V_{3D} + V_M}{-1+\alpha} = 0 \end{cases}$$

$$p_M^* = \frac{1}{2}(\alpha + c_L + F_M + V_M) \tag{5.41}$$

$$p_{3DL}^* = \frac{1}{2}(1 + F_{3D} + V_{3D}) \tag{5.42}$$

So,

$$q_M^* = \frac{c_L + F_M - \alpha(F_{3D} + V_{3D}) + V_M}{2(-1+\alpha)\alpha} \tag{5.43}$$

$$q_{3DL}^* = \frac{1 - \alpha + c_L - F_{3D} + F_M - V_{3D} + V_M}{2 - 2\alpha} \tag{5.44}$$

$$\prod\nolimits_{3DLB}^{*} SC\,(p_{3DL}, p_L) = \frac{1}{4(-1+\alpha)\alpha}(-\alpha(-1 + F_{3D} + V_{3D})(-1 + \alpha - c_L + F_{3D} - F_M + V_{3D} - V_M) + (\alpha - c_L - F_M - V_M)(c_L + F_M - \alpha(F_{3D} + V_{3D}) + V_M)) \tag{5.45}$$

Proof of *PROPOSITION* 5-2.

(1) According to Table 5-2, the first-order-conditions and the second-order-conditions of $\prod_{TF} M(p_M, p_{TF})$ and $\prod_{TF} L(p_{3DL}, p_L)$ in Equation (5.6) and Equation (5.7)

$$\frac{\partial \prod_{TF} M(p_M, p_{TF})}{\partial p_M} = \frac{\alpha(F_{\mathrm{TF}} + p_L - 2p_{\mathrm{TF}}) - \beta(F_M + p_L - 2p_M + V_M - \alpha V_{\mathrm{TF}})}{\alpha(\alpha - \beta)}$$

$$\frac{\partial \prod_{TF} M(p_M, p_{TF})}{\partial p_{TF}} = \frac{1}{(-1+\beta)(-\alpha+\beta)}(-(-1+\beta)F_M + (-1+\alpha)F_{\mathrm{TF}} - 2p_M + \alpha(p_{\mathrm{3DL}} + p_L - 2p_{\mathrm{TF}}) + 2p_{\mathrm{TF}} + V_M - \beta(p_{\mathrm{3DL}} + p_L - 2p_M + V_M + V_{\mathrm{TF}} - \alpha V_{\mathrm{TF}}))$$

$$\frac{\partial \prod_{TF} L(p_{3DL}, p_L)}{\partial p_{3DL}} = \frac{1 - \beta - c_L + F_{3D} - 2p_{\mathrm{3DL}} + p_L + p_{\mathrm{TF}} + V_{3D}}{1 - \beta}$$

$$\frac{\partial \prod_{3D}^2 M(p_M, p_{TF})}{\partial p_M^2} = \frac{2\beta}{\alpha^2 - \alpha\beta} < 0$$

$$\frac{\partial \prod_{3D}^2 M(p_M, p_{TF})}{\partial p_{TF}^2} = 2\left(\frac{1}{\alpha - \beta} + \frac{1}{-1+\beta}\right) < 0$$

$$\frac{\partial \prod_{3D}^2 L(p_{3DL}, p_L)}{\partial p_{3DL}^2} = \frac{2}{-1+\beta} < 0$$

the solution to the first-order-conditions gives the unique maximizer.

$$p_M^* = \frac{1}{8 - 2\beta}(2\alpha - 2\alpha\beta - 2\alpha c_L + 2\alpha F_{3D} - (-4+\beta)F_M + \alpha F_{\mathrm{TF}} + 4p_L + 3\alpha p_L - \beta p_L + 2\alpha V_{3D} + 4V_M - \beta V_M + \alpha\beta V_{\mathrm{TF}})$$

$$p_{TF}^* = \frac{(-1+\beta)\beta + \beta c_L - 2F_{\mathrm{TF}} - 2p_L - \beta(F_{3D} + p_L + V_{3D} + 2V_{\mathrm{TF}})}{-4+\beta}$$

$$p_{3DL}^* = \frac{2 - 2\beta - 2c_L + 2F_{3D} + F_{\mathrm{TF}} + 3p_L + 2V_{3D} + \beta V_{\mathrm{TF}}}{4 - \beta}$$

Then, the logistics vendor’s profit function (5.7) can be updated as

$$\prod_{TF} L(p_{3DL}, p_L)$$

$$= \frac{1}{2(-4+\beta)^2(-1+\beta)}(\frac{1}{\alpha}(-4+\beta)(c_L - p_L)(2\alpha(-1+\beta) + 2\alpha c_L - 2\alpha F_{3D} + (-4+\beta)(-1+\beta)F_M + 3\alpha F_{\mathrm{TF}} - \alpha\beta F_{\mathrm{TF}} + 4p_L + \alpha p_L - 5\beta p_L - \alpha\beta p_L + \beta^2 p_L - 2\alpha V_{3D} + 4V_M - 5\beta V_M + \beta^2 V_M - \alpha(-3+\beta)\beta V_{\mathrm{TF}}) + 2(2 - 2\beta - 2c_L + (-2+\beta)F_{3D} + F_{\mathrm{TF}} + 3p_L + (-2+\beta)V_{3D} + \beta V_{\mathrm{TF}})((-2+\beta)c_L - (-2+\beta)F_{3D} - F_{\mathrm{TF}} + p_L + 2(-1+\beta+V_{3D}) - \beta(p_L + V_{3D} + V_{\mathrm{TF}})))$$

which is convex in p_L, so the first-order-conditions of Equation (5.7) gives the maximum profit.

$$\frac{\partial \prod_{TF} L(p_{3DL}, p_L)}{\partial p_L}$$

$$= \frac{1}{2\alpha(-4+\beta)^2}((-\alpha(-12+\beta) + (-4+\beta)^2)c_L - 2\alpha\beta F_{3D} + 8\beta F_M - \beta^2 F_M - 8\alpha F_{\mathrm{TF}} + \alpha\beta F_{\mathrm{TF}} - 20\alpha p_L + 16\beta p_L + 2\alpha\beta p_L - 2\beta^2 p_L - 2\alpha\beta V_{3D} + 2(\alpha(8+\beta) - 8F_M - 16p_L - 8V_M) + 8\beta V_M - \beta^2 V_M + \alpha(-8+\beta)\beta V_{\mathrm{TF}}) = 0$$

$$p_L^* = \frac{1}{2\alpha(-10+\beta) - 2(-4+\beta)^2}((\alpha(-12+\beta) - (-4+\beta)^2)c_L + 2\alpha\beta F_{3D} + 8\alpha F_{\mathrm{TF}} - 2(\alpha(8+\beta) - 8F_M - 8V_M) + \beta((-8+\beta)F_M + (-8+\beta)V_M - \alpha(F_{\mathrm{TF}} - 2V_{3D} + (-8+\beta)V_{\mathrm{TF}})))$$

The final optimal decisions are

$$p_L^* = \frac{1}{2\alpha(-10+\beta) - 2(-4+\beta)^2}((\alpha(-12+\beta) - (-4+\beta)^2)c_L + 2\alpha\beta F_{3D} + 8\alpha F_{\mathrm{TF}} - 2(\alpha(8+\beta) - 8F_M - 8V_M) + \beta((-8+\beta)F_M + (-8+\beta)V_M - \alpha(F_{\mathrm{TF}} - 2V_{3D} + (-8+\beta)V_{\mathrm{TF}}))) \tag{5.46}$$

$$p_M^* = -\frac{1}{4\alpha(-10+\beta)-4(-4+\beta)^2}(2\alpha(16+\alpha(11-2\beta)+\beta(-9+2\beta)) + (-(-8+\alpha)\alpha+(-4+\beta)^2)c_L + 2\alpha(8+5\alpha-3\beta)F_{3D} + 16F_M + 8\alpha F_M - 8\beta F_M + \alpha\beta F_M + \beta^2 F_M - \alpha^2 F_{\mathrm{TF}} - \alpha\beta F_{\mathrm{TF}} + 16\alpha V_{3D} + 10\alpha^2 V_{3D} - 6\alpha\beta V_{3D} + 16V_M + 8\alpha V_M - 8\beta V_M + \alpha\beta V_M + \beta^2 V_M - \alpha\beta(\alpha+\beta)V_{\mathrm{TF}}) \tag{5.47}$$

$$p_{TF}^* = \frac{1}{2\alpha(-10+\beta)-2(-4+\beta)^2}((\alpha(-6+\beta)-(-4+\beta)(-2+\beta))c_L + 2\beta(-4-2\alpha+\beta)F_{3D} - 6\alpha F_{\mathrm{TF}} + 2(-(-4+\beta)(-1+\beta)\beta + \alpha(-4+(-6+\beta)\beta) + 4F_M - 8F_{\mathrm{TF}} + 4V_M) + \beta(-(-2+\beta)F_M + (4+\alpha)F_{\mathrm{TF}} + \beta(2V_{3D} - V_M + (4+\alpha)V_{\mathrm{TF}}) - 2(2(2+\alpha)V_{3D} - V_M + (8+3\alpha)V_{\mathrm{TF}}))) \tag{5.48}$$

$$p_{3DL}^* = \frac{1}{2\alpha(-10+\beta)-2(-4+\beta)^2}((4+\alpha-\beta)c_L - 2(8+5\alpha-2\beta)F_{3D} + 12F_M - 3\beta F_M + (-8+\alpha)F_{\mathrm{TF}} + 2\beta F_{\mathrm{TF}} - 10\alpha V_{3D} + 4\beta V_{3D} - 3\beta V_M + 2(-8-11\alpha+2(5+\alpha)\beta-2\beta^2-8V_{3D}+6V_M) + \beta(-8+\alpha + 2\beta)V_{\mathrm{TF}}) \tag{5.49}$$

$$q_M^* = \frac{1}{4\alpha(\alpha(-10+\beta)-(-4+\beta)^2)(\alpha-\beta)}(2\alpha(\alpha-\beta)(8+\beta) - (\alpha(-12+\beta) - (-4+\beta)^2)(\alpha-\beta)c_L + 2\alpha\beta(-\alpha+\beta)F_{3D} - 16\alpha F_M - 16\beta F_M - 12\alpha\beta F_M + 8\beta^2 F_M + \alpha\beta^2 F_M - \beta^3 F_M + 32\alpha F_{\mathrm{TF}} + 12\alpha^2 F_{\mathrm{TF}} - 8\alpha\beta F_{\mathrm{TF}} - \alpha^2\beta F_{\mathrm{TF}} + \alpha\beta^2 F_{\mathrm{TF}} - 2\alpha^2\beta V_{3D} + 2\alpha\beta^2 V_{3D} - 16\alpha V_M - 16\beta V_M - 12\alpha\beta V_M + 8\beta^2 V_M + \alpha\beta^2 V_M - \beta^3 V_M + \alpha\beta(4(8+3\alpha) - (8+\alpha)\beta + \beta^2)V_{\mathrm{TF}}) \tag{5.50}$$

$$q^{*}_{TF} = \frac{1}{4(\alpha(-10+\beta)-(-4+\beta)^2)(\alpha-\beta)(-1+\beta)}((\alpha(-13+\beta)-(-5+\beta)(-4+\beta))(\alpha-\beta)c_L+2(\alpha-\beta)(8-2\beta+\alpha(5+\beta))F_{3D} - 16\alpha F_M+44\beta F_M+17\alpha\beta F_M-13\beta^2F_M-\alpha\beta^2F_M+\beta^3F_M - 4\alpha F_{\mathrm{TF}}-13\alpha^2F_{\mathrm{TF}}-24\beta F_{\mathrm{TF}}+5\alpha\beta F_{\mathrm{TF}}+\alpha^2\beta F_{\mathrm{TF}}+4\beta^2F_{\mathrm{TF}} - \alpha\beta^2F_{\mathrm{TF}}+16\alpha V_{3D}+10\alpha^2V_{3D}-16\beta V_{3D}-14\alpha\beta V_{3D}+2\alpha^2\beta V_{3D} + 4\beta^2V_{3D}-2\alpha\beta^2V_{3D}-16\alpha V_M+44\beta V_M+17\alpha\beta V_M-13\beta^2V_M - \alpha\beta^2V_M+\beta^3V_M-2((8+3\alpha-2\beta)(\alpha-\beta)(-1+\beta)+16F_M - 16F_{\mathrm{TF}}+16V_M)+(\alpha^2(-13+\beta)+4(-4+\beta)(-2+\beta)-\alpha(-4+\beta)(-1+\beta))\beta V_{\mathrm{TF}}) \tag{5.51}$$

$$q^{*}_{3DL} = \frac{1}{2(-\alpha(-10+\beta)+(-4+\beta)^2)(-1+\beta)}((\alpha(-7+\beta)-(-4+\beta)(-3+\beta))c_L+2(8+5\alpha-2(3+\alpha)\beta+\beta^2)F_{3D}-4F_M+5\beta F_M-\beta^2F_M - (8+7\alpha)F_{\mathrm{TF}}+2\beta F_{\mathrm{TF}}+\alpha\beta F_{\mathrm{TF}}+10\alpha V_{3D}-12\beta V_{3D}-4\alpha\beta V_{3D} + 2\beta^2V_{3D}+2((8+3\alpha-2\beta)(-1+\beta)+8V_{3D}-2V_M)+5\beta V_M - \beta^2V_M+\beta(-8-7\alpha+(2+\alpha)\beta)V_{\mathrm{TF}}) \tag{5.52}$$

The maximized profits are

$$
\begin{aligned}
&\prod\nolimits_{TFB}^{*} M(p_M, p_{TF}) \\
&= -\frac{1}{4(\alpha(-10+\beta)-(-4+\beta)^2)(\alpha-\beta)}(\frac{1}{4\alpha(\alpha(-10+\beta)-(-4+\beta)^2)}(2\alpha(\alpha \\
&-\beta)(-11+2\beta)+(\alpha^2-2\alpha(-8+\beta)+(-4+\beta)^2)c_L+2\alpha(-8-5\alpha+\beta)F_{3D} \\
&+16F_M+32\alpha F_M-8\beta F_M-5\alpha\beta F_M+\beta^2 F_M-16\alpha F_{\mathrm{TF}}+\alpha^2 F_{\mathrm{TF}}+3\alpha\beta F_{\mathrm{TF}} \\
&-16\alpha V_{3D}-10\alpha^2 V_{3D}+2\alpha\beta V_{3D}+16V_M+32\alpha V_M-8\beta V_M-5\alpha\beta V_M+\beta^2 V_M \\
&+\alpha\beta(-16+\alpha+3\beta)V_{\mathrm{TF}})(-2\alpha(\alpha-\beta)(8+\beta)+(\alpha(-12+\beta) \\
&-(-4+\beta)^2)(\alpha-\beta)c_L+2\alpha(\alpha-\beta)\beta F_{3D}+16\alpha F_M+16\beta F_M+12\alpha\beta F_M \\
&-8\beta^2 F_M-\alpha\beta^2 F_M+\beta^3 F_M-32\alpha F_{\mathrm{TF}}-12\alpha^2 F_{\mathrm{TF}}+8\alpha\beta F_{\mathrm{TF}}+\alpha^2\beta F_{\mathrm{TF}} \\
&-\alpha\beta^2 F_{\mathrm{TF}}+2\alpha^2\beta V_{3D}-2\alpha\beta^2 V_{3D}+16\alpha V_M+16\beta V_M+12\alpha\beta V_M-8\beta^2 V_M \\
&-\alpha\beta^2 V_M+\beta^3 V_M+\alpha\beta(-32+\alpha(-12+\beta)-(-8+\beta)\beta)V_{\mathrm{TF}}) \\
&+\frac{1}{(-\alpha(-10+\beta)+(-4+\beta)^2)(-1+\beta)}((\alpha(-13+\beta)-(-5+\beta)(-4 \\
&+\beta))(\alpha-\beta)c_L+2(\alpha-\beta)(8-2\beta+\alpha(5+\beta))F_{3D}-16\alpha F_M+44\beta F_M \\
&+17\alpha\beta F_M-13\beta^2 F_M-\alpha\beta^2 F_M+\beta^3 F_M-4\alpha F_{\mathrm{TF}}-13\alpha^2 F_{\mathrm{TF}}-24\beta F_{\mathrm{TF}} \\
&+5\alpha\beta F_{\mathrm{TF}}+\alpha^2\beta F_{\mathrm{TF}}+4\beta^2 F_{\mathrm{TF}}-\alpha\beta^2 F_{\mathrm{TF}}+16\alpha V_{3D}+10\alpha^2 V_{3D}-16\beta V_{3D} \\
&-14\alpha\beta V_{3D}+2\alpha^2\beta V_{3D}+4\beta^2 V_{3D}-2\alpha\beta^2 V_{3D}-16\alpha V_M+44\beta V_M+17\alpha\beta V_M \\
&-13\beta^2 V_M-\alpha\beta^2 V_M+\beta^3 V_M-2((8+3\alpha-2\beta)(\alpha-\beta)(-1+\beta)+16F_M \\
&-16F_{\mathrm{TF}}+16V_M)+(\alpha^2(-13+\beta)+4(-4+\beta)(-2+\beta)-\alpha(-4+\beta)(-1 \\
&+\beta))\beta V_{\mathrm{TF}})((\alpha-\beta)(-4+\beta)(-1+\beta)+(4+3\alpha-\beta)c_L+\beta(-4-3\alpha \\
&+\beta)F_{3D}-4F_M+8F_{\mathrm{TF}}+3\alpha F_{\mathrm{TF}}-4V_M+\beta(-(-5+\beta)F_M+(-6+\beta)F_{\mathrm{TF}}-(4 \\
&+3\alpha)V_{3D}+5V_M+(8+3\alpha)V_{\mathrm{TF}}+\beta(V_{3D}-V_M+(-6+\beta)V_{\mathrm{TF}}))))
\end{aligned}
\tag{5.53}
$$

$$\prod_{TFB}^{*} L\,(p_{3DL}, p_L)$$

$$= -\frac{1}{8\alpha(-\alpha(-10+\beta)+(-4+\beta)^2)^2(-1+\beta)}(2\alpha((\alpha(-7+\beta) - (-4+\beta)(-3+\beta))c_L + 2(8+5\alpha-2(3+\alpha)\beta+\beta^2)F_{3D} - 4F_M + 5\beta F_M - \beta^2 F_M - (8+7\alpha)F_{\mathrm{TF}} + 2\beta F_{\mathrm{TF}} + \alpha\beta F_{\mathrm{TF}} + 10\alpha V_{3D} - 12\beta V_{3D} - 4\alpha\beta V_{3D} + 2\beta^2 V_{3D} + 2((8+3\alpha-2\beta)(-1 + \beta) + 8V_{3D} - 2V_M) + 5\beta V_M - \beta^2 V_M + \beta(-8-7\alpha+(2 + \alpha)\beta)V_{\mathrm{TF}})((4+\alpha-\beta)c_L + 2(8+5\alpha-(6+\alpha)\beta+\beta^2)F_{3D} + \alpha(F_{\mathrm{TF}} + 10V_{3D}) + 2(-8-11\alpha+2(5+\alpha)\beta - 2\beta^2 + 6F_M - 4F_{\mathrm{TF}} + 8V_{3D} + 6V_M) + \beta(-3F_M + 2F_{\mathrm{TF}} - 2(6+\alpha-\beta)V_{3D} - 3V_M + (-8+\alpha+2\beta)V_{\mathrm{TF}})) + ((\alpha^2(-13+\beta) + (-4+\beta)^2(-1 + \beta) - 2\alpha(16+(-11+\beta)\beta))c_L + 2\alpha(8-\beta(1+\beta)+\alpha(5 + \beta))F_{3D} - 16\alpha F_M + 24\beta F_M + 17\alpha\beta F_M - 9\beta^2 F_M - \alpha\beta^2 F_M + \beta^3 F_M - 16\alpha F_{\mathrm{TF}} - 13\alpha^2 F_{\mathrm{TF}} + 5\alpha\beta F_{\mathrm{TF}} + \alpha^2\beta F_{\mathrm{TF}} - \alpha\beta^2 F_{\mathrm{TF}} + 16\alpha V_{3D} + 10\alpha^2 V_{3D} - 2\alpha\beta V_{3D} + 2\alpha^2\beta V_{3D} - 2\alpha\beta^2 V_{3D} - 16\alpha V_M + 24\beta V_M + 17\alpha\beta V_M - 9\beta^2 V_M - \alpha\beta^2 V_M + \beta^3 V_M - 2(3\alpha(\alpha - \beta)(-1+\beta) + 8F_M + 8V_M) + \alpha\beta(-16+\alpha(-13+\beta) - (-5 + \beta)\beta)V_{\mathrm{TF}})((\alpha(-8+\beta) - (-4+\beta)^2)c_L - 2\alpha\beta F_{3D} - 8\alpha F_{\mathrm{TF}} + 2(\alpha(8+\beta) - 8F_M - 8V_M) + \beta(-(-8+\beta)F_M - (-8+\beta)V_M + \alpha(F_{\mathrm{TF}} - 2V_{3D} + (-8+\beta)V_{\mathrm{TF}})))) \tag{5.54}$$

(2) The first-order-conditions and the second-order-conditions of $\prod_{TF} L(p_{3DL}, p_L)$ in Equation (5.7)

$$\frac{\partial \prod_{TF} L(p_{3DL}, p_L)}{\partial p_{3DL}} = \frac{1-\beta-c_L+F_{3D}-2p_{\mathrm{3DL}}+p_L+p_{\mathrm{TF}}+V_{3D}}{1-\beta}$$

$$\frac{\partial \prod_{3D}^2 L(p_{3DL}, p_L)}{\partial p_{3DL}^2} = \frac{2}{-1+\beta} < 0$$

$\prod_{TF} L(p_{3DL}, p_L)$ is convex in p_{3DL}, the solution to the first-order-conditions gives the unique maximizer.

$$p_{3DL}^{*} = \frac{1}{2}(1-\beta-c_L+F_{3D}+p_L+p_{\mathrm{TF}}+V_{3D})$$

Then, the $\prod_{TF} M(p_M, p_{TF})$ can be updated as

$$\prod_{TF} M(p_M, p_{TF})$$

$$= -\frac{(\beta p_M - \alpha p_{\mathrm{TF}})(F_M + p_L - p_M + V_M)}{\alpha(\alpha - \beta)} + (\frac{-p_M + p_{\mathrm{TF}}}{\alpha - \beta}$$

$$+ \frac{1 - \beta - c_L + F_{3D} + p_L - p_{\mathrm{TF}} + V_{3D}}{2 - 2\beta})(-F_{\mathrm{TF}} - p_L + p_{\mathrm{TF}} - \beta V_{\mathrm{TF}})$$

Next, the traditional manufacturer sets the price of the TM and TF product synchronically, the first and the second order condition of $\prod_{TF} M(p_M, p_{TF})$ are

$$\frac{\partial \prod_{TF} M(p_M, p_{TF})}{\partial p_M} = \frac{\alpha(F_{\mathrm{TF}} + p_L - 2p_{\mathrm{TF}}) - \beta(F_M + p_L - 2p_M + V_M - \alpha V_{\mathrm{TF}})}{\alpha(\alpha - \beta)}$$

$$\frac{\partial \prod_{TF} M(p_M, p_{TF})}{\partial p_{TF}}$$

$$= \frac{1}{2(-1 + \beta)(-\alpha + \beta)}(2(-1 + \beta)(p_M - p_{\mathrm{TF}}) + (\alpha - \beta)(1 - \beta - c_L$$

$$+ F_{3D} + p_L - p_{\mathrm{TF}} + V_{3D}) - 2(-1 + \beta)(F_M + p_L - p_M + V_M) + (-2 + \alpha$$

$$+ \beta)(F_{\mathrm{TF}} + p_L - p_{\mathrm{TF}} + \beta V_{\mathrm{TF}}))$$

$$\begin{cases} \dfrac{\partial \prod_{TF}^2 M(p_M, p_{TF})}{\partial p_M^2} = \dfrac{2\beta}{\alpha^2 - \alpha\beta} < 0 \\ \dfrac{\partial \prod_{TF}^2 M(p_M, p_{TF})}{\partial p_{TF}^2} = \dfrac{2}{\alpha - \beta} + \dfrac{1}{-1 + \beta} < 0 \\ \dfrac{\partial \prod_{TF}^2 M(p_M, p_{TF})}{\partial p_M \partial p_{TF}} = \dfrac{2}{-\alpha + \beta} > 0 \\ \dfrac{\partial \prod_{TF}^2 M(p_M, p_{TF})}{\partial p_{TF} \partial p_M} = \dfrac{2}{-\alpha + \beta} > 0 \end{cases}$$

So, the determinant of the Hessian Matrix can be written as

$$H = \begin{vmatrix} \dfrac{2\beta}{\alpha^2 - \alpha\beta} & \dfrac{2}{-\alpha + \beta} \\ \dfrac{2}{-\alpha + \beta} & \dfrac{2}{\alpha - \beta} + \dfrac{1}{-1 + \beta} \end{vmatrix} = \frac{2\beta}{\alpha^2 - \alpha\beta} \times \left(\frac{2}{\alpha - \beta} + \frac{1}{-1 + \beta}\right) - \left(\frac{2}{-\alpha + \beta}\right)^2$$

$$= -\frac{2(-2 + \beta)}{\alpha(\alpha - \beta)(-1 + \beta)} > 0$$

Therefore, this Hessian Matrix is a negative-definite matrix, the solution to the first-order-conditions gives the unique maximizer of $\prod_{TF} M(p_M, p_{TF})$.

$$p_M^* = \frac{\alpha(-1+\beta) + \alpha c_L - \alpha F_{3D} - 2F_M + \beta F_M - (2+\alpha)p_L + \beta p_L - \alpha V_{3D} - 2V_M + \beta V_M}{2(-2+\beta)}$$

$$p_{3DL}^* = \frac{(-1+\beta)\beta - 2F_{\mathrm{TF}} - 2p_L + \beta(c_L - F_{3D} + F_{\mathrm{TF}} - V_{3D} + (-2+\beta)V_{\mathrm{TF}})}{2(-2+\beta)}$$

$\prod_{TF} L(p_{3DL}, p_L)$ can be rewritten as

$$\prod\nolimits_{TF} L(p_{3Dl}, p_L)$$

$$= -\frac{1}{16(-1+\beta)}\Big(\frac{1}{(-2+\beta)^2}(-4+5\beta-\beta^2+(-4+3\beta)c_L+(4-3\beta)F_{3D}-2F_{\mathrm{TF}}$$
$$+2p_L+4V_{3D}+\beta(F_{\mathrm{TF}}-2p_L-3V_{3D}+(-2+\beta)V_{\mathrm{TF}}))(-4+5\beta-\beta^2-(-4+\beta)c_L$$
$$+(4-3\beta)F_{3D}-2F_{\mathrm{TF}}-6p_L+4V_{3D}+\beta(F_{\mathrm{TF}}+2p_L-3V_{3D}+(-2+\beta)V_{\mathrm{TF}}))$$
$$+\frac{4(c_L-p_L)((-1+\beta)(\alpha-2F_M-2p_L-2V_M)+\alpha(c_L-F_{3D}+F_{\mathrm{TF}}-V_{3D}+\beta V_{\mathrm{TF}}))}{\alpha}\Big)$$

Which is convex in p_L, therefore, the first condition gives the unique maximizer. Accordingly, the optimal decisions are

$$p_L^* = \frac{1}{2(\alpha(-3+\beta)-2(-2+\beta)^2)}(-\alpha(8+(-5+\beta)\beta)+(\alpha(-4+\beta) - 2(-2+\beta)^2)c_L+\alpha\beta F_{3D}+8F_M+2\alpha F_{\mathrm{TF}}+8V_M+\beta(2(-4 + \beta)F_M+2(-4+\beta)V_M+\alpha(-F_{\mathrm{TF}}+V_{3D}-(-2+\beta)V_{\mathrm{TF}}))) \tag{5.55}$$

$$p_M^* = \frac{1}{4(\alpha(-3+\beta)-2(-2+\beta)^2)}(\alpha(-16+(17-5\beta)\beta+\alpha(-7+3\beta)) + (8(-1+\beta)+(\alpha-2\beta)(\alpha+\beta))c_L+\alpha(-8-3\alpha+5\beta)F_{3D} - 8F_M-2\alpha F_M+8\beta F_M-2\beta^2F_M+2\alpha F_{\mathrm{TF}}+\alpha^2F_{\mathrm{TF}}-\alpha\beta F_{\mathrm{TF}} - 8\alpha V_{3D}-3\alpha^2V_{3D}+5\alpha\beta V_{3D}-8V_M-2\alpha V_M+8\beta V_M-2\beta^2V_M + \alpha(2+\alpha-\beta)\beta V_{\mathrm{TF}}) \tag{5.56}$$

$$p_{TF}^* = \frac{1}{2(\alpha(-3+\beta)-2(-2+\beta)^2)}(-2(-2+\beta)(-1+\beta)\beta+\alpha(-4+(-1 + \beta)\beta)+(2+\alpha-2\beta)(-2+\beta)c_L+\beta(-4-\alpha+2\beta)F_{3D}+4F_M - 8F_{\mathrm{TF}}-2\alpha F_{\mathrm{TF}}+4V_M+\beta(-2F_M+(8+\alpha-2\beta)F_{\mathrm{TF}}-(4+\alpha - 2\beta)V_{3D}-2V_M+(4+\alpha-2\beta)(-2+\beta)V_{\mathrm{TF}})) \tag{5.57}$$

$$p_{3DL}^{*} = \frac{1}{2(\alpha(-3+\beta)-2(-2+\beta)^2)}(-\alpha(-3+\beta)^2+(-4+\beta)(-2+\beta)(-1 \\ +\beta)-(-2+\beta)c_L+(\alpha(-3+\beta)-(-4+\beta)(-2+\beta))F_{3D}+6F_M \\ -4F_{\mathrm{TF}}-8V_{3D}-3\alpha V_{3D}+6V_M+\beta((-5+\beta)F_M+4F_{\mathrm{TF}}+(6 \\ +\alpha)V_{3D}-5V_M-4V_{\mathrm{TF}}-\beta(F_{\mathrm{TF}}+V_{3D}-V_M+(-4+\beta)V_{\mathrm{TF}}))) \tag{5.58}$$

$$q_{M}^{*} = \frac{1}{4\alpha(\alpha(-3+\beta)-2(-2+\beta)^2)(\alpha-\beta)}(\alpha(\alpha-\beta)(8+(-5+\beta)\beta)-(\alpha(-4 \\ +\beta)-2(-2+\beta)^2)(\alpha-\beta)c_L+\alpha\beta(-\alpha+\beta)F_{3D}-8\alpha F_M-8\beta F_M \\ +2\alpha\beta F_M+8\beta^2F_M-2\beta^3F_M+16\alpha F_{\mathrm{TF}}+4\alpha^2F_{\mathrm{TF}}-14\alpha\beta F_{\mathrm{TF}} \\ -\alpha^2\beta F_{\mathrm{TF}}+3\alpha\beta^2F_{\mathrm{TF}}-\alpha^2\beta V_{3D}+\alpha\beta^2V_{3D}-8\alpha V_M-8\beta V_M \\ +2\alpha\beta V_M+8\beta^2V_M-2\beta^3V_M+\alpha\beta(4(4+\alpha)-(14+\alpha)\beta \\ +3\beta^2)V_{\mathrm{TF}}) \tag{5.59}$$

$$q_{TF}^{*} = \frac{1}{4(\alpha-\beta)(-1+\beta)}((\alpha-\beta)(-1+\beta)+(\alpha-\beta)c_L+(-\alpha+\beta)F_{3D}+2F_M \\ -2F_{\mathrm{TF}}+\alpha(F_{\mathrm{TF}}-V_{3D})+2V_M+\beta(-2F_M+F_{\mathrm{TF}}+V_{3D}-2V_M \\ +(-2+\alpha+\beta)V_{\mathrm{TF}})) \tag{5.60}$$

$$q_{3DL}^{*} = \frac{1}{2(-\alpha(-3+\beta)+2(-2+\beta)^2)(-1+\beta)}((-1+\beta)(8+\alpha-6\beta+\beta^2) \\ +(3+\alpha-2\beta)(-2+\beta)c_L+(8+3\alpha-2(5+\alpha)\beta+3\beta^2)F_{3D} \\ -2F_M+3\beta F_M-\beta^2F_M-2(2+\alpha)F_{\mathrm{TF}}+4\beta F_{\mathrm{TF}}+\alpha\beta F_{\mathrm{TF}}-\beta^2F_{\mathrm{TF}} \\ +8V_{3D}+3\alpha V_{3D}-10\beta V_{3D}-2\alpha\beta V_{3D}+3\beta^2V_{3D}-2V_M+3\beta V_M \\ -\beta^2V_M+(2+\alpha-\beta)(-2+\beta)\beta V_{\mathrm{TF}}) \tag{5.61}$$

The maximized profits are

$$
\begin{aligned}
&\prod\nolimits_{FTS}^{*} M(p_M, p_{TF}) \\
&= -\frac{1}{16(\alpha(-3+\beta)-2(-2+\beta)^2)^2(\alpha-\beta)(\alpha-\alpha\beta))}(((-1 \\
&+\beta)(\alpha(\alpha-\beta)(-7+3\beta)+(\alpha^2+\alpha(8-3\beta)+2(-2+\beta)^2)c_L \\
&+\alpha(-8-3\alpha+3\beta)F_{3D}+8F_M+10\alpha F_M-8\beta F_M-4\alpha\beta F_M \\
&+2\beta^2 F_M-2\alpha F_{\mathrm{TF}}+\alpha^2 F_{\mathrm{TF}}+\alpha\beta F_{\mathrm{TF}}-8\alpha V_{3D}-3\alpha^2 V_{3D}+3\alpha\beta V_{3D} \\
&+8V_M+10\alpha V_M-8\beta V_M-4\alpha\beta V_M+2\beta^2 V_M+\alpha\beta(-2+\alpha \\
&+\beta)V_{\mathrm{TF}})(\alpha(\alpha-\beta)(8+(-5+\beta)\beta)-(\alpha(-4+\beta) \\
&-2(-2+\beta)^2)(\alpha-\beta)c_L+\alpha\beta(-\alpha+\beta)F_{3D}-8\alpha F_M-8\beta F_M \\
&+2\alpha\beta F_M+8\beta^2 F_M-2\beta^3 F_M+16\alpha F_{\mathrm{TF}}+4\alpha^2 F_{\mathrm{TF}}-14\alpha\beta F_{\mathrm{TF}} \\
&-\alpha^2\beta F_{\mathrm{TF}}+3\alpha\beta^2 F_{\mathrm{TF}}-\alpha^2\beta V_{3D}+\alpha\beta^2 V_{3D}-8\alpha V_M-8\beta V_M \\
&+2\alpha\beta V_M+8\beta^2 V_M-2\beta^3 V_M+\alpha\beta(4(4+\alpha)-(14+\alpha)\beta \\
&+3\beta^2)V_{\mathrm{TF}})+4\alpha(\alpha(-3+\beta)-2(-2+\beta)^2)((\alpha-\beta)(-1+\beta) \\
&+(\alpha-\beta)c_L+(-\alpha+\beta)F_{3D}+2F_M-2F_{\mathrm{TF}}+\alpha(F_{\mathrm{TF}}-V_{3D})+2V_M \\
&+\beta(-2F_M+F_{\mathrm{TF}}+V_{3D}-2V_M+(-2+\alpha+\beta)V_{\mathrm{TF}}))((\alpha-\beta)(-2 \\
&+\beta)(-1+\beta)+(2+\alpha-\beta)c_L+\beta(-2-\alpha+\beta)F_{3D}-2F_M+4F_{\mathrm{TF}} \\
&+\alpha F_{\mathrm{TF}}-2V_M+\beta(-(-3+\beta)F_M+(-4+\beta)F_{\mathrm{TF}}-(2+\alpha)V_{3D} \\
&+3V_M+(4+\alpha)V_{\mathrm{TF}}+\beta(V_{3D}-V_M+(-4+\beta)V_{\mathrm{TF}})))))
\end{aligned}
\tag{5.62}
$$

$$\prod_{FTS}^{*} L(p_{3DL}, p_L)$$

$$= \frac{1}{8\alpha(\alpha(-3+\beta)-2(-2+\beta)^2)^2(-1+\beta)}(2\alpha((-1+\beta)(8+\alpha - 6\beta+\beta^2)+(3+\alpha-2\beta)(-2+\beta)c_L+(8+3\alpha-2(5+\alpha)\beta + 3\beta^2)F_{3D}-2F_M+3\beta F_M-\beta^2 F_M-2(2+\alpha)F_{\mathrm{TF}}+4\beta F_{\mathrm{TF}} + \alpha\beta F_{\mathrm{TF}}-\beta^2 F_{\mathrm{TF}}+8V_{3D}+3\alpha V_{3D}-10\beta V_{3D}-2\alpha\beta V_{3D}+3\beta^2 V_{3D} - 2V_M+3\beta V_M-\beta^2 V_M+(2+\alpha-\beta)(-2+\beta)\beta V_{\mathrm{TF}})(\alpha(-3+\beta)^2 - (-4+\beta)(-2+\beta)(-1+\beta)+(-2+\beta)c_L+(-8-3\alpha+(10 + \alpha)\beta-3\beta^2)F_{3D}-6F_M+4F_{\mathrm{TF}}-8V_{3D}-3\alpha V_{3D}-6V_M+\beta(-(-5 + \beta)F_M+(-4+\beta)F_{\mathrm{TF}}+(10+\alpha)V_{3D}+5V_M-\beta(3V_{3D}+V_M) + 4V_{\mathrm{TF}}+(-4+\beta)\beta V_{\mathrm{TF}}))-(\alpha(\alpha-\beta)(-3+\beta)(-1+\beta) + (\alpha^2(-3+\beta)+2(-2+\beta)^2(-1+\beta)-\alpha(-3+\beta)(-4+3\beta))c_L + \alpha(8+3\alpha-(7+\alpha)\beta+\beta^2)F_{3D}-8F_M-6\alpha F_M+16\beta F_M + 8\alpha\beta F_M-10\beta^2 F_M-2\alpha\beta^2 F_M+2\beta^3 F_M-6\alpha F_{\mathrm{TF}}-3\alpha^2 F_{\mathrm{TF}} + 5\alpha\beta F_{\mathrm{TF}}+\alpha^2\beta F_{\mathrm{TF}}-\alpha\beta^2 F_{\mathrm{TF}}+8\alpha V_{3D}+3\alpha^2 V_{3D}-7\alpha\beta V_{3D} - \alpha^2\beta V_{3D}+\alpha\beta^2 V_{3D}-8V_M-6\alpha V_M+16\beta V_M+8\alpha\beta V_M-10\beta^2 V_M - 2\alpha\beta^2 V_M+2\beta^3 V_M+\alpha(2+\alpha-\beta)(-3+\beta)\beta V_{\mathrm{TF}})(\alpha(8+(-5 + \beta)\beta)+(4+\alpha-2\beta)(-2+\beta)c_L-\alpha\beta F_{3D}-8F_M-2\alpha F_{\mathrm{TF}}-8V_M + \beta(-2(-4+\beta)F_M-2(-4+\beta)V_M+\alpha(F_{\mathrm{TF}}-V_{3D}+(-2 + \beta)V_{\mathrm{TF}}))))) \tag{5.63}$$

(3) The first-order-conditions of $\prod_{TF} SC(p_M, p_{TF}, p_{3DL})$ in Equation (5.8)

$$\frac{\partial \prod_{TF} SC(p_M, p_{TF}, p_{3DL})}{\partial p_M} = \frac{(\alpha-\beta)c_L+\alpha(F_{\mathrm{TF}}-2p_{\mathrm{TF}})-\beta(F_M-2p_M+V_M-\alpha V_{\mathrm{TF}})}{\alpha(\alpha-\beta)}$$

$$\frac{\partial \prod_{TF} SC(p_M, p_{TF}, p_{3DL})}{\partial p_{TF}} = \frac{1}{(-1+\beta)(-\alpha+\beta)}((\alpha-\beta)c_L+(-\alpha+\beta)F_{3D}+F_M-F_{\mathrm{TF}}-2p_M + 2p_{\mathrm{TF}}+\alpha(F_{\mathrm{TF}}+2p_{\mathrm{3DL}}-2p_{\mathrm{TF}}-V_{3D})+V_M-\beta(F_M+2p_{\mathrm{3DL}}-2p_M - V_{3D}+V_M+V_{\mathrm{TF}}-\alpha V_{\mathrm{TF}}))$$

$$\frac{\partial \prod_{TF} SC(p_M, p_{TF}, p_{3DL})}{\partial p_{3DL}} = \frac{-1+\beta+c_L-F_{3D}+F_{\mathrm{TF}}+2p_{\mathrm{3DL}}-2p_{\mathrm{TF}}-V_{3D}+\beta V_{\mathrm{TF}}}{-1+\beta}$$

So, the determinant of the Hessian Matrix can be written as

$$H = \begin{vmatrix} \frac{2\beta}{\alpha^2 - \alpha\beta} & \frac{2}{-\alpha + \beta} & 0 \\ \frac{2}{-\alpha + \beta} & 2(\frac{1}{\alpha - \beta} + \frac{1}{-1 + \beta}) & -\frac{2}{-1 + \beta} \\ 0 & -\frac{2}{-1 + \beta} & \frac{2}{-1 + \beta} \end{vmatrix} = -\frac{8}{\alpha(\alpha - \beta)(-1 + \beta)} < 0$$

Therefore, the solution to the first-order-conditions gives the unique maximizer.

$$p_M^* = \frac{1}{2}(\alpha + c_L + F_M + V_M) \tag{5.64}$$

$$p_{TF}^* = \frac{1}{2}(\beta + c_L + F_{\mathrm{TF}} + \beta V_{\mathrm{TF}}) \tag{5.65}$$

$$p_{3DL}^* = \frac{1}{2}(1 + F_{3D} + V_{3D}) \tag{5.66}$$

And the optimal sales amounts are

$$q_M^* = \frac{\beta(\alpha + c_L + F_M + V_M) - \alpha(\beta + c_L + F_{\mathrm{TF}} + \beta V_{\mathrm{TF}})}{2\alpha(\alpha - \beta)} \tag{5.67}$$

$$q_{TF}^* = \frac{1}{2(-1 + \beta)(-\alpha + \beta)}((-\alpha + \beta)c_L + (\alpha - \beta)F_{3D} - F_M + F_{\mathrm{TF}} + \alpha(-F_{\mathrm{TF}} + V_{3D}) - V_M + \beta(F_M - V_{3D} + V_M + V_{\mathrm{TF}} - \alpha V_{\mathrm{TF}})) \tag{5.68}$$

$$q_{3DL}^* = \frac{1 - \beta + c_L - F_{3D} + F_{\mathrm{TF}} - V_{3D} + \beta V_{\mathrm{TF}}}{2 - 2\beta} \tag{5.69}$$

The maximized profits are

$$\begin{aligned} &\prod\nolimits_{FTB}^{*} SC(p_M, p_{TF}, p_{3DL}) \\ &= \frac{1}{4}\Big(\frac{(-1 + F_{3D} + V_{3D})(1 - \beta + c_L - F_{3D} + F_{\mathrm{TF}} - V_{3D} + \beta V_{\mathrm{TF}})}{-1 + \beta} \\ &+ \frac{1}{(-1 + \beta)(-\alpha + \beta)}((c_L + F_{\mathrm{TF}} + \beta(-1 + V_{\mathrm{TF}}))((\alpha - \beta)c_L + (-\alpha + \beta)F_{3D} \\ &+ F_M - \beta F_M + (-1 + \alpha)F_{\mathrm{TF}} - \alpha V_{3D} + \beta V_{3D} + V_M - \beta V_M + (-1 + \alpha)\beta V_{\mathrm{TF}})) \\ &- \frac{(\alpha - c_L - F_M - V_M)((\alpha - \beta)c_L + \alpha F_{\mathrm{TF}} - \beta(F_M + V_M - \alpha V_{\mathrm{TF}}))}{\alpha(\alpha - \beta)}\Big) \end{aligned} \tag{5.70}$$

Proof of *PROPOSITION* 5-9.

(1) The first-order-conditions and the second-order-conditions of $\prod_{TFB} M(p_{TF})$ and $\prod_{TFB} L(p_{3DL}, p_L)$ in Equation (5.9) and Equation (5.10),

$$\begin{cases} \frac{\partial \prod_{TFB} M(p_{TF})}{\partial p_{TF}} = \frac{F_{\mathrm{TF}} + \beta p_{\mathrm{3DL}} + p_L - 2p_{\mathrm{TF}} + \beta V_{\mathrm{TF}}}{\beta - \beta^2} \\ \frac{\partial \prod_{TFB} L(p_{3DL}, p_L)}{\partial p_{3DL}} = \frac{1 - \beta - c_L + F_{3D} - 2p_{\mathrm{3DL}} + p_L + p_{\mathrm{TF}} + V_{3D}}{1 - \beta} \end{cases}$$

$$\begin{cases} \frac{\partial \prod_{3DL}^2 M(p_M)}{\partial p_{TF}^2} = \frac{2}{(-1+\beta)\beta} < 0 \\ \frac{\partial \prod_{3DL}^2 L(p_{3D}, p_L)}{\partial p_{3D}^2} = \frac{2}{-1+\beta} < 0 \end{cases}$$

So, the solution to the first-order-conditions gives the unique maximizer.

$$\begin{cases} \frac{\partial \prod_{TFB} M(p_{TF})}{\partial p_{TF}} = \frac{F_{\mathrm{TF}} + \beta p_{\mathrm{3DL}} + p_L - 2p_{\mathrm{TF}} + \beta V_{\mathrm{TF}}}{\beta - \beta^2} = 0 \\ \frac{\partial \prod_{TFB} L(p_{3DL}, p_L)}{\partial p_{3DL}} = \frac{1 - \beta - c_L + F_{3D} - 2p_{\mathrm{3DL}} + p_L + p_{\mathrm{TF}} + V_{3D}}{1 - \beta} = 0 \end{cases}$$

$$\begin{cases} p_{TF}^* = \frac{(-1+\beta)\beta + \beta c_L - 2F_{\mathrm{TF}} - 2p_L - \beta(F_{3D} + p_L + V_{3D} + 2V_{\mathrm{TF}})}{-4+\beta} \\ p_{3DL}^* = \frac{2 - 2\beta - 2c_L + 2F_{3D} + F_{\mathrm{TF}} + 3p_L + 2V_{3D} + \beta V_{\mathrm{TF}}}{4 - \beta} \end{cases}$$

Then, the logistics vendor's profit function (5.10) can be updated as

$$\begin{aligned} \prod\nolimits_{TFB} L(p_{3DL}, p_L) \\ = \frac{1}{(-4+\beta)^2(-1+\beta)\beta}(\beta(2 - 2\beta - 2c_L + (-2+\beta)F_{3D} + F_{\mathrm{TF}} + 3p_L \\ + (-2+\beta)V_{3D} + \beta V_{\mathrm{TF}})((-2+\beta)c_L - (-2+\beta)F_{3D} - F_{\mathrm{TF}} + p_L + 2(-1 \\ + \beta + V_{3D}) - \beta(p_L + V_{3D} + V_{\mathrm{TF}})) - (-4+\beta)(c_L - p_L)(\beta - \beta^2 - 2F_{\mathrm{TF}} \\ - 2p_L + \beta(-c_L + F_{3D} + F_{\mathrm{TF}} + 2p_L + V_{3D} + (-2+\beta)V_{\mathrm{TF}}))) \end{aligned}$$

which is convex in p_L, so the first-order-conditions of it gives the maximum profit.

$$\begin{aligned} \frac{\partial \prod_{TFB} L(p_{3DL}, p_L)}{\partial p_L} \\ = \frac{\beta(8+\beta) + 2(4+\beta)c_L - 8F_{\mathrm{TF}} - 16p_L - \beta(\beta F_{3D} + 2p_L + \beta V_{3D} + 8V_{\mathrm{TF}})}{(-4+\beta)^2\beta} = 0 \end{aligned}$$

$$p_L^* = \frac{\beta(8+\beta) + 2(4+\beta)c_L - 8F_{\mathrm{TF}} - \beta(\beta(F_{3D} + V_{3D}) + 8V_{\mathrm{TF}})}{2(8+\beta)}$$

The final optimal decisions are

$$p_L^* = \frac{\beta(8+\beta) + 2(4+\beta)c_L - 8F_{\mathrm{TF}} - \beta(\beta(F_{3D}+V_{3D}) + 8V_{\mathrm{TF}})}{2(8+\beta)} \tag{5.71}$$

$$p_{TF}^* = \frac{\beta(8+\beta) + 4c_L + 4F_{\mathrm{TF}} + \beta(4+\beta)(F_{3D}+V_{3D}) + 4\beta V_{\mathrm{TF}}}{2(8+\beta)} \tag{5.72}$$

$$p_{3DL}^* = \frac{8+\beta - 2c_L + (8+3\beta)F_{3D} - 2F_{\mathrm{TF}} + (8+3\beta)V_{3D} - 2\beta V_{\mathrm{TF}}}{2(8+\beta)} \tag{5.73}$$

$$q_{TF}^* = \frac{(2+\beta)(c_L + F_{\mathrm{TF}} - \beta(F_{3D}+V_{3D}-V_{\mathrm{TF}}))}{(-1+\beta)\beta(8+\beta)} \tag{5.74}$$

$$q_{3DL}^* = -\frac{1}{2(-1+\beta)(8+\beta)}(-(-1+\beta)(8+\beta) + 6c_L + (-8+\beta+\beta^2)F_{3D} + 6F_{\mathrm{TF}} + (-8+\beta+\beta^2)V_{3D} + 6\beta V_{\mathrm{TF}}) \tag{5.75}$$

The maximized profits are

$$\prod\nolimits_{TFB}^{*} M(p_{TF}) = -\frac{(2+\beta)^2(c_L + F_{\mathrm{TF}} - \beta(F_{3D}+V_{3D}-V_{\mathrm{TF}}))^2}{(-1+\beta)\beta(8+\beta)^2} \tag{5.76}$$

$$\begin{aligned}\prod\nolimits_{TFB}^{*} L\,(p_{3DL}, p_L) &= \frac{1}{4(-1+\beta)(8+\beta)^2}(-(8+\beta-2c_L+(-8+\beta)F_{3D}-2F_{\mathrm{TF}} \\ &+ (-8+\beta)V_{3D} - 2\beta V_{\mathrm{TF}})(-(-1+\beta)(8+\beta) + 6c_L + (-8+\beta \\ &+ \beta^2)F_{3D} + 6F_{\mathrm{TF}} + (-8+\beta+\beta^2)V_{3D} + 6\beta V_{\mathrm{TF}}) \\ &+ \frac{1}{\beta}(2(2+\beta)(-c_L - F_{\mathrm{TF}} + \beta(F_{3D}+V_{3D}-V_{\mathrm{TF}}))(-\beta(8+\beta) \\ &+ 8c_L + 8F_{\mathrm{TF}} + \beta(\beta(F_{3D}+V_{3D}) + 8V_{\mathrm{TF}}))))\end{aligned} \tag{5.77}$$

(2) Here, $\prod_{TF} L(p_{3DL}, p_L)$ is convex in p_{3DL}, therefore, the solution of the first-order-condition gives the unique maximizer

$$\frac{\partial \prod_{TF} L(p_{3DL}, p_L)}{\partial p_{3DL}} = \frac{1-\beta-c_L+F_{3D}-2p_{\mathrm{3DL}}+p_L+p_{\mathrm{TF}}+V_{3D}}{1-\beta} = 0$$

$$p_{3DL}^* = \frac{1}{2}(1-\beta-c_L+F_{3D}+p_L+p_{\mathrm{TF}}+V_{3D})$$

Then, the $\prod_{TFB} M(p_{TF})$ can be updated as

$$\prod\nolimits_{TF} M(p_{TF}) = -\frac{1}{2(-1+\beta)\beta}(((-1+\beta)\beta + \beta c_L + 2p_{\mathrm{TF}} - \beta(F_{3D}+p_L+p_{\mathrm{TF}} + V_{3D}))(F_{\mathrm{TF}} + p_L - p_{\mathrm{TF}} + \beta V_{\mathrm{TF}}))$$

Which is convex in p_{TF}, the solution of the first-order-condition gives the maximum value,

$$\frac{\partial \prod_{TF} M(p_{TF})}{\partial p_{TF}} = \frac{(-1+\beta)\beta - 2F_{\mathrm{TF}} - 2p_L + 4p_{\mathrm{TF}} + \beta(c_L - F_{3D} + F_{\mathrm{TF}} - 2p_{\mathrm{TF}} - V_{3D} + (-2+\beta)V_{\mathrm{TF}})}{2(-1+\beta)\beta} = 0$$

$$p_{TF}^{*} = \frac{(-1+\beta)\beta - 2F_{\mathrm{TF}} - 2p_L + \beta(c_L - F_{3D} + F_{\mathrm{TF}} - V_{3D} + (-2+\beta)V_{\mathrm{TF}})}{2(-2+\beta)}$$

Therefore, $\prod_{TF} L(p_{3DL}, p_L)$ could be rewritten as

$$\prod\nolimits_{TF} L(p_{3DL}, p_L) = \frac{1}{16(-2+\beta)^2(-1+\beta)\beta}(-\beta(-4+5\beta-\beta^2+(-4+3\beta)c_L+(4-3\beta)F_{3D}-2F_{\mathrm{TF}}+2p_L+4V_{3D}+\beta(F_{\mathrm{TF}}-2p_L-3V_{3D}+(-2+\beta)V_{\mathrm{TF}}))(-4+5\beta-\beta^2-(-4+\beta)c_L+(4-3\beta)F_{3D}-2F_{\mathrm{TF}}-6p_L+4V_{3D}+\beta(F_{\mathrm{TF}}+2p_L-3V_{3D}+(-2+\beta)V_{\mathrm{TF}}))+4(-2+\beta)^2(c_L-p_L)(\beta-\beta^2-2F_{\mathrm{TF}}-2p_L+\beta(-c_L+F_{3D}+F_{\mathrm{TF}}+2p_L+V_{3D}+(-2+\beta)V_{\mathrm{TF}})))$$

Which is convex in p_L and the solutions to the first-order-condition give the unique maximizer.

$$\frac{\partial \prod_{TF} L(p_{3DL}, p_L)}{\partial p_L} = \frac{1}{4(-2+\beta)^2\beta}(\beta(8+(-5+\beta)\beta)+(8+(-4+\beta)\beta)c_L-8F_{\mathrm{TF}}-16p_L+\beta(6F_{\mathrm{TF}}+10p_L-\beta(F_{3D}+F_{\mathrm{TF}}+2p_L+V_{3D})-(-4+\beta)(-2+\beta)V_{\mathrm{TF}})) = 0$$

$$p_L^{*} = \frac{1}{2(8+(-5+\beta)\beta)}(\beta(8+(-5+\beta)\beta)+(8+(-4+\beta)\beta)c_L-8F_{\mathrm{TF}}-\beta(\beta F_{3D}+(-6+\beta)F_{\mathrm{TF}}+\beta V_{3D})-(-4+\beta)(-2+\beta)\beta V_{\mathrm{TF}})$$

The final optimal decisions are

$$p_L^* = \frac{1}{2(8+(-5+\beta)\beta)}(\beta(8+(-5+\beta)\beta)+(8+(-4+\beta)\beta)c_L - 8F_{\mathrm{TF}} - \beta(\beta F_{3D}+(-6+\beta)F_{\mathrm{TF}}+\beta V_{3D}) - (-4+\beta)(-2+\beta)\beta V_{\mathrm{TF}}) \tag{5.78}$$

$$p_{TF}^* = \frac{1}{2(8+(-5+\beta)\beta)}(\beta(8+(-5+\beta)\beta)+(-2+\beta)^2 c_L + 4F_{\mathrm{TF}} - (-4+\beta)\beta(F_{3D}-F_{\mathrm{TF}}+V_{3D})+(-2+\beta)^2\beta V_{\mathrm{TF}}) \tag{5.79}$$

$$p_{3DL}^* = \frac{1}{2(8+(-5+\beta)\beta)}\ (8+(-5+\beta)\beta+(-2+\beta)c_L+(8-3\beta)F_{3D}-2F_{\mathrm{TF}} + 8V_{3D}+\beta(F_{\mathrm{TF}}-3V_{3D}+(-2+\beta)V_{\mathrm{TF}})) \tag{5.80}$$

$$q_{TF}^* = -\frac{(-2+\beta)(c_L+F_{\mathrm{TF}}-\beta(F_{3D}+V_{3D}-V_{\mathrm{TF}}))}{(-1+\beta)\beta(8+(-5+\beta)\beta)} \tag{5.81}$$

$$q_{3DL}^* = \frac{1}{2(-1+\beta)(8+(-5+\beta)\beta)}((-1+\beta)(8+(-5+\beta)\beta)-(-3+\beta)(-2+\beta)c_L+(8+(-7+\beta)\beta)F_{3D}-6F_{\mathrm{TF}}+8V_{3D}+\beta(-(-5+\beta)F_{\mathrm{TF}} + (-7+\beta)V_{3D}-(-3+\beta)(-2+\beta)V_{\mathrm{TF}})) \tag{5.82}$$

The maximized profits are

$$\prod\nolimits_{TFB}^{*} M(p_{TF}) = \frac{2(-2+\beta)(c_L+F_{\mathrm{TF}}-\beta(F_{3D}+V_{3D}-V_{\mathrm{TF}}))^2}{(-1+\beta)\beta(8+(-5+\beta)\beta)^2} \tag{5.83}$$

$$\prod\nolimits_{TFB}^{*} L\,(p_{3DL},p_L) = \frac{1}{4(-1+\beta)(8+(-5+\beta)\beta)^2}(-\frac{1}{\beta}\Big(2(-2+\beta)\big(-c_L-F_{\mathrm{TF}} + \beta(F_{3D}+V_{3D}-V_{\mathrm{TF}})\big)\big(-\beta(8+(-5+\beta)\beta) + (-4+\beta)(-2+\beta)c_L+8F_{\mathrm{TF}} + \beta(\beta F_{3D}+(-6+\beta)F_{\mathrm{TF}}+\beta V_{3D}+(-4+\beta)(-2+\beta)V_{\mathrm{TF}})\big)\Big) + (-8-(-5+\beta)\beta-(-2+\beta)c_L+(8+\beta(-7+2\beta))F_{3D} + 2F_{\mathrm{TF}}+8V_{3D}+\beta(-F_{\mathrm{TF}}+(-7+2\beta)V_{3D}-(-2 + \beta)V_{\mathrm{TF}}))(-(-1+\beta)(8+(-5+\beta)\beta)+(-3+\beta)(-2+\beta)c_L - (8+(-7+\beta)\beta)F_{3D}+6F_{\mathrm{TF}}-8V_{3D}+\beta((-5+\beta)F_{\mathrm{TF}}-(-7 + \beta)V_{3D}+(-3+\beta)(-2+\beta)V_{\mathrm{TF}}))) \tag{5.84}$$

(3) The first-order-conditions and the second-order-conditions of $\prod_{TFB} M(p_{TF})$ and $\prod_{TFB} L(p_{3DL},p_L)$ in Equation (5.9) and Equation (5.10),

$$\begin{cases} \dfrac{\partial \prod_{TFB} SC(p_{TF}, p_{3DL})}{\partial p_{TF}} = \dfrac{c_L - \beta F_{3D} + F_{\mathrm{TF}} + 2\beta p_{\mathrm{3DL}} - 2p_{\mathrm{TF}} - \beta V_{3D} + \beta V_{\mathrm{TF}}}{\beta - \beta^2} \\ \dfrac{\partial \prod_{TFB} SC(p_{TF}, p_{3DL})}{\partial p_{3DL}} = \dfrac{-1 + \beta + c_L - F_{3D} + F_{\mathrm{TF}} + 2p_{\mathrm{3DL}} - 2p_{\mathrm{TF}} - V_{3D} + \beta V_{\mathrm{TF}}}{-1 + \beta} \end{cases}$$

$$\begin{cases} \dfrac{\partial \prod_{3DL}^2 SC(p_{TF}, p_{3DL})}{\partial p_{TF}^2} = \dfrac{2}{(-1+\beta)\beta} < 0 \\ \dfrac{\partial \prod_{3DL}^2 SC(p_{TF}, p_{3DL})}{\partial p_{3D}^2} = \dfrac{2}{-1+\beta} < 0 \\ \dfrac{\partial \prod_{3DL}^2 SC(p_{TF}, p_{3DL})}{\partial p_{TF} \partial p_{3DL}} = \dfrac{\partial \prod_{3DL}^2 SC(p_{TF}, p_{3DL})}{\partial p_{3DL} \partial p_{TF}} = -\dfrac{2}{-1+\beta} > 0 \end{cases}$$

So, the determinant of the Hessian Matrix can be written as

$$H = \begin{vmatrix} \dfrac{2}{(-1+\beta)\beta} & -\dfrac{2}{-1+\beta} \\ -\dfrac{2}{-1+\beta} & \dfrac{2}{-1+\beta} \end{vmatrix} = \frac{2}{(-1+\beta)\beta} \times \left(-\frac{2}{-1+\beta}\right) - \left(-\frac{2}{-1+\beta}\right)^2 = \frac{4}{\beta - \beta^2} > 0$$

Thus, it is a negative-definite matrix, the solution to the first-order-conditions gives the unique maximizer.

$$p_{TF}^* = \frac{1}{2}(\beta + c_L + F_{\mathrm{TF}} + \beta V_{\mathrm{TF}}) \tag{5.85}$$

$$p_{3DL}^* = \frac{1}{2}(1 + F_{3D} + V_{3D}) \tag{5.86}$$

Accordingly,

$$q_{TF}^* = \frac{c_L + F_{\mathrm{TF}} - \beta(F_{3D} + V_{3D} - V_{\mathrm{TF}})}{2(-1+\beta)\beta} \tag{5.87}$$

$$q_{3DL}^* = \frac{1 - \beta + c_L - F_{3D} + F_{\mathrm{TF}} - V_{3D} + \beta V_{\mathrm{TF}}}{2 - 2\beta} \tag{5.88}$$

$$\prod\nolimits_{FTB}^{*} SC(p_{TF}, p_{3DL}) = \frac{1}{4(-1+\beta)}\Bigg(-\frac{(c_L + F_{\mathrm{TF}} - \beta(F_{3D} + V_{3D} - V_{\mathrm{TF}}))(c_L + F_{\mathrm{TF}} + \beta(-1 + V_{\mathrm{TF}}))}{\beta} + (-1 + F_{3D} + V_{3D})(1 - \beta + c_L - F_{3D} + F_{\mathrm{TF}} - V_{3D} + \beta V_{\mathrm{TF}})\Bigg) \tag{5.89}$$

Proof of *PROPOSITION* 5-19.

(1) According to Equation (5.15), the first-order-conditions and the second-order-condition are

$$\frac{\partial \prod_{3DM} M(p_M, p_{TF}, p_{3DM})}{\partial p_M} = \frac{\alpha(F_{\mathrm{TF}} + p_L - 2p_{\mathrm{TF}}) - \beta(F_M + p_L - 2p_M + V_M - \alpha V_{\mathrm{TF}})}{\alpha(\alpha - \beta)}$$

$$\frac{\partial \prod_{3DM} M(p_M, p_{TF}, p_{3DM})}{\partial p_{TF}}$$

$$= \frac{1}{(-1+\beta)(-\alpha+\beta)}((-\alpha+\beta)F_{3D} - (-1+\beta)F_M + (-1+\alpha)F_{\mathrm{TF}}$$

$$+ 2\alpha p_{3\mathrm{DM}} - 2p_M + 2p_{\mathrm{TF}} - 2\alpha p_{\mathrm{TF}} - \alpha V_{3D} + V_M + \beta(-2p_{3\mathrm{DM}} + 2p_M$$

$$+ V_{3D} - V_M + (-1+\alpha)V_{\mathrm{TF}}))$$

$$\frac{\partial \prod_{3DM} M(p_M, p_{TF}, p_{3DM})}{\partial p_{3DM}} = \frac{-1 + \beta - F_{3D} + F_{\mathrm{TF}} + 2p_{3\mathrm{DM}} - 2p_{\mathrm{TF}} - V_{3D} + \beta V_{\mathrm{TF}}}{-1+\beta}$$

So, the determinant of the Hessian Matrix can be written as

$$H = \begin{bmatrix} \frac{2\beta}{\alpha^2 - \alpha\beta} & \frac{2}{-\alpha+\beta} & 0 \\ \frac{2}{-\alpha+\beta} & 2(\frac{1}{\alpha-\beta} + \frac{1}{-1+\beta}) & -\frac{2}{-1+\beta} \\ 0 & -\frac{2}{-1+\beta} & \frac{2}{-1+\beta} \end{bmatrix} = -\frac{8}{\alpha(\alpha-\beta)(-1+\beta)} < 0$$

Therefore, the solution to the first-order-conditions gives the unique maximizer.

$$p_M^* = \frac{1}{2}(\alpha + F_M + p_L + V_M)$$

$$p_{TF}^* = \frac{1}{2}(\beta + F_{\mathrm{TF}} + p_L + \beta V_{\mathrm{TF}})$$

$$p_{3DM}^* = \frac{1}{2}(1 + F_{3D} + p_L + V_{3D})$$

The $\prod_{3DM} L(p_L)$ can be updated as

$$\prod\nolimits_{3DM} L(p_L) = \frac{(c_L - p_L)(-\alpha + F_M + p_L + V_M)}{2\alpha}$$

Which is convex in p_L, thus, the first-order-condition gives the unique maximizer,

$$\frac{\partial \prod_{3DM} L(p_L)}{\partial p_L} = \frac{\alpha + c_L - F_M - 2p_L - V_M}{2\alpha}$$

$$p_L^* = \frac{1}{2}(\alpha + c_L - F_M - V_M)$$

Accordingly, the optimal decisions are

$$p_L^* = \frac{1}{2}(\alpha + c_L - F_M - V_M) \tag{5.90}$$

$$p_M^* = \frac{1}{4}(3\alpha + c_L + F_M + V_M) \tag{5.91}$$

$$p_{TF}^* = \frac{1}{4}(\alpha + 2\beta + c_L - F_M + 2F_{\mathrm{TF}} - V_M + 2\beta V_{\mathrm{TF}}) \tag{5.92}$$

$$p_{3DM}^* = \frac{1}{4}(2 + \alpha + c_L + 2F_{3D} - F_M + 2V_{3D} - V_M) \tag{5.93}$$

and

$$q_M^* = \frac{\alpha(-\alpha + \beta) + (-\alpha + \beta)c_L + (\alpha + \beta)F_M - 2\alpha F_{\mathrm{TF}} + \alpha V_M + \beta V_M - 2\alpha\beta V_{\mathrm{TF}}}{4\alpha(\alpha - \beta)} \tag{5.94}$$

$$q_{TF}^* = \frac{1}{4\alpha(\alpha - \beta)}((-\alpha + \beta)F_{3D} - (-1 + \beta)F_M + (-1 + \alpha)F_{\mathrm{TF}} - \alpha V_{3D} + V_M + \beta(V_{3D} - V_M + (-1 + \alpha)V_{\mathrm{TF}})) \tag{5.95}$$

$$q_{3DM}^* = \frac{-1 + \beta + F_{3D} - F_{\mathrm{TF}} + V_{3D} - \beta V_{\mathrm{TF}}}{2(-1 + \beta)} \tag{5.96}$$

$$\begin{aligned}\prod\nolimits_{3DM}^{*} M(p_M, p_{TF}, p_{3DM}) = \frac{1}{16}\Bigg(& -\frac{1}{-1 + \beta}(2(-2 + \alpha + c_L + 2F_{3D} - F_M + 2V_{3D} - V_M)(-1 + \beta + F_{3D} - F_{\mathrm{TF}} + V_{3D} - \beta V_{\mathrm{TF}})) \\ & - \frac{1}{\alpha(\alpha - \beta)}((\alpha - c_L - F_M - V_M)(\alpha^2 - \alpha\beta + (\alpha - \beta)c_L - (\alpha + \beta)F_M + 2\alpha F_{\mathrm{TF}} - \alpha V_M - \beta V_M + 2\alpha\beta V_{\mathrm{TF}})) \\ & - \frac{1}{(\alpha - \beta)(-1 + \beta)}(2(\alpha - 2\beta + c_L - F_M + 2F_{\mathrm{TF}} - V_M + 2\beta V_{\mathrm{TF}})((-\alpha + \beta)F_{3D} - (-1 + \beta)F_M + (-1 + \alpha)F_{\mathrm{TF}} - \alpha V_{3D} \\ & + V_M + \beta(V_{3D} - V_M + (-1 + \alpha)V_{\mathrm{TF}})))\Bigg)\end{aligned} \tag{5.97}$$

$$\prod\nolimits_{3DM}^{*} L(p_L) = \frac{(-\alpha + c_L + F_M + V_M)^2}{8\alpha} \tag{5.98}$$

(2) According to Equation (5.17), the first-order-conditions are

$$\frac{\partial \prod_{3DM} SC(p_M, p_{TF}, p_{3DM})}{\partial p_M} = \frac{(\alpha-\beta)c_L + \alpha(F_{\mathrm{TF}} - 2p_{\mathrm{TF}}) - \beta(F_M - 2p_M + V_M - \alpha V_{\mathrm{TF}})}{\alpha(\alpha-\beta)}$$

$$\frac{\partial \prod_{3DM} SC(p_M, p_{TF}, p_{3DM})}{\partial p_{TF}} = \frac{1}{(-1+\beta)(-\alpha+\beta)}((-\alpha+\beta)F_{3D} - (-1+\beta)F_M + (-1+\alpha)F_{\mathrm{TF}} + 2\alpha p_{\mathrm{3DM}} - 2p_M + 2p_{\mathrm{TF}} - 2\alpha p_{\mathrm{TF}} - \alpha V_{3D} + V_M + \beta(-2p_{\mathrm{3DM}} + 2p_M + V_{3D} - V_M + (-1+\alpha)V_{\mathrm{TF}}))$$

$$\frac{\partial \prod_{3DM} SC(p_M, p_{TF}, p_{3DM})}{\partial p_{3DM}} = \frac{-1+\beta - F_{3D} + F_{\mathrm{TF}} + 2p_{\mathrm{3DM}} - 2p_{\mathrm{TF}} - V_{3D} + \beta V_{\mathrm{TF}}}{-1+\beta}$$

So, the determinant of the Hessian Matrix can be written as

$$H = \begin{bmatrix} \frac{2\beta}{\alpha^2 - \alpha\beta} & \frac{2}{-\alpha+\beta} & 0 \\ \frac{2}{-\alpha+\beta} & 2\left(\frac{1}{\alpha-\beta} + \frac{1}{-1+\beta}\right) & -\frac{2}{-1+\beta} \\ 0 & -\frac{2}{-1+\beta} & \frac{2}{-1+\beta} \end{bmatrix} = -\frac{8}{\alpha(\alpha-\beta)(-1+\beta)} < 0$$

Therefore, the solution to the first-order-conditions gives the unique maximizer.

$$p_M^* = \frac{1}{2}(\alpha + c_L + F_M + V_M) \tag{5.99}$$

$$p_{TF}^* = \frac{1}{2}(\beta + c_L + F_{\mathrm{TF}} + \beta V_{\mathrm{TF}}) \tag{5.100}$$

$$p_{3DM}^* = \frac{1}{2}(1 + c_L + F_{3D} + V_{3D}) \tag{5.101}$$

Accordingly, the optimal sales amount and the maximized profit of the supply chain are

$$q_M^* = \frac{\beta(\alpha + c_L + F_M + V_M) - \alpha(\beta + c_L + F_{\mathrm{TF}} + \beta V_{\mathrm{TF}})}{2\alpha(\alpha-\beta)} \tag{5.102}$$

$$q_{TF}^* = \frac{1}{2(-1+\beta)(-\alpha+\beta)}((\alpha-\beta)F_{3D} + (-1+\beta)F_M - (-1+\alpha)F_{\mathrm{TF}} + \alpha V_{3D} - V_M + \beta(-V_{3D} + V_M + V_{\mathrm{TF}} - \alpha V_{\mathrm{TF}})) \tag{5.103}$$

$$q_{3DM}^* = \frac{-1+\beta + F_{3D} - F_{\mathrm{TF}} + V_{3D} - \beta V_{\mathrm{TF}}}{2(-1+\beta)} \tag{5.104}$$

$$\prod\nolimits_{3DM}^{*} SC(p_M, p_{TF}, p_{3DM})$$
$$= \frac{1}{4}\left(-\frac{(-1+c_L+F_{3D}+V_{3D})(-1+\beta+F_{3D}-F_{\mathrm{TF}}+V_{3D}-\beta V_{\mathrm{TF}})}{-1+\beta}\right.$$
$$+\frac{1}{(-1+\beta)(-\alpha+\beta)}((c_L+F_{\mathrm{TF}}+\beta(-1+V_{\mathrm{TF}}))((-\alpha+\beta)F_{3D}-(-1+\beta)F_M \tag{5.105}$$
$$+(-1+\alpha)F_{\mathrm{TF}}-\alpha V_{3D}+V_M+\beta(V_{3D}-V_M+(-1+\alpha)V_{\mathrm{TF}})))$$
$$\left.-\frac{(\alpha-c_L-F_M-V_M)((\alpha-\beta)c_L+\alpha F_{\mathrm{TF}}-\beta(F_M+V_M-\alpha V_{\mathrm{TF}}))}{\alpha(\alpha-\beta)}\right)$$

Proof of *PROPOSITION* 5-26.

(1) According to Equation (5.20), the first-order-conditions are

$$\frac{\partial \prod_{3DM} M(p_M, p_{3DM})}{\partial p_M} = -\frac{F_M+p_L-2p_M-\alpha(F_{3D}-2p_{3\mathrm{DM}}+p_L+V_{3D})+V_M}{(-1+\alpha)\alpha}$$
$$\frac{\partial \prod_{3DM} M(p_M, p_{3DM})}{\partial p_{3DM}} = \frac{-1+\alpha-F_{3D}+F_M+2p_{3\mathrm{DM}}-2p_M-V_{3D}+V_M}{-1+\alpha}$$

So, the determinant of the Hessian Matrix can be written as

$$H = \begin{vmatrix} \frac{2}{(-1+\alpha)\alpha} & -\frac{2}{-1+\alpha} \\ -\frac{2}{-1+\alpha} & \frac{2}{-1+\alpha} \end{vmatrix} = \frac{2}{(-1+\alpha)\alpha} \times \frac{2}{-1+\alpha} - \left(-\frac{2}{-1+\alpha}\right)^2 = \frac{4}{\alpha-\alpha^2} < 0$$

Therefore, the first-order-conditions gives the unique maximizer,

$$\frac{\partial \prod_{3DM} M(p_M, p_{3DM})}{\partial p_M} = -\frac{F_M+p_L-2p_M-\alpha(F_{3D}-2p_{3\mathrm{DM}}+p_L+V_{3D})+V_M}{(-1+\alpha)\alpha} = 0$$
$$\frac{\partial \prod_{3DM} M(p_M, p_{3DM})}{\partial p_{3DM}} = \frac{-1+\alpha-F_{3D}+F_M+2p_{3\mathrm{DM}}-2p_M-V_{3D}+V_M}{-1+\alpha} = 0$$
$$p_M = \frac{1}{2}(\alpha+F_M+p_L+V_M)$$
$$p_{3\mathrm{DM}} = \frac{1}{2}(1+F_{3D}+p_L+V_{3D}$$

So, $\prod_{3DM} L(p_L)$ can be updated as

$$\prod\nolimits_{3DM} L(p_L) = \frac{(c_L-p_L)(-\alpha+F_M+p_L+V_M)}{2\alpha}$$

Which is convex in p_L, thus, the solution to the first-order-condition gives the maximizer,

$$\frac{\partial \prod_{3DM} L(p_L)}{\partial p_L} = \frac{\alpha + c_L - F_M - 2p_L - V_M}{2\alpha} = 0$$

$$p_L^* = \frac{1}{2}(\alpha + c_L - F_M - V_M)$$

And the optimal decision and the maximized profits of the traditional manufacturer and the logistics vendor are

$$p_L^* = \frac{1}{2}(\alpha + c_L - F_M - V_M) \quad (5.106)$$

$$p_M^* = \frac{1}{4}(3\alpha + c_L + F_M + V_M) \quad (5.107)$$

$$p_{3DM}^* = \frac{1}{4}(2 + \alpha + c_L + 2F_{3D} - F_M + 2V_{3D} - V_M) \quad (5.108)$$

$$q_M^* = \frac{\alpha - \alpha^2 - (-1+\alpha)c_L + F_M + V_M + \alpha(-2F_{3D} + F_M - 2V_{3D} + V_M)}{4(-1+\alpha)\alpha} \quad (5.109)$$

$$q_{3DM}^* = \frac{-1 + \alpha + F_{3D} - F_M + V_{3D} - V_M}{2(-1+\alpha)} \quad (5.110)$$

$$\prod\nolimits_{3DM}^{*} M(p_M, p_{3DM}) = \frac{1}{16(-1+\alpha)\alpha}(-2\alpha(-1 + \alpha + F_{3D} - F_M + V_{3D} - V_M)(-2 + \alpha + c_L + 2F_{3D} - F_M + 2V_{3D} - V_M) + (\alpha - c_L - F_M - V_M)(\alpha - \alpha^2 - (-1+\alpha)c_L + F_M + V_M + \alpha(-2F_{3D} + F_M - 2V_{3D} + V_M))) \quad (5.111)$$

$$\prod\nolimits_{3DM}^{*} L(p_L) = \frac{(-\alpha + c_L + F_M + V_M)^2}{8\alpha} \quad (5.112)$$

(2) According to Equation (5.22), the first-order-conditions are

$$\frac{\partial \prod_{3DM} SC(p_M, p_{3DM})}{\partial p_M} = \frac{(-1+\alpha)c_L - F_M + 2p_M + \alpha(F_{3D} - 2p_{3\mathrm{DM}} + V_{3D}) - V_M}{(-1+\alpha)\alpha}$$

$$\frac{\partial \prod_{3DM} SC(p_M, p_{3DM})}{\partial p_{3DM}} = \frac{-1 + \alpha - F_{3D} + F_M + 2p_{3\mathrm{DM}} - 2p_M - V_{3D} + V_M}{-1+\alpha}$$

So, the determinant of the Hessian Matrix can be written as

$$H = \begin{vmatrix} \frac{2}{(-1+\alpha)\alpha} & -\frac{2}{-1+\alpha} \\ -\frac{2}{-1+\alpha} & \frac{2}{-1+\alpha} \end{vmatrix} = \frac{2}{(-1+\alpha)\alpha} \times \frac{2}{-1+\alpha} - \left(-\frac{2}{-1+\alpha}\right)^2 = \frac{4}{\alpha - \alpha^2} < 0$$

Therefore, the first-order-conditions gives the unique maximizer,

$$\frac{\partial \prod_{3DM} M(p_M, p_{3DM})}{\partial p_M} = -\frac{F_M + p_L - 2p_M - \alpha(F_{3D} - 2p_{3\mathrm{DM}} + p_L + V_{3D}) + V_M}{(-1+\alpha)\alpha} = 0$$

$$\frac{\partial \prod_{3DM} M(p_M, p_{3DM})}{\partial p_{3DM}} = \frac{-1 + \alpha - F_{3D} + F_M + 2p_{3\mathrm{DM}} - 2p_M - V_{3D} + V_M}{-1+\alpha} = 0$$

So, we can have

$$p_M^* = \frac{1}{2}(\alpha + c_L + F_M + V_M) \quad (5.113)$$

$$p_{3DM}^* = \frac{1}{2}(1 + c_L + F_{3D} + V_{3D}) \quad (5.114)$$

And the optimal sales amount and the maximized profit of the supply chain is

$$q_M^* = \frac{-(-1+\alpha)c_L + F_M - \alpha(F_{3D} + V_{3D}) + V_M}{2(-1+\alpha)\alpha} \quad (5.115)$$

$$q_{3DM}^* = \frac{-1 + \alpha + F_{3D} - F_M + V_{3D} - V_M}{2(-1+\alpha)} \quad (5.116)$$

$$\prod\nolimits_{3DM}^{*} SC(p_M, p_{3DM})$$
$$= -\frac{1}{4(-1+\alpha)}\Bigg((-1 + c_L + F_{3D} + V_{3D})(-1 + \alpha + F_{3D} - F_M + V_{3D} - V_M) \quad (5.117)$$
$$+ \frac{(\alpha - c_L - F_M - V_M)((-1+\alpha)c_L - F_M + \alpha(F_{3D} + V_{3D}) - V_M)}{\alpha}\Bigg)$$

Proof of *PROPOSITION* 5-31.

(1) Here, Equation (5.23) is convex in p_{3DM}, therefore, the first-order-conditions gives the maximizer,

$$\frac{\partial \prod_{3DM} M(p_{3DM})}{\partial p_{3DM}} = 1 + F_{3D} - 2p_{3\mathrm{DM}} + p_L + V_{3D} = 0$$

$$p_{3DM} = \frac{1}{2}(1 + F_{3D} + p_L + V_{3D})$$

Then, the Equation (5.24) can be rewritten as

$$\prod_{3DM} L(p_L) = 1 + F_{3D} - 2p_{\text{3DM}} + p_L + V_{3D} = 0$$

It is convex in p_L, again, the first-order-conditions gives the maximized value of $\prod_{3DM} L(p_L)$,

$$\frac{\partial \prod_{3DM} L(p_L)}{\partial p_L} = \frac{1}{2}(1 + c_L - F_{3D} - 2p_L - V_{3D}) = 0$$

$$p_L^* = \frac{1}{2}(1 + c_L - F_{3D} - V_{3D})$$

Therefore, the optimal prices are

$$p_L^* = \frac{1}{2}(1 + c_L - F_{3D} - V_{3D}) \tag{5.118}$$

$$p_{3DM}^* = \frac{1}{4}(3 + c_L + F_{3D} + V_{3D}) \tag{5.119}$$

And the optimal sales amount and the maximized profit of the supply chain is

$$q_{3DM}^* = \frac{1}{4}(1 - c_L - F_{3D} - V_{3D}) \tag{5.120}$$

$$\prod_{3DM}^* M(p_{3DM}) = \frac{1}{16}(-1 + c_L + F_{3D} + V_{3D})^2 \tag{5.121}$$

$$\prod_{3DM}^* L(p_L) = \frac{1}{8}(-1 + c_L + F_{3D} + V_{3D})^2 \tag{5.122}$$

(2) Equation (5.23) is convex in p_{3DM}, therefore, the first-order-conditions gives the maximizer,

$$\frac{\partial \prod_{3DM} SC(p_{3DM})}{\partial p_{3DM}} = 1 + c_L + F_{3D} - 2p_{\text{3DM}} + V_{3D} = 0$$

$$p_{3DM}^* = \frac{1}{2}(1 + c_L + F_{3D} + V_{3D}) \tag{5.123}$$

So, the optimal sales volume of the 3DP product and the maximized profit of the supply chain is

$$q^*_{3DM} = \frac{1}{2}(1 - c_L - F_{3D} - V_{3D}) \tag{5.124}$$

$$\prod\nolimits^*_{3DM} SC(p_{3DM}) = \frac{1}{4}(-1 + c_L + F_{3D} + V_{3D})^2 \tag{5.125}$$

Proof of *PROPOSITION* 5-38.

The logistics vendor's profit functions under the TMTF3DM model, TM3DM model, and 3DM model are (5.98), (5.112), and (5.122)

$$\prod\nolimits^*_{TMTF3DM} L(p_L) = \frac{(-\alpha + c_L + F_M + V_M)^2}{8\alpha}$$

$$\prod\nolimits^*_{TM3DM} L(p_L) = \frac{(-\alpha + c_L + F_M + V_M)^2}{8\alpha}$$

$$\prod\nolimits^*_{3DM} L(p_L) = \frac{1}{8}(-1 + c_L + F_{3D} + V_{3D})^2$$

Thus,

1) If $\left|\frac{-\alpha+c_L+F_M+V_M}{\sqrt{\alpha}}\right| > |-1 + c_L + F_{3D} + V_{3D}|$,

   then $\prod^*_{TMTF3DM} L(p_L) = \prod^*_{TM3DM} L(p_L) > \prod^*_{3DM} L(p_L)$;

2) If $\left|\frac{-\alpha+c_L+F_M+V_M}{\sqrt{\alpha}}\right| < |-1 + c_L + F_{3D} + V_{3D}|$;

   then $\prod^*_{TMTF3DM} L(p_L) = \prod^*_{TM3DM} L(p_L) < \prod^*_{3DM} L(p_L)$.

Appendix C-2: Sensitivity Analysis of Chapter 5

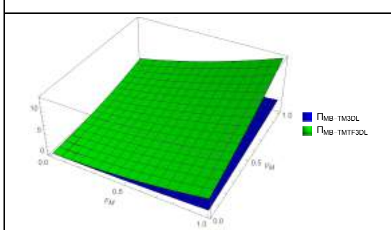
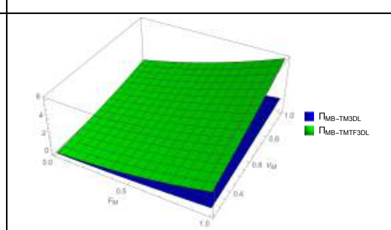
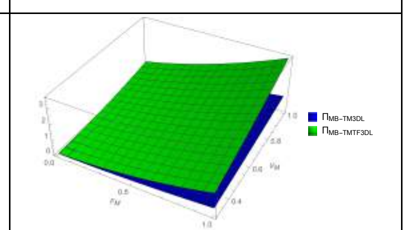
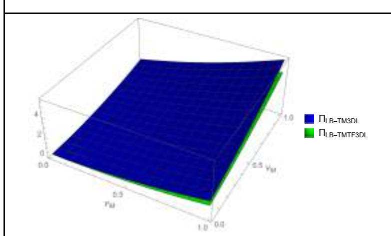
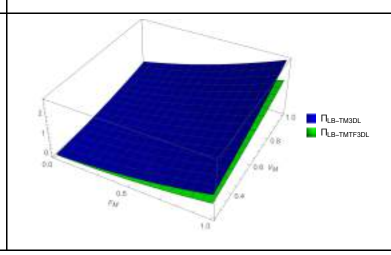
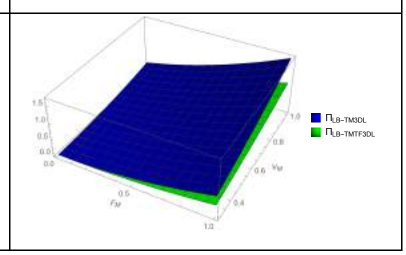
TMTF3DM Model

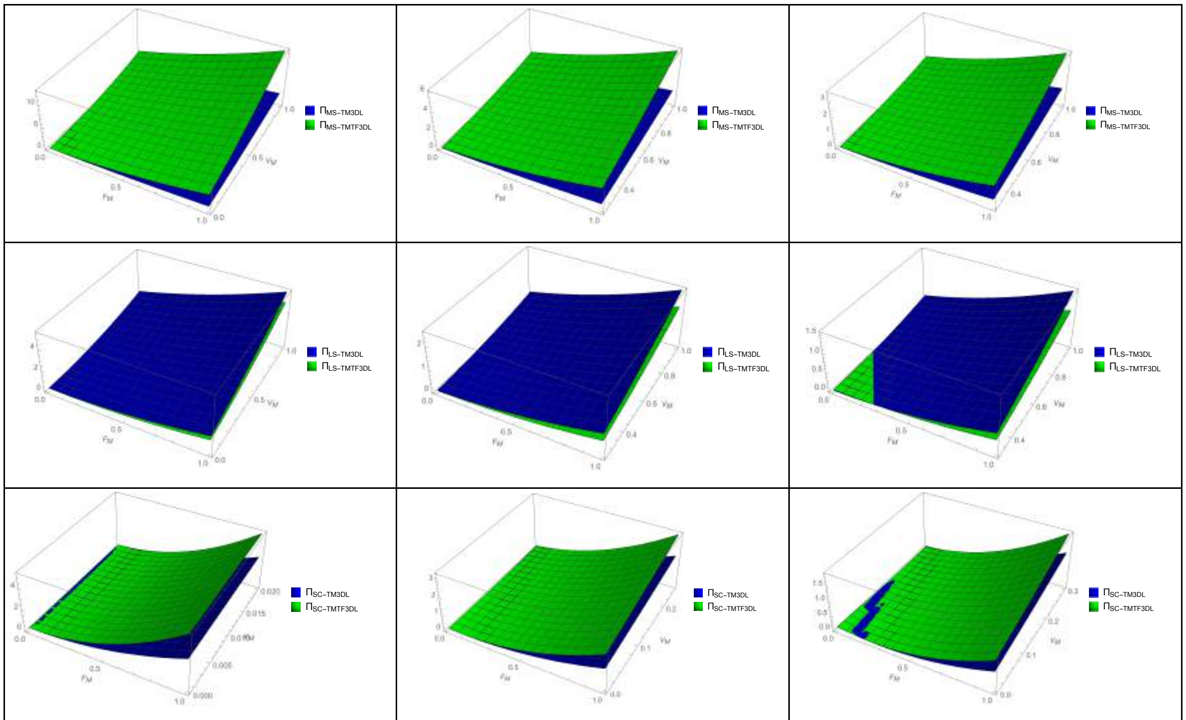
The Impact of the TM Product Costs

PROPOSITION ***1.*** *If the traditional manufacturer adds the TF product to compete with the logistics vendor's 3DP product,*

1. *The supply chain with the low setting is profitable for the traditional manufacturer but is not profitable for the logistics vendor in the decentralized supply chain. The integrated supply chain can also gain more profits except when the fixed TM product cost is extremely low.*
2. *If the product costs and the customization level are at the medium setting supply chain, it is profitable to the traditional manufacturer, but it is not profitable to the logistics vendor in the decentralized supply chain. The integrated supply chain can also obtain more profits.*
3. *If the product costs and the customization level are at the high setting, in the decentralized supply chain, this strategy is always profitable to the traditional manufacturer. Overall, the logistics vendor cannot gain more profits, but if the costs of the TM product are sufficiently low, the logistics vendor can also obtain more profits if the traditional manufacturer use both TM and TF manufacturing technology. This strategy can improve the integrated supply chain's profitability; however, there is a scenario where the costs of TM are located at a low-level, and the integrated supply chain cannot make more profit.*

Table 1 Comparison of Maximized Profit by TM Product Cost – TM3DL and TMTF3DL

Low	Medium	High
		
		



	TM Product			TF Product			3DP Product		Delivery
	F_M	V_M	α	F_{TF}	V_{TF}	β	F_{3D}	V_{3D}	c_L
Low	-	-	0.1	0.025	0.02	0.2	0.1	0.03	0.01
Medium	-	-	0.2	0.1	0.25	0.4	0.3	0.3	0.01
High	-	-	0.3	0.3	0.3	0.6	0.6	0.35	0.01

Table 1 illustrates how the profits of the benchmarking model and the TMTF3DL model change as the TM product cost increases. Remarkably, we find that the traditional manufacturer always benefits from offering the TF products, regardless of the TM product costs. At the same time, the claim that this strategy hurts the logistics vendor's profitability does not always hold. Furthermore, this strategy contributes to the development of the integrated supply chain in most cases as well. Another key finding here is that in a market led by the traditional manufacturer, if the TM product costs are low enough, the traditional manufacturer's flexible manufacturing strategy is beneficial to all supply chain stakeholders in the decentralized supply chain and the integrated supply chain.

Specifically, in the decentralized Bertrand supply chain, adding the new TF product can bring more profits to the traditional manufacturer because of the cannibalization effect on the TM and 3DP product market. Consequently, the logistics vendor loses profit due to both the shrunken 3DP product market and the reduced delivery service for the TM product. In the Stackelberg supply chain, the insights are almost the same. However, if the TM product cost are extremely low, the logistics vendor can also enjoy more profits. When the TM product costs are low, the new TF product forces the logistics vendor to price the 3DP product higher to maximize the 3DP product's margin, although it results in more price-sensitive consumers switching to the TF or the TM product instead. Overall, the logistics vendor can gain more profits. For the integrated supply chain, on the low setting, when the fixed TM product cost is extremely low, the supply chain loses some profit because some customization-sensitive consumers start to buy the newly introduced TF product. In the supply chain with the medium setting, the system always attains more profits because of the newly created TF product market. However, under the high setting, generally the new TF product contributes to the system's performance; but if the costs of TF are low, the new TF product cannibalizes the TM product market. Therefore, the system cannot achieve better financial performance.

The Impact of the TF Product Costs

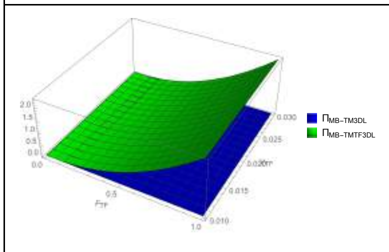
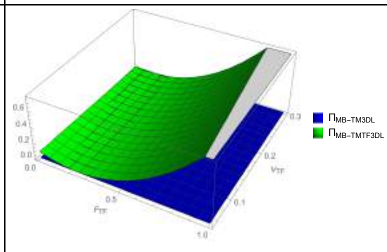
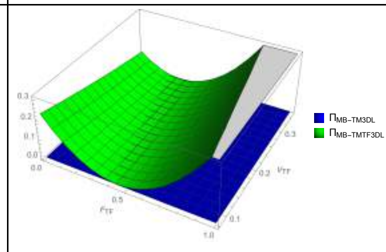
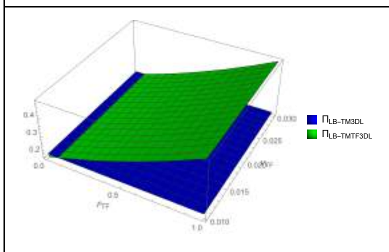
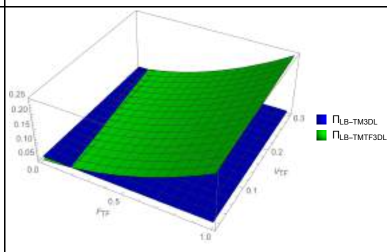
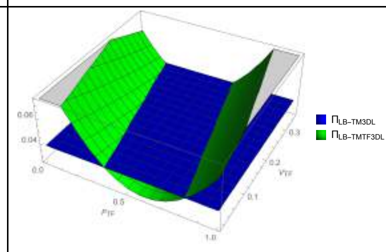
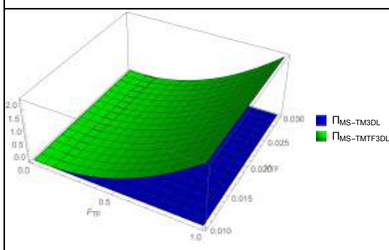
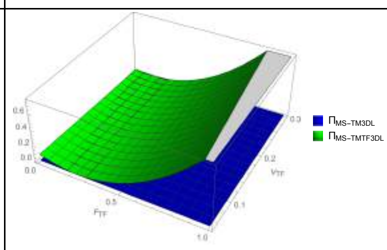
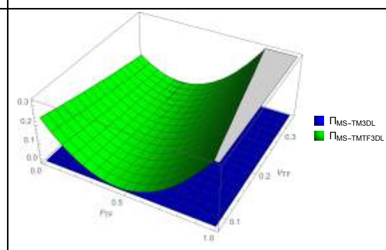
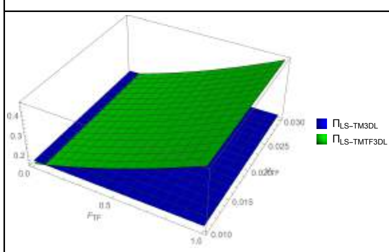
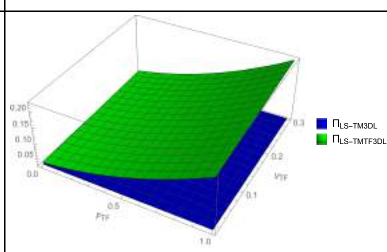
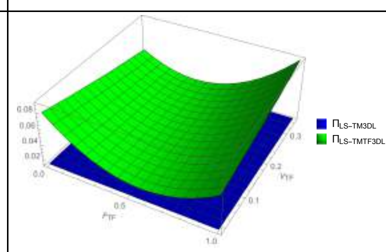
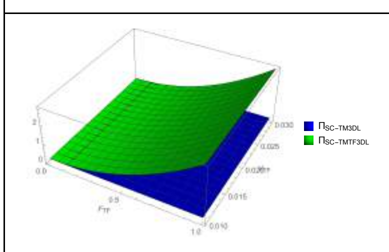
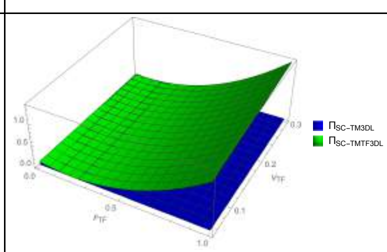
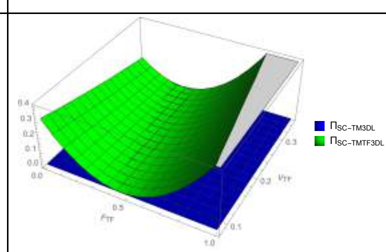
PROPOSITION ***2.*** *If the traditional manufacturer adds the TF product to compete with the logistics vendor's 3DP product,*

(1) At the low-cost structure and low product customization supply chain, it is profitable to the traditional manufacturer. The logistics vendor can also enjoy the benefits of this strategy, except when the fixed TF cost is extremely low. The integrated supply chain can also attain better profitability.

(2) If the product costs and the customization level are at the medium level, it is profitable for the traditional manufacturer. But adding TF manufacturing technology by the traditional manufacturer is not always profitable to the logistics vendor in the decentralized supply chain. In the Bertrand supply chain, if the fixed TF product cost is located in the extremely low range, this strategy has a negative impact on the logistics vendor's maximized profit. The integrated supply chain can also gain more profits.

(3) If the product costs and the customization level are high, in the decentralized supply chain, this strategy is always profitable to the traditional manufacturer. Overall, the logistics vendor cannot attain more profit, but under the Bertrand supply chain, if the fixed cost of the TF product is low or high enough, the logistics vendor can also obtain more profits. This strategy can improve the integrated supply chain's profitability.

Table 2 Maximized Profit Comparison by TF Product Cost – TM3DL and TMTF3DL

Low	Medium	High
		
		
		
		
		

	TM Product			TF Product			3DP Product		Delivery
	F_M	V_M	α	F_{TF}	V_{TF}	β	F_{3D}	V_{3D}	c_L

Low	0.01	0.01	0.1	-	-	0.2	0.1	0.03	0.01
Medium	0.05	0.05	0.2	-	-	0.4	0.3	0.3	0.01
High	0.1	0.08	0.3	-	-	0.6	0.6	0.35	0.01

Table 2 summarizes the impact of the TF product costs on the results of the overall comparison between the TM3DL and TMTF3DL models. No matter the TF product cost level, it is positive for the integrated supply chain and the traditional manufacturer in the decentralized supply chain. The new TF product brings more profits to the supply chain either through the newly created TF product business or the increased sales of the TM or 3DP product. The traditional manufacturer can obtain more profits from the increased TM product sales if the TM product costs are high, or from the new TF product sales if the TF product costs are low. However, the impact of this strategy on the logistics vendor's overall profitability differs across supply chain structures.

a) In the decentralized Stackelberg supply chain on the low setting, if the fixed cost of the TF product is extremely low, the traditional manufacturer prices both the TM and the TF product low for the purpose of keeping his/her pricing advantages. However, more customization-sensitive consumers choose to buy the TF product instead of the TM or the 3DP product. Overall, the impact of this strategy is negative for the logistics vendor.

b) In the supply chain with the medium setting, the logistics vendor can gain more profits in most cases. However, in the Bertrand supply chain, if the fixed cost of the TF product is low, the traditional manufacturer prices the TM and TF product low. Accordingly, the sales of TM products drop, and the logistics vendor loses revenue on the traditional delivery service.

c) In the supply chain with the high setting, if the fixed cost of the TF product is low, the low TF price helps the TF product acquire more customization-sensitive consumers who previously chose to buy the TM product; if the TF product's fixed cost is high, the high TF product price helps the logistics vendor gain more consumers for his/her 3DP product. The logistics vendor can benefit from both of these different scenarios.

The Impact of the 3DP Product Costs

PROPOSITION 3. *If the traditional manufacturer adds the TF product to compete with the logistics vendor's 3DP product,*

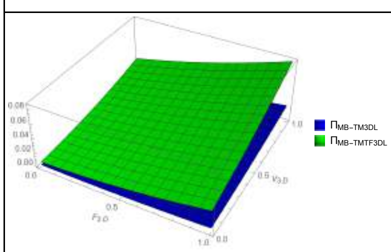
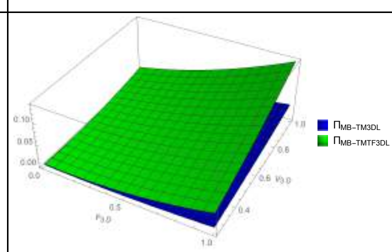
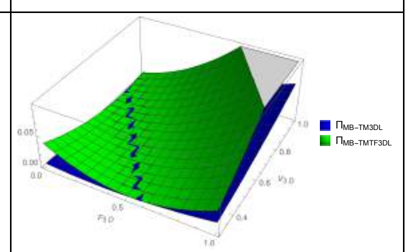
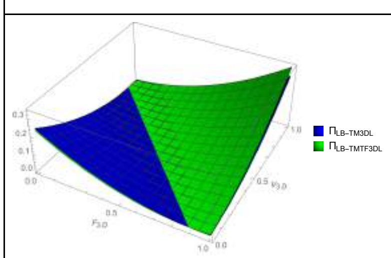
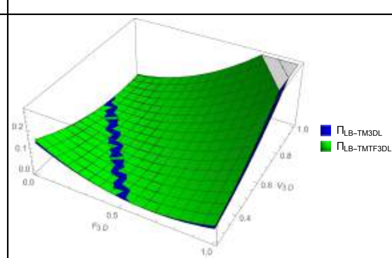
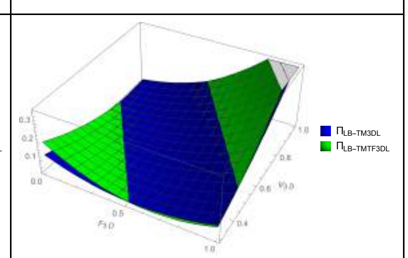
(1) As for the low-cost structure and low product customization supply chain, it is profitable to the traditional manufacturer. The logistics vendor can also enjoy the benefits of this strategy if the costs of the 3DP product are low in the Bertrand supply chain or the variable cost of the 3DP product is low enough. The integrated supply chain can also attain better profitability.

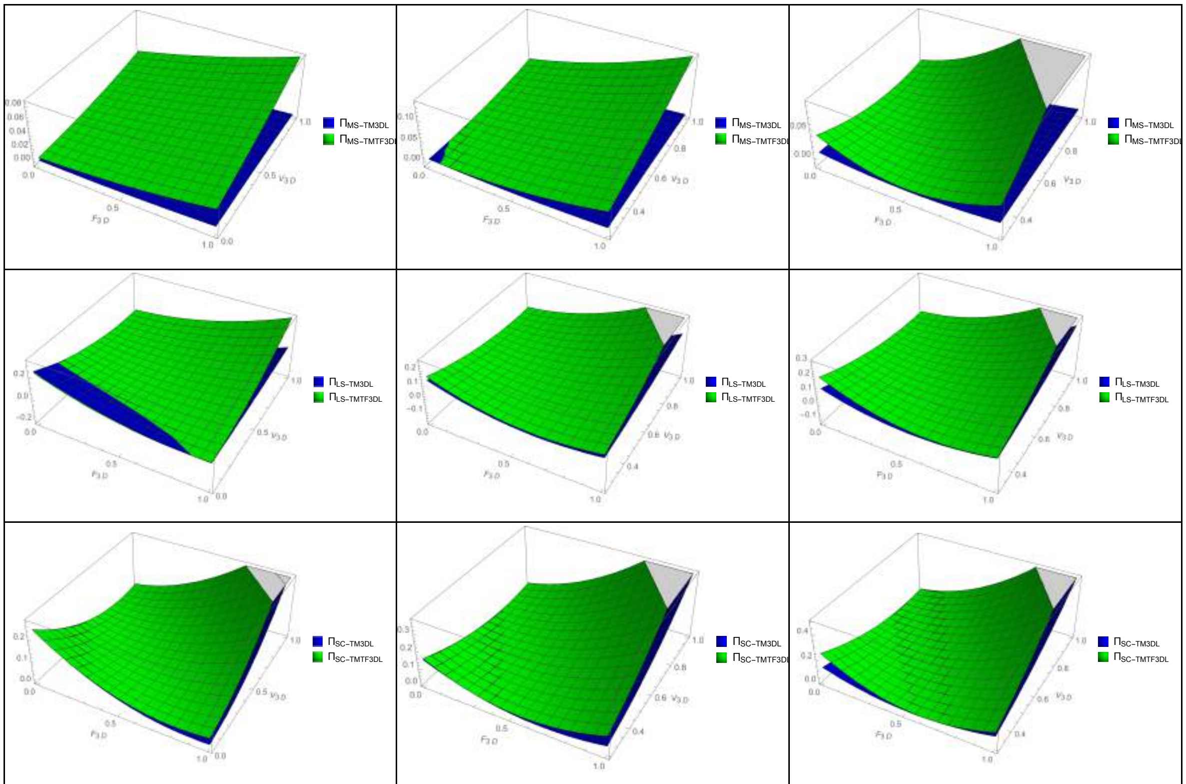
(2) If the product costs and the customization level are at the medium level, generally, this is profitable for the traditional manufacturer to use this strategy. Meanwhile, in the Stackelberg supply chain, if the costs of the 3DP product are low enough, the traditional manufacturer cannot gain more profits by using this strategy. In the decentralized Bertrand supply chain, if the costs of the 3DP product are located in a certain low range, this strategy has a negative impact on the logistics vendor's profitability. Otherwise, the logistics vendor can always achieve better profitability, whilst the integrated supply chain can always attain more profits.

(3) If the product costs and the customization level are high, both the traditional manufacturer and the logistics vendor can always gain more profits in the decentralized Stackelberg supply chain by this strategy. Meanwhile, in the decentralized Bertrand supply chain, if the 3DP product is located in a low-cost range, it is not profitable to the traditional manufacturer; and if the 3DP product is located at a medium cost range, the logistics vendor cannot achieve better business performance. In the other scenarios, both parties can attain more profits. This strategy has a positive impact on the integrated supply chain's development.

Generally, whatever the 3DP product costs are, adding a new TF product is beneficial to the integrated supply chain's development. In a supply chain with the low setting (Table 3), if the costs of the 3DP product are low, the new TF product with a pricing advantage cannibalizes the 3DP product market even if the price of the 3DP product is low. Therefore, the logistics vendor cannot achieve better profitability. With the supply chain on the medium setting, overall, this strategy is beneficial to the traditional manufacturer's new TF product business and also beneficial to the logistics vendor due to the increased use of the product delivery service. However, in the decentralized Bertrand supply chain, if the 3DP product is located in the low-cost range, the logistics vendor cannot obtain more profits because the new TF product results in the cannibalization of the 3DP product. In the decentralized Stackelberg supply chain, if the costs of the 3DP product are low enough, for the traditional manufacturer, the introduction of a new TF product results in profit loss on the TM product. In a supply chain on the high setting, in the decentralized Bertrand supply chain, if the costs of 3DP are low, the new TF product helps the traditional manufacturer generate new profits from TM product sales. The logistics vendor can also gain more profits on the goods delivery service. If the 3DP product costs are high, the new TF product forces the logistics vendor to use a high-price regime on the 3DP product. Therefore, the traditional manufacturer can gain more price-sensitive consumers for its TM and TF product. Overall, the profitability of the traditional manufacturer and the logistics vendor is improved. In the decentralized Stackelberg supply chain, because the logistics vendor prices the 3DP product later, the logistics vendor uses a different price strategy to maximize his/her profit. As we explained above, the logistics vendor's profitable 3DP pricing strategy can also help the traditional manufacturer generate more profits.

Table 3 Maximized Profit Comparison by 3DP Product Cost – TM3DL and TMTF3DL

Low	Medium	High
		
		



	TM Product			TF Product			3DP Product		Delivery
	F_M	V_M	α	F_{TF}	V_{TF}	β	F_{3D}	V_{3D}	c_L
Low	0.01	0.01	0.1	0.025	0.02	0.2	-	-	0.01
Medium	0.05	0.05	0.2	0.1	0.25	0.4	-	-	0.01
High	0.1	0.08	0.3	0.3	0.3	0.6	-	-	0.01

The Impact of the Logistics Delivery Cost

PROPOSITION ***4.*** *If the traditional manufacturer adds the TF product to compete with the logistics vendor's 3DP product,*

(1) If the product costs and the customization level are at the medium level, it is profitable to the traditional manufacturer but not to the logistics vendor in the decentralized supply chain. The integrated supply chain can achieve better profitability.

(2) If the product costs and the customization level are at the medium level, generally it is profitable to the traditional manufacturer but not to the logistics vendor in the decentralized Bertrand supply chain. In the decentralized Stackelberg supply chain, this strategy benefits supply chain stakeholders. The integrated supply chain can always gain more profits by the introduction of this new TF product.

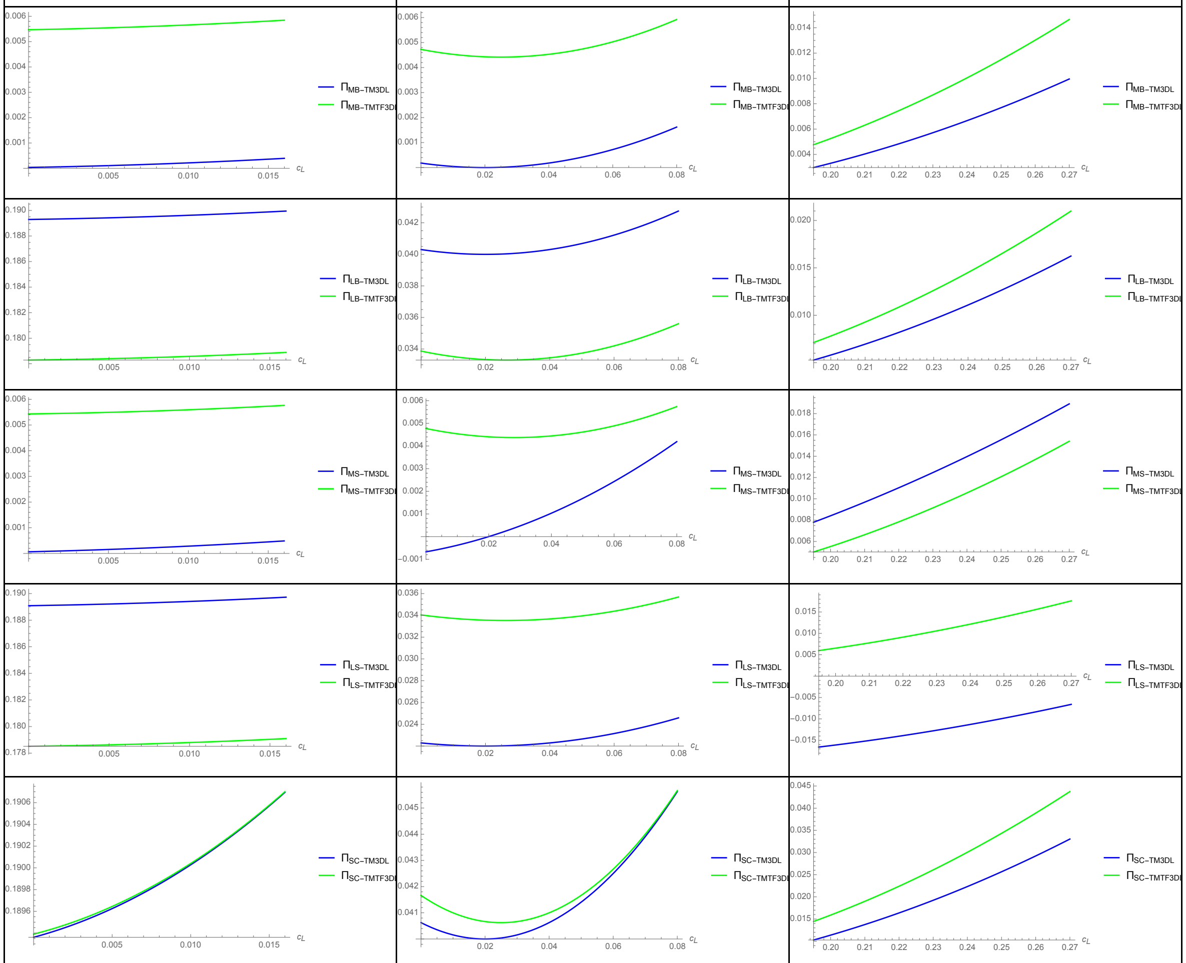
(3) If the product costs and the customization level are high, both the traditional manufacturer and the logistics vendor can always gain more profits in the decentralized Bertrand supply chain from this strategy. However, in the decentralized Stackelberg supply chain, this strategy is beneficial to the logistics vendor but not to

the traditional manufacturer. The integrated supply chain can obtain more profits from this strategy.

As Table 4 indicates, whatever the costs of the logistics delivery are, the whole supply chain achieves better financial performance either from the newly created TF product sales or the increased TM or 3DP product sales. In a supply chain on the low setting, the introduction of the TF product helps the traditional manufacturer generate more profits on the new TF product. But the logistics vendor loses profit on 3DP product sales. On the medium setting, in the decentralized Bertrand supply chain, the new TF product helps the traditional manufacturer obtain more profits on the new TF product. Because some price-sensitive consumers choose to buy the new TF product instead of the 3DP product, the logistics vendor loses part of the revenue. However, under the decentralized Stackelberg supply chain, for the purpose of maximizing his/her profit, the logistics vendor always prices the 3DP product after s/he receives the prices of the TF and the TM product. On the high setting, in the decentralized Bertrand supply chain, the logistics vendor uses a high price to maximize the 3DP product margin, which leads to increases in the TM and TF product sales. Thus, it brings more profit to the traditional manufacturer through the TM and the TF product sales, whilst the logistics vendor gains more profit on the goods delivery service. However, under the decentralized Stackelberg supply chain, because of the high cost structure, the traditional manufacturer 'defaults' the price of the 3DP product is high and uses high price regimes for the TM and the TF product. However, the logistics vendor uses a low-price regime to maximize profits from 3DP product sales. In the end, the traditional manufacturer loses profit due to the high price strategy, but the logistics vendor gains more profit due to the high 3DP product margin.

Table 4 Maximized Profit: Comparison by Logistics Service Cost – TM3DL and TMTF3DL

Low	Medium	High



	TM Product			TF Product			3DP Product		Delivery
	F_M	V_M	α	F_{TF}	V_{TF}	β	F_{3D}	V_{3D}	c_L
Low	0.01	0.01	0.1	0.025	0.02	0.2	0.1	0.03	-
Medium	0.05	0.05	0.2	0.1	0.25	0.4	0.3	0.3	-
High	0.1	0.08	0.3	0.3	0.3	0.6	0.6	0.35	-

The Impact of the TM Product Customization Level

PROPOSITION 5. *If the traditional manufacturer adds the TF product to compete with the logistics vendor's 3DP product,*

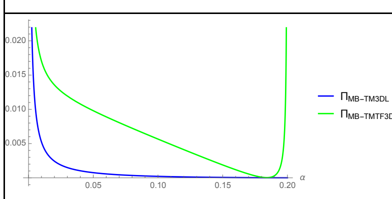
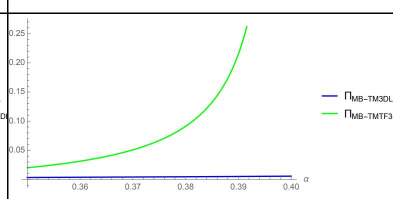
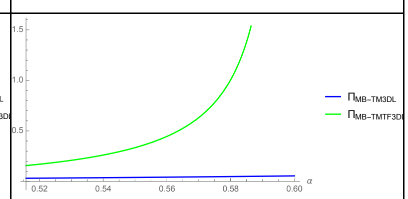
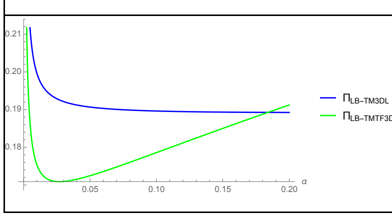
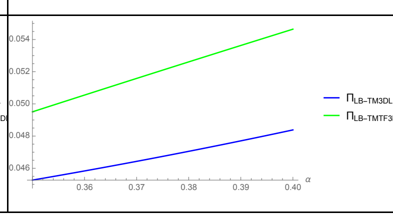
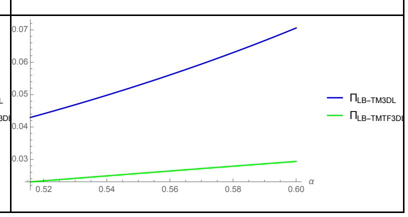
(1) In the low-cost structure supply chain, this strategy is profitable to the traditional manufacturer in the decentralized supply chain. It is not profitable to the logistics vendor except when the TM product customization level is extremely high. This strategy contributes more profits to the integrated supply chain.
(2) In the medium cost structure supply chain, both the traditional manufacturer and the logistics vendor can share the benefits of this strategy. The integrated supply chain can achieve better financial performance as well after the traditional manufacturer replaces the TM product with the TF product.
(3) In the high cost structure supply chain, it is profitable for the traditional manufacturer but not for the logistics vendor in the decentralized Bertrand supply chain. In the decentralized Stackelberg supply chain, it is profitable to the traditional manufacturer, but the logistics vendor can only obtain more profit if the TM product's customization level is low enough. It is profitable for the integrated supply chain.

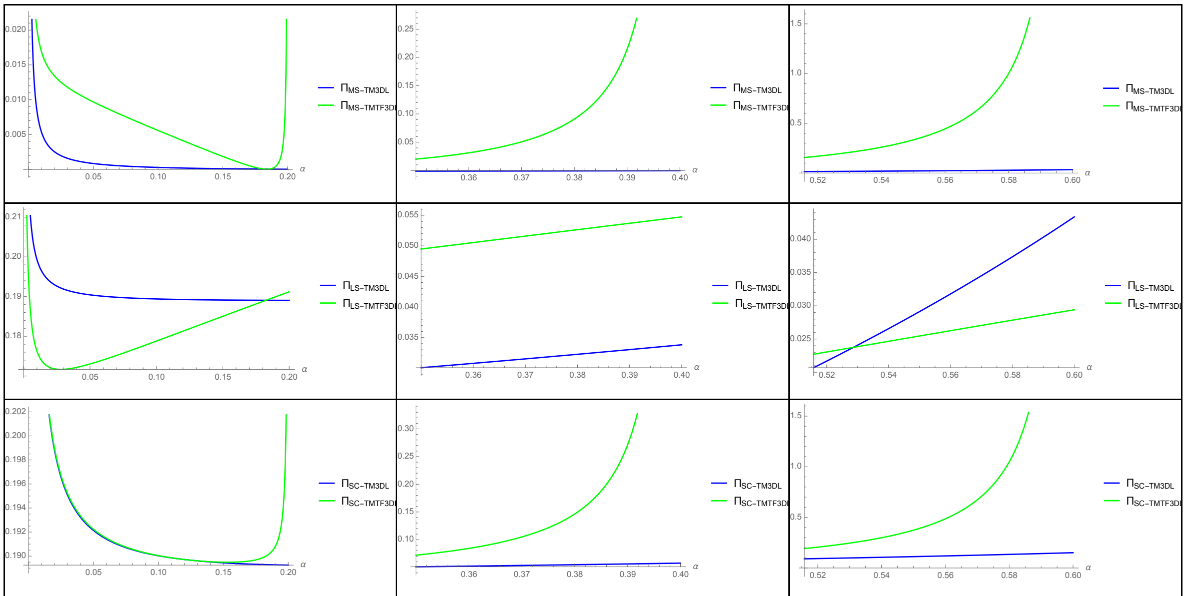
As seen in Table 5, in a supply chain on the low setting, the TF product with its higher customization level can help the traditional manufacturer acquire more price-sensitive consumers from the 3DP product's consumer base. Therefore, the traditional manufacturer can achieve better financial performance. However, if the TM product's customization level is low (low customization, low product price), some customization-sensitive consumers switch to the TF product and some price-sensitive consumers choose to buy the TF product instead of the 3DP product. As a result, the logistics vendor loses profit from both the traditional logistics delivery service and 3DP product sales. But, if the customization level of the TM product is high, the new TF product has no significant impact on market demand. However, the new TF product helps with the acquisition of more price-sensitive and customization-sensitive consumers, which contributes to the logistics vendor's profitability. Overall, in the integrated supply chain, the new TF product helps the supply chain gain more profits through the newly created TF product market.

In a supply chain on the medium setting, the new TF product helps the traditional manufacturer create a new revenue stream and the logistics vendor can also enjoy more business for its product delivery service. Therefore, supply chain stakeholders can achieve better performance and the integrated suppliers' profitability might be improved by this new TF product adoption as well.

Under a supply chain on the high setting, the new TF product can also help the traditional manufacturer generate more profits on the new TF product in the decentralized supply chain. The integrated supply chain can make more profit through the TF product. However, in the decentralized Bertrand supply chain, the new TF product forces the logistics vendor to use a high-price regime for his/her 3DP product to increase the product margin. Consequently, the logistics vendor's profitability declines due to both the reduced 3DP product sales and TM product delivery. However, in the decentralized Stackelberg supply chain, if the TM product customization level is extremely low, the introduction of a new TF product can help the traditional manufacturer acquire more customization-sensitive consumers and the logistics vendor can benefit from the new TF product delivery service. In general, the new TF product helps the development of the integrated supply chain.

Table 5 Maximized Supply Chain Profit: Comparison by TM Product Customization Level – TM3DL and TMTF3DL

Low	Medium	High
		
		



	TM Product			TF Product			3DP Product		Delivery
	F_M	V_M	α	F_{TF}	V_{TF}	β	F_{3D}	V_{3D}	c_L
Low	0.01	0.01	-	0.025	0.02	0.2	0.1	0.03	0.01
Medium	0.05	0.05	-	0.1	0.25	0.4	0.3	0.3	0.01
High	0.1	0.08	-	0.3	0.3	0.6	0.6	0.35	0.01

The Impact of the TF Product Customization Level

PROPOSITION 6. *If the traditional manufacturer adds a TF product to compete with the logistics vendor's 3DP product,*

(1) In the low-cost structure supply chain, this strategy is profitable to the traditional manufacturer in the decentralized supply chain. It is not profitable to the logistics vendor except when the TM product customization level is extremely high. This strategy contributes more profits to the integrated supply chain.

(2) In the medium cost structure supply chain, the traditional manufacturer can always gain more profits by adding a new TF product into the market. However, in the decentralized Bertrand supply chain, the logistics vendor can also obtain more profit only if the TF product's customization level is high. In the decentralized Stackelberg supply chain, the logistics vendor gains the benefits of this strategy if the TF product's customization level is extremely high or low. The integrated supply chain can achieve better financial performance by this strategy.

(3) In the high cost structure supply chain, the traditional manufacturer can attain better profitability in the decentralized supply chain. The logistics vendor can also share the benefits of this strategy in the decentralized Stackelberg supply chain. However, the logistics vendor can only gain more profits if the TF product's customization level

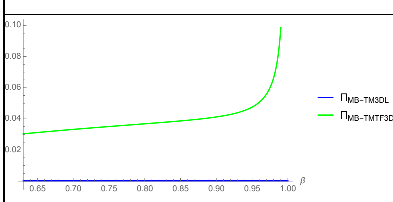
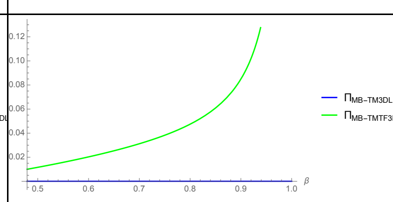
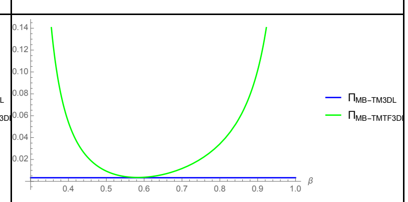
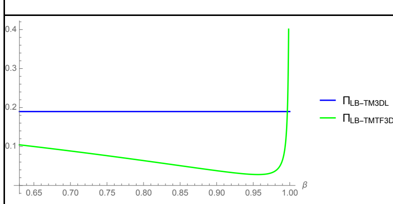
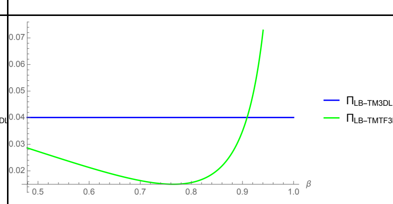
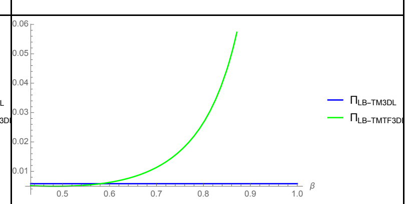
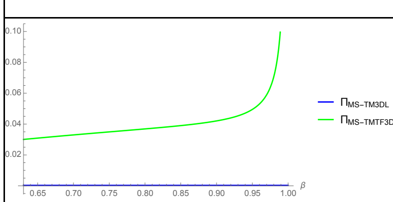
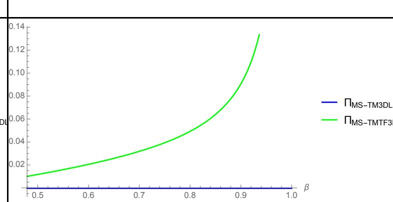
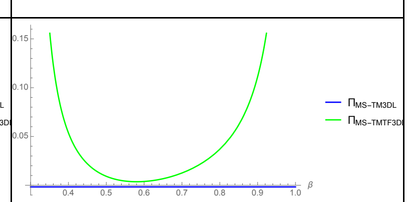
is located in the high region. The integrated supply chain can achieve better performance.

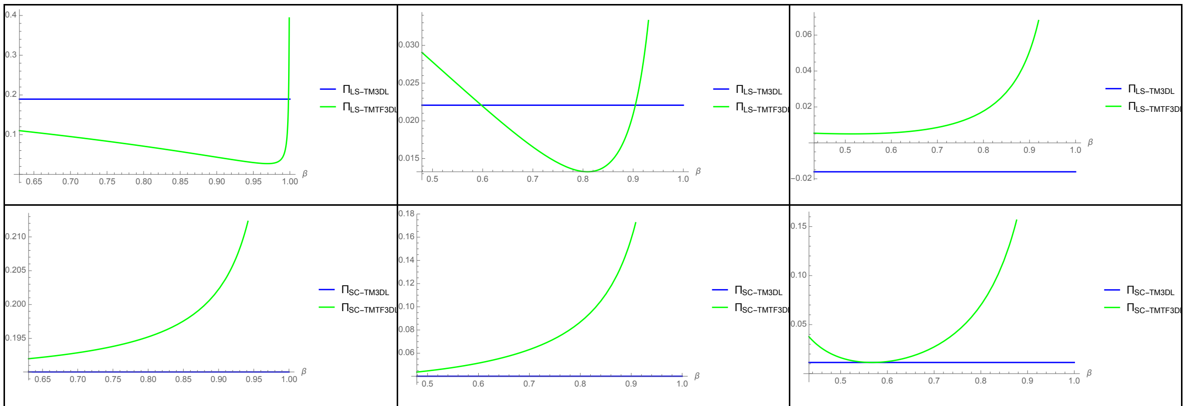
As shown in below table, in a supply chain on the low setting, the TF product with a higher product customization level can help the traditional manufacturer acquire more price-sensitive consumers from the 3DP product's consumer base. Therefore, the traditional manufacturer can achieve better financial performance through the newly created TF product market. For the logistics vendor, s/he loses profit due to the cannibalization of the TF product. However, if the customization level of the TF product is similar to the 3DP product, the logistics vendor can generate more profits from goods delivery.

In a supply chain on the medium setting, the traditional manufacturer can attain better financial performance due to the newly created TF product market. But in the decentralized Bertrand supply chain, if the TM product's customization level is low, the TM product not only cannibalizes the 3DP product market but also the TM product market. Therefore, the logistics vendor loses profits overall. However, if the TF product customization level is nearly the same as that of the 3DP product, the new TF product only has a cannibalization effect on the 3DP product. Thus, the logistics vendor can make more profit on its traditional goods delivery business. In the decentralized Stackelberg supply chain, if the TF product customization level is sufficiently low (i.e. the TF price is low, as formalized in *PROPOSITION* 2), the new TF product strategy pushes the logistics vendor to set the 3DP product price low to attract more customization-sensitive consumers. If the TF product customization level is higher, the introduction of the TF product pushes the logistics vendor to price the 3DP product higher to maximizing his/her profits. In general, the logistics vendor can increase his/her profits, either from 3DP product sales or from the newly created traditional delivery requirements.

In a supply chain on the high setting, the new TF product creates a new profit stream for the traditional manufacturer and the integrated supply chain. However, the logistics vendor's profitability depends on the TM product's customization level. In the decentralized Bertrand supply chain, if the TM product's customization level is low, the TF product cannibalizes the TM product market. Thus, the logistics vendor loses profit on traditional goods delivery. But, if the TM product's customization level is high, the traditional manufacturer could use a low TF product price to attract more price-sensitive consumers to switch from the 3DP product, and the logistics vendor benefits from the increased TF product goods delivery. But, in the decentralized Stackelberg supply chain, this does not hold true if the TM product customization level is low. After the traditional manufacturer uses a low-price regime for the TF product, the logistics vendor could use a high price strategy for the 3DP product to achieve a larger margin on the 3DP product. The logistics vendor can always attain better profitability in the decentralized Stackelberg supply chain.

Table 6 Maximized Supply Chain Profit: Comparison by TF Product Customization Level – TM3DL and TMTF3DL

Low	Medium	High
		
		
		



	TM Product			TF Product			3DP Product		Delivery
	F_M	V_M	α	F_{TF}	V_{TF}	β	F_{3D}	V_{3D}	c_L
Low	0.01	0.01	0.1	0.025	0.02	-	0.1	0.03	0.01
Medium	0.05	0.05	0.2	0.1	0.25	-	0.3	0.3	0.01
High	0.1	0.08	0.3	0.3	0.3	-	0.6	0.35	0.01

TF3DL Model

In below section, we test whether the traditional manufacturer using TF production to fully replace TM production is a profitable manufacturing strategy for the traditional manufacturer and the logistics vendor. We also analyze whether this strategy is beneficial for the integrated supply chain or not.

The Impact of the TM Product Costs

PROPOSITION 7. *If the traditional manufacturing decides fully use TF product to replace TM product for the purpose of coping with the logistics vendor's 3DP technology,*

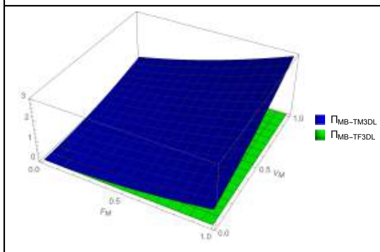
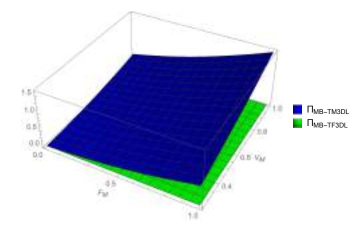
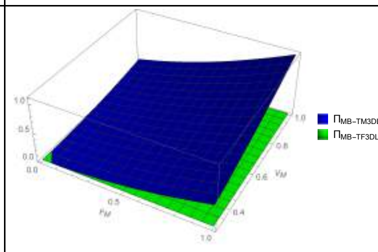
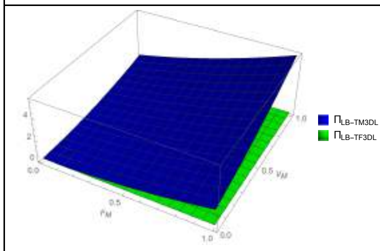
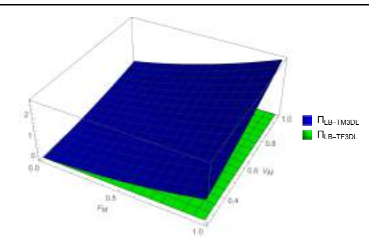
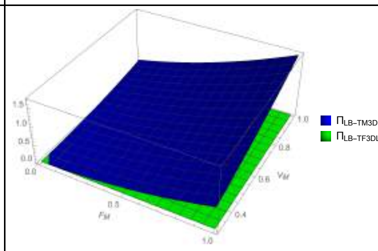
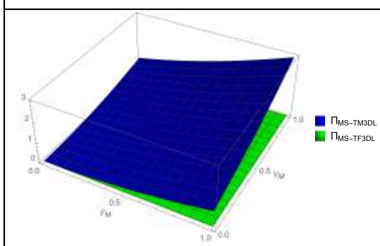
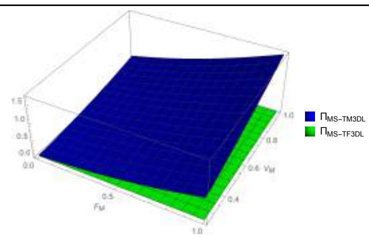
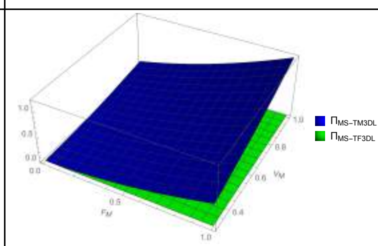
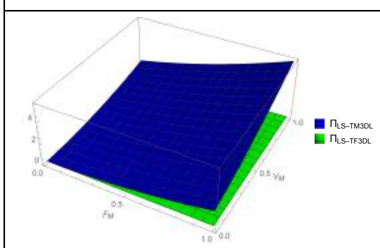
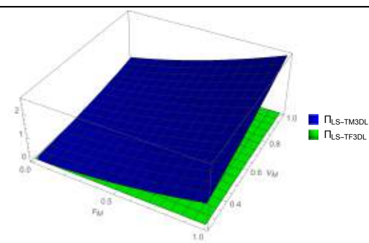
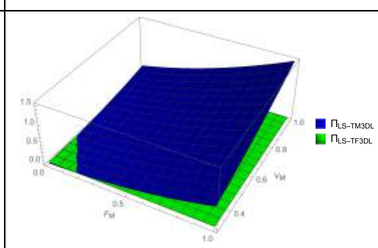
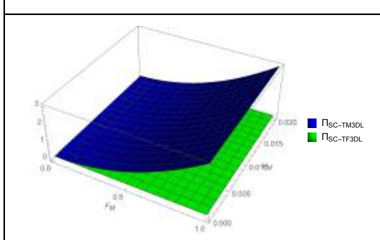
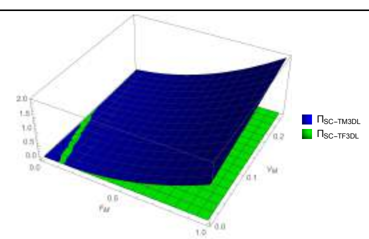
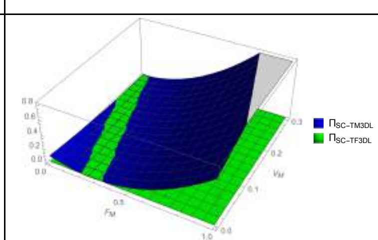
(1) For the low-cost structure and low product customization supply chain, fully replacing TM production with TF production is not a profitable strategy for either the traditional manufacturer or the logistics vendor in the decentralized supply chain. It cannot bring any benefits to the integrated supply chain either.

(2) If the product costs and the customization level are at the medium level, fully replacing TM production with TF production is not a profitable strategy for either the traditional manufacturer or the logistics vendor in the decentralized supply chain.

However, if the costs of TM are within a certain low range, the integrated supply chain can attain better profitability.*

(3) If the product costs and the customization level are high, in the decentralized Bertrand supply chain, if the TM product costs are sufficiently low, this strategy is beneficial to both the traditional manufacturer and the logistics vendor. However, in the decentralized Stackelberg supply chain, this strategy is not profitable to the traditional manufacturer, whilst the logistics vendor can attain more profit if the costs of TM are low. There exists a low TM product cost setting, and if the TM product costs are located in that region, the integrated supply chain can obtain more profit.

Table 7 Maximized Profit: Comparison by TM Product Cost – TM3DL and TF3DL

Low	Medium	High
		
		
		
		
		

	TM Product			TF Product			3DP Product		Delivery
	F_M	V_M	α	F_{TF}	V_{TF}	β	F_{3D}	V_{3D}	c_L
Low	-	-	0.1	0.025	0.02	0.2	0.1	0.03	0.01
Medium	-	-	0.2	0.1	0.25	0.4	0.3	0.3	0.01
High	-	-	0.3	0.3	0.3	0.6	0.6	0.35	0.01

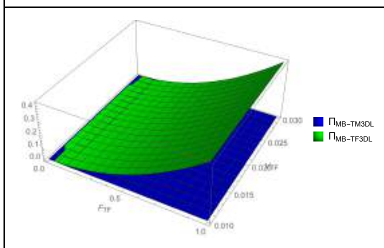
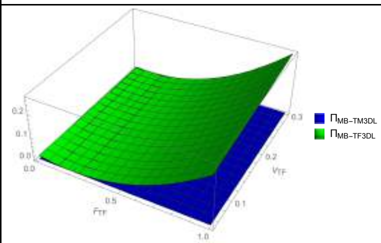
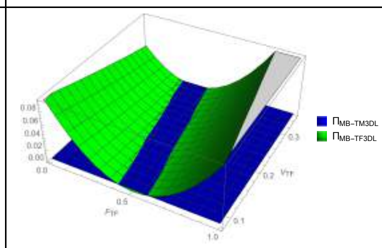
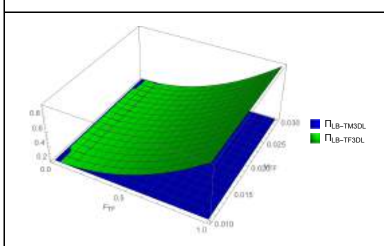
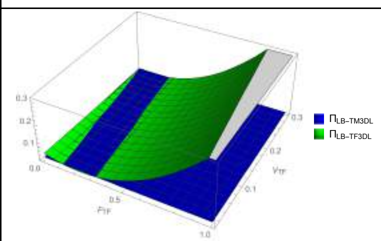
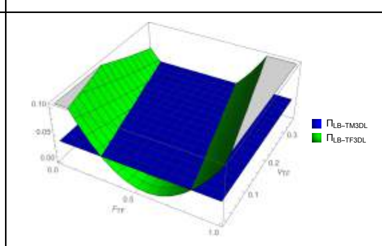
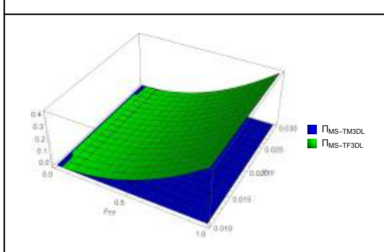
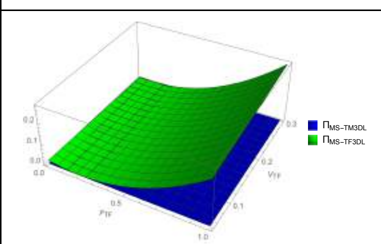
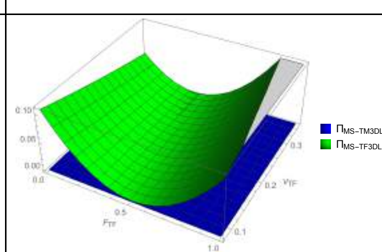
Overall, fully replacing the TM product with the TF product is not a profitable strategy for the traditional manufacturer (seen in Table 7). However, in the decentralized Bertrand supply chain on the high cost setting, if the TM product costs are very low, introducing the TF product means the traditional manufacturer can set a higher margin per TF product. Thus, the traditional manufacturer can achieve better profitability. Although the logistics vendor loses revenue from TM product sales, his/her profit on the 3DP product increases. And in the decentralized Stackelberg supply chain on the high setting, if the costs of the TM product are sufficiently low, because the TF price is higher than that of the TM product, the logistics vendor can benefit from a higher 3DP product margin. Therefore, the logistics vendor can attain better profitability under this scenario. In the integrated supply chain, on the low setting, the system cannot generate more profit because of the loss of TM product sales. However, on the medium and high settings, although the price of the TF product is higher than that of the TM product (the costs of the TF product are higher than for the TM product), the new TF product can help the system achieve more 3DP product sales. Therefore, there exists a region in which the system can gain more profits on the 3DP product sales than the loss incurred on the traditional manufacturer's product sales.

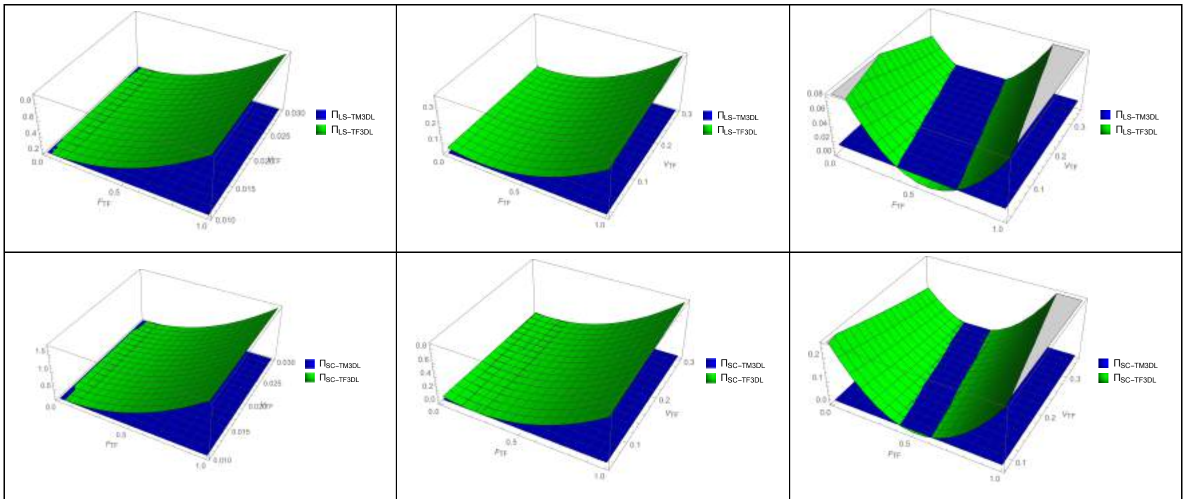
The Impact of the TF Product Costs

PROPOSITION *8.* *If the traditional manufacturing decides fully use TF product to replace TM product for the purpose of coping with the logistics vendor's 3DP technology,*

(1) *For the low-cost structure and low product customization supply chain, fully replacing the TM production by new TF production is a profitable strategy for both the traditional manufacturer and the logistics vendor in the decentralized supply chain and the integrated supply chain – except when the fixed TF product cost is extremely low.*
(2) *If the product costs and the customization level are at the medium level, fully replacing the TM production by new TF production is a profitable strategy for the traditional manufacturer and the logistics vendor in the decentralized Stackelberg supply chain. In the decentralized Bertrand supply chain, this strategy is beneficial to the traditional manufacturer. However, the logistics vendor can only gain more profits if the fixed cost of the TF product is sufficiently low or high. Under this scenario, it is profitable for the integrated supply chain.*
(3) *If the product costs and the customization level are high, in the decentralized Bertrand supply chain, if the fixed TF product cost is sufficiently low or sufficiently high, this strategy is beneficial to both the traditional manufacturer and the logistics vendor. However, in the decentralized Stackelberg supply chain, this strategy is profitable to the traditional manufacturer, whilst the logistics vendor can gain more profits if the fixed cost of the TF product is within a specified low or high region. As for the integrated supply chain, it can attain more profits if the fixed cost of the TF product is in a low or high region.*

Table 8 Maximized Profit: Comparison by TF Product Cost – TM3DL and TF3DL

Low	Medium	High
		
		
		



	TM Product			TF Product			3DP Product		Delivery
	F_M	V_M	α	F_{TF}	V_{TF}	β	F_{3D}	V_{3D}	c_L
Low	0.01	0.01	0.1	-	-	0.2	0.1	0.03	0.01
Medium	0.05	0.05	0.2	-	-	0.4	0.3	0.3	0.01
High	0.1	0.08	0.3	-	-	0.6	0.6	0.35	0.01

According to above table, in a supply chain on the low setting, overall, fully replacing TM production by TF production is profitable to the traditional manufacturer and the logistics vendor in the decentralized supply chain and the integrated supply chain. However, if the fixed cost of the TF product is extremely low, because the TM product's variable cost is higher than the TF product's variable cost, the price of the TF product is higher than that of the TM product. Therefore, under this scenario, the traditional manufacturer loses profit because he/she loses some price-sensitive consumers. Accordingly, the logistics vendor also loses profits on the goods delivery service. As for the integrated supply chain, due to their being fewer price-sensitive consumers, the system cannot generate more profit than the TM3DL supply chain. However, if the fixed cost of the TF product is in the high region, the traditional manufacturer can attain more profit on the TF product due to the higher product margin and the logistics vendor can gain more profits on 3DP product sales. Meanwhile, the integrated supply chain benefits from the increased 3DP product sales.

The Impact of the 3DP Product Costs

PROPOSITION *9.* *If the traditional manufacturing decides fully use TF product to replace TM product for the purpose of coping with the logistics vendor's 3DP technology,*

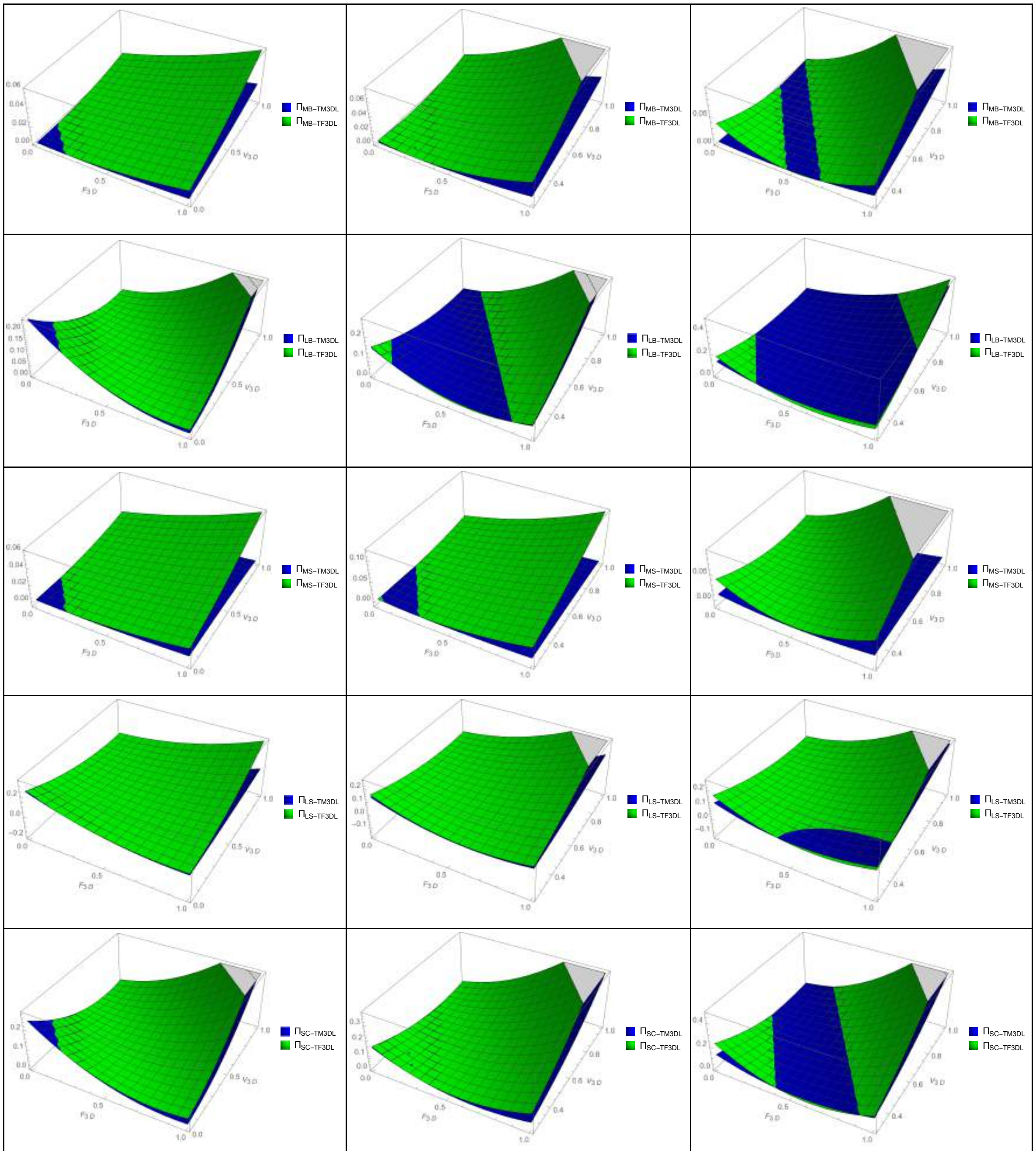
(1) For the low-cost structure and low product customization supply chain, fully replacing TM production by TF production is a profitable strategy for both the traditional manufacturer and the logistics vendor in the decentralized Bertrand supply chain and the integrated supply chain – as long as the 3DP product costs are not extremely low. In the decentralized Stackelberg supply chain, it is profitable for the logistics vendor and it is also profitable for the traditional manufacturer – except when the 3DP product costs are extremely low.

(2) If the product costs and the customization level are at the medium level, in the decentralized Bertrand supply chain, this strategy is profitable for the traditional manufacturer, but the logistics vendor can only attain more profit if the costs of the 3DP product are extremely low or the costs of the 3DP product are high. Under the decentralized Stackelberg supply chain, this strategy is profitable for the logistics vendor, but the traditional manufacturer can also gain more profits – except when the 3DP product costs are low. The integrated supply chain can always attain more profits.

(3) If the product costs and the customization level are high, under the decentralized Bertrand supply chain, if the costs of the 3DP product are sufficiently low or extremely high, it is profitable to both the traditional manufacturer and the logistics vendor. Otherwise, both parties cannot benefit from this strategy at the same time. In the decentralized Stackelberg supply chain, the traditional manufacturer can gain more profits from this strategy. However, the logistics vendor can also obtain more profits – except when the fixed 3DP product cost is high and the variable 3DP product cost is low. The integrated supply chain can gain more profits if the 3DP product costs are located in a considerably low or a considerably high region.

Table 9 Maximized Profit: Comparison by 3DP Product Cost – TM3DL and TF3DL

Low	Medium	High



	TM Product			TF Product			3DP Product		Delivery
	F_M	V_M	α	F_{TF}	V_{TF}	β	F_{3D}	V_{3D}	c_L
Low	0.01	0.01	0.1	0.025	0.02	0.2	-	-	0.01
Medium	0.05	0.05	0.2	0.1	0.25	0.4	-	-	0.01
High	0.1	0.08	0.3	0.3	0.3	0.6	-	-	0.01

As shown in above table, in a supply chain on the low setting, if the 3DP product costs are low, the new TF product cannot benefit from obvious advantages in terms of product cost and product customization. Therefore, the traditional manufacturer cannot generate more profits on the new TF product and the logistics vendor loses profits on the associated delivery service. However, in the Stackelberg supply chain, because the logistics vendor prices the 3DP product later, the logistics vendor uses an appropriate price for the 3DP product in terms of maximizing his/her profit.

On the medium supply chain setting, the traditional manufacturer can attain more profit in the decentralized Bertrand supply chain. The logistics vendor can only gain more profits under two scenarios: a) the 3DP product costs are extremely low, and so the high price TF product pushes more consumers to buy the 3DP product; and b) 3DP production is considerably costly, and so a portion of the customization-sensitive consumers choose to buy the TF product in view of the product's price. Meanwhile, the logistics vendor benefits from the increased TF product delivery service. In the decentralized Stackelberg supply chain, the logistics vendor can always generate more profits either from the increased goods delivery service or from the increased 3DP product sales. However, when the 3DP product costs are low, the traditional manufacturer loses product sales because the TF product cannot attain the price advantage. If the 3DP product costs are high, the TF product can bring more profits to the traditional manufacturer because it can attract more customization-sensitive consumers than the TM product. Overall, the integrated supply chain can derive more profits, either from the TF product or the 3DP product.

On the high supply chain setting, in the decentralized Bertrand supply chain, according to the different levels of the 3DP product cost, the results of the comparison of outcomes for the traditional manufacturer and the logistics vendor could be summarized into five different scenarios (Figure 1). a) In Region I, the traditional manufacturer can attain more profits from the TF product's high margin and the logistics vendor can make more profits from 3DP product sales. b) In Region II, the traditional manufacturer can still make more profits on the high TF product margin, but the logistics vendor loses profits on the goods delivery service. c) In Region III, both parties lose their profits; although the TF product has a customization advantage over the TM product, it has no price advantage. Therefore, under this scenario, the traditional manufacturer loses overall revenue on product sales. Besides, the logistics vendor cannot make more profit on goods delivery. In addition, when the 3DP price is high, price-sensitive consumers leave the 3DP product market. d) In Region IV, the TF product has a price advantage, and so the traditional manufacturer can make more profit. But the logistics vendor's overall performance is worse due to the loss of the 3DP product sales. e) In Region V, the costs of the 3DP product are extremely high; therefore, the new TF product contributes more TF product sales revenue to the traditional manufacturer and increased TF product delivery revenue to the logistics vendor. Therefore, it is a win-win strategy under this supply chain structure. Compared to the decentralized Bertrand supply chain, the insights from the decentralized Stackelberg supply chain are simpler. Firstly, the traditional manufacturer can always attain more profits because the logistics vendor decides the 3DP product pricing strategy later. For example, if the costs of the 3DP product are high, the traditional manufacturer prices the TF product high for the purpose of maximizing the TF product's margin. The market demand for the TF product drops, but the logistics vendor can use the high-price regime on the 3DP product to maintain his/her income from the logistics delivery service. However, the logistics vendor cannot always obtain more profit under the scenario where the 3DP product's fixed cost is high, but the variable cost is low. In this situation, the low 3DP pricing strategy causes more price-sensitive consumers to leave the market with empty hands. Although the traditional manufacturer derives more profits from the high TF product margin, the logistics vendor loses profit from both the goods delivery service and the 3DP product sales.

If the 3DP product costs are sufficiently low or considerably high, the integrated supply chain can achieve better profitability. Specifically, if the 3DP product costs are low, the new TF product pushes more customization-sensitive consumers to choose the 3DP product. This helps the supply chain by bringing benefits from the increased 3DP product sales. If the 3DP product costs are high, the TF product can attract more customization-sensitive consumers than the previous TM product. Therefore, the supply chain can make more profit on the traditional manufacturer's product sales.

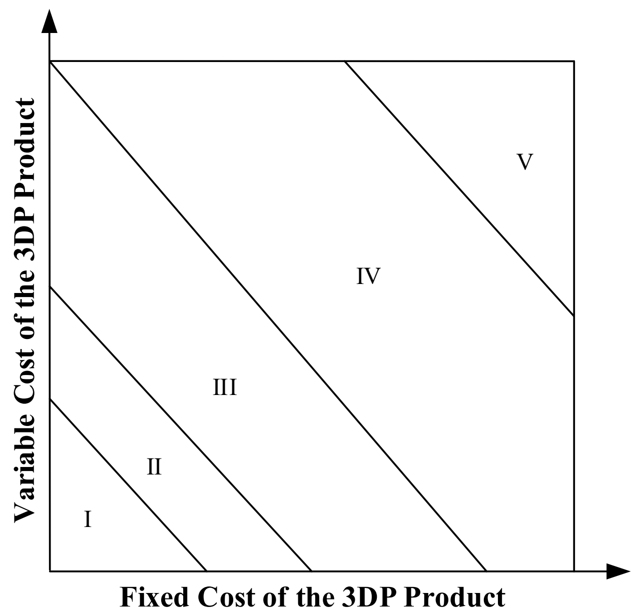


Figure 1 3DP Product Cost Level

The Impact of the Logistics Delivery Cost

PROPOSITION *0-10.* *If the traditional manufacturing decides fully use TF product to replace TM product for the purpose of coping with the logistics vendor's 3DP technology,*

(1) In the low-cost structure and low product customization supply chain, this strategy is not profitable to either the traditional manufacturer or the logistics vendor in the decentralized Bertrand supply chain. However, in the decentralized Stackelberg

supply chain, although it is not profitable to the traditional manufacture all the timer, if the logistics delivery cost is sufficiently low, it is profitable to the logistics vendor. The integrated supply chain cannot achieve better profitability.

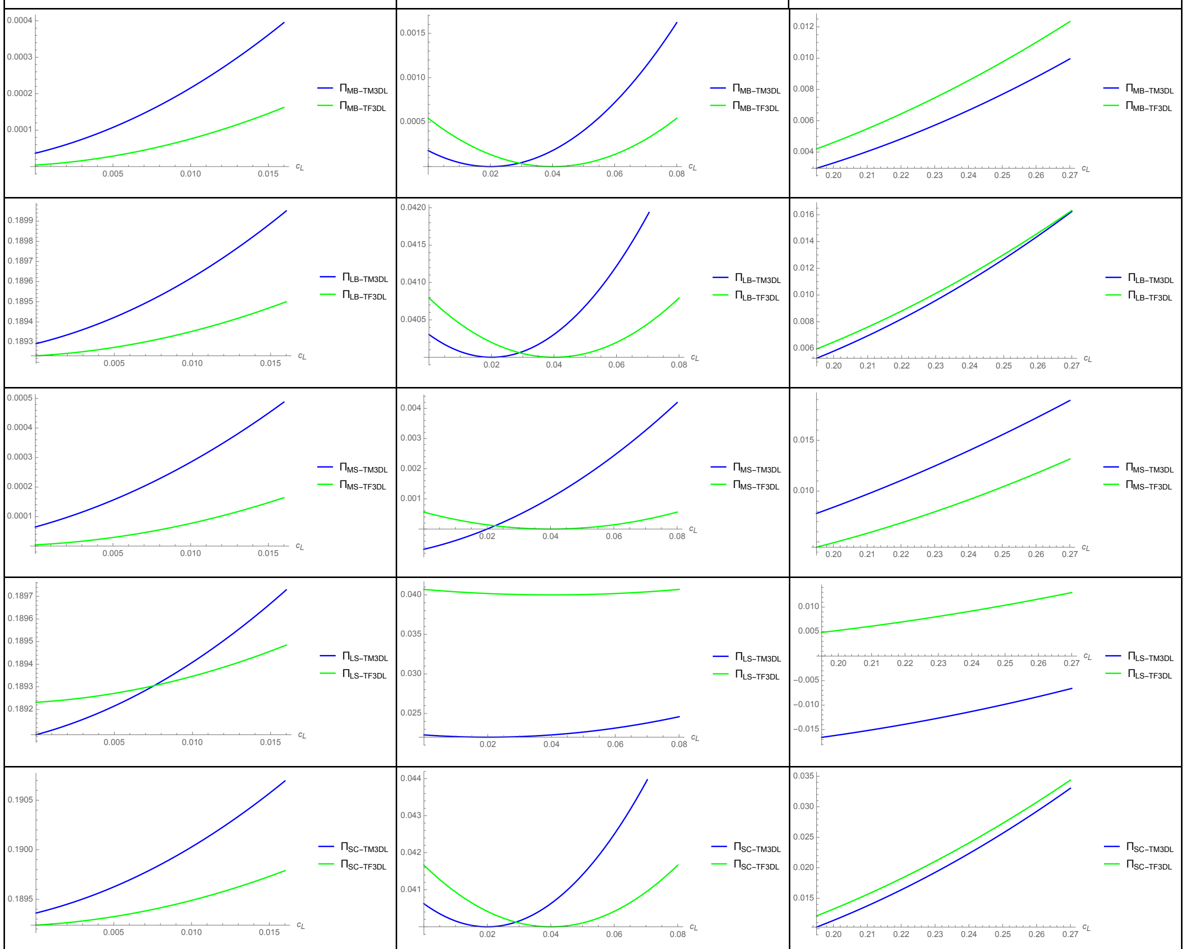
(2) If the product costs and the customization level are at the medium level, generally this strategy is profitable to the traditional manufacturer and the logistics vendor if the logistics delivery cost is low – in the decentralized Bertrand supply chain. In the decentralized Stackelberg supply chain, this strategy benefits the logistics vendor, but the traditional manufacturer can only benefit if the delivery cost is low. The integrated supply chain can only gain more profits by the introduction of a new TF product if the delivery cost is sufficiently low.

(3) If the product costs and the customization level are high, both the traditional manufacturer and the logistics vendor can always gain more profits in the decentralized Bertrand supply chain. However, in the decentralized Stackelberg supply chain, it is beneficial for the logistics vendor but not for the traditional manufacturer. The integrated supply chain can enjoy more profits through this strategy.

On the low-cost structure supply chain setting (Table 10), the logistics delivery cost has no impact on the integrated supply chain's profitability because the introduction of a new TF product results in fewer product sales. Meanwhile, in the decentralized Bertrand supply chain, neither party can generate more profits because the TF product has no advantages over the previous TM product. However, in the Stackelberg supply chain, if the delivery cost is sufficiently low, the logistics vendor can still make more profits on TF product delivery to cover his/her loss on 3DP product sales. With the medium supply chain setting, if the delivery cost is low, the traditional manufacturer can use the TF product with its higher customization level to earn more profits than the TM product, whilst the logistics vendor can also generate more revenue from the logistics service in the decentralized Bertrand supply chain. But in the Stackelberg supply chain, if the logistics cost is high, the logistics vendor can make more profit by increasing the 3DP product margin. Overall, the integrated supply chain can only gain more profits in the low delivery cost scenarios. With the high supply chain setting, both the traditional manufacturer and the logistics vendor benefit from the TF product in the decentralized Bertrand supply chain. But in the decentralized Stackelberg supply chain, the traditional manufacturer cannot make more profit because the price of the TF product is higher than the TM product. As for the integrated supply chain, either the new high margin on the TF product or the increased 3DP product sales can help it achieve more profit.

Table 10 Maximized Profit: Comparison by Logistics Service Cost – TM3DL and TF3DL

Low	Medium	High



	TM Product			TF Product			3DP Product		Delivery
	F_M	V_M	α	F_{TF}	V_{TF}	β	F_{3D}	V_{3D}	c_L
Low	0.01	0.01	0.1	0.025	0.02	0.2	0.1	0.03	-
Medium	0.05	0.05	0.2	0.1	0.25	0.4	0.3	0.3	-
High	0.1	0.08	0.3	0.3	0.3	0.6	0.6	0.35	-

The Impact of the TM Product Customization Level

PROPOSITION ***11.*** *If the traditional manufacturing decides fully use TF product to replace TM product for the purpose of coping with the logistics vendor's 3DP technology,*

(1) In the decentralized supply chain with the low-cost structure and low TM product customization level, both the traditional manufacturer and the logistics vendor can gain more profits if the TM product customization level is high. As for the integrated supply chain, it can also achieve better profitability if the TM product's customization level is high.

(2) In the decentralized Bertrand supply chain with the medium cost structure and TM product customization level, it is not profitable for either the traditional manufacturer or the logistics vendor. However, it is profitable for both parties under the decentralized Stackelberg supply chain. The integrated supply chain cannot attain more profit under the new TF3DL model.

(3) If the product costs are high and the TM product customization level is located in a high region, this strategy is not profitable to the traditional manufacturer or the logistics vendor in the decentralized supply chain. The integrated supply chain cannot gain more profits from this strategy.

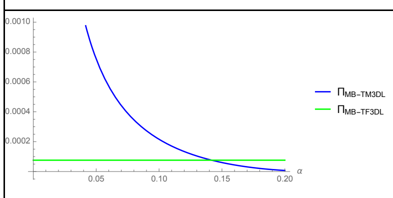
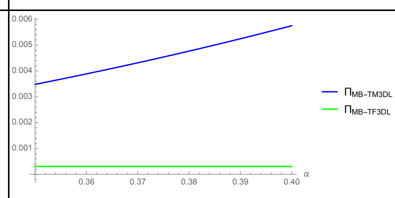
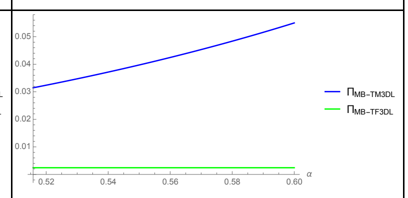
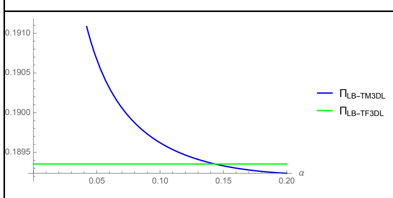
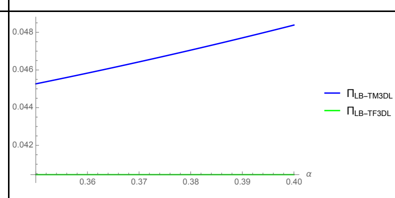
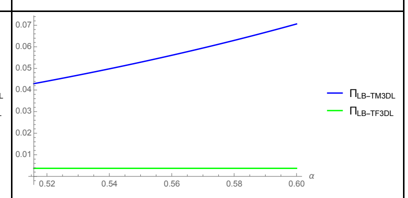
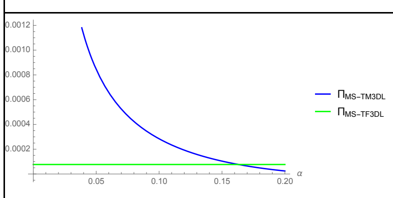
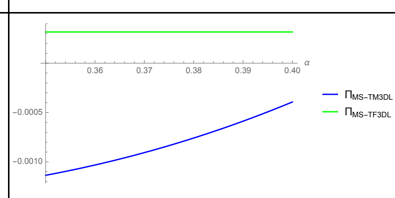
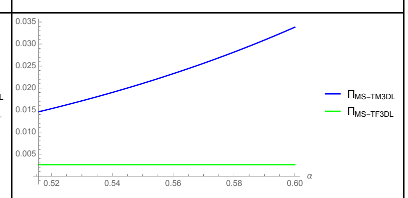
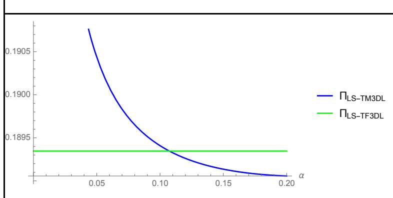
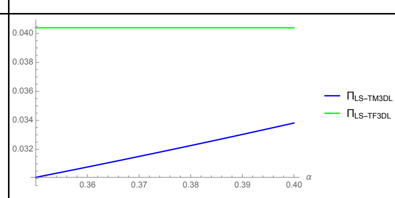
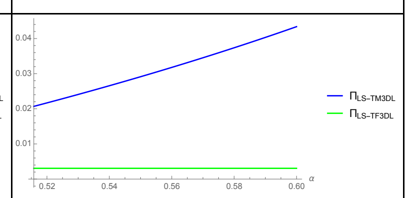
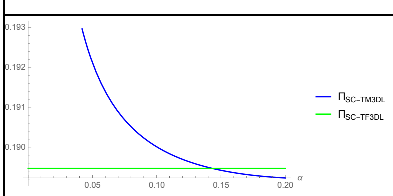
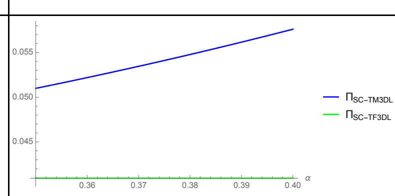
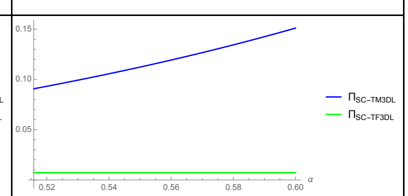
As seen in Table 11, with the low supply chain setting, if TM product customization is high, using a TF product with a higher customization level (and with a higher product price) results in the loss of price-sensitive consumers. Overall, this new TF product strategy has a negative impact on the traditional manufacturer's product sales and the logistics vendor loses profits on the goods delivery service. The integrated supply chain cannot achieve better financial performance due to the shrunken market demand.

On the medium supply chain setting, in the decentralized Bertrand supply chain, the new TF product has less advantage with regard to pricing strategy. Thus the traditional manufacturer prefers to use a high-price regime to maximize its product's unit margin, which results in a decrease in product sales. In addition, it causes the traditional manufacturer and the logistics vendor to lose profits. However, under the decentralized Stackelberg supply chain, after the logistics vendor receives the high TF price, for the purpose of insuring the traditional delivery service, the logistics vendor prices the 3DP product high to push more consumers to buy the

TF product. Therefore, both parties can attain better profitability overall. But the integrated supply chain cannot generate more profit on product sales.

On the high supply chain setting, the new TF product results in a loss on product sales, not only for the supply chain stakeholders in the decentralized supply chain but also for the integrated supply chain, because the TF product has less of a customization and price advantage over the previous TM product and the 3DP product. A portion of the price-sensitive consumers leave the market with empty hands.

Table 11 Maximized Supply Chain Profit: Comparison by Product Customization Level – TM3DL and TF3DL (Decentralized Bertrand Supply Chain)

Low	Medium	High
		
		
		
		
		

	TM Product	TF Product	3DP Product	Delivery

	F_M	V_M	α	F_{TF}	V_{TF}	β	F_{3D}	V_{3D}	c_L
Low	0.01	0.01	-	0.025	0.02	0.2	0.1	0.03	0.01
Medium	0.05	0.05	-	0.1	0.25	0.4	0.3	0.3	0.01
High	0.1	0.08	-	0.3	0.3	0.6	0.6	0.35	0.01

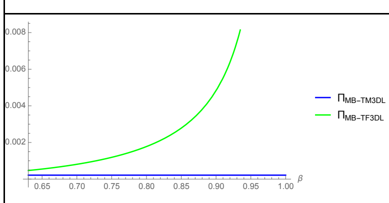
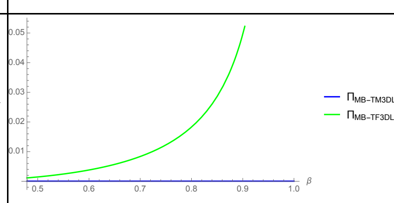
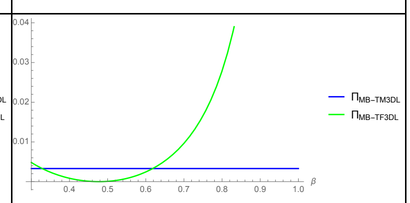
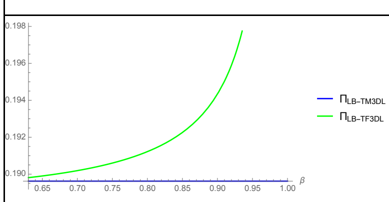
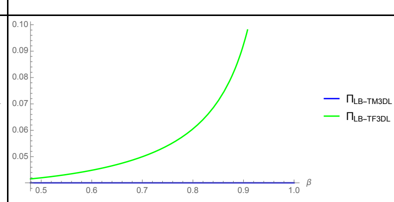
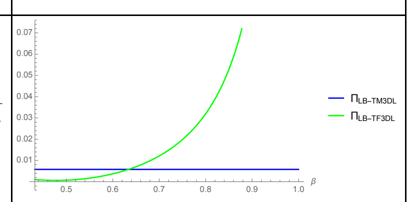
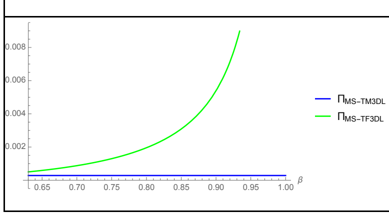
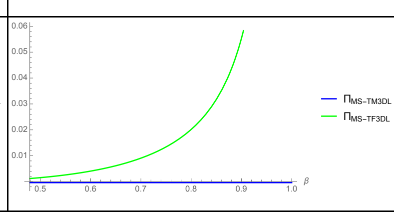
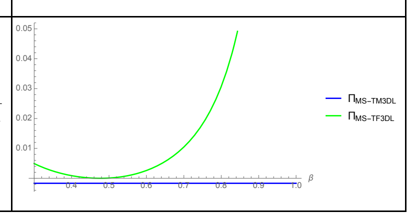
The Impact of the TF Product Customization Level

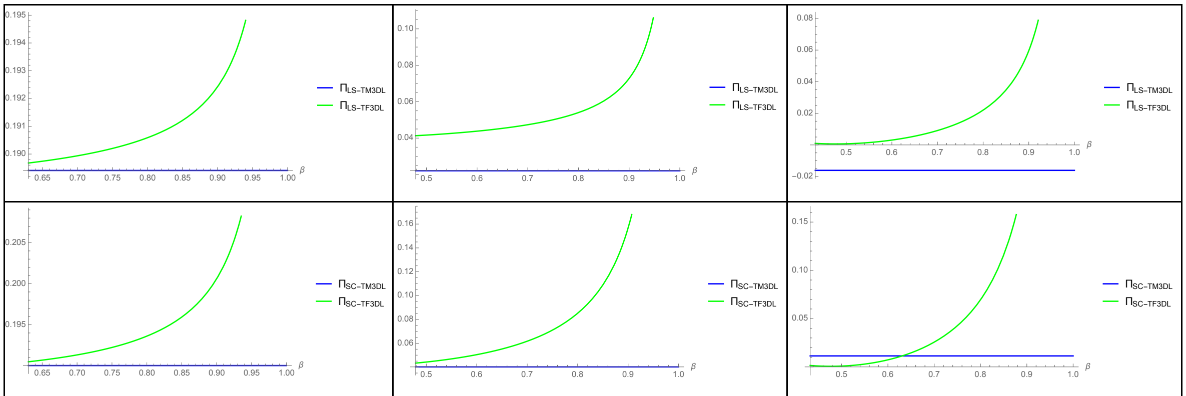
PROPOSITION ***12.*** *If the traditional manufacturing decides fully use TF product to replace TM product for the purpose of coping with the logistics vendor's 3DP technology,*

(1) It is a profitable strategy for the stakeholders in the decentralized supply chain, and the integrated supply chain can also benefit when the cost structure and TM product customization level of the supply chain are low or medium.

(2) If the product costs are high and the TM product customization level is in the high region, then in the decentralized Bertrand supply chain, this strategy is profitable to the traditional manufacturer if the TF product customization level is sufficiently low or high. The logistics vendor can also make more profit, but only if the TM product customization level is high. It is profitable for the traditional manufacturer and the logistics vendor in the decentralized Stackelberg supply chain. The integrated supply chain can also gain more profits from this strategy, but only if the TF product customization level is considerably high.

Table 12 Maximized Supply Chain Profit: Comparison by Product Customization Level –TM3DL and TF3DL (Decentralized Stackelberg Supply Chain)

Low	Medium	High
		
		
		



	TM Product			TF Product			3DP Product		Delivery
	F_M	V_M	α	F_{TF}	V_{TF}	β	F_{3D}	V_{3D}	c_L
Low	0.01	0.01	0.1	0.025	0.02	-	0.1	0.03	0.01
Medium	0.05	0.05	0.2	0.1	0.25	-	0.3	0.3	0.01
High	0.1	0.08	0.3	0.3	0.3	-	0.6	0.35	0.01

On the low and medium supply chain settings (Table 12), although the TF product has the advantage in terms of customization, the TF product price is higher than that of the TM product. Therefore, the traditional manufacturer loses some price-sensitive consumers. Consequently, the traditional manufacturer's profitability becomes worse. And the logistics vendor loses business for its traditional product delivery service. In the integrated supply chain, the new TF product cannot generate more profits. In the decentralized Bertrand supply chain on the high setting, the impact of the new TF manufacturing strategy could be summarized into three different scenarios. Firstly, if the customization level of the TF product is extremely low, the new TF product has no advantage with regard to customization, but the TF price is higher than for the TM product. Therefore, both the traditional manufacturer and the logistics vendor use a high-price regime to maximize the product margin. The traditional manufacturer can generate more profit. Although the logistics vendor can attain a higher margin for each 3DP product, the market sales of the 3DP product drop. Meanwhile, the overall quantity of the TF product is lower than for the TM product. Taking all these results into consideration, the logistics vendor loses profit in this supply chain structure. However, if the customization level of the TF product is slightly higher, the TF product has fewer consumers. Therefore, the traditional manufacturer also loses profits under this scenario. The logistics vendor still cannot make more profit due to the shrunken TF product delivery service.

If the TF product's customization level is high, the traditional manufacturer prices the TF product high and the logistics vendor sets the 3DP product price low to secure 3DP product sales. Therefore, the traditional manufacturer can attain more profits due to the high TF product price. Meanwhile, the logistics vendor can also gain more profits on the 3DP product sales. In the decentralized Stackelberg supply chain, whatever the TF product's customization level is, the logistics vendor always chooses a price to maximize his/her own profit. For example, if the TM product customization level is low and the TF product costs are high, the traditional manufacturer prices the TF product high to obtain a larger product margin. Based on this, the logistics vendor prices the 3DP product high to increase the 3DP product margin, which also helps to create more business for the delivery service. Therefore, the traditional manufacturer can attain better profitability. Overall, in the integrated supply chain, if the TF product customization level is low, product sales decline after the traditional manufacturer uses TF product manufacturing, which results in a worse supply chain performance. However, if the TF product customization level is higher, TF production contributes to the overall performance of the supply chain by a higher product margin.

TMTF3DM Model

The Impact of the TM Product Costs

PROPOSITION *13.* *If the traditional manufacturer tries to offer a TM, TF and 3DP product at the same time,*

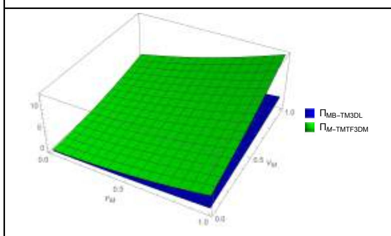
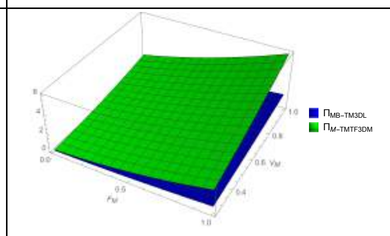
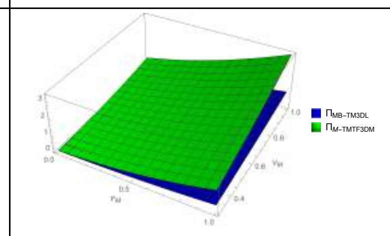
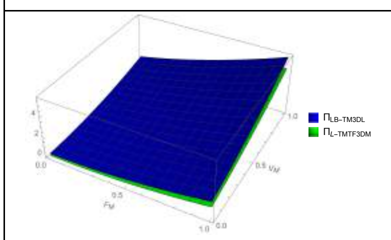
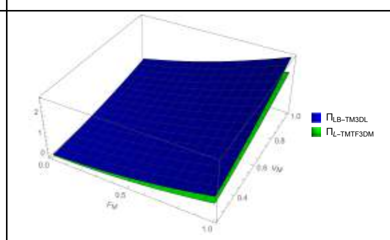
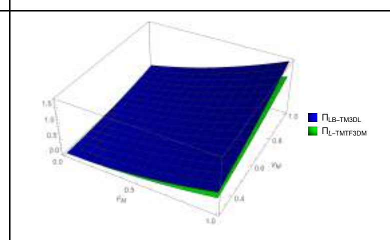
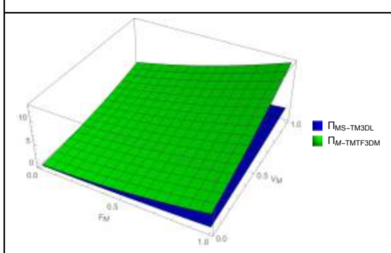
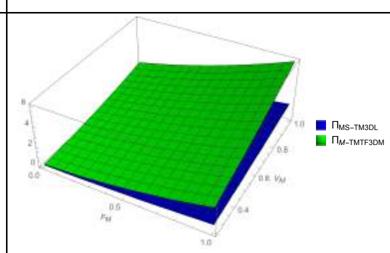
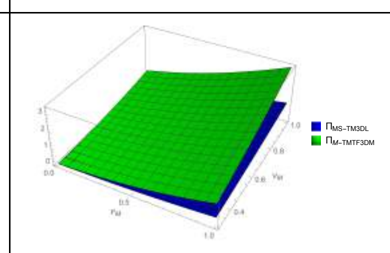
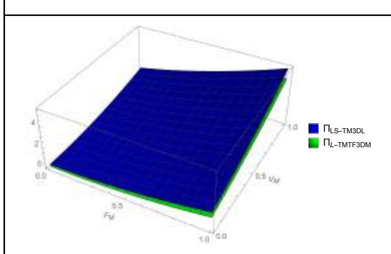
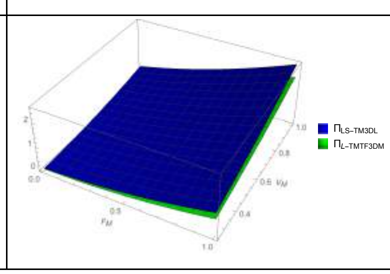
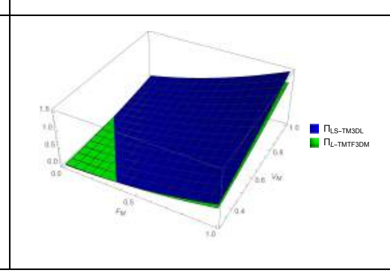
(1) For the low-cost structure and low product customization supply chain, in the decentralized supply chain, it is profitable to the traditional manufacturer but not at all profitable to the logistics vendor. The integrated supply chain can also enjoy the benefits, unless the fixed TM product cost is extremely low;

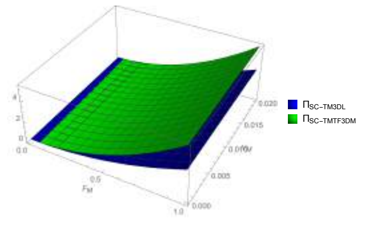
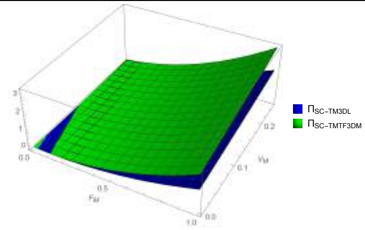
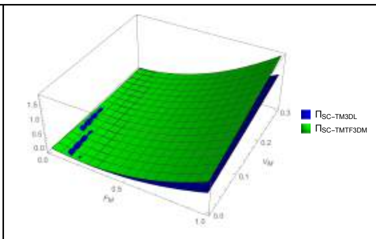
(2) If the product costs and the customization level are at the medium level, it is profitable to the traditional manufacturer but not to the logistics vendor. Generally, this strategy is beneficial to the integrated supply chain, but there exists a region where both the fixed TM and variable TM costs are at a low level, and the integrated supply chain cannot obtain more profit.

(3) If the product costs and the customization level are high, in the decentralized Bertrand supply chain, it is profitable to the traditional manufacturer but not profitable to the logistics vendor. In the decentralized Stackelberg supply chain, this strategy brings more profits to the traditional manufacturer. If both the costs of the TM products are sufficiently low, the logistics vendor can also enjoy the benefits of this strategy. Overall, the integrated supply chain can also obtain more profits, but the integrated supply chain cannot gain more profits if both the TM product costs are located in the low regions.

As shown in Table 13, it is clear that in the decentralized supply chain, it is beneficial to the traditional manufacturer to add a 3DP product into his/her manufacturing system because of the extended product range. But the logistics vendor loses profits because it can only make profit from its logistics delivery service. However, on the high supply chain setting, if the costs of the TM product are sufficiently low, the logistics vendor can also make more profit, because the logistics vendor can gain more profits on the delivery service. In the integrated supply chain, the new TMTF3DM model generally helps the supply chain generate more profit on 3DP product sales. Because the traditional manufacturer's 3DP product price is lower than the logistics vendor's in the TM3DL model, more price sensitive consumers would like to choose the traditional manufacturer's 3DP product. However, if the fixed cost of the TM product is low on the low supply chain setting, more consumers select the low-price TM product instead of the high price 3DP product. Therefore, overall the supply chain cannot make more profit. On the medium and high supply chain settings, if the TM product costs are extremely low, there are more TM product buyers. If the costs of the TM product are high, some customization-sensitive consumers choose the TF or the 3DP product. Therefore, in both scenarios, the integrated supply chain can make more profit. In summary, in the supply chain on the high setting, if the TM product costs are low, both the traditional manufacturer and the logistics vendor can share the benefits of the traditional manufacturer's 3 product line strategy. This strategy also contributes to the industry's development.

Table 13 Maximized Profit: Comparison by TM Product Cost – TM3DL and TMTF3DM

Low	Medium	High
		
		
		
		

	TM Product			TF Product			3DP Product		Delivery
	F_M	V_M	α	F_{TF}	V_{TF}	β	F_{3D}	V_{3D}	c_L
Low	-	-	0.1	0.025	0.02	0.2	0.1	0.03	0.01
Medium	-	-	0.2	0.1	0.25	0.4	0.3	0.3	0.01
High	-	-	0.3	0.3	0.3	0.6	0.6	0.35	0.01

The Impact of the TF Product Costs

PROPOSITION ***14.*** *If the traditional manufacturer tries to offer TM, TF and 3DP products at the same time,*

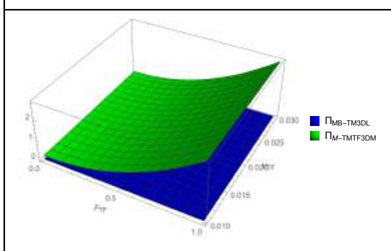
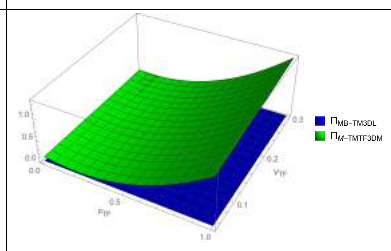
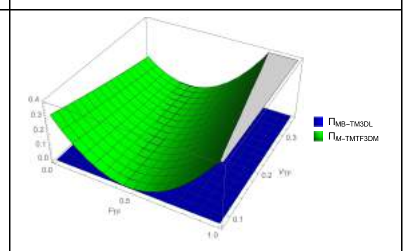
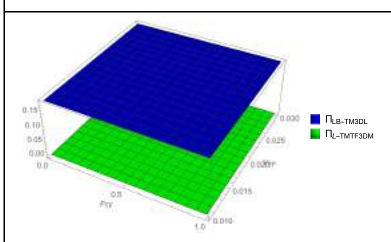
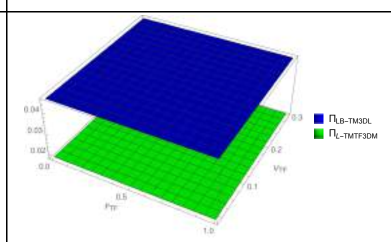
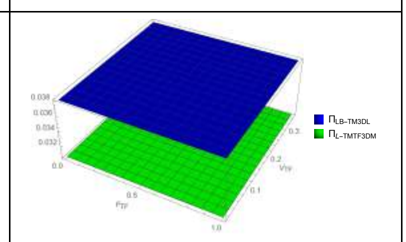
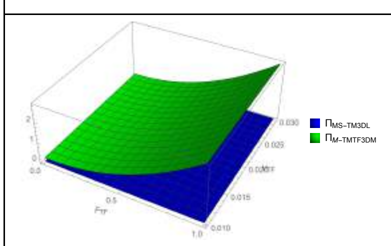
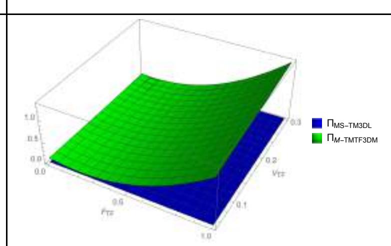
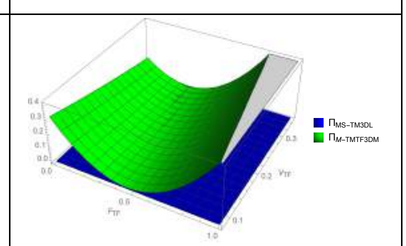
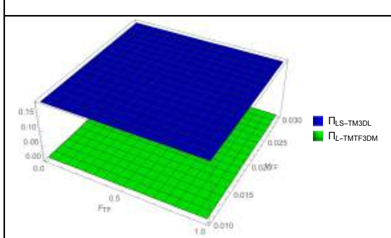
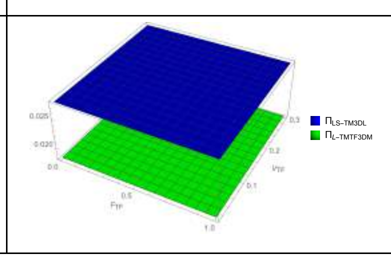
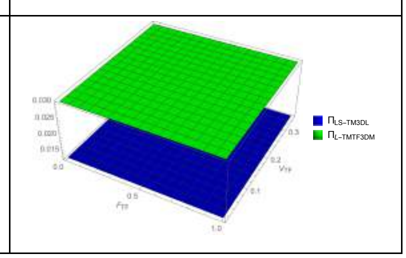
(1) As for the low-cost structure and low product customization supply chain, in the decentralized supply chain, it is profitable to the traditional manufacturer but not at all profitable to the logistics vendor. The integrated supply chain can also enjoy the benefits of this supply chain – except when the fixed TF product cost is extremely low.

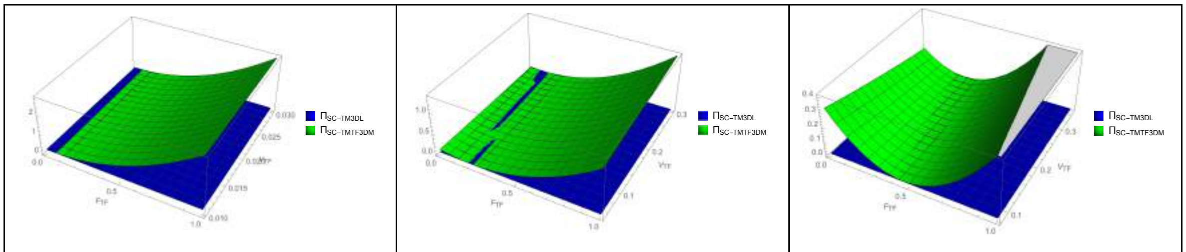
(2) If the product costs and the customization level are at the medium level, it is profitable to the traditional manufacturer but not to the logistics vendor. Generally, this strategy is beneficial to the integrated supply chain, but there exists a region where both the fixed TF and variable TF cost are at a certain low level, and the integrated supply chain cannot make more profit.

(3) If the product costs and the customization level are high, in the decentralized Bertrand supply chain, it is profitable to the traditional manufacturer but not profitable to the logistics vendor. In the decentralized Stackelberg supply chain, it brings more profits to both the traditional manufacturer and the logistics vendor. Overall, the integrated supply chain can also gain more profits from this strategy.

In the decentralized supply chain, it is beneficial to the traditional manufacturer to also offer a 3DP product because it helps him/her to achieve full market coverage (Table 14). But the logistics vendor loses profits because it can only gain profits from its logistics delivery service. On the medium supply chain setting, the insights are almost the same, but if the fixed TM product cost is sufficiently low, the integrated supply chain can obtain more profits due to the increased TF product sales; and if the fixed TF product cost is high, the new 3DP product offering can force more consumers to buy the 3DP product. Therefore, the integrated supply chain can also gain more profits. However, there still exists one situation where the fixed TF product cost is located in between the cost of the other products, and the new 3DP product cannot help the system make more profit due to the cannibalization effect on the 3DP and the TF product. In the market led by the traditional manufacturer, on the high supply chain setting, the introduction of a new high price 3DP product by the traditional manufacturer can help the traditional manufacturer make more profit and the logistics vendor can also make more profit on the increased product delivery service. At the integrated supply chain level, this strategy also helps the industry's development.

Table 14 Maximized Profit: Comparison by TF Product Cost – TM3DL and TMTF3DM

Low	Medium	High
		
		
		
		



	TM Product			TF Product			3DP Product		Delivery
	F_M	V_M	α	F_{TF}	V_{TF}	β	F_{3D}	V_{3D}	c_L
Low	0.01	0.01	0.1	-	-	0.2	0.1	0.03	0.01
Medium	0.05	0.05	0.2	-	-	0.4	0.3	0.3	0.01
High	0.1	0.08	0.3	-	-	0.6	0.6	0.35	0.01

The Impact of the 3DP Product Costs

PROPOSITION ***15.*** *If the traditional manufacturer tries to offer TM, TF and 3DP products at the same time,*

(1) As for the low-cost structure and low product customization supply chain, in the decentralized Bertrand supply chain, it is profitable to the traditional manufacturer but not at all profitable to the logistics vendor. In the decentralized Stackelberg supply chain, it is still profitable to the traditional manufacturer, but the logistics vendor can only gain more profits if the fixed 3DP product cost is high and the variable 3DP product cost is low or the fixed 3DP product cost is low and the variable 3DP product cost is high. The integrated supply chain can also enjoy the benefits of this strategy, except when the 3DP product costs are extremely low.

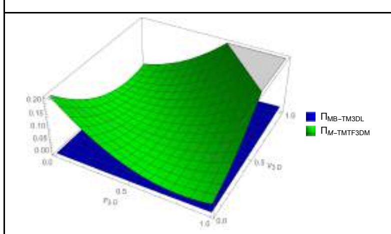
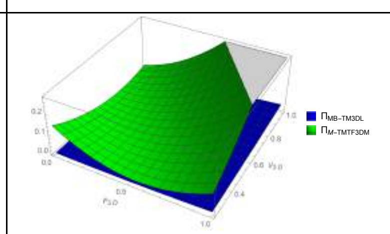
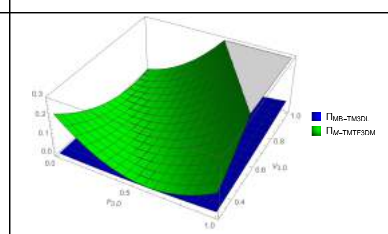
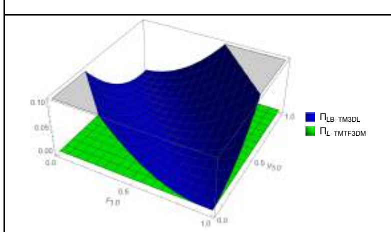
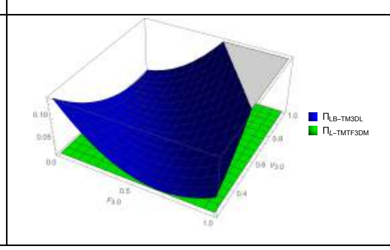
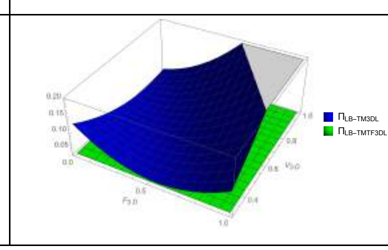
(2) If the product costs and the customization level are at the medium level, in the decentralized Bertrand supply chain, it is profitable to the traditional manufacturer but not at all profitable to the logistics vendor. In the decentralized Stackelberg supply chain, it is still profitable to the traditional manufacturer, but the logistics vendor can only gain more profits if the fixed 3DP product cost is high or both the fixed 3DP product cost and the variable 3DP product cost are low. The integrated supply chain can also enjoy the benefits of this strategy, but only if the 3DP product costs are extremely low or generally high.

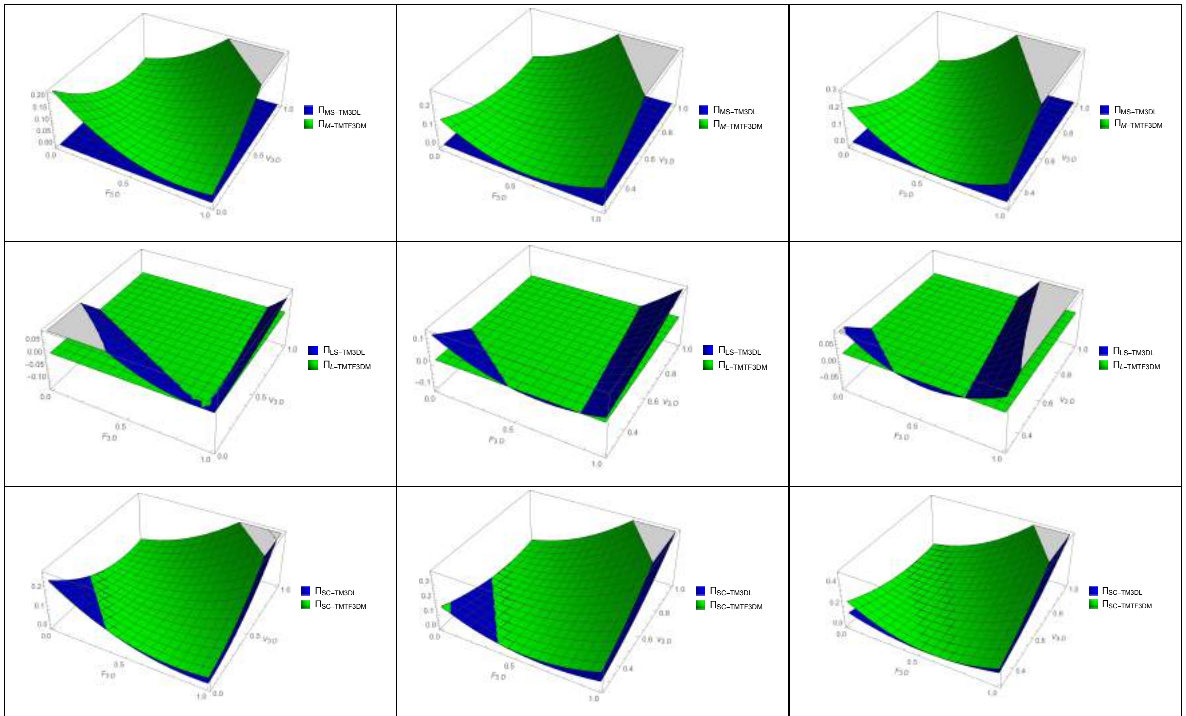
(3) If the product costs and the customization level are high, in the decentralized Bertrand supply chain, it is profitable to the traditional manufacturer but not at all profitable to the logistics vendor. In the decentralized Stackelberg supply chain, it is still profitable to the traditional manufacturer, but the logistics vendor can only gain more profits if the fixed 3DP product cost is high or both the fixed 3DP product cost and the variable 3DP product cost are low. The integrated supply chain can also enjoy the benefits of this strategy.

According to Table 15, in the decentralized Bertrand supply chain, the traditional manufacturer is always better off operating the TM, TF, and 3DP product, because s/he can benefit from three different revenue streams. However, the logistics vendor cannot gain more profits. Therefore, it is risky for the logistics vendor to lose the 3DP product market. In the decentralized Stackelberg supply chain, no matter the 3DP product costs, it is still profitable to the traditional manufacturer to operate the three different products. However, on the low supply chain setting, the logistics vendor can also enjoy the benefits of this strategy, except in two scenarios: a) where the variable 3DP product cost is sufficiently low or b) the fixed TF cost is notably high. Specifically, if the variable 3DP product cost is low, then it is easier for the traditional manufacturer to set up the 3DP product manufacturing system. Therefore, the price of the traditional manufacturer's 3DP product is considerably low. Accordingly, more customization-sensitive consumers choose the 3DP product over the TF product which leads to profit being lost on the TM and the TF product delivery service operated by the logistics vendor. If the fixed cost of the 3DP product is high, the price of the 3DP product is located at a high level, and fewer consumers buy the 3DP product. Therefore, the logistics vendor not only loses profits on the 3DP product business but also cannot generate more profits on product delivery.

At the integrated supply chain level, if the 3DP product costs are low, the 3DP product cannibalizes the high customization level TF product, and the integrated supply chain loses profits overall. On the medium supply chain setting, the logistics vendor can in general also make more profit because s/he can gain more profits on goods delivery. However, if a) the 3DP product costs are extremely low or b) the fixed 3DP product cost is extremely high, the logistics vendor cannot make more profit. When the 3DP product costs are low, the more customization-sensitive consumers choose the 3DP product over the TF or TM product. Therefore, the logistics vendor cannot make more profit on product delivery. When the 3DP product's fixed cost is low, if the logistics vendor loses the 3DP product, s/he cannot generate a significant amount of revenue on 3DP product sales, although s/he can make some more profits on goods delivery. As for the integrated supply chain, overall, it is better off when the traditional manufacturer starts to operate three different products, although this may not hold in some cases. a) When the 3DP product cost is sufficiently low, after the traditional manufacturer starts to offer a low-price 3DP product, then the integrated supply chain can gain more profits on 3DP product sales. b) If the 3DP product cost is considerably high, the traditional manufacturer can use this 3DP product pricing strategy to boost the sales of the TF and the TM product. Overall, the integrated supply chain can generate more profits than when operating only the TM product. In the supply chain on the high setting, when the 3DP product costs are low and when the fixed 3DP product cost is high, the logistics vendor cannot gain more profits. It is the same as on the medium supply chain setting. However, the integrated supply chain can always make more profit under this supply chain structure because there are more consumers who choose the TM/TF product under this scenario.

Table 15 Maximized Profit: Comparison by 3DP Product Cost – TM3DL and TMTF3DM

Low	Medium	High
		
		



	TM Product			TF Product			3DP Product		Delivery
	F_M	V_M	α	F_{TF}	V_{TF}	β	F_{3D}	V_{3D}	c_L
Low	0.01	0.01	0.1	0.025	0.02	0.2	-	-	0.01
Medium	0.05	0.05	0.2	0.1	0.25	0.4	-	-	0.01
High	0.1	0.08	0.3	0.3	0.3	0.6	-	-	0.01

The Impact of the Logistics Delivery Cost

PROPOSITION *16.* *If the traditional manufacturer tries to offer TM, TF and 3DP products at the same time,*

(1) For the low-cost structure and low product customization supply chain, the traditional manufacturer is always better off operating 3 different products at the same time. However, it is not profitable for the logistics vendor. The integrated supply chain can always gain more profits.

(2) If the product costs and the customization level are at the medium level, irrespective of the logistics delivery cost, it is profitable to the traditional manufacturer but not to the logistics vendor. As for the integrated supply chain, it is beneficial only if the logistics delivery cost is sufficiently low.

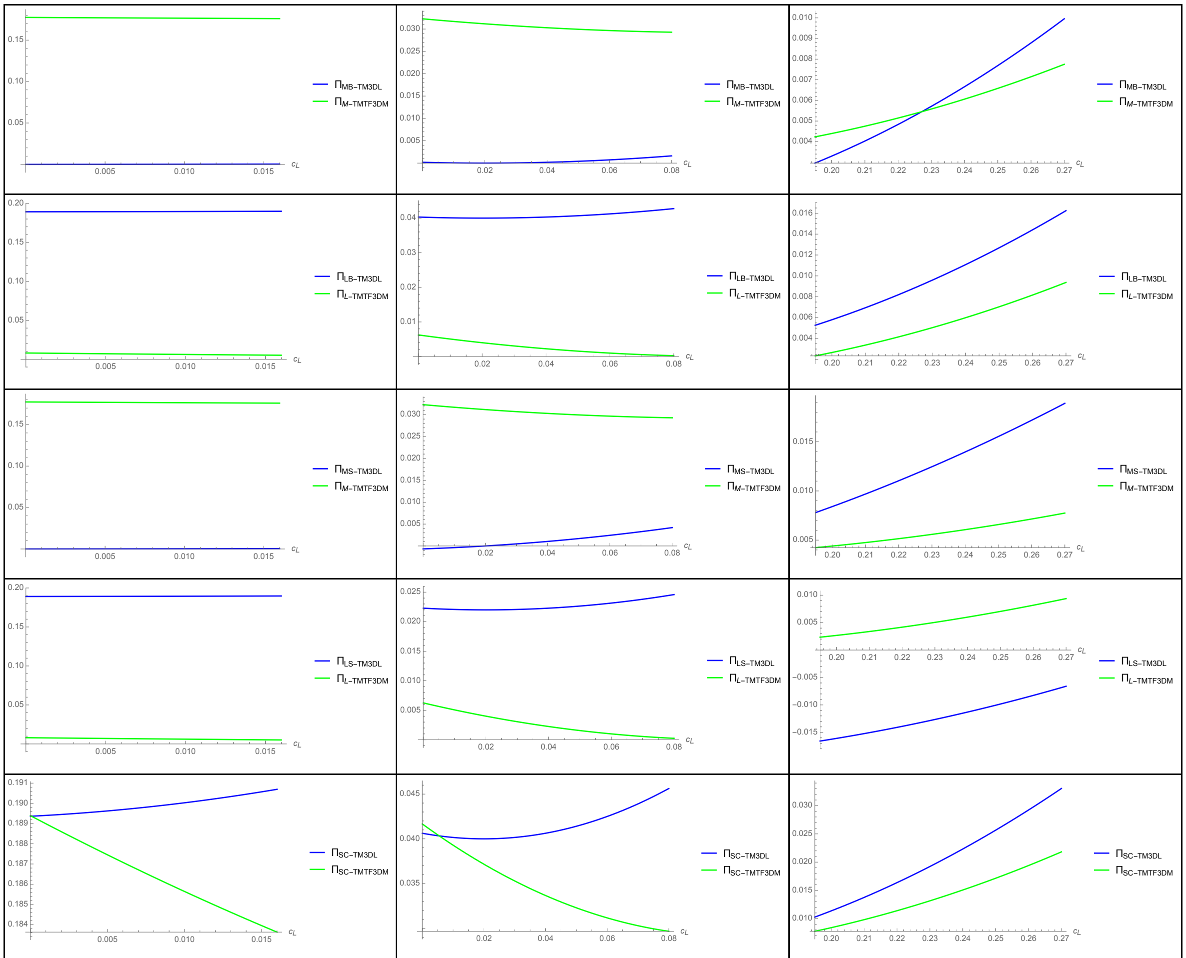
(3) If the product costs and the customization level are high, in the decentralized Bertrand supply chain, it is profitable to the traditional manufacturer if the logistics delivery cost is low – otherwise it is not profitable. It is not profitable to the logistics vendor. In the decentralized Stackelberg supply chain, the traditional manufacturer

cannot obtain more profits, but the logistics vendor can gain more profits instead. This strategy cannot help the improvement of the integrated supply chain.

With the supply chain on the low setting (Table 16), the traditional manufacturer can generate more profits from the 3 product lines. At the same time, although the logistics vendor can gain more profits on its product delivery service, it loses profits on the 3DP product. Because of the traditional manufacturer's 3DP product, the logistics vendor uses a high-price regime on its logistics delivery service for the purpose of maximizing its overall profits. Consequently, the traditional manufacturer has to use a high price on all the product to cover his/her high cost of product delivery. Therefore, overall, the integrated supply chain cannot gain more profits due to the shrunken product sales. But on the medium supply chain setting, if the cost of the delivery service is sufficiently low, the goods delivery price charged by the logistics vendor can still be located in the low range. Therefore, the integrated supply chain can still obtain more profit under this scenario. In the decentralized Bertrand supply chain, on the high setting, if the logistics delivery cost is low, the traditional manufacturer can use a low-pricing strategy on the TM, TF and 3DP product. Therefore, the traditional manufacturer can make more profit. However, if the logistics delivery costs are high, it pushes the traditional manufacturer to use a high-price regime on his/her product. Therefore, s/he cannot make more profit due to the loss of price-sensitive consumers. However, in the decentralized Stackelberg supply chain, no matter the logistics delivery cost, the average price of all three products is high. Therefore, the traditional manufacturer loses its profits on product sales overall. However, the logistics vendor benefits from the increased requirement for its goods delivery service. As for the integrated supply chain, the system loses profit on product sales.

Table 16 Maximized Profit: Comparison by Logistics Delivery Cost – TM3DL and TMTF3DM

Low	Medium	High



	TM Product			TF Product			3DP Product		Delivery
	F_M	V_M	α	F_{TF}	V_{TF}	β	F_{3D}	V_{3D}	c_L
Low	0.01	0.01	0.1	0.025	0.02	0.2	0.1	0.03	-
Medium	0.05	0.05	0.2	0.1	0.25	0.4	0.3	0.3	-
High	0.1	0.08	0.3	0.3	0.3	0.6	0.6	0.35	-

The Impact of the TM Product Customization Level

PROPOSITION ***17.*** *If the traditional manufacturer tries to offer TM, TF and 3DP products at the same time,*

(1) In the low-cost structure and low TF product customization level supply chain, it is profitable to the traditional manufacturer but not profitable to the logistics vendor in the decentralized supply chain. The integrated supply chain can only gain more profits if the TM product customization level is extremely high.

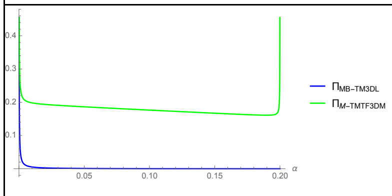
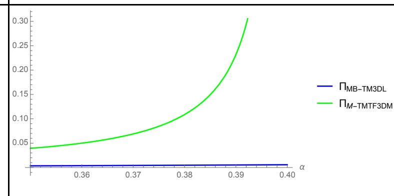
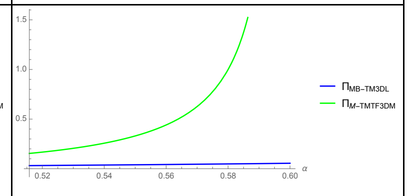
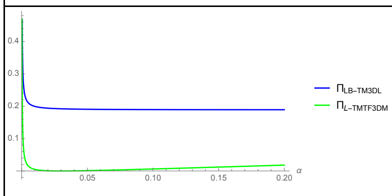
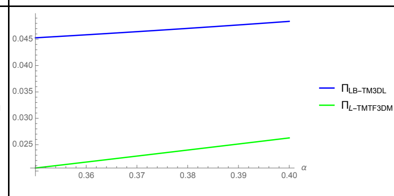
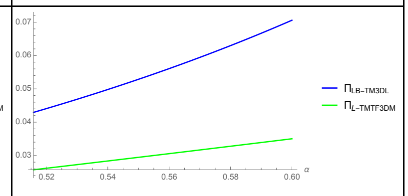
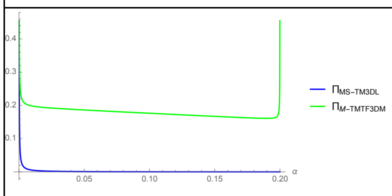
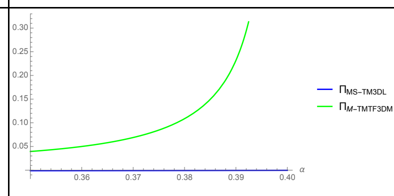
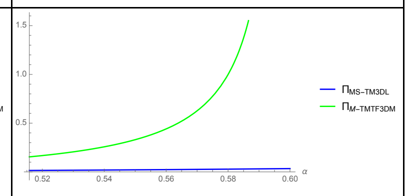
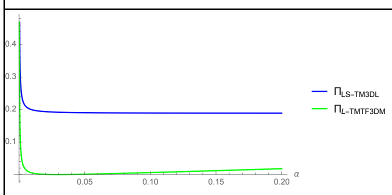
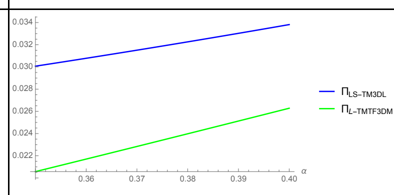
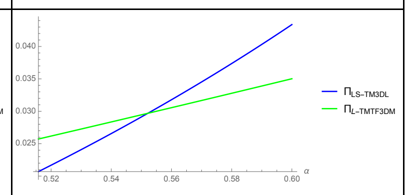
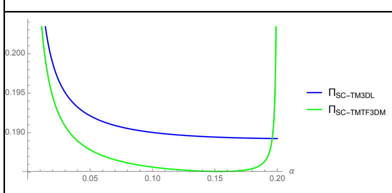
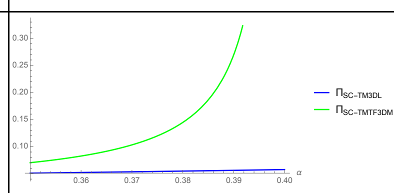
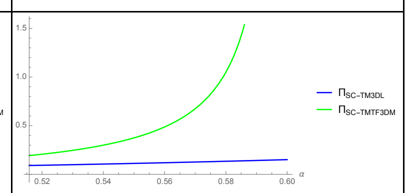
(2) In the medium-cost structure and medium TF product customization level supply chain, the traditional manufacturer is always better off using this strategy, but the

logistics vendor always loses profits. The integrated supply chain can also gain more profits.

(3) *If the product costs are high and the TF product customization level is located in the high region, then this strategy is not profitable to the traditional manufacturer or the logistics vendor in the decentralized supply chain. The integrated supply chain also cannot gain more profits from this strategy.*

On the low supply chain setting (Table 17), if the TM product customization level is high, use of a higher customization level TF product (with a higher product price) results in the loss of price-sensitive consumers. Overall, the new TF product strategy has a negative impact on the traditional manufacturer's product sales and the logistics vendor loses profit on the goods delivery service. The integrated supply chain cannot generate more profits overall due to the TM and the 3DP product having cannibalization effects on the market. Therefore, it is not a profitable strategy for the integrated supply chain's development. However, if the TM product customization level is extremely high, the cannibalization effect is not obvious. Thus, operating three products with different customization levels can help the system gain more consumers which helps the integrated supply chain attain better performance. On the high supply chain setting, in the decentralized Bertrand supply chain, this strategy helps the traditional manufacturer to take the 3DP product benefits from the logistics vendor. This follows from the fact that, in general, market domination can help any party to maximize profits (Porter, 1991). However, the integrated supply chain cannot gain more profits through this strategy because of the loss on the product delivery service. On the high supply chain setting, the overall insights are the same, but the logistics vendor can also obtain more profits if the TM product customization level is low. When the TM product customization level is low but all the product costs are high, if the traditional manufacturer chooses to operate three different products, the logistics vendor can use a high-price regime to save the profit lost on the 3DP product.

Table 17 Maximized Supply Chain Profit: Comparison by TM Product Customization Level – TM3DL and TMTF3DM

Low	Medium	High
		
		
		
		
		

	TM Product			TF Product			3DP Product		Delivery
	F_M	V_M	α	F_{TF}	V_{TF}	β	F_{3D}	V_{3D}	c_L
Low	0.01	0.01	-	0.025	0.02	0.2	0.1	0.03	0.01
Medium	0.05	0.05	-	0.1	0.25	0.4	0.3	0.3	0.01
High	0.1	0.08	-	0.3	0.3	0.6	0.6	0.35	0.01

The Impact of the TF Product Customization Level

Proposition 18. *If the traditional manufacturer tries to offer a TM, TF and 3DP product at the same time,*

(1) In the low-cost structure and low TM product customization level supply chain, it is profitable to the traditional manufacturer but not to the logistics vendor. The

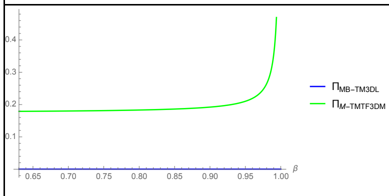
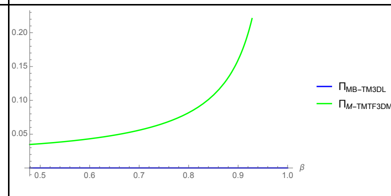
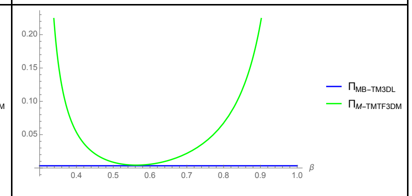
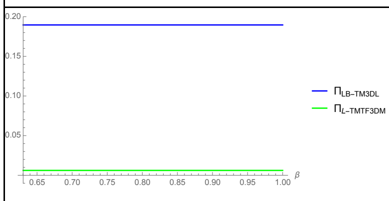
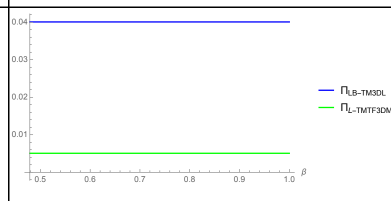
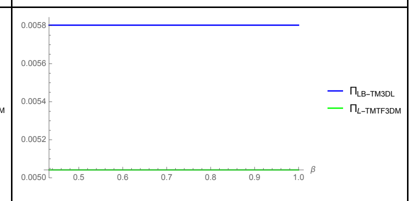
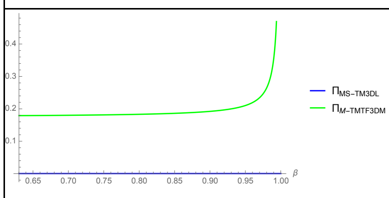
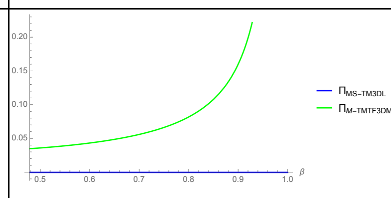
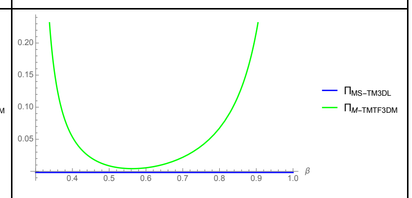
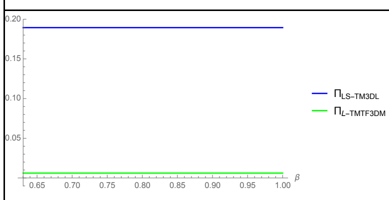
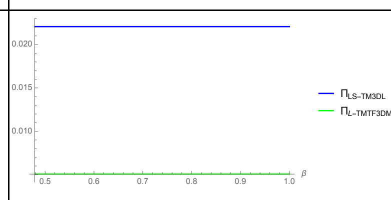
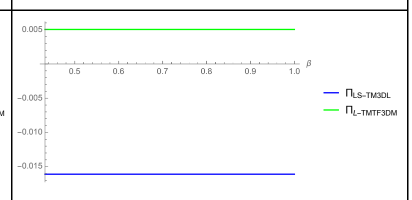
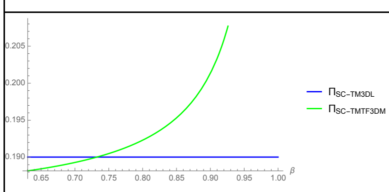
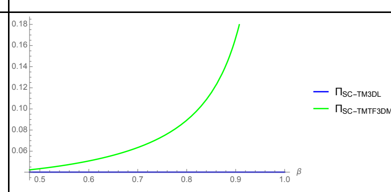
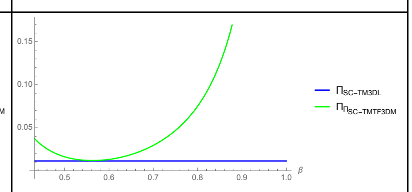
integrated supply chain can also obtain more profits if the TF product customization level is high.

(2) *In a supply chain with the medium-cost structure and medium TM product customization level, the traditional manufacturer is always better off using this strategy, but the logistics vendor always loses profits. The integrated supply chain can also attain more profit.*

(3) *If the product costs are high and the TM product customization level is located in the high region, then in the decentralized Bertrand supply chain this strategy is profitable to the traditional manufacturer but not to the logistics vendor. However, in the decentralized Stackelberg supply chain, it is profitable to both parties. The integrated supply chain can also generate more profits from this strategy.*

According to Table 18, within the supply chain on the low setting, the new 3 product strategy can help the traditional manufacturer make more profit, but the logistics vendor loses profit on 3DP product sales. However, if the TF product's customization level is extremely low, there is product competition between the TM and TF product. Therefore, the traditional manufacturer operating 3 different products hurts the overall sales for the TM product and the integrated supply chain cannot attain more profit under this scenario. However, as long as the TF product's customization level is high, the three different products can attract consumers with different levels of sensitivity to customization. This helps the supply chain attain more profit. On the medium supply chain setting, it is better for the traditional manufacturer to handle all three different products for a large range of consumers. At the same time, although the logistics vendor can gain more profits on the traditional delivery service, s/he loses profits on 3DP product sales. At the supply chain level, the integrated supply chain can also benefit from the strategy due to the obvious differentiation between the products. Interestingly, in the Stackelberg supply chain, this strategy brings benefits to both the supply chain stakeholders and the integrated supply chain. In this scenario, both parties, and even the integrated supply chain, can enjoy the benefits of increased product sales.

Table 18 Maximized Supply Chain Profit: Comparison by TF Product Customization Level – TM3DL and TMTF3DM

Low	Medium	High
		
		
		
		
		

	TM Product			TF Product			3DP Product		Delivery
	F_M	V_M	α	F_{TF}	V_{TF}	β	F_{3D}	V_{3D}	c_L
Low	0.01	0.01	0.1	0.025	0.02	-	0.1	0.03	0.01
Medium	0.05	0.05	0.2	0.1	0.25	-	0.3	0.3	0.01
High	0.1	0.08	0.3	0.3	0.3	-	0.6	0.35	0.01

TM3DM Model

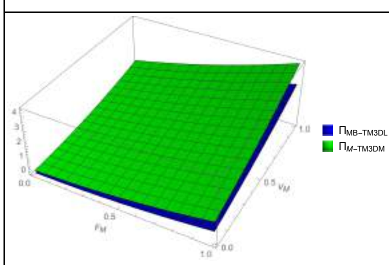
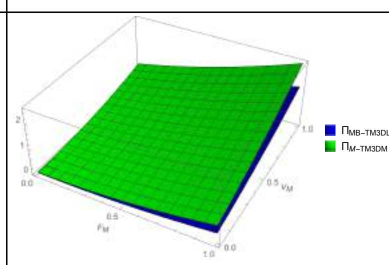
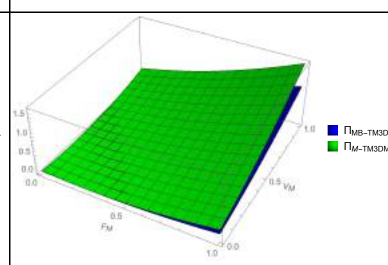
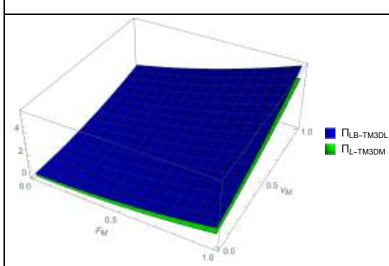
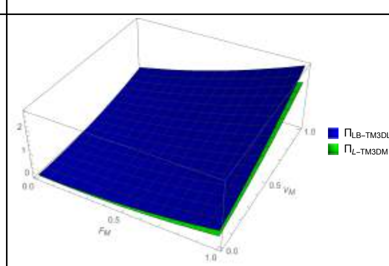
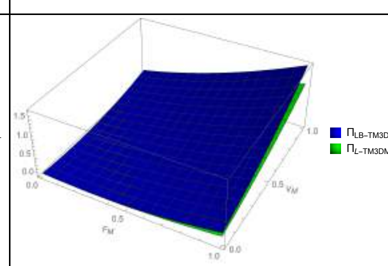
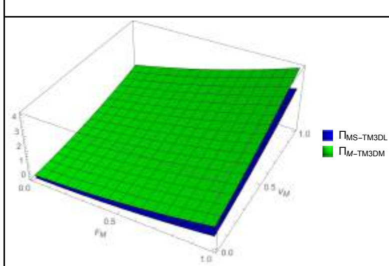
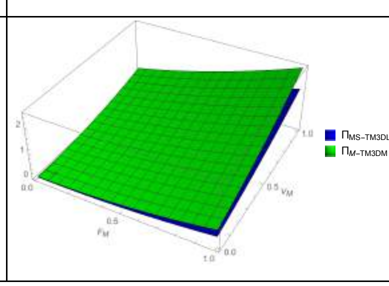
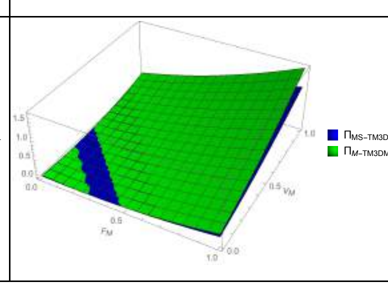
The Impact of the TM Product Costs

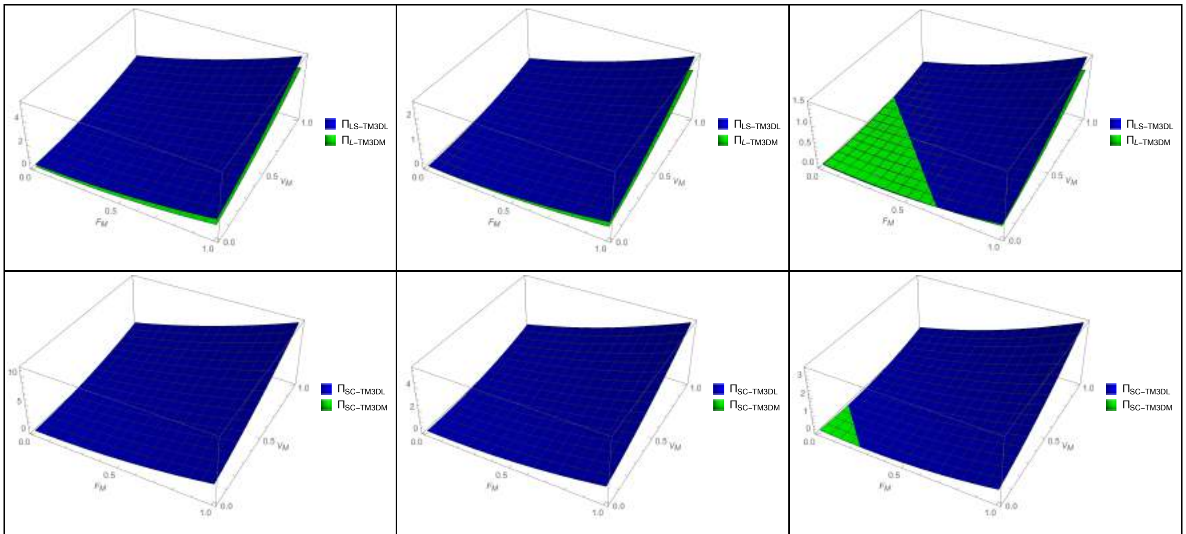
PROPOSITION ***19.*** *If the traditional manufacturer tries to offer a TM and 3DP product simultaneously,*

(1) With the low/medium cost structure and low/medium product customization level, in the decentralized supply chain, it is profitable to the traditional manufacturer but not at all profitable to the logistics vendor. This strategy is also not profitable to the integrated supply chain.

(2) If the product costs and the customization level are high, in the decentralized Bertrand supply chain, it is profitable to the traditional manufacturer but not profitable to the logistics vendor. In the decentralized Stackelberg supply chain, depending on different TM product costs, the impacts of the strategy on the traditional manufacturer and the logistics vendor are different. However, there exists a situation where the 3DP product costs are sufficiently low, and both the traditional manufacturer and the logistics vendor can make more profit. The integrated supply chain can also share the profits of this strategy when the costs of the 3DP product are low.

Table 19 Maximized Profit: Comparison by TM Product Cost – TM3DL and TM3DM

Low	Medium	High
		
		
		



	TM Product			3DP Product		Delivery
	F_M	V_M	α	F_{3D}	V_{3D}	c_L
Low	-	-	0.1	0.1	0.03	0.01
Medium	-	-	0.2	0.3	0.3	0.01
High	-	-	0.3	0.6	0.35	0.01

Therefore, according to above table, on the low or medium supply chain setting, if the traditional manufacturer starts to engage in 3DP, it is profitable to the traditional manufacturer but not to the logistics vendor. This is because the traditional manufacturer can gain one more profit stream whilst the logistics vendor loses revenue from the 3DP product. For the integrated supply chain, in general, because the logistics vendor uses a high-price regime to maximize profits, after the traditional manufacturer starts to offer a 3DP product, the actual 3DP product sales shrink. Therefore, the integrated supply chain cannot generate more profit.

In the decentralized Bertrand supply chain on the high setting, it is profitable to the traditional manufacturer but not to the logistics vendor for the same reason. However, under the decentralized Stackelberg supply chain, there are four different situations, depending on the costs of the TM product (Figure 2). a) If the TM costs are sufficiently low (Region I), both the traditional manufacturer and the logistics vendor can gain more profits, because under this scenario, the 3DP product price is higher than that of the logistics vendor's 3DP product, and with the lower TM product cost, more price-sensitive consumers choose the TM product. Therefore, the traditional manufacturer can generate more profits on the TM product and the logistics vendor can also obtain more profits on the goods delivery service. b) If the costs of the TM product are located in Region II, the traditional manufacturer cannot make more profit on TM product sales because of the low-pricing strategy. However, the logistics vendor can still derive more profits from the logistics service. c) If the costs of the TM product are in Region III, the traditional manufacturer and the logistics vendor are better off with this strategy. As for the traditional manufacturer, the profits generated from the TM and the 3DP product are more than the profits s/he can obtain by operating only the TM product. And the logistics vendor can also gain more profits on product delivery. d) When the cost of the TM product is high, the new high-price 3DP product can help the traditional manufacturer make more profit, but the logistics vendor loses the profit on the 3DP product sales. As for the integrated supply chain, only if the costs of the TM product are sufficiently low can the system generate more profit on the TM and 3DP product sales. Otherwise, the new 3DP product cannot help the supply chain to obtain more profit.

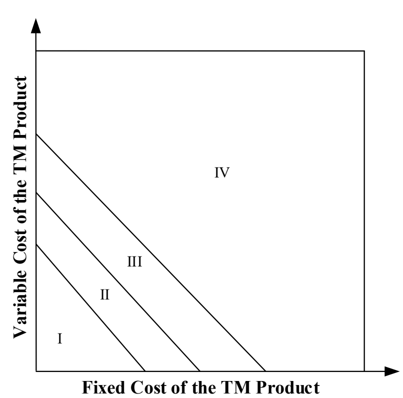


Figure 2 Comparison of the Profit by TM Product Costs – TM3DL and TM3DM

The Impact of the 3DP Product Costs

PROPOSITION *20.* *If the traditional manufacturer tries to offer a TM and 3DP product simultaneously,*

(1) In the decentralized Bertrand supply chain, no matter the 3DP product costs, the traditional manufacturer is better off operating the 3DP product, but it has a negative impact on the logistics vendor's profitability.

(2) In the decentralized Stackelberg supply chain, the traditional manufacturer can also obtain more profits by this strategy, whilst the logistics vender does not always lose profits. The logistics vendor cannot gain more profits if the 3DP product's variable cost is sufficiently low or the fixed cost of the 3DP product is extremely high.

(3) As for the integrated supply chain, it can also gain more profits if the costs of the 3DP product are high; otherwise, this strategy is not profitable to the supply chain.

As seen in table below, in the decentralized Bertrand supply chain, as long as the traditional manufacturer starts to operate the 3DP product on his/her own, s/he can generate more profits. The reason behind this is quite clear; the traditional manufacturer can generate profits from not only the TM product but also the new 3DP product. And the high 3DP product price helps to lead more price-sensitive consumers to buy the low-price TM product. In the decentralized Stackelberg supply chain, the traditional manufacturer can still make more profit, either from the new 3DP product or the increased TM product sales, depending on the cost of the 3DP product. At the same time, the conclusion that the logistics vendor instead loses profits does not always hold. a) The logistics vendor only loses profits if the variable cost of the 3DP product is sufficiently low, in which case there are more customization-sensitive consumers who choose the 3DP product. And the traditional manufacturer's 3DP product price is higher than that of the logistics vendor's 3DP product. Therefore, fewer consumers buy the traditional manufacturer's 3DP product, and the logistics vendor not only loses the profit on the 3DP product sales but also loses the profit on the goods delivery service. b) If the fixed cost of the 3DP product is extremely high, which means the overall cost of the 3DP product is at a high level, fewer consumers buy the 3DP product. After the traditional manufacturer starts to operate the 3DP product, the logistics vendor loses the profits on the 3DP product sales. As for the integrated supply chain, if the 3DP product costs are high, after the traditional manufacturer adopts a 3DP product, the logistics vendor uses a low-price regime on the logistics delivery service for the purpose of lowering the product price to lead to increased delivery service requirements. Therefore, the supply chain can benefit from the increased sales of the TM and the 3DP product.

Table 20 Maximized Profit: Comparison by 3DP Product Cost – TM3DL and TM3DM

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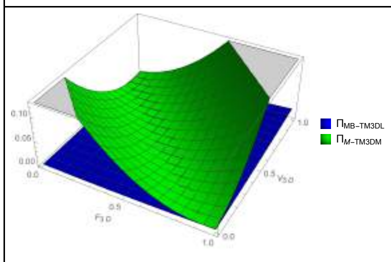
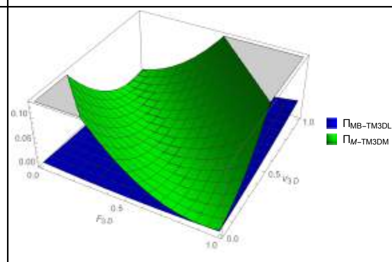
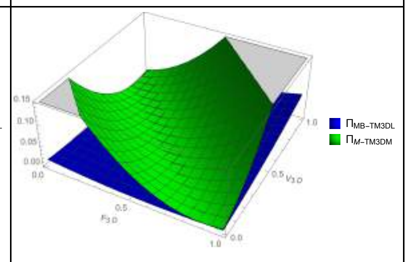
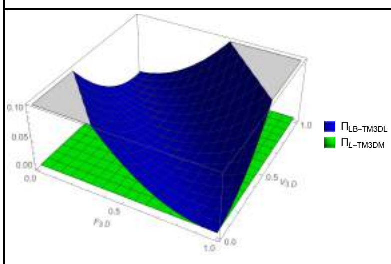
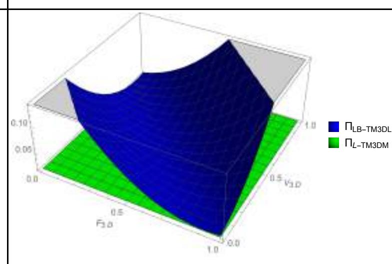
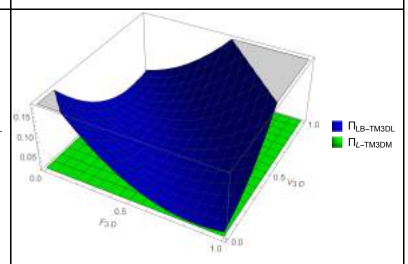
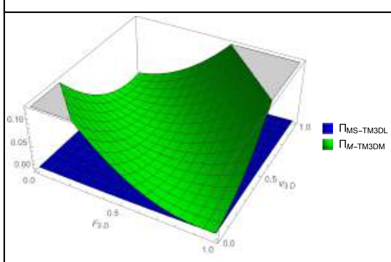
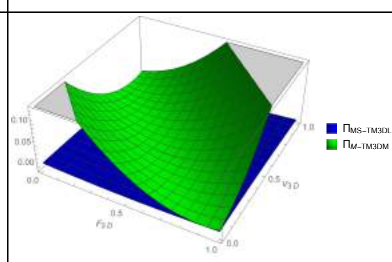
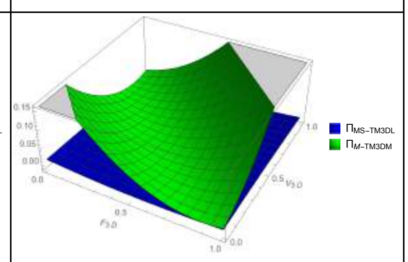
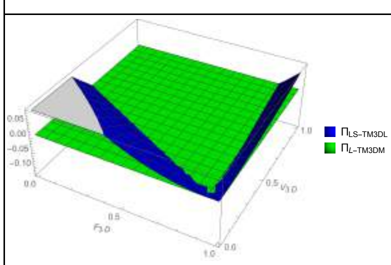
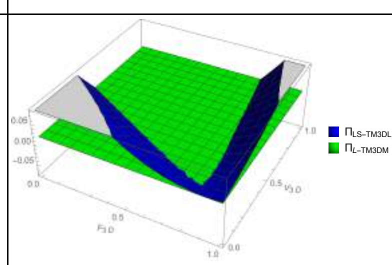
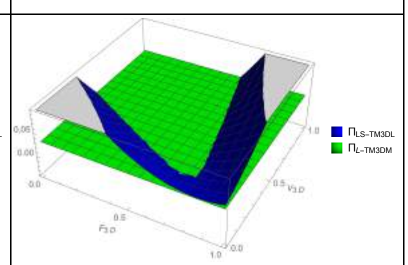
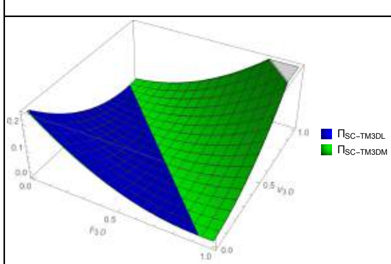
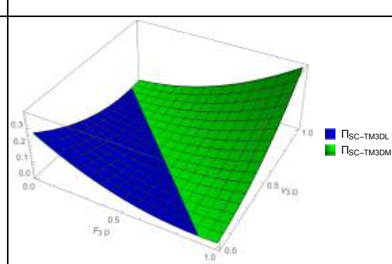
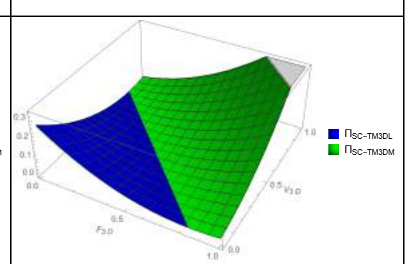
		
		
		
		
		

	TM Product			3DP Product		Delivery
	F_M	V_M	α	F_{3D}	V_{3D}	c_L
Low	0.01	0.01	0.1	-	-	0.01
Medium	0.05	0.05	0.2	-	-	0.01
High	0.1	0.08	0.3	-	-	0.01

The Impact of the Logistics Delivery Cost

PROPOSITION ***21.*** *If the traditional manufacturer tries to offer a TM and 3DP product at the same time,*

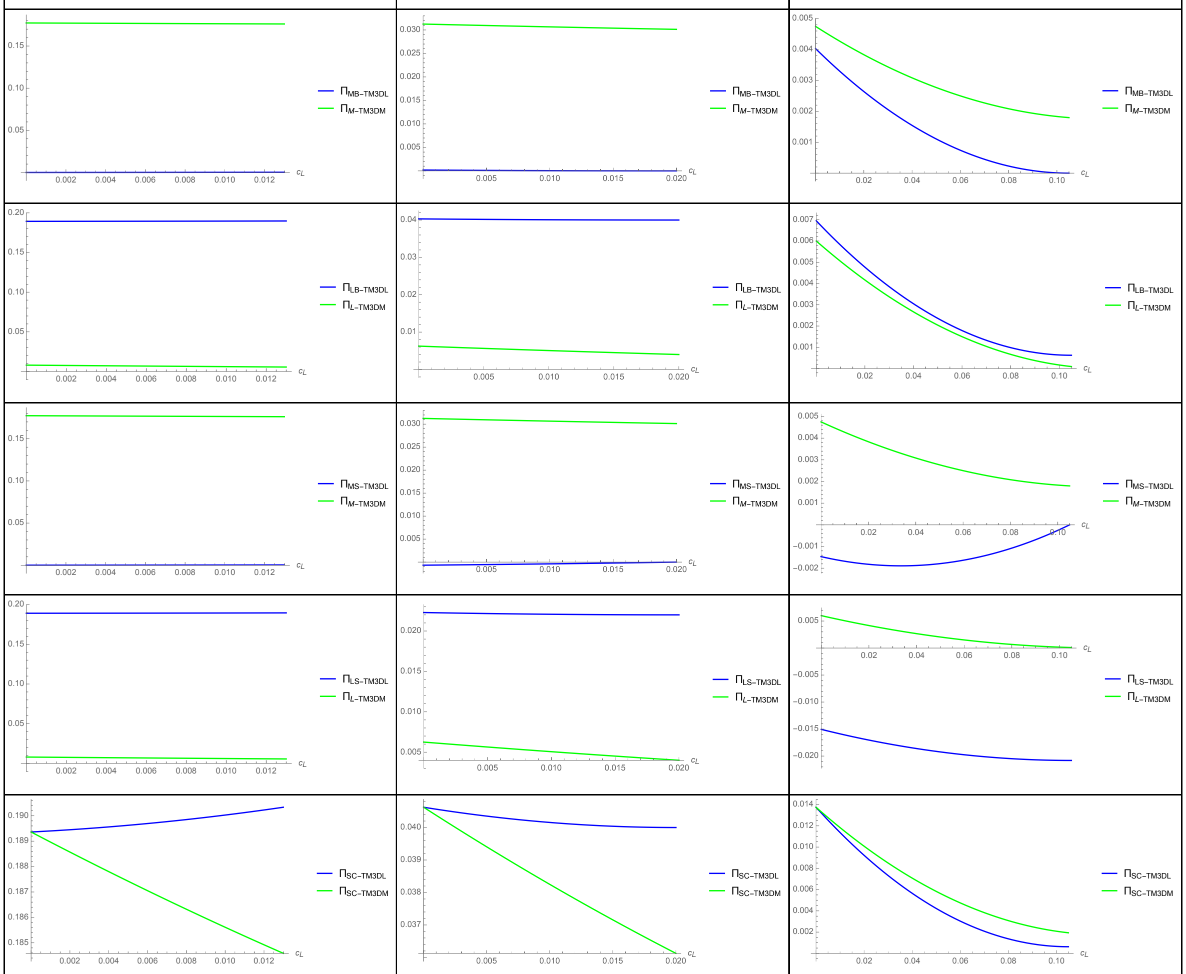
(1) In the supply chain with the low/medium cost structure and low/medium TM product customization level, it is always profitable to the traditional manufacturer but not profitable to the logistics vendor in the decentralized supply chain. The integrated supply chain cannot gain more profits.

(2) If the product costs are high and the TM product customization level is located in the high region, this strategy is profitable to the traditional manufacturer but not profitable to the logistics vendor in the decentralized Bertrand supply chain. However, in the decentralized Stackelberg supply chain, both parties can always gain more profits. And the integrated supply chain can also attain more profit under this scenario.

From this proposition, we can see that no matter the logistics delivery cost, on the low or medium supply chain setting, the new strategy can help the traditional manufacturer generate more profits either from the new 3DP product or the increased TM product sales (Table 21). Although the logistics vendor might make more profit on the delivery service, s/he still loses more on the 3DP product. Therefore, from the perspective of the integrated supply chain, it is not a profitable strategy in terms of total product sales. But this strategy is a triple-win strategy under the Stackelberg supply chain. Under the TM3DL model, the logistics vendor sets the price of the 3DP product after s/he receives the TM product price. However, in the TM3DM model, the manufacturer decides the price of both products at the same time, and so the traditional manufacturer can use the best price for maximizing profit. And under this scenario, the logistics vendor's profits only depend on goods delivery, so s/he uses a high price regime to increase the margin on the delivery service. As a result, both parties can enjoy the benefits of this strategy and even the integrated supply chain can achieve better profitability on product sales.

Table 21 Maximized Profit: Comparison by Logistics Delivery Cost – TM3DL and TM3DM

Low	Medium	High



	TM Product			3DP Product		Delivery
	F_M	V_M	α	F_{3D}	V_{3D}	c_L
Low	0.01	0.01	0.1	0.1	0.03	0.01
Medium	0.05	0.05	0.2	0.3	0.3	0.01
High	0.1	0.08	0.3	0.6	0.35	0.01

The Impact of the TM Product Customization Level

PROPOSITION 22. *If the traditional manufacturer tries to offer a TM and 3DP product at the same time,*

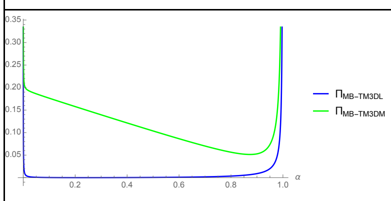
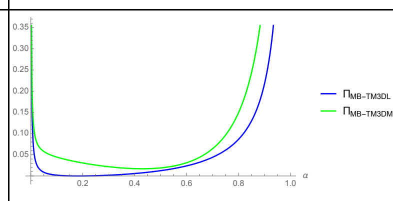
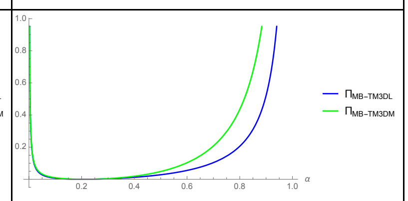
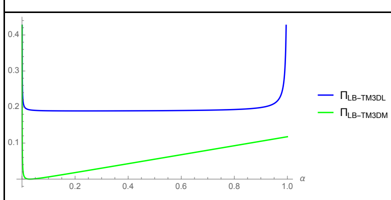
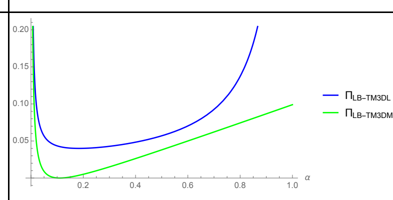
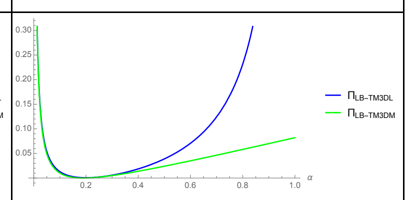
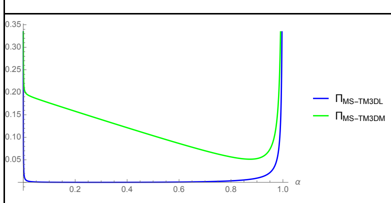
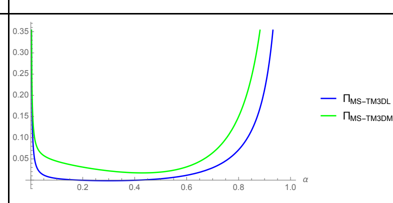
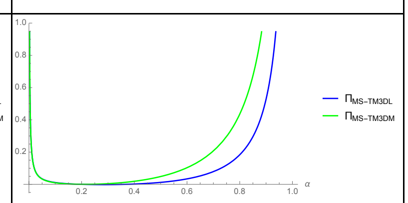
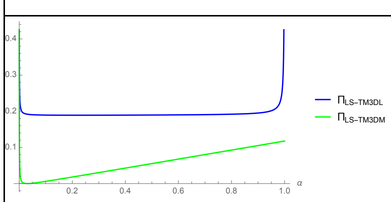
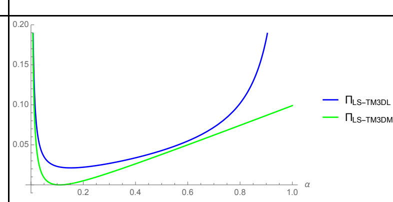
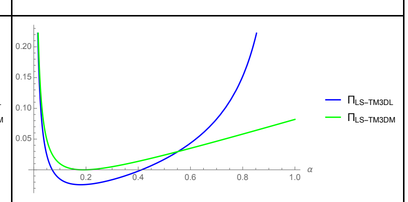
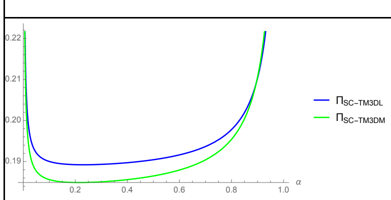
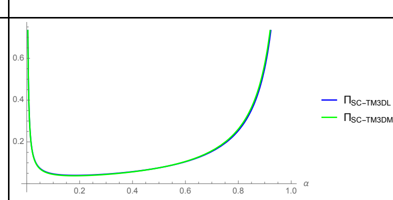
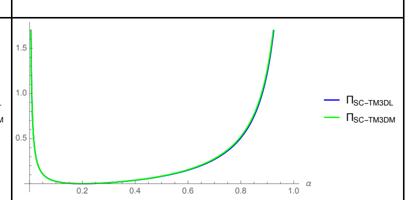
(1) In the low cost structure supply chain, it is always profitable to the traditional manufacturer but not profitable to the logistics vendor in the decentralized supply chain. The integrated supply chain cannot gain more profits.

(2) With the medium cost structure, in the decentralized supply chain, it is always profitable to the traditional manufacturer but not profitable to the logistics vendor. The integrated supply chain can gain more profits if the TM product customization level is high.

(3) If the product costs are high and the TM product customization level is in the high region, this strategy is profitable to the traditional manufacturer and not profitable to the logistics vendor in the decentralized Bertrand supply chain if the TM product customization level is high. Otherwise, there is no difference. However, in the decentralized Stackelberg supply chain, if the TM product customization level is high, it is also profitable to the traditional manufacturer but not profitable to the logistics vendor. However, when the TM product customization level is low, there is no difference to the traditional manufacturer's profit after s/he offers a 3DP product – but the logistics vendor can gain more profits. The integrated supply chain can gain more profits if the TM product customization level is high.

This proposition indicates that under the low-cost supply chain structure, the new high-price 3DP product helps the traditional manufacturer gain more price-sensitive consumers for the TM product (Table 22). Therefore, the traditional manufacturer can make more profit on the increased TM product sales. Due to the profit lost on the 3DP product, although the logistics vendor gains more business for the delivery service, this strategy still has a negative impact on his/her profitability. As for the integrated supply chain, the loss due to the shrunken 3DP product sales has a negative impact on its overall profitability. In the medium cost structure supply chain, the impacts on the traditional manufacturer's profitability and the logistics vendor's profitability are the same. However, for the integrated supply chain, if the TM product customization level is high, the 3DP product can increase the market demand for the TM and the 3DP product, and therefore the integrated supply chain can gain more profits. In the high cost decentralized Bertrand supply chain, if the customization level of the TM product is high, the new 3DP product helps the TM product to gain more price-sensitive consumers, and therefore the traditional manufacturer can obtain more profits. However, the logistics vendor loses 3DP product revenue at the same time. In the decentralized Stackelberg supply chain, when the TM product customization level is sufficiently low, the logistics vendor can gain more profits from the delivery service. As for the integrated supply chain, only if the TM product customization level is high can the supply chain benefit from the new TM3DM model due to the increased TM product sales.

Table 22 Maximized Supply Chain Profit: Comparison by TM Product Customization –TM3DL and TM3DM

Low	Medium	High
		
		
		
		
		

	TM Product	3DP Product	Delivery

	F_M	V_M	α	F_{3D}	V_{3D}	c_L
Low	0.01	0.01	-	0.1	0.03	0.01
Medium	0.05	0.05	-	0.3	0.3	0.01
High	0.1	0.08	-	0.6	0.35	0.01

3DM Model

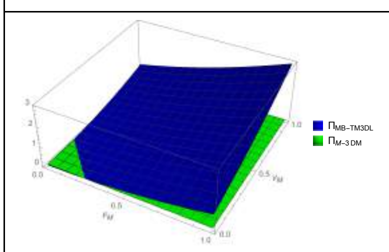
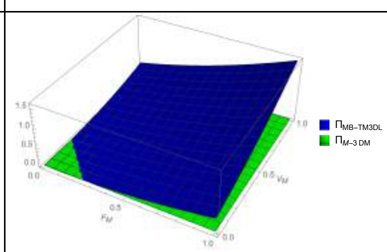
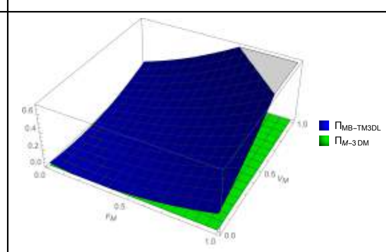
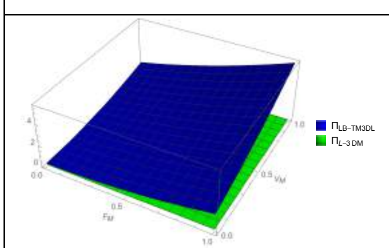
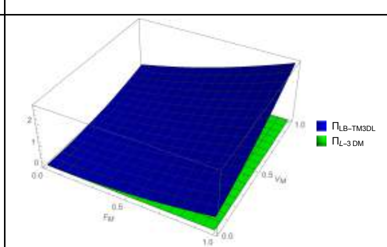
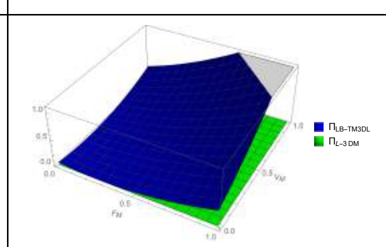
The Impact of the TM Product Costs

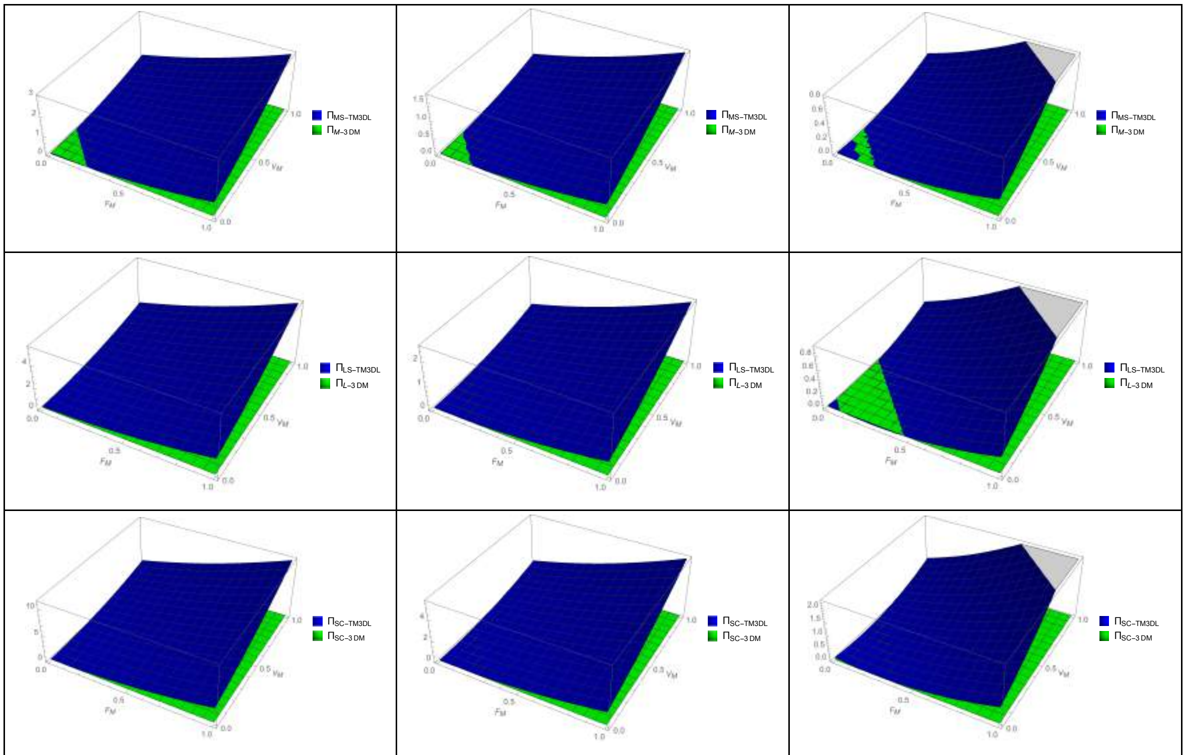
PROPOSITION ***23.*** *If the traditional manufacturer tries to use a 3DP product to fully replace the TM product,*

(1) For the low/medium cost structure and low/medium product customization supply chain, overall, the traditional manufacturer and the logistics vendor cannot generate more profits in the decentralized supply chain. However, if the costs of the TM product are sufficiently low, the traditional manufacturer can still make more profits. The integrated supply chain cannot benefit from this 3DP-only supply chain.

(2) If the product costs and the customization level are high, in the decentralized Bertrand supply chain, it is profitable to the traditional manufacturer and the logistics vendor. In the decentralized Stackelberg supply chain, depending on different TM product costs, the impacts of the strategy on the traditional manufacturer and the logistics vendor are different. There exists a scenario where both party can generate more profits. However, for the integrated supply chain, it is not a beneficial strategy at all.

Table 23 Maximized Profit: Comparison by TM Product Cost – TM3DL and 3DM

Low	Medium	High
		
		



	TM Product			3DP Product		Delivery
	F_M	V_M	α	F_{3D}	V_{3D}	c_L
Low	-	-	0.1	0.1	0.03	0.01
Medium	-	-	0.2	0.3	0.3	0.01
High	-	-	0.3	0.6	0.35	0.01

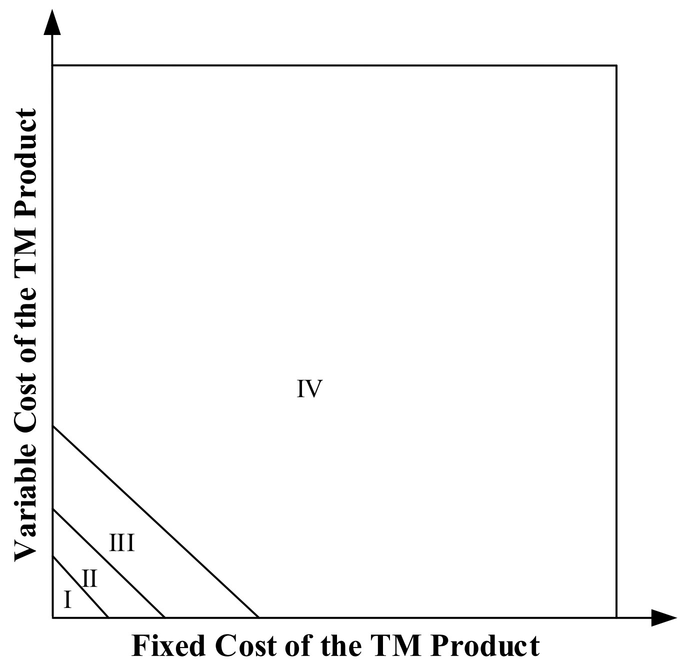


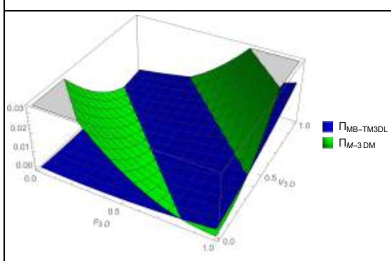
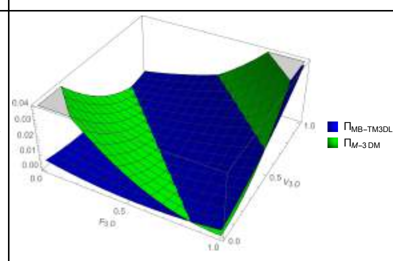
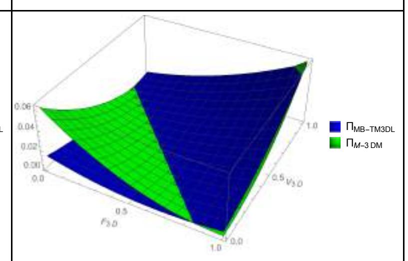
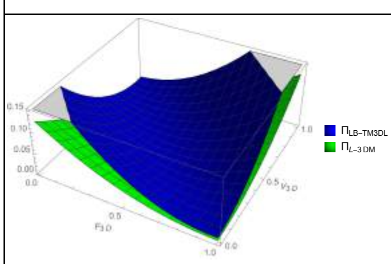
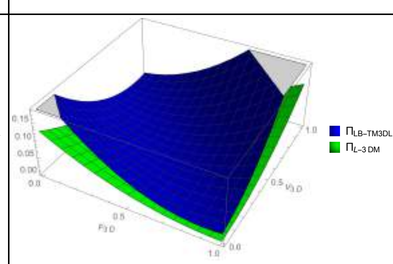
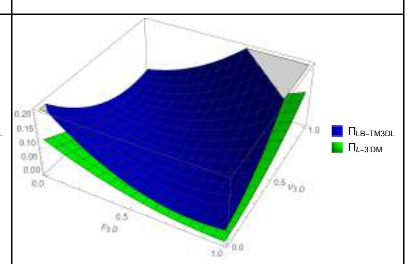
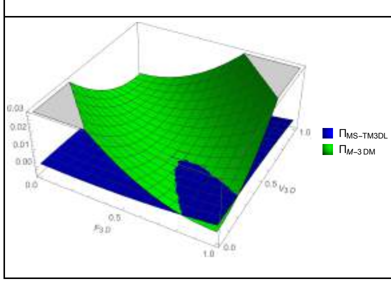
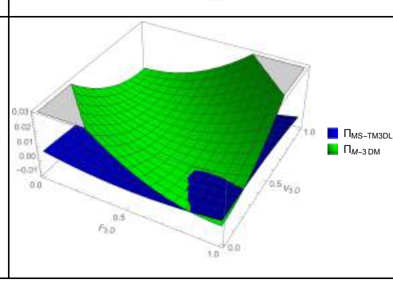
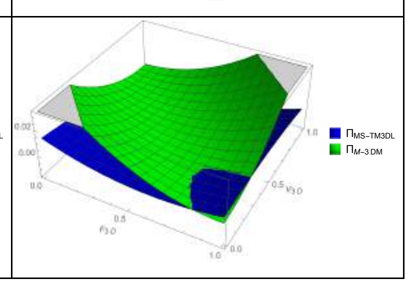
Figure 3 Profit Comparison by TM Product Costs – TM3DL vs 3DM

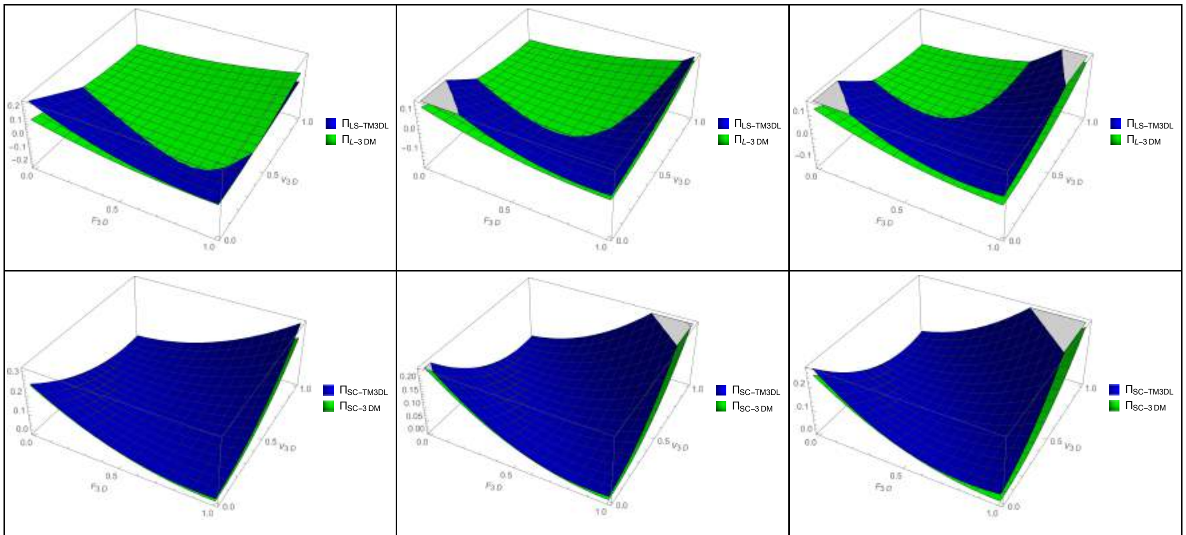
As shown in Table 23, it is obvious that under the low and medium supply chain setting, if the costs of the TM product are sufficiently low, it is profitable to the traditional manufacturer to fully replace the TM product with the 3DP product. This is because the traditional manufacturer can make more profits on the 3DP product sales, even though the overall amount of sales reduces. Under the high supply chain setting (Figure 3), if the TM product cost is located in Region I, and if the costs of the TM product are low, it is not profitable to either the traditional manufacturer or the logistics vendor because of the loss on the TM product sales. However, if the cost of the 3DP product is located in Region II, after the traditional manufacturer exclusively offers the 3DP product, the traditional manufacturer can make more profits due to the high margin on the 3DP product, whilst the logistics vendor can make more profits due to the high delivery service price. If the costs of the TM product are located in Region III, the traditional manufacturer loses profits on the low-price TM product sales, but the logistics vendor can still gain more profits on the high price delivery service. If the TM product costs are much higher, neither party can obtain the profit because of the shrunken product sales. At the integrated supply chain level, profit is lost because of the loss of TM product sales.

The Impact of the 3DP Product Costs

PROPOSITION ***24.*** *If the traditional manufacturer tries to use a 3DP product to fully replace the TM product, in the Bertrand supply chain, the traditional manufacturer can gain more profits if the 3DP product costs are sufficiently low or high. However, if the TM product cost is high, the traditional manufacturer can only make more profits if the 3DP product costs are low, whilst the logistics vendor cannot make more profits at all. In the Stackelberg supply chain, if the 3DP product costs are sufficiently high and the variable cost is low, the traditional manufacturer cannot gain more profits; otherwise, this strategy can bring more profits to the traditional manufacturer. The logistics vendor can also gain more profits if the variable cost of the 3DP product is high. Overall, the integrated supply chain cannot gain any profits.*

Table 24 Maximized Profit: Comparison by 3DP Product Cost – TM3DL and 3DM

Low	Medium	High
		
		
		



	TM Product			3DP Product		Delivery
	F_M	V_M	α	F_{3D}	V_{3D}	c_L
Low	0.01	0.01	0.1	-	-	0.01
Medium	0.05	0.05	0.2	-	-	0.01
High	0.1	0.08	0.3	-	-	0.01

According to above table, in the supply chain on the low/medium setting, both the traditional manufacturer and the logistics vendor can gain more profits if the 3DP product is priced low (leading to more 3DP product sales) or the 3DP product is priced high (yielding a high 3DP product margin). However, if the TM product costs are high, the traditional manufacturer can only make more profits if the 3DP product costs are low (yielding a high 3DP product margin). In addition, the logistics vendor always loses the profits on product delivery and 3DP product sales. In the Stackelberg supply chain, if the fixed 3DP product cost is high and its variable cost is low, it is not easy for the traditional manufacturer to invest in the 3DP product business, and therefore the traditional manufacturer cannot make more profits. Otherwise, the traditional manufacturer can generate more profit by offering only a 3DP product because of the high price margin. Meanwhile, if the 3DP product's variable cost is low, the logistics vendor cannot make more profit because of the low margin on the 3DP product. As for the integrated supply chain, only offering a 3DP product has a negative impact on product sales, and thus the supply chain's profitability does not show any improvement.

The Impact of the Logistics Delivery Cost

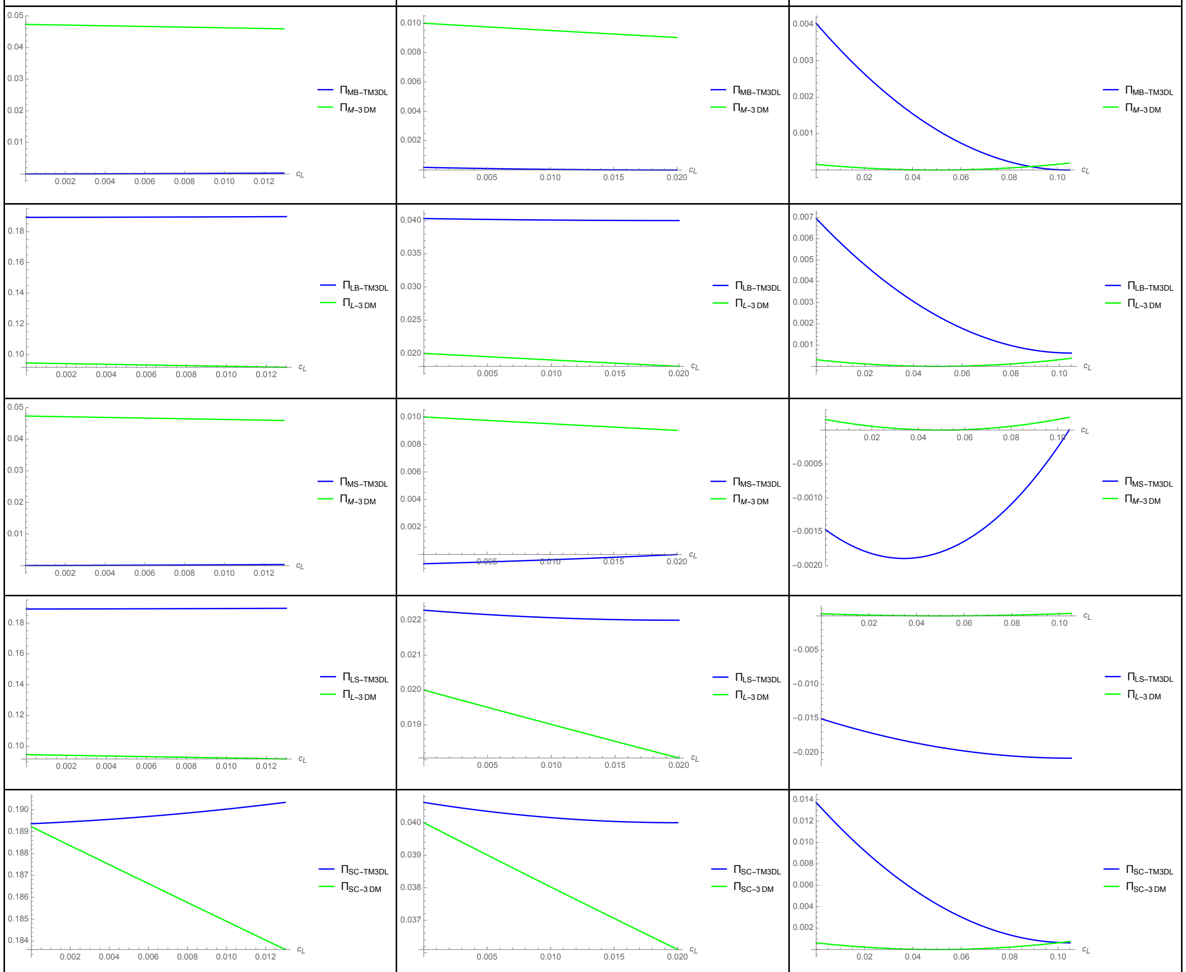
PROPOSITION 25. *If the traditional manufacturer tries to use a 3DP product to fully replace the TM product,*

(1) *In the supply chain with the low/medium cost structure and low/medium TM product customization level, it is always profitable to the traditional manufacturer but not profitable to the logistics vendor in the decentralized supply chain. The integrated supply chain cannot gain more profits.*
(2) *If the product costs are high and the TM product customization level is located in a high region, then in the decentralized Bertrand supply chain, this strategy is profitable to the traditional manufacturer but not profitable to the logistics vendor. However, under the decentralized Stackelberg supply chain, both parties can always gain more profits. And the integrated supply chain can also make more profits, except when the TM product customization level is extremely high.*

Basically, the insights from this proposition are straightforward as shown in Table 25. The only interesting finding is that when the logistics delivery cost is high, in the supply chain with high TM product costs and a high TM product customization level, the integrated supply can also enjoy more profits because in the TM3DL model, the integrated supply chain also cannot achieve good financial performance. Therefore, after the traditional manufacturer starts to sell only the 3DP product, the integrated supply chain can also enjoy the 3DP product's high margin.

Table 25 Maximized Profit: Comparison by Logistics Delivery Cost – TM3DL and 3DM

Low	Medium	High



	TM Product			3DP Product		Delivery
	F_M	V_M	α	F_{3D}	V_{3D}	c_L
Low	0.01	0.01	0.1	0.1	0.03	-
Medium	0.05	0.05	0.2	0.3	0.3	-
High	0.1	0.08	0.3	0.6	0.35	-

The Impact of the TM Product Customization Level

PROPOSITION 26. *If the traditional manufacturer tries to use a 3DP product to fully replace the TM product,*

(1) In the supply chain with the low-cost structure and low TM product customization level, it is profitable to the traditional manufacturer. Only when the TM product customization level is extremely high is this strategy not profitable to the traditional manufacturer. The logistics vendor cannot gain more profits under the decentralized supply chain. The integrated supply chain cannot generate more profit.

(2) In the supply chain with the medium cost structure and medium TM product customization level, if the TM product customization level is extremely low or high, the traditional manufacturer cannot make more profit. Otherwise, this strategy can bring more profits to the traditional manufacturer. The logistics vendor cannot make more profits in the decentralized supply chain. The integrated supply chain cannot generate more profit.

(3) If the product costs are high and the TM product customization level is located in a high region, in the decentralized Bertrand supply chain, neither the traditional manufacturer nor the logistics vendor can make more profits. In the decentralized Stackelberg supply chain, the traditional manufacturer cannot gain more profits. As for the logistics vendor, s/he fails to make more profits only if the TM product customization level is located in an extremely low or high region. The integrated supply chain cannot attain more profits under this supply chain structure.

As seen in below table, in the low-cost supply chain, if the TM product customization level is high, then if the traditional manufacturer starts to engage in the 3DP business by himself/herself, it hurts the TM product business. Thus, it is not profitable to the traditional manufacturer to use this strategy. However, if the TM product customization level is low, the new 3DP product can lead more customization-sensitive consumers to buy the 3DP product. Accordingly, the traditional manufacturer can generate more profit. However, as for the integrated supply chain, it cannot attain more profits due to the shrunken TM product sales.

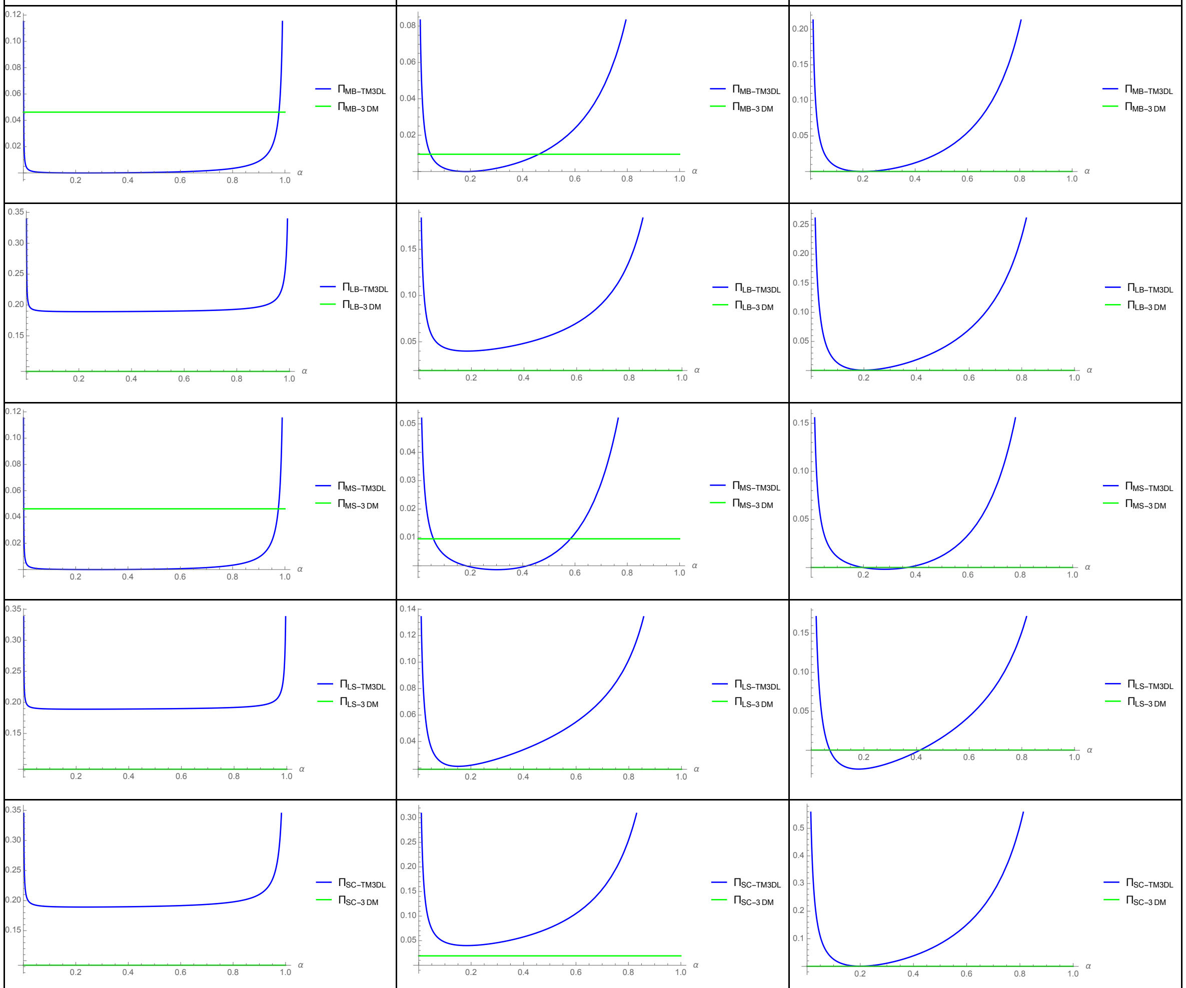
In the medium cost supply chain, if the TM product customization level is low, operating a high customization level 3DP product means the traditional manufacturer has to use a low-price strategy, and so it has a negative impact on the TM product business. Under this scenario, it is not profitable to the traditional manufacturer. However, if the TM product customization level is high, the new 3DP product also has a negative impact on the TM product due to the cannibalization effect. Meanwhile, the logistics vendor loses profits on the 3DP product business, although the profits on goods delivery slightly increase. As for the integrated supply chain, after the traditional manufacturer uses the 3DP product strategy, it cannot attain more profits because of the shrunken sales of the TM product.

In the high cost supply chain, where a decentralized Bertrand supply chain is used, it is not profitable to either the traditional manufacturer or the logistics vendor because of the low TM product sales. In the Stackelberg supply chain, if the TM product customization level is low, the new high-price 3DP product pushes the traditional manufacturer to raise the TM product price to yield a higher margin, and therefore fewer price-sensitive consumers buy the TM product. Consequently, the logistics vendor loses profit from the TM product delivery. If the TM product customization level is high, the traditional manufacturer uses a low-price strategy on the TM product for the purpose of increasing product sales, but due the loss on the 3DP product sale, the logistics vendor cannot attain better financial performance. As for the traditional manufacturer, after s/he adopts the 3DP product, it has a negative cannibalization effect on the TM product sales. Therefore, it is not profitable to the traditional manufacturer. For the integrated supply chain, the shrunken sales of the TM product and the 3DP product cause worse overall profitability in the system.

Therefore, under the low and medium supply chain setting, a sensible strategy is to give up the traditional manufacturing technology and fully use 3DP manufacturing.

Table 26 Maximized Supply Chain Profit: Comparison by TM Product Customization – TM3DL and 3DM

Low	Medium	High



	TM Product			3DP Product		Delivery
	F_M	V_M	α	F_{3D}	V_{3D}	c_L
Low	0.01	0.01	-	0.1	0.03	0.01
Medium	0.05	0.05	-	0.3	0.3	0.01
High	0.1	0.08	-	0.6	0.35	0.01

Appendix D: Proofs of Chapter 6

Proof of *PROPOSITION* 6-1.

Under decentralized supply chain, accordingly to Equation (6.1), the first-order-conditions and the second-order-conditions of $\prod_X M(p_M, p_{3D})$ by p_M and p_{3D} are

$$\begin{cases} \dfrac{\partial \prod_X M(p_M, p_{3D})}{\partial p_M} = \dfrac{\alpha\delta c_{3D} - c_M - 2\alpha\delta p_{3D} + (-1+\alpha\delta)p_L + 2p_M}{(-1+\alpha\delta)\alpha\delta} \\ \dfrac{\partial \prod_X M(p_M, p_{3D})}{\partial p_{3D}} = \dfrac{-1+\alpha\delta - c_{3D} + c_M + 2p_{3D} - 2p_M}{-1+\alpha\delta} \end{cases}$$

$$\begin{cases} \dfrac{\partial \prod_X^2 M(p_M, p_{3D})}{\partial p_M^2} = \dfrac{2}{(-1+\alpha\delta)\alpha\delta} < 0 \\ \dfrac{\partial \prod_X^2 M(p_M, p_{3D})}{\partial p_{3D}^2} = \dfrac{2}{-1+\alpha\delta} < 0 \\ \dfrac{\partial \prod_X^2 M(p_M, p_{3D})}{\partial p_M \partial p_{3D}} = -\dfrac{2}{-1+\alpha\delta} > 0 \\ \dfrac{\partial \prod_X^2 M(p_M, p_{3D})}{\partial p_{3D} \partial p_M} = -\dfrac{2}{-1+\alpha\delta} > 0 \end{cases}$$

So, the determinant of the Hessian Matrix can be written as

$$H = \begin{vmatrix} \dfrac{2}{(-1+\alpha\delta)\alpha\delta} & -\dfrac{2}{-1+\alpha\delta} \\ -\dfrac{2}{-1+\alpha\delta} & \dfrac{2}{-1+\alpha\delta} \end{vmatrix} = \frac{2}{(-1+\alpha\delta)\alpha\delta} \times \left(\frac{2}{-1+\alpha\delta}\right) - \left(-\frac{2}{-1+\alpha\delta}\right)^2$$

$$= \frac{4}{\alpha\delta(1-\alpha\delta)} > 0$$

Therefore, this Hessian Matrix is a negative-definite matrix, So, the solution to the first-order-conditions gives the unique maximizer.

$$\begin{cases} \dfrac{\partial \prod_X M(p_M, p_{3D})}{\partial p_M} = \dfrac{\alpha\delta c_{3D} - c_M - 2\alpha\delta p_{3D} + (-1+\alpha\delta)p_L + 2p_M}{(-1+\alpha\delta)\alpha\delta} = 0 \\ \dfrac{\partial \prod_X M(p_M, p_{3D})}{\partial p_{3D}} = \dfrac{-1+\alpha\delta - c_{3D} + c_M + 2p_{3D} - 2p_M}{-1+\alpha\delta} = 0 \end{cases}$$

$$\begin{cases} p_M^* = \dfrac{1}{2}(\alpha\delta + c_M + p_L) \\ p_{3D}^* = \dfrac{1}{2}(1 + c_{3D} + p_L) \end{cases}$$

Then, the logistics vendor's profit function (6.2) can be updated as

$$\prod_X L(p_L) = \frac{(c_L - p_L)(-\alpha\delta + c_M + p_L)}{2\alpha\delta} = \frac{-\alpha\delta c_L + c_L c_M}{2\alpha\delta} + \frac{(\alpha\delta + c_L - c_M)p_L}{2\alpha\delta} - \frac{p_L^2}{2\alpha\delta}$$

which is convex in p_L, so the first-order-conditions gives the maximum profit.

$$\frac{\partial \prod_X L(p_L)}{\partial p_L} = \frac{\alpha\delta + c_L - c_M - 2p_L}{2\alpha\delta} = 0$$

$$p_L^* = \frac{1}{2}(\alpha\delta + c_L - c_M)$$

The final optimal decisions are

$$p_L^* = \frac{1}{2}(\alpha\delta + c_L - c_M) \tag{6.10}$$

$$p_M^* = \frac{1}{4}(3\alpha\delta + c_L + c_M) \tag{6.11}$$

$$p_{3D}^* = \frac{1}{4}(2 + \alpha\delta + 2c_{3D} + c_L - c_M) \tag{6.12}$$

$$q_M^* = \frac{-2\alpha\delta c_{3D} - (-1 + \alpha\delta)(\alpha\delta + c_L) + (1 + \alpha\delta)c_M}{4(-1 + \alpha\delta)\alpha\delta} \tag{6.13}$$

$$q_{3D}^* = \frac{-1 + \alpha\delta + c_{3D} - c_M}{2(-1 + \alpha\delta)} \tag{6.14}$$

The maximized profits are

$$\begin{aligned}\prod\nolimits_X^* M(p_M, p_{3D}) = &-\frac{1}{16\alpha\delta(-1 + \alpha\delta)}(4\alpha\delta c_{3D}^2 + (-1 + \alpha\delta)(\alpha\delta(-4 + 3\alpha\delta) \\ &+ 2\alpha\delta c_L - c_L^2) - 2(-1 + \alpha\delta)(3\alpha\delta + c_L)c_M + (1 + 3\alpha\delta)c_M^2 \\ &- 8\alpha\delta c_{3D}(1 - \alpha\delta + c_M))\end{aligned} \tag{6.15}$$

$$\prod\nolimits_X^* L(p_L) = \frac{(-\alpha\delta + c_L + c_M)^2}{8\alpha\delta} \tag{6.16}$$

For the integrated supply chain, the first-order-conditions and the second-order-conditions of $\prod_X SC(p_M, p_{3D})$ by p_M and p_{3D} in Equation (6.3) are

$$\begin{cases}\dfrac{\partial \prod_X SC(p_M, p_{3D})}{\partial p_M} = \dfrac{\alpha\delta c_{3D} + (-1 + \alpha\delta)c_L - c_M - 2\alpha\delta p_{3D} + 2p_M}{(-1 + \alpha\delta)\alpha\delta} \\ \dfrac{\partial \prod_X SC(p_M, p_{3D})}{\partial p_{3D}} = \dfrac{-1 + \alpha\delta - c_{3D} + c_M + 2p_{3D} - 2p_M}{-1 + \alpha\delta}\end{cases}$$

$$\begin{cases} \dfrac{\partial \prod_X^2 SC(p_M, p_{3D})}{\partial p_M^2} = \dfrac{2}{(-1+\alpha\delta)\alpha\delta} < 0 \\ \dfrac{\partial \prod_X^2 SC(p_M, p_{3D})}{\partial p_{3D}^2} = \dfrac{2}{-1+\alpha\delta} < 0 \\ \dfrac{\partial \prod_X^2 SC(p_M, p_{3D})}{\partial p_M \partial p_{3D}} = -\dfrac{2}{-1+\alpha\delta} > 0 \\ \dfrac{\partial \prod_X^2 SC(p_M, p_{3D})}{\partial p_{3D} \partial p_M} = -\dfrac{2}{-1+\alpha\delta} > 0 \end{cases}$$

So, the determinant of the Hessian Matrix can be written as

$$H = \begin{vmatrix} \dfrac{2}{(-1+\alpha\delta)\alpha\delta} & -\dfrac{2}{-1+\alpha\delta} \\ -\dfrac{2}{-1+\alpha\delta} & \dfrac{2}{-1+\alpha\delta} \end{vmatrix} = \frac{2}{(-1+\alpha\delta)\alpha\delta} \times \left(\frac{2}{-1+\alpha\delta}\right) - \left(-\frac{2}{-1+\alpha\delta}\right)^2$$

$$= \frac{4}{\alpha\delta(1-\alpha\delta)} > 0$$

Therefore, this Hessian Matrix is a negative-definite matrix, the solution to the first-order-conditions gives the unique maximizer of $\prod_X SC(p_M, p_{3D})$.

$$\begin{cases} \dfrac{\partial \prod_X SC(p_M, p_{3D})}{\partial p_M} = \dfrac{\alpha\delta c_{3D} + (-1+\alpha\delta)c_L - c_M - 2\alpha\delta p_{3D} + 2p_M}{(-1+\alpha\delta)\alpha\delta} = 0 \\ \dfrac{\partial \prod_X SC(p_M, p_{3D})}{\partial p_{3D}} = \dfrac{-1+\alpha\delta - c_{3D} + c_M + 2p_{3D} - 2p_M}{-1+\alpha\delta} = 0 \end{cases}$$

$$p_M^* = \frac{1}{2}(\alpha\delta + c_L + c_M) \tag{6.17}$$

$$p_{3D}^* = \frac{1}{2}(1 + c_{3D} + c_L) \tag{6.18}$$

So,

$$q_M^* = \frac{c_L - \alpha\delta(c_{3D} + c_L) + c_M}{2(-1+\alpha\delta)\alpha\delta} \tag{6.19}$$

$$q_{3D}^* = \frac{-1+\alpha\delta + c_{3D} - c_M}{2(-1+\alpha\delta)} \tag{6.20}$$

$$\prod_{X}^{*} SC(p_M, p_{3D}) = \frac{1}{4(-1+\alpha\delta)\alpha\delta}(\alpha\delta(-1+\alpha\delta) - \alpha\delta c_{3D}^2 + (-1+\alpha\delta)c_L(-2\alpha\delta + c_L) + 2(-1+\alpha\delta)c_L c_M - c_M^2 + 2\alpha\delta c_{3D}(1-\alpha\delta+c_M)) \tag{6.21}$$

Proof of *PROPOSITION* 6-2. Under the decentralized supply chain, it is easy to find out that,

$$\frac{\partial p_L^*}{\partial c_M} = -\frac{1}{2} \quad \frac{\partial p_L^*}{\partial c_L} = \frac{1}{2} \quad \frac{\partial p_L^*}{\partial c_{3D}} = N/A \quad \frac{\partial q_M^*}{\partial c_M} = -\frac{1+\alpha\delta}{4\alpha\delta(1-\alpha\delta)} < 0 \quad \frac{\partial q_{3D}^*}{\partial c_M} = \frac{1}{2-2\alpha\delta} > 0$$

$$\frac{\partial p_M^*}{\partial c_M} = \frac{1}{4} \quad \frac{\partial p_M^*}{\partial c_L} = \frac{1}{4} \quad \frac{\partial p_M^*}{\partial c_{3D}} = N/A \quad \frac{\partial q_M^*}{\partial c_L} = -\frac{1}{4\alpha\delta} < 0 \quad \frac{\partial q_{3D}^*}{\partial c_L} = N/A$$

$$\frac{\partial p_{3D}^*}{\partial c_M} = -\frac{1}{4} \quad \frac{\partial p_{3D}^*}{\partial c_L} = \frac{1}{4} \quad \frac{\partial p_{3D}^*}{\partial c_{3D}} = \frac{1}{2} \quad \frac{\partial q_M^*}{\partial c_{3D}} = \frac{1}{2-2\alpha\delta} > 0 \quad \frac{\partial q_{3D}^*}{\partial c_{3D}} = \frac{1}{-2+2\alpha\delta} < 0$$

From Equation (6.15), it is easy to find out that

(1) $\prod_X^* M(p_M, p_{3D})$ is concave in c_M, therefore, when

$$\frac{\partial \prod_X^* M(p_M, p_{3D})}{\partial c_M} = \frac{4\alpha\delta c_{3D} + (-1+\alpha\delta)(3\alpha\delta + c_L) - (1+3\alpha\delta)c_M}{8\alpha\delta(-1+\alpha\delta)} = 0$$

$$c_M^* = \frac{4\alpha\delta c_{3D} + (-1+\alpha\delta)(3\alpha\delta + c_L)}{1+3\alpha\delta}$$

gives the unique minimum value. However, because $\alpha\delta c_{3D} > c_L + c_M$, therefore,

If $\frac{4\alpha\delta c_{3D}+(-1+\alpha\delta)(3\alpha\delta+c_L)}{1+3\alpha\delta} > \alpha\delta c_{3D} - c_L$, that is $\frac{3}{4}(-1+\alpha\delta)(-1+c_{3D}) < c_L < 1$ $\prod_X^* M(p_M, p_{3D})$ decreases in c_M;

If $\frac{4\alpha\delta c_{3D}+(-1+\alpha\delta)(3\alpha\delta+c_L)}{1+3\alpha\delta} < \alpha\delta c_{3D} - c_L$, that is $0 < c_L < \frac{3}{4}(-1+\alpha\delta)(-1+c_{3D})$, then,

i) when $0 < c_M < c_M^*$, $\prod_X^* M(p_M, p_{3D})$ decreases in c_M;
ii) when $c_M^* < c_M < 1$, $\prod_X^* M(p_M, p_{3D})$ increases in c_M.

(2) $\prod_X^* M(p_M, p_{3D})$ is concave in c_L, therefore, when

$$\frac{\partial \prod_X^* M(p_M, p_{3D})}{\partial c_L} = \frac{-\alpha\delta + c_L + c_M}{8\alpha\delta} = 0$$

$$c_L^* = \alpha\delta - c_M$$

gives the unique minimum value. Because $\alpha\delta c_{3D} > c_L + c_M$, therefore, $c_L^* > \alpha\delta c_{3D} - c_M$, $\prod_X^* M(p_M, p_{3D})$ decreases in c_L.

(3) $\prod_X^* M(p_M, p_{3D})$ is concave in c_{3D}, therefore, when

$$\frac{\partial \prod_X^* M(p_M, p_{3D})}{\partial c_{3D}} = \frac{1 - \alpha\delta - c_{3D} + c_M}{-2 + 2\alpha\delta} = 0$$

$$c_{3D}^* = 1 - \alpha\delta + c_M$$

gives the minimum value. However, because $\alpha\delta c_{3D} > c_L + c_M$, therefore,

If $1 - \alpha\delta + c_M < \frac{c_L + c_M}{\alpha\delta}$, that is $\frac{c_M}{\delta} < \alpha < 1$ and $-(-1 + \alpha\delta)(\alpha\delta - c_M) < c_L < \alpha\delta - c_M$ $\prod_X^* M(p_M, p_{3D})$ increases in c_{3D};

If $1 - \alpha\delta + c_M > \frac{c_L + c_M}{\alpha\delta}$, that is $0 < c_L < -(-1 + \alpha\delta)(\alpha\delta - c_M)$, then,

i) when $\frac{c_L + c_M}{\alpha\delta} < c_{3D} < c_{3D}^*$, $\prod_X^* M(p_M, p_{3D})$ decreases in c_{3D};
ii) when $c_{3D}^* < c_{3D} < 1$, $\prod_X^* M(p_M, p_{3D})$ increases in c_{3D}.

In detail,

For the logistics vendor's maximized profit (Equation (6.16)) under the decentralized supply chain,

(1) $\prod_X^* L(p_L)$ is concave in c_M, therefore, when

$$\frac{\partial \prod_X^* L(p_L)}{\partial c_M} = \frac{-\alpha\delta + c_L + c_M}{4\alpha\delta} = 0$$

$$c_M^* = \alpha\delta - c_L$$

gives the unique minimum value. Because $\alpha\delta c_{3D} > c_L + c_M$, therefore, $\prod_X^* L(p_L)$ decreases in c_M.

(2) $\prod_X^* L(p_L)$ is concave in c_L, therefore, when

$$\frac{\partial \prod_X^* L(p_L)}{\partial c_L} = \frac{-\alpha\delta + c_L + c_M}{4\alpha\delta} = 0$$

$$c_L^* = \alpha\delta - c_M$$

gives the unique minimum value. Because $\alpha\delta c_{3D} > c_L + c_M$, therefore, $\prod_X^* L(p_L)$ decreases in c_L.

Proof of *PROPOSITION* 6-3. Under the integrated supply chain,

$$\frac{\partial p_M^*}{\partial c_M} = \frac{1}{2} \quad \frac{\partial p_{3D}^*}{\partial c_M} = N/A \quad \frac{\partial q_M^*}{\partial c_M} = -\frac{1}{2\alpha\delta(1-\alpha\delta)} < 0 \quad \frac{\partial q_{3D}^*}{\partial c_M} = \frac{1}{2-2\alpha\delta} > 0$$

$$\frac{\partial p_M^*}{\partial c_L} = \frac{1}{2} \quad \frac{\partial p_{3D}^*}{\partial c_L} = \frac{1}{2} \quad \frac{\partial q_M^*}{\partial c_L} = -\frac{1}{2\alpha\delta} < 0 \quad \frac{\partial q_{3D}^*}{\partial c_L} = N/A$$

$$\frac{\partial p_M^*}{\partial c_{3D}} = N/A \quad \frac{\partial p_{3D}^*}{\partial c_{3D}} = \frac{1}{2} \quad \frac{\partial q_M^*}{\partial c_{3D}} = \frac{1}{2-2\alpha\delta} > 0 \quad \frac{\partial q_{3D}^*}{\partial c_{3D}} = \frac{1}{-2+2\alpha\delta} < 0$$

For the maximized supply chain profit (Equation (6.21)),

(1) $\prod_X^* SC(p_M, p_{3D})$ is concave in c_M, therefore, when

$$\frac{\partial \prod_X^* SC(p_M, p_{3D})}{\partial c_M} = \frac{\alpha\delta c_{3D} + (-1+\alpha\delta)c_L - c_M}{2\alpha\delta(-1+\alpha\delta)} = 0$$

$$c_M^* = \alpha\delta c_{3D} + (-1+\alpha\delta)c_L$$

gives the unique minimum value. Because $\alpha\delta c_{3D} > c_L + c_M$, therefore, $c_M^* > \alpha\delta c_{3D} - c_L$, $\prod_X^* SC(p_M, p_{3D})$ decreases in c_M.

(2) $\prod_X^* SC(p_M, p_{3D})$ is concave in c_L, therefore, when

$$\frac{\partial \prod_X^* SC(p_M, p_{3D})}{\partial c_L} = \frac{-\alpha\delta + c_L + c_M}{2\alpha\delta} = 0$$

$$c_L^* = \alpha\delta - c_M$$

gives the unique minimum value. Because $\alpha\delta c_{3D} > c_L + c_M$, therefore, $\prod_X^* SC(p_M, p_{3D})$ decreases in c_L.

(3) $\prod_X^* SC(p_M, p_{3D})$ is concave in c_{3D}, therefore, when

$$\frac{\partial \prod_X^* SC(p_M, p_{3D})}{\partial c_{3D}} = \frac{1 - \alpha\delta - c_{3D} + c_M}{-2 + 2\alpha\delta} = 0$$

$$c_{3D}^* = 1 - \alpha\delta + c_M$$

gives the minimum value. However, because $\alpha\delta c_{3D} > c_L + c_M$, therefore,

If $1 - \alpha\delta + c_M < \frac{c_L + c_M}{\alpha\delta}$, that is $\frac{c_M}{\delta} < \alpha < 1$ and $-(-1 + \alpha\delta)(\alpha\delta - c_M) < c_L < \alpha\delta - c_M$, $\prod_X^* M(p_M, p_{3D}) \prod_X^* SC(p_M, p_{3D})$ increases in c_{3D};

If $1 - \alpha\delta + c_M > \frac{c_L + c_M}{\alpha\delta}$, that is $0 < c_L < -(-1 + \alpha\delta)(\alpha\delta - c_M)$, then,

i) when $\frac{c_L + c_M}{\alpha\delta} < c_{3D} < c_{3D}^*$, $\prod_X^* SC(p_M, p_{3D})$ decreases in c_{3D};
ii) when $c_{3D}^* < c_{3D} < 1$, $\prod_X^* SC(p_M, p_{3D})$ increases in c_{3D}.

Proof of *PROPOSITION* 6-4.

Under decentralized supply chain,

$$\frac{\partial p_L^*}{\partial \alpha} = \frac{\delta}{2} \qquad \frac{\partial p_M^*}{\partial \alpha} = \frac{3\delta}{4} \qquad \frac{\partial p_{3D}^*}{\partial \alpha} = \frac{\delta}{4} \qquad \frac{\partial p_L^*}{\partial \delta} = \frac{\alpha}{2} \qquad \frac{\partial p_M^*}{\partial \delta} = \frac{3\alpha}{4} \qquad \frac{\partial p_{3D}^*}{\partial \delta} = \frac{\alpha}{4}$$

Under integrated supply chain,

$$\frac{\partial p_M^*}{\partial \alpha} = \frac{1}{2} \qquad \frac{\partial p_{3D}^*}{\partial \alpha} = \text{N/A} \qquad \frac{\partial p_M^*}{\partial \delta} = \frac{1}{2} \qquad \frac{\partial p_{3D}^*}{\partial \delta} = \text{N/A}$$

Proof of PROPOSITION *6-5.*

Under decentralized supply chain, the first-order-conditions and the second-order-conditions of $\prod_Y L(p_L, p_{3D})$ by p_{3D} are

$$\frac{\partial \prod_Y L(p_L, p_{3D})}{\partial p_{3D}} = \frac{\gamma + \delta - \alpha\delta + c_{3D} - c_L - 2p_{3D} + p_L + p_M}{\delta - \alpha\delta}$$

$$\frac{\partial \prod_Y^2 L(p_L, p_{3D})}{\partial p_{3D}^2} = \frac{2}{(-1+\alpha)\delta} < 0$$

So, the solution to the first-order-conditions gives the unique maximizer.

$$\frac{\partial \prod_Y L(p_L, p_{3D})}{\partial p_{3D}} = \frac{\gamma + \delta - \alpha\delta + c_{3D} - c_L - 2p_{3D} + p_L + p_M}{\delta - \alpha\delta} = 0$$

$$p_{3D}^* = \frac{1}{2}(\gamma + \delta - \alpha\delta + c_{3D} - c_L + p_L + p_M)$$

Then, the traditional manufacturer's profit function (6.4) can be updated as

$$\prod\nolimits_Y M(p_M) = \frac{(c_M + p_L - p_M)(\alpha(\gamma + \delta - \alpha\delta + c_{3D} - c_L + p_L) + (-2+\alpha)p_M)}{2(-1+\alpha)\alpha\delta}$$

which is convex in p_M, so the first-order-conditions gives the maximum profit.

$$\frac{\partial \prod_Y M(p_M)}{\partial p_M} = \frac{(-2+\alpha)(c_M + p_L - p_M)}{2(-1+\alpha)\alpha\delta} - \frac{\alpha(\gamma + \delta - \alpha\delta + c_{3D} - c_L + p_L) + (-2+\alpha)p_M}{2(-1+\alpha)\alpha\delta} = 0$$

$$p_M^* = \frac{-\alpha\gamma + (-1+\alpha)\alpha\delta - \alpha c_{3D} + \alpha c_L + (-2+\alpha)c_M - 2p_L}{2(-2+\alpha)}$$

Then, the $\prod_Y L(p_L, p_{3D})$ can be rewritten as

$$\prod\nolimits_Y L(p_L, p_{3D}) = -\frac{1}{16(-1+\alpha)\delta}\Big(\frac{1}{(-2+\alpha)^2}((-4+3\alpha)\gamma + (-4+\alpha)(-1+\alpha)\delta + (-4+3\alpha)c_{3D} + (-4+\alpha)c_L - (-2+\alpha)c_M + 6p_L - 2\alpha p_L)((-4+3\alpha)\gamma + (-4+\alpha)(-1+\alpha)\delta + (-4+3\alpha)c_{3D} + (4-3\alpha)c_L - (-2+\alpha)c_M - 2p_L + 2\alpha p_L) + \frac{4(c_L - p_L)(-\alpha\gamma + (-1+\alpha)\alpha\delta + 2c_M + 2p_L - \alpha(c_{3D} - c_L + c_M + 2p_L))}{\alpha}\Big)$$

Which is convex in p_L, therefore, the first-order-conditions gives the maximum profit.

$$\frac{\partial \prod_Y M(p_M)}{\partial p_L} = -\frac{1}{4(-2+\alpha)^2\alpha\delta}(\alpha(\alpha\gamma - (8 + (-5+\alpha)\alpha)\delta) + \alpha^2 c_{3D} - (8 + (-4 + \alpha)\alpha)c_L + (-4+\alpha)(-2+\alpha)c_M + 16p_L + 2(-5+\alpha)\alpha p_L) = 0$$

$$p_L^* = \frac{\alpha(-\alpha\gamma + (8 + (-5+\alpha)\alpha)\delta) - \alpha^2 c_{3D} + (8 + (-4+\alpha)\alpha)c_L - (-4+\alpha)(-2+\alpha)c_M}{2(8 + (-5+\alpha)\alpha)}$$

The final optimal decisions are

$$p_L^* = (\alpha(-\alpha\gamma + (8 + (-5+\alpha)\alpha)\delta) - \alpha^2 c_{3D} + (8 + (-4+\alpha)\alpha)c_L - (-4 + \alpha)(-2+\alpha)c_M)/2(8 + (-5+\alpha)\alpha) \tag{6.22}$$

$$p_M^* = (\alpha(-(-4+\alpha)\gamma + (8 + (-5+\alpha)\alpha)\delta) - (-4+\alpha)\alpha c_{3D} + (-2+\alpha)^2 c_L + (-2+\alpha)^2 c_M)/2(8 + (-5+\alpha)\alpha) \tag{6.23}$$

$$p_{3D}^* = \frac{(8-3\alpha)\gamma + 8\delta + (-5+\alpha)\alpha\delta + (8-3\alpha)c_{3D} + (-2+\alpha)c_L + (-2+\alpha)c_M}{2(8 + (-5+\alpha)\alpha)} \tag{6.24}$$

$$q_M^* = \frac{(-2+\alpha)(\alpha\gamma + \alpha c_{3D} - c_L - c_M)}{(-1+\alpha)\alpha(8 + (-5+\alpha)\alpha)\delta} \tag{6.25}$$

$$q_{3D}^* = \frac{1}{2(-1+\alpha)(8 + (-5+\alpha)\alpha)\delta}((8 + (-7+\alpha)\alpha)\gamma + (-1+\alpha)(8 + (-5 + \alpha)\alpha)\delta + (8 + (-7+\alpha)\alpha)c_{3D} - 6c_L - 6c_M - (-5+\alpha)\alpha(c_L + c_M)) \tag{6.26}$$

The maximized profits are

$$\prod_Y^* M(p_M, p_{3D}) = \frac{2(-2+\alpha)(-\alpha\gamma - \alpha c_{3D} + c_L + c_M)^2}{(-1+\alpha)\alpha(8 + (-5+\alpha)\alpha)^2\delta} \tag{6.27}$$

$$\prod_Y^* L\,(p_L, p_{3D}) = \frac{1}{4(-1+\alpha)\alpha(8 + (-5+\alpha)\alpha)\delta}(\alpha((-8 + (9-2\alpha)\alpha)\gamma^2 - 2(-1 + \alpha)(8 + (-5+\alpha)\alpha)\gamma\delta + (-1+\alpha)(8 + (-5+\alpha)\alpha)\delta^2) + \alpha(-8 + (9-2\alpha)\alpha)c_{3D}^2 + (-2+\alpha)^2(2\alpha\gamma - c_L - c_M)(c_L + c_M) + 2\alpha c_{3D}((-8 + (9-2\alpha)\alpha)\gamma - (-1+\alpha)(8 + (-5+\alpha)\alpha)\delta + (-2+\alpha)^2 c_L + (-2+\alpha)^2 c_M)) \tag{6.28}$$

Under the integrated supply chain, the first-order-conditions and the second-order-conditions of $\prod_Y SC(p_M, p_{3D})$ by p_M and p_{3D} in Equation (6.6) are

$$\begin{cases} \dfrac{\partial \prod_Y SC(p_M, p_{3D})}{\partial p_M} = -\dfrac{-\alpha c_{3D} + c_L + c_M + 2\alpha p_{3D} - 2p_M}{(-1+\alpha)\alpha\delta} \\ \dfrac{\partial \prod_Y SC(p_M, p_{3D})}{\partial p_{3D}} = \dfrac{(-1+\alpha)\delta - c_{3D} + c_L + c_M + 2p_{3D} - 2p_M}{(-1+\alpha)\delta} \end{cases}$$

$$\begin{cases} \dfrac{\partial \prod_Y^2 SC(p_M, p_{3D})}{\partial p_M^2} = \dfrac{2}{(-1+\alpha)\alpha\delta} < 0 \\ \dfrac{\partial \prod_Y^2 SC(p_M, p_{3D})}{\partial p_{3D}^2} = \dfrac{2}{(-1+\alpha)\delta} < 0 \\ \dfrac{\partial \prod_Y^2 SC(p_M, p_{3D})}{\partial p_M \partial p_{3D}} = \dfrac{2}{\delta - \alpha\delta} > 0 \\ \dfrac{\partial \prod_Y^2 SC(p_M, p_{3D})}{\partial p_{3D} \partial p_M} = \dfrac{2}{\delta - \alpha\delta} > 0 \end{cases}$$

So, the determinant of the Hessian Matrix can be written as

$$H = \begin{vmatrix} \dfrac{2}{(-1+\alpha)\alpha\delta} & \dfrac{2}{\delta - \alpha\delta} \\ \dfrac{2}{\delta - \alpha\delta} & \dfrac{2}{(-1+\alpha)\delta} \end{vmatrix} = \frac{2}{(-1+\alpha)\alpha\delta} \times \frac{2}{(-1+\alpha)\delta} - \left(\frac{2}{\delta - \alpha\delta}\right)^2$$

$$= -\frac{4}{(-1+\alpha)\alpha\delta^2} > 0$$

Therefore, this Hessian Matrix is a negative-definite matrix, the solution to the first-order-conditions gives the unique maximizer of $\prod_Y SC(p_M, p_{3D})$.

$$\begin{cases} \dfrac{\partial \prod_Y SC(p_M, p_{3D})}{\partial p_M} = -\dfrac{-\alpha c_{3D} + c_L + c_M + 2\alpha p_{3D} - 2p_M}{(-1+\alpha)\alpha\delta} = 0 \\ \dfrac{\partial \prod_Y SC(p_M, p_{3D})}{\partial p_{3D}} = \dfrac{(-1+\alpha)\delta - c_{3D} + c_L + c_M + 2p_{3D} - 2p_M}{(-1+\alpha)\delta} = 0 \end{cases}$$

$$p_M^* = \frac{1}{2}(\alpha\delta + c_L + c_M) \tag{6.29}$$

$$p_{3D}^* = \frac{1}{2}(\delta + c_{3D}) \tag{6.30}$$

So,

$$q_M^* = \frac{-\alpha c_{3D} + c_L + c_M}{2(-1+\alpha)\alpha\delta} \tag{6.31}$$

$$q_{3D}^{*} = \frac{\delta - \alpha\delta - c_{3D} + c_L + c_M}{2\delta - 2\alpha\delta} \tag{6.32}$$

$$\prod\nolimits_{Y}^{*} SC(p_M, p_{3D}) = -\frac{-(-1+\alpha)\alpha\delta^2 + \alpha c_{3D}^2 + (c_L + c_M)^2 - 2\alpha c_{3D}(\delta - \alpha\delta + c_L + c_M)}{4(-1+\alpha)\alpha\delta} \tag{6.33}$$

Proof of PROPOSITION *6-6.*

Under the decentralized Y supply chain, it is easy to find out that

$$\frac{\partial p_L^*}{\partial c_M} = \frac{1}{2}\left(-1 + \frac{\alpha}{8 + (-5+\alpha)\alpha}\right) < 0 \quad \frac{\partial p_M^*}{\partial c_M} = \frac{(-2+\alpha)^2}{2(8+(-5+\alpha)\alpha)} > 0 \quad \frac{\partial p_{3D}^*}{\partial c_M} = \frac{-2+\alpha}{2(8+(-5+\alpha)\alpha)} < 0$$

$$\frac{\partial p_L^*}{\partial c_L} = \frac{1}{2}\left(1 + \frac{\alpha}{8 + (-5+\alpha)\alpha}\right) > 0 \quad \frac{\partial p_M^*}{\partial c_L} = \frac{(-2+\alpha)^2}{2(8+(-5+\alpha)\alpha)} > 0 \quad \frac{\partial p_{3D}^*}{\partial c_L} = \frac{-2+\alpha}{2(8+(-5+\alpha)\alpha)} < 0$$

$$\frac{\partial p_L^*}{\partial c_{3D}} = -\frac{\alpha^2}{2(8+(-5+\alpha)\alpha)} < 0 \quad \frac{\partial p_M^*}{\partial c_{3D}} = -\frac{(-4+\alpha)\alpha}{2(8+(-5+\alpha)\alpha)} > 0 \quad \frac{\partial p_{3D}^*}{\partial c_{3D}} = \frac{8-3\alpha}{2(8+(-5+\alpha)\alpha)} > 0$$

$$\frac{\partial p_L^*}{\partial \gamma} = -\frac{\alpha^2}{2(8+(-5+\alpha)\alpha)} < 0 \quad \frac{\partial p_M^*}{\partial \gamma} = -\frac{(-4+\alpha)\alpha}{2(8+(-5+\alpha)\alpha)} > 0 \quad \frac{\partial p_{3D}^*}{\partial \gamma} = \frac{8-3\alpha}{2(8+(-5+\alpha)\alpha)} > 0$$

and

$$\frac{\partial q_M^*}{\partial c_M} = -\frac{-2+\alpha}{(-1+\alpha)\alpha(8+(-5+\alpha)\alpha)\delta} < 0 \quad \frac{\partial q_{3D}^*}{\partial c_M} = -\frac{6+(-5+\alpha)\alpha}{2(-1+\alpha)(8+(-5+\alpha)\alpha)\delta} > 0$$

$$\frac{\partial q_M^*}{\partial c_L} = -\frac{-2+\alpha}{(-1+\alpha)\alpha(8+(-5+\alpha)\alpha)\delta} < 0 \quad \frac{\partial q_{3D}^*}{\partial c_L} = -\frac{6+(-5+\alpha)\alpha}{2(-1+\alpha)(8+(-5+\alpha)\alpha)\delta} > 0$$

$$\frac{\partial q_M^*}{\partial c_{3D}} = \frac{-2+\alpha}{(-1+\alpha)(8+(-5+\alpha)\alpha)\delta} > 0 \qquad \frac{\partial q_{3D}^*}{\partial c_{3D}} = \frac{8+(-7+\alpha)\alpha}{2(-1+\alpha)(8+(-5+\alpha)\alpha)\delta} < 0$$

$$\frac{\partial q_M^*}{\partial \gamma} = \frac{-2+\alpha}{(-1+\alpha)(8+(-5+\alpha)\alpha)\delta} > 0 \qquad \frac{\partial q_{3D}^*}{\partial \gamma} = \frac{8+(-7+\alpha)\alpha}{2(-1+\alpha)(8+(-5+\alpha)\alpha)\delta} < 0$$

From Equation (6.27), it is easy to find out that

(1) $\prod_Y^* M(p_M)$ is concave in c_M, therefore, when

$$\frac{\partial \prod_Y^* M(p_M)}{\partial c_M} = \frac{4(-2+\alpha)(-\alpha\gamma - \alpha c_{3D} + c_L + c_M)}{(-1+\alpha)\alpha(8+(-5+\alpha)\alpha)^2\delta} = 0$$

$$c_M^* = \alpha(\gamma + c_{3D}) - c_L$$

gives the unique minimum value. However, because $\alpha\delta(c_{3D}+\gamma) > c_L + c_M$, therefore, $c_M^* > \alpha\delta(c_{3D}+\gamma) - c_L$, $\prod_Y^* M(p_M)$ decreases in c_M.

(2) $\prod_Y^* M(p_M)$ is concave in c_L, therefore, when

$$\frac{\partial \prod_Y^* M(p_M)}{\partial c_L} = \frac{4(-2+\alpha)(-\alpha\gamma - \alpha c_{3D} + c_L + c_M)}{(-1+\alpha)\alpha(8+(-5+\alpha)\alpha)^2\delta} = 0$$

$$c_L^* = \alpha(\gamma + c_{3D}) - c_M$$

gives the unique minimum value. Because $\alpha\delta(c_{3D}+\gamma) > c_L + c_M$, therefore, $c_L^* > \alpha\delta(c_{3D}+\gamma) - c_M$, $\prod_Y^* M(p_M)$ decreases in c_L.

(3) $\prod_Y^* M(p_M)$ is concave in c_{3D}, therefore, when

$$\frac{\partial \prod_Y^* M(p_M)}{\partial c_{3D}} = -\frac{4(-2+\alpha)(-\alpha\gamma - \alpha c_{3D} + c_L + c_M)}{(-1+\alpha)(8+(-5+\alpha)\alpha)^2\delta} = 0$$

$$c_{3D}^* = \frac{-\alpha\gamma + c_L + c_M}{\alpha}$$

gives the minimum value. However, because $\alpha\delta(c_{3D}+\gamma) > c_L + c_M$, therefore, $c_{3D}^* < \frac{c_L + c_M}{\alpha\delta} - \gamma$, $\prod_Y^* M(p_M)$ increases in c_{3D}.

(4) $\prod_Y^* M(p_M)$ is concave in γ, therefore, when

$$\frac{\partial \prod_Y^* M(p_M)}{\partial \gamma} = -\frac{4(-2+\alpha)(-\alpha\gamma - \alpha c_{3D} + c_L + c_M)}{(-1+\alpha)(8+(-5+\alpha)\alpha)^2\delta} = 0$$

$$\gamma^* = \frac{-\alpha c_{3D} + c_L + c_M}{\alpha}$$

gives the minimum value. However, because $\alpha\delta(c_{3D} + \gamma) > c_L + c_M$, therefore, $\gamma^* > \frac{c_L + c_M}{\alpha\delta} - \gamma$, $\prod_Y^* M(p_M)$ increases in γ.

For the logistics vendor's maximized profit (Equation (6.28)) under the decentralized supply chain,

(1) $\prod_Y^* L(p_L, p_{3D})$ is concave in c_M, therefore, when

$$\frac{\partial \prod_Y^* L(p_L, p_{3D})}{\partial c_M} = \frac{(-2+\alpha)^2(\alpha\gamma + \alpha c_{3D} - c_L - c_M)}{2(-1+\alpha)\alpha(8+(-5+\alpha)\alpha)\delta} = 0$$

$$c_M^* = \alpha(\gamma + c_{3D}) - c_L$$

gives the unique minimum value. Because $\alpha\delta(c_{3D} + \gamma) > c_L + c_M$, therefore, $\prod_Y^* L(p_L, p_{3D})$ decreases in c_M.

(2) $\prod_Y^* L(p_L, p_{3D})$is concave in c_L, therefore, when

$$\frac{\partial \prod_Y^* L(p_L, p_{3D})}{\partial c_L} = \frac{(-2+\alpha)^2(\alpha\gamma + \alpha c_{3D} - c_L - c_M)}{2(-1+\alpha)\alpha(8+(-5+\alpha)\alpha)\delta} = 0$$

$$c_L^* = \alpha(\gamma + c_{3D}) - c_M$$

gives the unique minimum value. Because $\alpha\delta(c_{3D} + \gamma) > c_L + c_M$therefore, $\prod_Y^* L(p_L, p_{3D})$ decreases in c_L.

(3) $\prod_Y^* L(p_L, p_{3D})$is concave in c_{3D}, therefore, when

$$\frac{\partial \prod_Y^* L(p_L, p_{3D})}{\partial c_{3D}} = \frac{1}{2(-1+\alpha)(8+(-5+\alpha)\alpha)\delta}((-8+(9-2\alpha)\alpha)\gamma-(-1+\alpha)(8 + (-5+\alpha)\alpha)\delta+(-8+(9-2\alpha)\alpha)c_{3D}+(-2+\alpha)^2c_L+(-2+\alpha)^2c_M) = 0$$

$$c_{3D}^* = \frac{(-8+(9-2\alpha)\alpha)\gamma-(-1+\alpha)(8+(-5+\alpha)\alpha)\delta+(-2+\alpha)^2c_L+(-2+\alpha)^2c_M}{8+\alpha(-9+2\alpha)}$$

gives the unique minimum value. Because $\alpha\delta(c_{3D}+\gamma) > c_L + c_M$, therefore,

If $\frac{(-8+(9-2\alpha)\alpha)\gamma-(-1+\alpha)(8+(-5+\alpha)\alpha)\delta+(-2+\alpha)^2c_L+(-2+\alpha)^2c_M}{8+\alpha(-9+2\alpha)} < \frac{c_L+c_M}{\alpha\delta}-\gamma$, that is when i) $0 < c_L < \frac{(-1+\alpha)\alpha(8+(-5+\alpha)\alpha)\delta^2}{-8+\alpha(9-2\alpha+(-2+\alpha)^2\delta)}$ and $\frac{(-1+\alpha)\alpha(8+(-5+\alpha)\alpha)\delta^2}{-8+\alpha(9-2\alpha+(-2+\alpha)^2\delta)} < c_M + c_L < 1$ or ii) $\frac{(-1+\alpha)\alpha(8+(-5+\alpha)\alpha)\delta^2}{-8+\alpha(9-2\alpha+(-2+\alpha)^2\delta)} \leq c_L < 1$, $\prod_Y^* L(p_L, p_{3D})$ increases in c_{3D};

If $\frac{(-8+(9-2\alpha)\alpha)\gamma-(-1+\alpha)(8+(-5+\alpha)\alpha)\delta+(-2+\alpha)^2c_L+(-2+\alpha)^2c_M}{8+\alpha(-9+2\alpha)} > \frac{c_L+c_M}{\alpha\delta}-\gamma$, that is $c_L + c_M < \frac{(-1+\alpha)\alpha(8+(-5+\alpha)\alpha)\delta^2}{-8+\alpha(9-2\alpha+(-2+\alpha)^2\delta)}$, then,

i) when $\frac{c_L+c_M}{\alpha\delta}-\gamma < c_{3D} < c_{3D}^*$, $\prod_Y^* L(p_L, p_{3D})$ decreases in c_{3D};
ii) when $c_{3D}^* < c_{3D} < 1$, $\prod_Y^* L(p_L, p_{3D})$ increases in c_{3D}.

(4) $\prod_Y^* L(p_L, p_{3D})$ is concave in γ, therefore, when

$$\frac{\partial \prod_Y^* L(p_L, p_{3D})}{\partial \gamma} = \frac{1}{2(-1+\alpha)(8+(-5+\alpha)\alpha)\delta}((-8+(9-2\alpha)\alpha)\gamma-(-1+\alpha)(8 + (-5+\alpha)\alpha)\delta+(-8+(9-2\alpha)\alpha)c_{3D}+(-2+\alpha)^2(c_L+c_M)) = 0$$

$$\gamma^* = \frac{-(-1+\alpha)(8+(-5+\alpha)\alpha)\delta+(-8+(9-2\alpha)\alpha)c_{3D}+(-2+\alpha)^2c_L+(-2+\alpha)^2c_M}{8+\alpha(-9+2\alpha)}$$

gives the unique minimum value. Because $\alpha\delta(c_{3D}+\gamma) > c_L + c_M$, therefore, If $\frac{-(-1+\alpha)(8+(-5+\alpha)\alpha)\delta+(-8+(9-2\alpha)\alpha)c_{3D}+(-2+\alpha)^2c_L+(-2+\alpha)^2c_M}{8+\alpha(-9+2\alpha)} < \frac{c_L+c_M}{\alpha\delta} - c_{3D}$, that is when i) $0 < c_L < \frac{(-1+\alpha)\alpha(8+(-5+\alpha)\alpha)\delta^2}{-8+\alpha(9-2\alpha+(-2+\alpha)^2\delta)}$ and $\frac{(-1+\alpha)\alpha(8+(-5+\alpha)\alpha)\delta^2}{-8+\alpha(9-2\alpha+(-2+\alpha)^2\delta)} < c_M + c_L < 1$ or ii) $\frac{(-1+\alpha)\alpha(8+(-5+\alpha)\alpha)\delta^2}{-8+\alpha(9-2\alpha+(-2+\alpha)^2\delta)} \leq c_L < 1$, $\prod_Y^* L(p_L, p_{3D})$ increases in γ;

If $\frac{(-8+(9-2\alpha)\alpha)\gamma-(-1+\alpha)(8+(-5+\alpha)\alpha)\delta+(-2+\alpha)^2c_L+(-2+\alpha)^2c_M}{8+\alpha(-9+2\alpha)} > \frac{c_L+c_M}{\alpha\delta} - c_{3D}$, that is $c_L + c_M < \frac{(-1+\alpha)\alpha(8+(-5+\alpha)\alpha)\delta^2}{-8+\alpha(9-2\alpha+(-2+\alpha)^2\delta)}$, then,

i) when $\frac{c_L+c_M}{\alpha\delta} - c_{3D} < \gamma < \gamma^*$, $\prod_Y^* L(p_L, p_{3D})$ decreases in γ;
ii) when $\gamma^* < \gamma < 1$, $\prod_Y^* L(p_L, p_{3D})$ increases in γ.

Proof of PROPOSITION *6-7*.

Under the integrated supply chain,

$$\frac{\partial p_M^*}{\partial c_M} = \frac{1}{2} \quad \frac{\partial p_{3D}^*}{\partial c_M} = N/A \quad \frac{\partial q_M^*}{\partial c_M} = -\frac{1}{2\alpha\delta - 2\alpha^2\delta} < 0 \quad \frac{\partial q_{3D}^*}{\partial c_M} = \frac{1}{2\delta - 2\alpha\delta} > 0$$

$$\frac{\partial p_M^*}{\partial c_L} = \frac{1}{2} \quad \frac{\partial p_{3D}^*}{\partial c_L} = \text{N/A} \quad \frac{\partial q_M^*}{\partial c_L} = -\frac{1}{2\alpha\delta - 2\alpha^2\delta} < 0 \quad \frac{\partial q_{3D}^*}{\partial c_L} = \frac{1}{2\delta - 2\alpha\delta} > 0$$

$$\frac{\partial p_M^*}{\partial c_{3D}} = N/A \quad \frac{\partial p_{3D}^*}{\partial c_{3D}} = \frac{1}{2} \quad \frac{\partial q_M^*}{\partial c_{3D}} = \frac{1}{2\delta - 2\alpha\delta} > 0 \quad \frac{\partial q_{3D}^*}{\partial c_{3D}} = -\frac{1}{2\delta - 2\alpha\delta} < 0$$

$$\frac{\partial p_M^*}{\partial \gamma} = N/A \quad \frac{\partial p_{3D}^*}{\partial \gamma} = N/A \quad \frac{\partial q_M^*}{\partial \gamma} = N/A \quad \frac{\partial q_{3D}^*}{\partial \gamma} = N/A$$

For the maximized supply chain profit (Equation (6.33)),

(1) $\prod_Y^* SC(p_M, p_{3D})$ is concave in c_M, therefore, when

$$\frac{\partial \prod_Y^* SC(p_M, p_{3D})}{\partial c_M} = -\frac{-\alpha c_{3D} + c_L + c_M}{2(-1+\alpha)\alpha\delta} = 0$$

$$c_M^* = \alpha c_{3D} - c_L$$

gives the unique minimum value. Because $\alpha\delta(c_{3D} + \gamma) > c_L + c_M$, therefore,

If $\alpha c_{3D} - c_L > \alpha\delta(c_{3D} + \gamma) - c_L$, that is $\delta < \frac{1}{1+\gamma}$ and $c_{3D} > -\frac{\gamma\delta}{-1+\delta}$, then $\prod_Y^* SC(p_M, p_{3D})$ decreases in c_M;

If $\alpha c_{3D} - c_L < \alpha\delta(c_{3D} + \gamma) - c_L$, that is 1) $0 < \delta < \frac{1}{1+\gamma}$ and $0 < c_{3D} < -\frac{\gamma\delta}{-1+\delta}$ or 2) $\frac{1}{1+\gamma} \leq \delta < 1$,

i) when $0 < c_M < c_M^*$, $\prod_Y^* SC(p_M, p_{3D})$ decreases in c_M;
ii) when $c_M^* < c_M < \alpha\delta(c_{3D} + \gamma) - c_L$, $\prod_Y^* SC(p_M, p_{3D})$ increases in c_M.

(2) $\prod_Y^* SC(p_M, p_{3D})$ is concave in c_L, therefore, when

$$\frac{\partial \prod_Y^* SC(p_M, p_{3D})}{\partial c_L} = -\frac{-\alpha c_{3D} + c_L + c_M}{2(-1+\alpha)\alpha\delta} = 0$$

$$c_L^* = \alpha c_{3D} - c_M$$

gives the unique minimum value. Because $\alpha\delta(c_{3D} + \gamma) > c_L + c_M$, therefore,

If $\alpha c_{3D} - c_L > \alpha\delta(c_{3D} + \gamma) - c_L$, that is $\delta < \frac{1}{1+\gamma}$ and $c_{3D} > -\frac{\gamma\delta}{-1+\delta}$, then $\prod_Y^* SC(p_M, p_{3D})$ decreases in c_L;

If $\alpha c_{3D} - c_L < \alpha\delta(c_{3D} + \gamma) - c_L$, that is 1) $0 < \delta < \frac{1}{1+\gamma}$ and $0 < c_{3D} < -\frac{\gamma\delta}{-1+\delta}$ or 2) $\frac{1}{1+\gamma} \leq \delta < 1$,

i) when $0 < c_L < c_L^*$, $\prod_Y^* SC(p_M, p_{3D})$ decreases in c_L;
ii) when $c_L^* < c_L < \alpha\delta(c_{3D} + \gamma) - c_L$, $\prod_Y^* SC(p_M, p_{3D})$ increases in c_L.

(3) $\prod_Y^* SC(p_M, p_{3D})$is concave in c_{3D}, therefore, when

$$\frac{\partial \prod_Y^* SC(p_M, p_{3D})}{\partial c_{3D}} = -\frac{\delta - \alpha\delta - c_{3D} + c_L + c_M}{2\delta - 2\alpha\delta} = 0$$

$$c_{3D}^* = \delta - \alpha\delta + c_L + c_M$$

gives the minimum value. However, because $\alpha\delta(c_{3D} + \gamma) > c_L + c_M$, therefore,

If $\gamma + \delta + c_L + c_M < \frac{c_L + c_M}{\alpha\delta} + \alpha\delta$, that is $\frac{\alpha^2\delta^2 + c_L + c_M}{\alpha\delta} - \gamma - \delta > c_L + c_M$ and 1) $c_L < \frac{(-1+\alpha)\alpha\delta^2}{-1+\alpha\delta}$ and $\frac{(-1+\alpha)\alpha\delta^2}{-1+\alpha\delta} < c_L + c_M$ or 2) $\frac{(-1+\alpha)\alpha\delta^2}{-1+\alpha\delta} \leq c_L < \alpha\delta$, $\prod_Y^* SC(p_M, p_{3D})$ increases in c_{3D};

If $1-\alpha\delta+c_M>\frac{c_L+c_M}{\alpha\delta}-\gamma$, that is 1) $c_L<\frac{(-1+\alpha)\alpha\delta^2}{-1+\alpha\delta}$ and $c_L+c_M\leq\frac{(-1+\alpha)\alpha\delta^2}{-1+\alpha\delta}$, or 2) $\frac{(-1+\alpha)\alpha\delta^2}{-1+\alpha\delta}<c_L+c_M$ and $\frac{\alpha^2\delta^2+c_L+c_M}{\alpha\delta}-\gamma-\delta<c_L+c_M$, or 3) $\frac{\alpha^2\delta^2+c_L+c_M}{\alpha\delta}-\gamma-\delta<c_L+c_M$ and $\frac{(-1+\alpha)\alpha\delta^2}{-1+\alpha\delta}\leq c_L$

i) when $\frac{c_L+c_M}{\alpha\delta}-\gamma<c_{3D}<c_{3D}^*$, $\prod_Y^* SC(p_M,p_{3D})$ decreases in c_{3D};
ii) when $c_{3D}^*<c_{3D}<1$, $\prod_Y^* SC(p_M,p_{3D})$ increases in c_{3D}.

Proof of. *PROPOSITION* 6-8

Under integrated supply chain,

$$\frac{\partial p_M^*}{\partial\alpha}=\frac{1}{2}\qquad\frac{\partial p_{3D}^*}{\partial\alpha}=\text{N/A}\qquad\frac{\partial p_M^*}{\partial\delta}=\frac{1}{2}\qquad\frac{\partial p_{3D}^*}{\partial\delta}=\frac{1}{2}$$

Proof of *PROPOSITION* 6-9.

Under the decentralized supply chain, according to Equation (6.8), the first-order-conditions and the second-order-conditions of $\prod_Z L(p_L,p_{3D})$ in p_{3D} are

$$\frac{\partial\prod_Z L(p_L,p_{3D})}{\partial p_{3D}}=\frac{1+\beta-\alpha\delta+c_{3D}-c_L-2p_{3D}+p_L+p_M}{1-\alpha\delta}$$

$$\frac{\partial\prod_Z^2 L(p_L,p_{3D})}{\partial p_{3D}^2}=\frac{2}{-1+\alpha\delta}<0$$

So, the solution to the first-order-conditions gives the unique maximizer.

$$\frac{\partial\prod_Z L(p_L,p_{3D})}{\partial p_{3D}}=\frac{1+\beta-\alpha\delta+c_{3D}-c_L-2p_{3D}+p_L+p_M}{1-\alpha\delta}=0$$

$$p_{3D}^*=\frac{1}{2}(1+\beta-\alpha\delta+c_{3D}-c_L+p_L+p_M)$$

Then, the traditional manufacturer's profit function (6.9) can be updated as

$$\prod\nolimits_Z M(p_M)=\frac{1}{\alpha\delta(-1+\alpha\delta)}\Big(\alpha\beta\delta(-1+\alpha\delta)-(\alpha\beta\delta+c_M+p_L)p_M+p_M^2+\frac{1}{2}\alpha\delta(\beta+c_M+p_L-p_M)(1+\beta-\alpha\delta+c_{3D}-c_L+p_L+p_M)\Big)$$

which is convex in p_M, so the first-order-conditions gives the maximum profit.

$$\frac{\partial \prod_Z M(p_M)}{\partial p_M} = \frac{\alpha\delta(-1-2\beta+\alpha\delta)-2c_M-2p_L+\alpha\delta(-c_{3D}+c_L+c_M-2p_M)+4p_M}{2\alpha\delta(-1+\alpha\delta)}$$

$$= 0$$

$$p_M^* = \frac{\alpha\delta(-1-2\beta+\alpha\delta)-2c_M+\alpha\delta(-c_{3D}+c_L+c_M)-2p_L}{-4+2\alpha\delta}$$

Then, the $\prod_Y L(p_L, p_{3D})$ can be rewritten as

$$\prod\nolimits_Y L(p_L, p_{3D})$$

$$= \frac{1}{-1+\alpha\delta}\Big(-\frac{1}{16(-2+\alpha\delta)^2}\big((-1+\alpha\delta)(-4+4\beta+\alpha\delta)+(-4 + 3\alpha\delta)c_{3D}+(-4+\alpha\delta)c_L+(2-\alpha\delta)c_M+6p_L-2\alpha\delta p_L\big)\big((-1+\alpha\delta)(-4 + 4\beta+\alpha\delta)+(-4+3\alpha\delta)c_{3D}+(4-3\alpha\delta)c_L+(2-\alpha\delta)c_M-2p_L + 2\alpha\delta p_L\big) - \frac{(c_L-p_L)(\alpha\delta(-1+\alpha\delta)+2c_M+2p_L-\alpha\delta(c_{3D}-c_L+c_M+2p_L))}{4\alpha\delta}\Big)$$

Which is convex in p_L, therefore, the first-order-conditions gives the maximum profit.

$$\frac{\partial \prod_Y M(p_M)}{\partial p_L} = \frac{1}{4\alpha\delta(-2+\alpha\delta)^2}(\alpha\delta(8-4\beta+\alpha\delta(-5+\alpha\delta))+8c_L-8c_M-16p_L - \alpha\delta(\alpha\delta c_{3D}+(4-\alpha\delta)c_L+(-6+\alpha\delta)c_M+2(-5+\alpha\delta)p_L)) = 0$$

$$p_L^* = \frac{\alpha\delta(8-4\beta+\alpha\delta(-5+\alpha\delta))+8c_L-8c_M-\alpha\delta(\alpha\delta c_{3D}+(4-\alpha\delta)c_L+(-6+\alpha\delta)c_M)}{2(8+\alpha\delta(-5+\alpha\delta))}$$

The final optimal decisions are

$$p_L^* = (\alpha\delta(8-4\beta+\alpha\delta(-5+\alpha\delta))+8c_L-8c_M-\alpha\delta(\alpha\delta c_{3D}+(4-\alpha\delta)c_L + (-6+\alpha\delta)c_M))/2(8+\alpha\delta(-5+\alpha\delta)) \quad (6.34)$$

$$p_M^* = (\alpha\delta\big(8+\beta(6-2\alpha\delta)+\alpha\delta(-5+\alpha\delta)\big)+4c_L+4c_M + \alpha\delta(-4+\alpha\delta)(-c_{3D}+c_L+c_M))/2(8+\alpha\delta(-5+\alpha\delta)) \quad (6.35)$$

$$p_{3D}^* = (8+\beta(8-4\alpha\delta)+\alpha\delta(-5+\alpha\delta)+(8-3\alpha\delta)c_{3D}+(-2+\alpha\delta)c_L - 2c_M+\alpha\delta c_M)/\,2(8+\alpha\delta(-5+\alpha\delta)) \quad (6.36)$$

$$q_M^* = \frac{\alpha\beta\delta(-1+\alpha\delta)+\alpha\delta(-2+\alpha\delta)c_{3D}+(2-\alpha\delta)c_L+(2-\alpha\delta)c_M}{\alpha\delta(-1+\alpha\delta)(8+\alpha\delta(-5+\alpha\delta))} \quad (6.37)$$

$$q_{3D}^{*}=\frac{1}{2(-1+\alpha\delta)(8+\alpha\delta(-5+\alpha\delta))}((-1+\alpha\delta)(8+\alpha\delta(-5+\alpha\delta)) + 2\beta(-4+\alpha\delta)) + (8+\alpha\delta(-7+\alpha\delta))c_{3D} - 6c_L - 6c_M - \alpha\delta(-5+\alpha\delta)(c_L+c_M)) \tag{6.38}$$

The maximized profits are

$$\prod\nolimits_{Z}^{*} M(p_M) = \frac{1}{2\alpha\delta(-1+\alpha\delta)(8+\alpha\delta(-5+\alpha\delta))^2}(-2(\alpha\beta\delta(-5+\alpha\delta) - 2\alpha\delta c_{3D} + 2c_L + 2c_M)(\alpha\beta\delta(-1+\alpha\delta) + \alpha\delta(-2+\alpha\delta)c_{3D} + (2-\alpha\delta)c_L + (2-\alpha\delta)c_M) + \alpha\beta\delta(8+\alpha\delta(-5+\alpha\delta))((-1+\alpha\delta)(8+\alpha\delta(-5 + \alpha\delta) + 2\beta(-4+\alpha\delta)) + (8+\alpha\delta(-7+\alpha\delta))c_{3D} - 6c_L - 6c_M - \alpha\delta(-5+\alpha\delta)(c_L+c_M))) \tag{6.39}$$

$$\prod\nolimits_{Z}^{*} L\,(p_L, p_{3D}) = \frac{1}{4\alpha\delta(-1+\alpha\delta)(8+\alpha\delta(-5+\alpha\delta))}(-\alpha\delta(-1 + \alpha\delta)(-8(-1+\beta)^2 + \alpha(5+2\beta(-5+2\beta))\delta + \alpha^2(-1+2\beta)\delta^2) + \alpha\delta(-8+\alpha\delta(9-2\alpha\delta))c_{3D}^2 + (-2+\alpha\delta)(c_L+c_M)(2\alpha\beta\delta(-1 + \alpha\delta) + (2-\alpha\delta)c_L + (2-\alpha\delta)c_M) + 2\alpha\delta c_{3D}(-(-1+\alpha\delta)(8 + \alpha\delta(-5+\alpha\delta) + \beta(-8+3\alpha\delta)) + (-2+\alpha\delta)^2 c_L + (-2+\alpha\delta)^2 c_M)) \tag{6.40}$$

Under the integrated supply chain, the first-order-conditions and the second-order-conditions of $\prod_Z SC(p_M, p_{3D})$ by p_M and p_{3D} in Equation (6.9) are

$$\begin{cases} \dfrac{\partial \prod_Z SC(p_M, p_{3D})}{\partial p_M} = -\dfrac{-\alpha\delta c_{3D} + c_L + c_M + 2\alpha\delta p_{3D} - 2p_M}{\alpha\delta(-1+\alpha\delta)} \\ \dfrac{\partial \prod_Z SC(p_M, p_{3D})}{\partial p_{3D}} = \dfrac{-1+\alpha\delta - c_{3D} + c_L + c_M + 2p_{3D} - 2p_M}{-1+\alpha\delta} \end{cases}$$

$$\begin{cases} \dfrac{\partial \prod_Y^2 SC(p_M, p_{3D})}{\partial p_M^2} = \dfrac{2}{\alpha\delta(-1+\alpha\delta)} < 0 \\ \dfrac{\partial \prod_Y^2 SC(p_M, p_{3D})}{\partial p_{3D}^2} = \dfrac{2}{-1+\alpha\delta} < 0 \\ \dfrac{\partial \prod_Y^2 SC(p_M, p_{3D})}{\partial p_M \partial p_{3D}} = -\dfrac{2}{-1+\alpha\delta} > 0 \\ \dfrac{\partial \prod_Y^2 SC(p_M, p_{3D})}{\partial p_{3D} \partial p_M} = -\dfrac{2}{-1+\alpha\delta} > 0 \end{cases}$$

So, the determinant of the Hessian Matrix can be written as

$$H = \begin{vmatrix} \frac{2}{\alpha\delta(-1+\alpha\delta)} & -\frac{2}{-1+\alpha\delta} \\ -\frac{2}{-1+\alpha\delta} & \frac{2}{-1+\alpha\delta} \end{vmatrix} = \frac{2}{(-1+\alpha)\alpha\delta} \times \frac{2}{(-1+\alpha)\delta} - \left(-\frac{2}{-1+\alpha\delta}\right)^2$$

$$= \frac{4}{\alpha\delta - \alpha^2\delta^2} > 0$$

Therefore, this Hessian Matrix is a negative-definite matrix, the solution to the first-order-conditions gives the unique maximizer of $\prod_Z SC(p_M, p_{3D})$.

$$\begin{cases} \frac{\partial \prod_Z SC(p_M, p_{3D})}{\partial p_M} = -\frac{-\alpha\delta c_{3D} + c_L + c_M + 2\alpha\delta p_{3D} - 2p_M}{\alpha\delta(-1+\alpha\delta)} = 0 \\ \frac{\partial \prod_Z SC(p_M, p_{3D})}{\partial p_{3D}} = \frac{-1 + \alpha\delta - c_{3D} + c_L + c_M + 2p_{3D} - 2p_M}{-1+\alpha\delta} = 0 \end{cases}$$

$$p_M^* = \frac{1}{2}(\alpha\delta + c_L + c_M) \tag{6.41}$$

$$p_{3D}^* = \frac{1}{2}(1 + c_{3D}) \tag{6.42}$$

So,

$$q_M^* = \frac{-\alpha\delta c_{3D} + c_L + c_M}{2\alpha\delta(-1+\alpha\delta)} \tag{6.43}$$

$$q_{3D}^* = \frac{1 - \alpha\delta - c_{3D} + c_L + c_M}{2 - 2\alpha\delta} \tag{6.44}$$

$$\prod\nolimits_Y^* SC(p_M, p_{3D}) = -\frac{\alpha\delta(1-\alpha\delta) + \alpha\delta c_{3D}^2 + (c_L + c_M)^2 - 2\alpha\delta c_{3D}(1 - \alpha\delta + c_L + c_M)}{4\alpha\delta(-1+\alpha\delta)} \tag{6.45}$$

Proof of PROPOSITION *6-10.* Under the decentralized supply chain, we can find out that,

$$\frac{\partial p_L^*}{\partial c_M} = \frac{1}{2}\left(-1 + \frac{\alpha\delta}{8 + \alpha\delta(-5+\alpha\delta)}\right) < 0 \quad \frac{\partial p_M^*}{\partial c_M} = \frac{(-2+\alpha\delta)^2}{2(8+\alpha\delta(-5+\alpha\delta))} > 0 \quad \frac{\partial p_{3D}^*}{\partial c_M} = \frac{-2+\alpha\delta}{2(8+\alpha\delta(-5+\alpha\delta))} < 0$$

$$\frac{\partial p_L^*}{\partial c_L} = \frac{1}{2}\left(1 + \frac{\alpha\delta}{8 + \alpha\delta(-5 + \alpha\delta)}\right) > 0 \qquad \frac{\partial p_M^*}{\partial c_L} = \frac{(-2 + \alpha\delta)^2}{2(8 + \alpha\delta(-5 + \alpha\delta))} > 0 \qquad \frac{\partial p_{3D}^*}{\partial c_L} = \frac{-2 + \alpha\delta}{2(8 + \alpha\delta(-5 + \alpha\delta))} < 0$$

$$\frac{\partial p_L^*}{\partial c_{3D}} = -\frac{\alpha^2\delta^2}{2\left(8 + \alpha\delta(-5 + \alpha\delta)\right)} < 0 \qquad \frac{\partial p_M^*}{\partial c_{3D}} = -\frac{\alpha\delta(-4 + \alpha\delta)}{2\left(8 + \alpha\delta(-5 + \alpha\delta)\right)} > 0 \qquad \frac{\partial p_{3D}^*}{\partial c_{3D}} = \frac{8 - 3\alpha\delta}{2(8 + \alpha\delta(-5 + \alpha\delta))} > 0$$

$$\frac{\partial p_L^*}{\partial \beta} = -\frac{2\alpha\delta}{8 + \alpha\delta(-5 + \alpha\delta)} < 0 \qquad \frac{\partial p_M^*}{\partial \beta} = \frac{\alpha\delta(3 - \alpha\delta)}{8 + \alpha\delta(-5 + \alpha\delta)} > 0 \qquad \frac{\partial p_{3D}^*}{\partial \beta} = \frac{4 - 2\alpha\delta}{8 + \alpha\delta(-5 + \alpha\delta)} > 0$$

and

$$\frac{\partial q_M^*}{\partial c_M} = \frac{2 - \alpha\delta}{\alpha\delta(-1 + \alpha\delta)(8 + \alpha\delta(-5 + \alpha\delta))} < 0 \qquad \frac{\partial q_{3D}^*}{\partial c_M} = -\frac{6 + \alpha\delta(-5 + \alpha\delta)}{2(-1 + \alpha\delta)\left(8 + \alpha\delta(-5 + \alpha\delta)\right)} > 0$$

$$\frac{\partial q_M^*}{\partial c_L} = \frac{2 - \alpha\delta}{\alpha\delta(-1 + \alpha\delta)(8 + \alpha\delta(-5 + \alpha\delta))} < 0 \qquad \frac{\partial q_{3D}^*}{\partial c_L} = -\frac{6 + \alpha\delta(-5 + \alpha\delta)}{2(-1 + \alpha\delta)\left(8 + \alpha\delta(-5 + \alpha\delta)\right)} > 0$$

$$\frac{\partial q_M^*}{\partial c_{3D}} = \frac{-2 + \alpha\delta}{(-1 + \alpha\delta)(8 + \alpha\delta(-5 + \alpha\delta))} > 0 \qquad \frac{\partial q_{3D}^*}{\partial c_{3D}} = \frac{8 + \alpha\delta(-7 + \alpha\delta)}{2(-1 + \alpha\delta)(8 + \alpha\delta(-5 + \alpha\delta))} < 0$$

$$\frac{\partial q_M^*}{\partial \beta} = \frac{1}{8 + \alpha\delta(-5 + \alpha\delta)} > 0 \qquad \frac{\partial q_{3D}^*}{\partial \beta} = \frac{-4 + \alpha\delta}{8 + \alpha\delta(-5 + \alpha\delta)} < 0$$

From Equation (6.39), it is easy to find out that

(1) $\prod_Z^* M(p_M)$ is concave in c_M, therefore, when

$$\frac{\partial \prod_Z^* M(p_M)}{\partial c_M} = \frac{1}{2\alpha\delta(-1 + \alpha\delta)(8 + \alpha\delta(-5 + \alpha\delta))^2}(-\alpha\beta\delta(-1 + \alpha\delta)(-24 + \alpha\delta(28 + \alpha\delta(-9 + \alpha\delta))) - 8\alpha\delta(-2 + \alpha\delta)c_{3D} + 8(-2 + \alpha\delta)c_L + 8(-2 + \alpha\delta)c_M) = 0$$

$$c_M^* = (\alpha\beta\delta(-1+\alpha\delta)\left(-24+\alpha\delta\big(28+\alpha\delta(-9+\alpha\delta)\big)\right) + 8\alpha\delta(-2+\alpha\delta)c_{3D} - 8(-2+\alpha\delta)c_L)/8(-2+\alpha\delta)$$

gives the unique minimum value. However, because $\alpha\delta(c_{3D}+\beta) > c_L + c_M$, therefore, $c_M^* < \alpha\delta(c_{3D}+\beta) - c_L$,

i) when $0 < c_M < c_M^*$, $\prod_Z^* M(p_M)$ decreases in c_M;
ii) when $c_M^* < c_M < \alpha\delta(c_{3D}+\beta) - c_L$; $\prod_Z^* M(p_M)$ increases in c_M.

(2) $\prod_Z^* M(p_M)$ is concave in c_L, therefore, when

$$\frac{\partial \prod_Z^* M(p_M)}{\partial c_L} = \frac{1}{2\alpha\delta(-1+\alpha\delta)(8+\alpha\delta(-5+\alpha\delta))^2}(-\alpha\beta\delta(-1+\alpha\delta)(-24+\alpha\delta(28 + \alpha\delta(-9+\alpha\delta))) - 8\alpha\delta(-2+\alpha\delta)c_{3D} + 8(-2+\alpha\delta)c_L + 8(-2 + \alpha\delta)c_M) = 0$$

$$c_L^* = (\alpha\beta\delta(-1+\alpha\delta)\left(-24+\alpha\delta\big(28+\alpha\delta(-9+\alpha\delta)\big)\right) + 8\alpha\delta(-2+\alpha\delta)c_{3D} - 8(-2+\alpha\delta)c_M)/8(-2+\alpha\delta)$$

gives the unique minimum value. Because $\alpha\delta(c_{3D}+\beta) > c_L + c_M$, therefore, $c_L^* < \alpha\delta(c_{3D}+\beta) - c_M$,

i) when $0 < c_L < c_L^*$, $\prod_Z^* M(p_M)$ decreases in c_L;
ii) when $c_L^* < c_L < \alpha\delta(c_{3D}+\beta) - c_M$; $\prod_Z^* M(p_M)$ increases in c_L.

(3) $\prod_Y^* M(p_M)$ is concave in c_{3D}, therefore, when

$$\frac{\partial \prod_Y^* M(p_M)}{\partial c_{3D}} = \frac{1}{2(-1+\alpha\delta)(8+\alpha\delta(-5+\alpha\delta))^2}(\beta(-1+\alpha\delta)(-64+\alpha\delta(56+\alpha\delta(-13 + \alpha\delta))) + 8\alpha\delta(-2+\alpha\delta)c_{3D} - 8(-2+\alpha\delta)c_L - 8(-2+\alpha\delta)c_M) = 0$$

$$c_{3D}^* = \frac{-\beta(-1+\alpha\delta)(-64+\alpha\delta(56+\alpha\delta(-13+\alpha\delta))) + 8(-2+\alpha\delta)c_L + 8(-2+\alpha\delta)c_M}{8\alpha\delta(-2+\alpha\delta)}$$

gives the minimum value. However, because $\alpha\delta(c_{3D}+\beta) > c_L + c_M$, therefore, $c_{3D}^* > \frac{c_L+c_M}{\alpha\delta} - \beta$,

i) when $\frac{c_L+c_M}{\alpha\delta} - \beta < c_{3D} < c_{3D}^*$, $\prod_Z^* M(p_M)$ decreases in c_{3D};

ii) when $c_{3D}^* < c_{3D} < 1$; $\prod_Z^* M(p_M)$ increases in c_{3D}.

(4) $\prod_Z^* M(p_M)$ is convex in β, therefore, when

$$\frac{\partial \prod_Z^* M(p_M)}{\partial \beta} = \frac{1}{2(8+\alpha\delta(-5+\alpha\delta))^2}((8+\alpha\delta(-5+\alpha\delta))^2 + 4\beta(-32+\alpha\delta(33 + \alpha\delta(-10+\alpha\delta))) + (-64+\alpha\delta(56+\alpha\delta(-13+\alpha\delta)))c_{3D} + 24c_L + 24c_M - \alpha\delta(28+\alpha\delta(-9+\alpha\delta))(c_L+c_M)) = 0$$

$$\beta^* = \frac{1}{4(-32+\alpha\delta(33+\alpha\delta(-10+\alpha\delta)))}(-(8+\alpha\delta(-5+\alpha\delta))^2 + (64-\alpha\delta(56 + \alpha\delta(-13+\alpha\delta)))c_{3D} - 24c_L - 24c_M + \alpha\delta(28+\alpha\delta(-9+\alpha\delta))(c_L + c_M))$$

gives the unique maximum value. However, because $\alpha\delta(c_{3D}+\beta) > c_L + c_M$, therefore, $\prod_Z^* M(p_M)$ decreases in β;

For the logistics vendor's maximized profit (Equation (6.40)) under the decentralized supply chain,

(1) $\prod_Z^* L(p_L, p_{3D})$ is concave in c_M, therefore, when

$$\frac{\partial \prod_Z^* L(p_L, p_{3D})}{\partial c_M} = \frac{(-2+\alpha\delta)(\alpha\beta\delta(-1+\alpha\delta) + \alpha\delta(-2+\alpha\delta)c_{3D} + (2-\alpha\delta)c_L + (2-\alpha\delta)c_M)}{2\alpha\delta(-1+\alpha\delta)(8+\alpha\delta(-5+\alpha\delta))} = 0$$

$$c_M^* = \alpha\delta(\beta + \frac{\beta}{-2+\alpha\delta} + c_{3D}) - c_L$$

gives the unique minimum value. Because $\alpha\delta(c_{3D}+\beta) > c_L + c_M$, therefore, $c_M^* < \alpha\delta(c_{3D}+\beta) - c_L$,

i) when $0 < c_M < c_M^*$, $\prod_Z^* L(p_L, p_{3D})$ decreases in c_M;
ii) when $c_M^* < c_M < \alpha\delta(c_{3D}+\beta) - c_L$, $\prod_Z^* L(p_L, p_{3D})$ increases in c_M.
(2) $\prod_Z^* L(p_L, p_{3D})$ is concave in c_L, therefore, when

$$\frac{\partial \prod_Z^* L(p_L, p_{3D})}{\partial c_L} = \frac{(-2+\alpha\delta)(\alpha\beta\delta(-1+\alpha\delta)+\alpha\delta(-2+\alpha\delta)c_{3D}+(2-\alpha\delta)c_L+(2-\alpha\delta)c_M)}{2\alpha\delta(-1+\alpha\delta)(8+\alpha\delta(-5+\alpha\delta))} = 0$$

$$c_L^* = \alpha\delta(\beta + \frac{\beta}{-2+\alpha\delta} + c_{3D}) - c_M$$

gives the unique minimum value. Because $\alpha\delta(c_{3D}+\beta) > c_L + c_M$, therefore, $c_L^* < \alpha\delta(c_{3D}+\beta) - c_M$,

i) when $0 < c_L < c_L^*$, $\prod_Z^* L(p_L, p_{3D})$ decreases in c_L;
ii) when $c_L^* < c_L < \alpha\delta(c_{3D}+\beta) - c_M$, $\prod_Z^* L(p_L, p_{3D})$ increases in c_L.

(3) $\prod_Z^* L(p_L, p_{3D})$is concave in c_{3D}, therefore, when

$$\frac{\partial \prod_Z^* L(p_L, p_{3D})}{\partial c_{3D}} = \frac{1}{2(-1+\alpha\delta)(8+\alpha\delta(-5+\alpha\delta))}((1-\alpha\delta)(8+\alpha\delta(-5+\alpha\delta)+\beta(-8+3\alpha\delta))+(-8+\alpha\delta(9-2\alpha\delta))c_{3D}+(-2+\alpha\delta)^2c_L+(-2+\alpha\delta)^2c_M) = 0$$

$$c_{3D}^* = \frac{-(-1+\alpha\delta)(8+\alpha\delta(-5+\alpha\delta)+\beta(-8+3\alpha\delta))+(-2+\alpha\delta)^2c_L+(-2+\alpha\delta)^2c_M}{8+\alpha\delta(-9+2\alpha\delta)}$$

gives the unique minimum value. Because $\alpha\delta(c_{3D}+\beta) > c_L + c_M$, therefore, $c_{3D}^* > \frac{c_L+c_M}{\alpha\delta} - \beta$,

i) when $\frac{c_L+c_M}{\alpha\delta} - \gamma < c_{3D} < c_{3D}^*$, $\prod_Z^* L(p_L, p_{3D})$ increases in c_{3D};

ii) when $c_{3D}^* < c_{3D} < 1$, $\prod_Z^* L(p_L, p_{3D})$ decreases in c_{3D}.

(4) $\prod_Z^* L(p_L, p_{3D})$ is concave in β, therefore, when

$$\frac{\partial \prod_Z^* L(p_L, p_{3D})}{\partial \beta} = \frac{-8+\beta(8-4\alpha\delta)+\alpha\delta(5-\alpha\delta)+(8-3\alpha\delta)c_{3D}+(-2+\alpha\delta)c_L-2c_M+\alpha\delta c_M}{2(8+\alpha\delta(-5+\alpha\delta))} = 0$$

$$\beta^* = \frac{-8 + \alpha\delta(5 - \alpha\delta) + (8 - 3\alpha\delta)c_{3D} + (-2 + \alpha\delta)c_L + (-2 + \alpha\delta)c_M}{-8 + 4\alpha\delta}$$

gives the unique minimum value. Because $\alpha\delta(c_{3D} + \beta) > c_L + c_M$, therefore, $\beta^* > \frac{c_L+c_M}{\alpha\delta} - c_{3D}$,

i) when $\frac{c_L+c_M}{\alpha\delta} - c_{3D} < \beta < \beta^*$, $\prod_Y^* L(p_L, p_{3D})$ decreases in β;
ii) when $\beta^* < \beta < 1$, $\prod_Y^* L(p_L, p_{3D})$ increases in β.

Proof of *PROPOSITION* 6-11. Under the integrated supply chain,

$$\frac{\partial p_M^*}{\partial c_M} = \frac{1}{2} \quad \frac{\partial p_{3D}^*}{\partial c_M} = N/A \quad \frac{\partial q_M^*}{\partial c_M} = -\frac{1}{2\alpha\delta - 2\alpha^2\delta} < 0 \quad \frac{\partial q_{3D}^*}{\partial c_M} = \frac{1}{2 - 2\alpha\delta} > 0$$

$$\frac{\partial p_M^*}{\partial c_L} = \frac{1}{2} \quad \frac{\partial p_{3D}^*}{\partial c_L} = \mathrm{N/A} \quad \frac{\partial q_M^*}{\partial c_L} = -\frac{1}{2\alpha\delta - 2\alpha^2\delta^2} < 0 \quad \frac{\partial q_{3D}^*}{\partial c_L} = \frac{1}{2 - 2\alpha\delta} > 0$$

$$\frac{\partial p_M^*}{\partial c_{3D}} = N/A \quad \frac{\partial p_{3D}^*}{\partial c_{3D}} = \frac{1}{2} \quad \frac{\partial q_M^*}{\partial c_{3D}} = \frac{1}{2 - 2\alpha\delta} > 0 \quad \frac{\partial q_{3D}^*}{\partial c_{3D}} = \frac{1}{2 - 2\alpha\delta} < 0$$

$$\frac{\partial p_M^*}{\partial \beta} = N/A \quad \frac{\partial p_{3D}^*}{\partial \beta} = N/A \quad \frac{\partial q_M^*}{\partial \beta} = N/A \quad \frac{\partial q_{3D}^*}{\partial \beta} = N/A$$

For the maximized supply chain profit (Equation (6.45)),

(1) $\prod_Z^* SC(p_M, p_{3D})$ is concave in c_M, therefore, when

$$\frac{\partial \prod_Z^* SC(p_M, p_{3D})}{\partial c_M} = -\frac{-\alpha\delta c_{3D} + c_L + c_M}{2\alpha\delta(-1 + \alpha\delta)} = 0$$

$$c_M^* = \alpha\delta c_{3D} - c_L$$

gives the unique minimum value. Because $\alpha\delta(c_{3D} + \beta) > c_L + c_M$, therefore, $c_M^* < \alpha\delta(c_{3D} + \beta) - c_L$,

i) when $0 < c_M < c_M^*$, $\prod_Z^* SC(p_M, p_{3D})$ decreases in c_M;

ii) when $c_M^* < c_M < \alpha\delta(c_{3D} + \beta) - c_L$, $\prod_Z^* SC(p_M, p_{3D})$ increases in c_M.

(2) $\prod_Z^* SC(p_M, p_{3D})$ is concave in c_L, therefore, when

$$\frac{\partial \prod_Z^* SC(p_M, p_{3D})}{\partial c_L} = -\frac{-\alpha\delta c_{3D} + c_L + c_M}{2\alpha\delta(-1 + \alpha\delta)} = 0$$

$$c_L^* = \alpha\delta c_{3D} - c_M$$

gives the unique minimum value. Because $\alpha\delta(c_{3D} + \beta) > c_L + c_M$, therefore, $c_L^* < \alpha\delta(c_{3D} + \beta) - c_M$,

i) when $0 < c_L < c_L^*$, $\prod_Z^* SC(p_M, p_{3D})$ decreases in c_L;

ii) when $c_L^* < c_L < \alpha\delta(c_{3D} + \beta) - c_M$, $\prod_Z^* SC(p_M, p_{3D})$ increases in c_L.

(3) $\prod_Z^* SC(p_M, p_{3D})$is concave in c_{3D}, therefore, when

$$\frac{\partial \prod_Z^* SC(p_M, p_{3D})}{\partial c_{3D}} = \frac{1 - \alpha\delta - c_{3D} + c_L + c_M}{-2 + 2\alpha\delta} = 0$$

$$c_{3D}^* = 1 - \alpha\delta + c_L + c_M$$

gives the minimum value. However, because $\alpha\delta(c_{3D} + \gamma) > c_L + c_M$, therefore, $c_{3D}^* > \frac{c_L + c_M}{\alpha\delta} - \beta$,

i) when $\frac{c_L + c_M}{\alpha\delta} - \beta < c_{3D} < c_{3D}^*$, $\prod_Z^* SC(p_M, p_{3D})$ decreases in c_{3D};

ii) when $c_{3D}^* < c_{3D} < 1$, $\prod_Z^* SC(p_M, p_{3D})$ increases in c_{3D}.

Proof of *PROPOSITION* 6-13.

Under integrated supply chain,

$$\frac{\partial p_M^*}{\partial \alpha} = \frac{1}{2} \qquad \frac{\partial p_{3D}^*}{\partial \alpha} = \mathrm{N/A} \qquad \frac{\partial p_M^*}{\partial \delta} = \frac{1}{2} \qquad \frac{\partial p_{3D}^*}{\partial \delta} = \mathrm{N/A}$$

Proof of *PROPOSITION* 6-14.

Under the decentralized supply chain, we compare the optimal results of model X and model Y,

1) We compare the traditional manufacturer's profit under two model,

$$\prod_X^* M(p_M, p_{3D}) - \prod_Y^* M(p_M)$$

$$= -\frac{1}{16\alpha\delta(-1+\alpha\delta)}\big(4\alpha\delta c_{3D}^2$$

$$+ (-1+\alpha\delta)(\alpha\delta(-4+3\alpha\delta) + 2\alpha\delta c_L - c_L^2)$$

$$- 2(-1+\alpha\delta)(3\alpha\delta + c_L)c_M + (1+3\alpha\delta)c_M^2 - 8\alpha\delta c_{3D}(1-\alpha\delta + c_M)\big)$$

$$-\frac{2(-2+\alpha)(-\alpha\gamma - \alpha c_{3D} + c_L + c_M)^2}{(-1+\alpha)\alpha(8+(-5+\alpha)\alpha)^2\delta}$$

Therefore, when

i) $\frac{-16\alpha+8\alpha^2}{-64+144\alpha-137\alpha^2+59\alpha^3-11\alpha^4+\alpha^5} < \delta < 1$, $\prod_X^* M(p_M, p_{3D}) - \prod_Y^* M(p_M)$ is concave in c_{3D}, therefore, when

$$\frac{\partial \prod_X^* M(p_M, p_{3D}) - \prod_Y^* M(p_M)}{\partial c_{3D}}$$

$$= \frac{-\frac{8\delta(-1+\alpha\delta + c_{3D} - c_M)}{-1+\alpha\delta} + \frac{64(-2+\alpha)(-\alpha\gamma - \alpha c_{3D} + c_L + c_M)}{(-1+\alpha)(8+(-5+\alpha)\alpha)^2}}{16\delta}$$

$$= 0$$

$$c_{3D}^* = \frac{1}{-8(-2+\alpha)\alpha + (-64+\alpha(144+\alpha(-137+\alpha(59+(-11+\alpha)\alpha))))\delta}(-(-1$$

$$+\alpha\delta)(8(-2+\alpha)\alpha\gamma + (-1+\alpha)(8+(-5+\alpha)\alpha)^2\delta - 8(-2+\alpha)c_L)$$

$$+ (16 - 64\delta + \alpha(-8 + (128 + \alpha(-113 + \alpha(51 + (-11$$

$$+\alpha)\alpha)))\delta))c_M) > 1$$

Therefore, when $c_{3D} = 1$, we can have the unique minimum value of $\prod_X^* M(p_M, p_{3D}) -$ $\prod_Y^* M(p_M, p_{3D})$

$$\prod\nolimits_X^* M(p_M, p_{3D}) - \prod\nolimits_Y^* M(p_M)\,|_{c_{3D}=1}$$

$$= -\frac{32(-2+\alpha)(-\alpha(1+\gamma)+c_L+c_M)^2}{16\alpha\delta(-1+\alpha)(8+(-5+\alpha)\alpha)^2}$$

$$+\frac{(-1+\alpha\delta)c_L^2 - 2(-1+\alpha\delta)c_L(\alpha\delta - c_M) - (1+3\alpha\delta)(-\alpha\delta+c_M)^2}{16\alpha\delta(-1+\alpha\delta)}$$

$$< 0$$

So, when $\prod_X^* M(p_M, p_{3D}) - \prod_Y^* M(p_M) = 0$

$$c_{3D1} = \frac{1}{2\left(8(-2+\alpha)\alpha+64\delta-\alpha\left(144+\alpha\left(-137+\alpha(59+(-11+\alpha)\alpha)\right)\right)\delta\right)}\Big(2(-1+\alpha\delta)(8(-2+\alpha)\alpha\gamma + (-1+\alpha)(8+(-5+\alpha)\alpha)^2\delta) - 16(-2+\alpha)(-1+\alpha\delta)c_L - 2\Big(16-64\delta + \alpha\Big(-8+\Big(128+\alpha\big(-113+\alpha(51+(-11+\alpha)\alpha)\big)\Big)\delta\Big)\Big)c_M - (-1+\alpha)(8 + (-5+\alpha)\alpha)^2\delta(-1+\alpha\delta)\sqrt{T}\Big)$$

$$c_{3D2} = \frac{1}{2(8(-2+\alpha)\alpha+64\delta-\alpha(144+\alpha(-137+\alpha(59+(-11+\alpha)\alpha)))\delta)}(2(-1 + \alpha\delta)(8(-2+\alpha)\alpha\gamma + (-1+\alpha)(8+(-5+\alpha)\alpha)^2\delta) - 16(-2 + \alpha)(-1+\alpha\delta)c_L - 2(16-64\delta+\alpha(-8+(128+\alpha(-113+\alpha(51 + (-11+\alpha)\alpha)))\delta))c_M + (-1+\alpha)(8+(-5+\alpha)\alpha)^2\delta(-1+\alpha\delta)\sqrt{T})$$

$$T=\frac{1}{(-1+\alpha)(8+(-5+\alpha)\alpha)^2\delta^2(-1+\alpha\delta)}(\alpha\delta(-32(-2+\alpha)(1+\gamma)^2+8(-2+\alpha)\alpha(7+8\gamma)\delta+(-64+\alpha(144+\alpha(-73+\alpha(27+(-11+\alpha)\alpha))))\delta^2)+(-8(-2+\alpha)+(112+\alpha(-137+\alpha(59+(-11+\alpha)\alpha)))\delta)c_L^2-2\delta(8(-2+\alpha)(-4+3\alpha+4(-1+\alpha)\gamma)+(-64+\alpha(80+\alpha(-41+\alpha(27+(-11+\alpha)\alpha))))\delta)c_M+(-8(-2+\alpha)+(-16+(-3+\alpha)\alpha(3+(-8+\alpha)\alpha))\delta)c_M^2+2c_L(\delta(8(-2+\alpha)(4+\alpha+4\gamma)-(-64+\alpha(80+(-3+\alpha)\alpha(35+(-8+\alpha)\alpha)))\delta)+(16+48\delta+\alpha(-8+(-3+\alpha)(35+(-8+\alpha)\alpha)\delta))c_M))>0$$

Here, $1>c_{3D1}>\frac{c_L+c_M}{\alpha\delta}-\gamma>0>c_{3D2}$, thus, if $c_{3D}\in\left[\frac{c_L+c_M}{\alpha\delta}-\gamma, c_{3D1}\right]$,

$\prod_X^* M(p_M,p_{3D})<\prod_Y^* M(p_M)$; If $c_{3D}\in[c_{3D1},1]$, $\prod_X^* M(p_M,p_{3D})>\prod_Y^* M(p_M)$.

ii) $0<\delta<\frac{-16\alpha+8\alpha^2}{-64+144\alpha-137\alpha^2+59\alpha^3-11\alpha^4+\alpha^5}$, $\prod_X^* M(p_M,p_{3D})-\prod_Y^* M(p_M)$ is concex in c_{3D}, use the same approach, when

$$\frac{\partial\prod_X^* M(p_M,p_{3D})-\prod_Y^* M(p_M)}{\partial c_{3D}}=\frac{-\frac{8\delta(-1+\alpha\delta+c_{3D}-c_M)}{-1+\alpha\delta}+\frac{64(-2+\alpha)(-\alpha\gamma-\alpha c_{3D}+c_L+c_M)}{(-1+\alpha)(8+(-5+\alpha)\alpha)^2}}{16\delta}=0$$

$$c_{3D}^*=\frac{1}{-8(-2+\alpha)\alpha+(-64+\alpha(144+\alpha(-137+\alpha(59+(-11+\alpha)\alpha))))\delta}(-(-1+\alpha\delta)(8(-2+\alpha)\alpha\gamma+(-1+\alpha)(8+(-5+\alpha)\alpha)^2\delta-8(-2+\alpha)c_L)+(16-64\delta+\alpha(-8+(128+\alpha(-113+\alpha(51+(-11+\alpha)\alpha)))\delta))c_M)<0$$

Therefore, when $c_{3D} = \frac{c_L + c_M}{\alpha\delta} - \gamma$, we can have the unique maximum value of $\prod_X^* M(p_M, p_{3D}) - \prod_Y^* M(p_M)$,

$$\prod_X^* M(p_M, p_{3D}) - \prod_Y^* M(p_M)\,|_{c_{3D}=\frac{c_L+c_M}{\alpha\delta}-\gamma}$$

$$= -\frac{32(-2+\alpha)(-1+\delta)^2(c_L+c_M)^2}{16\alpha\delta(-1+\alpha)(8+(-5+\alpha)\alpha)^2\delta^2}$$

$$-\frac{1}{16\alpha\delta(-1+\alpha\delta)}\Bigg((-1+\alpha\delta)(\alpha\delta(-4+3\alpha\delta)+2\alpha\delta c_L - c_L^2) - 8(-1$$

$$+\alpha\delta - c_M)(\alpha\gamma\delta - c_L - c_M) - 2(-1+\alpha\delta)(3\alpha\delta + c_L)c_M + (1$$

$$+3\alpha\delta)c_M^2 + \frac{4(-\alpha\gamma\delta + c_L + c_M)^2}{\alpha\delta}\Bigg) > 0$$

So, under this case, we do also have $1 > c_{3D1} > \frac{c_L+c_M}{\alpha\delta} - \gamma > 0 > c_{3D2}$, thus, when $c_{3D} \in \left[\frac{c_L+c_M}{\alpha\delta} - \gamma, c_{3D1}\right]$, $\prod_X^* M(p_M, p_{3D}) > \prod_Y^* M(p_M)$; When $c_{3D} \in [c_{3D1}, 1]$, $\prod_X^* M(p_M, p_{3D}) < \prod_Y^* M(p_M)$;

2) We compare the logistics vendor's profits under Model X and Model Y,

$$\prod_X^* L\,(p_L) - \prod_Y^* L\,(p_L, p_{3D})$$

$$= \frac{1}{8\alpha\delta}((-\alpha\delta + c_L + c_M)^2 - \frac{1}{(-1+\alpha)(8+(-5+\alpha)\alpha)}2(\alpha((-8+(9 - 2\alpha)\alpha)\gamma^2 - 2(-1+\alpha)(8+(-5+\alpha)\alpha)\gamma\delta + (-1+\alpha)(8+(-5 + \alpha)\alpha)\delta^2) + \alpha(-8+(9-2\alpha)\alpha)c_{3D}^2 + (-2+\alpha)^2(2\alpha\gamma - c_L - c_M)(c_L + c_M) + 2\alpha c_{3D}((-8+(9-2\alpha)\alpha)\gamma - (-1+\alpha)(8+(-5+\alpha)\alpha)\delta + (-2+\alpha)^2 c_L + (-2+\alpha)^2 c_M)))$$

It is convex in c_{3D}, therefore, when

$$\frac{\partial \prod_X^* L\,(p_L) - \prod_Y^* L\,(p_L, p_{3D})}{\partial c_{3D}}$$

$$= \frac{1}{2(-1+\alpha)(8+(-5+\alpha)\alpha)\delta}((8+\alpha(-9+2\alpha))\gamma + (-1+\alpha)(8 + (-5+\alpha)\alpha)\delta + (8+\alpha(-9+2\alpha))c_{3D} - (-2+\alpha)^2 c_L - (-2+\alpha)^2 c_M) = 0$$

$$c_{3D}^* = \frac{(-8+(9-2\alpha)\alpha)\gamma - (-1+\alpha)(8+(-5+\alpha)\alpha)\delta + (-2+\alpha)^2 c_L + (-2+\alpha)^2 c_M}{8+\alpha(-9+2\alpha)}$$

So, when $c_{3D}^* < 0$, when $c_{3D} = \frac{c_L + c_M}{\alpha\delta} - \gamma$, we can have the maximum value of $\prod_X^* L\,(p_L) - \prod_Y^* L\,(p_L, p_{3D})$

$$\prod_X^* L\,(p_L) - \prod_Y^* L\,(p_L, p_{3D})|_{c_{3D}=\frac{c_L+c_M}{\alpha\delta}-\gamma}$$

$$= \frac{1}{8\alpha\delta}((-\alpha\delta + c_L + c_M)^2 - \frac{1}{(-1+\alpha)(8+(-5+\alpha)\alpha)}2(\alpha((-8+(9$$

$$-2\alpha)\alpha)\gamma^2 - 2(-1+\alpha)(8+(-5+\alpha)\alpha)\gamma\delta + (-1+\alpha)(8+(-5$$

$$+\alpha)\alpha)\delta^2) + (-2+\alpha)^2(2\alpha\gamma - c_L - c_M)(c_L + c_M) + 2\alpha((-8+(9$$

$$-2\alpha)\alpha)\gamma - (-1+\alpha)(8+(-5+\alpha)\alpha)\delta + (-2+\alpha)^2 c_L$$

$$+(-2+\alpha)^2 c_M)(-\gamma + \frac{c_L + c_M}{\alpha\delta}) + \alpha(-8+(9$$

$$-2\alpha)\alpha)(-\gamma + \frac{c_L + c_M}{\alpha\delta})^2)) < 0$$

Thus, $\prod_X^* L\,(p_L) - \prod_Y^* L\,(p_L, p_{3D}) < 0$ always holds.

when $c_{3D}^* > 0$, when $c_{3D} = c_{3D}^*$, we can have the maximum value of $\prod_X^* L\,(p_L) -$ $\prod_Y^* L\,(p_L, p_{3D})$

$$\prod_X^* L(p_L) - \prod_Y^* L(p_L, p_{3D})|_{c_{3D}=c_{3D}^*}$$

$$= \frac{1}{8\alpha\delta}((-\alpha\delta + c_L + c_M)^2 - \frac{1}{(-1+\alpha)(8+(-5+\alpha)\alpha)} 2(\alpha((-8+(9-2\alpha)\alpha)\gamma^2$$

$$- 2(-1+\alpha)(8+(-5+\alpha)\alpha)\gamma\delta + (-1+\alpha)(8+(-5+\alpha)\alpha)\delta^2) + (-2+\alpha)^2(2\alpha\gamma$$

$$- c_L - c_M)(c_L + c_M)$$

$$+ \frac{1}{(8+\alpha(-9+2\alpha))^2}(\alpha(-8+(9$$

$$- 2\alpha)\alpha)((-8+(9-2\alpha)\alpha)\gamma - (-1+\alpha)(8+(-5+\alpha)\alpha)\delta + (-2+\alpha)^2 c_L$$

$$+ (-2+\alpha)^2 c_M)^2)$$

$$+ \frac{2\alpha((-8+(9-2\alpha)\alpha)\gamma - (-1+\alpha)(8+(-5+\alpha)\alpha)\delta + (-2+\alpha)^2 c_L + (-2+\alpha)^2 c_l}{8+\alpha(-9+2\alpha)}$$

$$< 0$$

So, in this case, $\prod_X^* L(p_L) - \prod_Y^* L(p_L, p_{3D}) < 0$ is always true. In summary, the logistics vendor's profit in the Model Y is always lower than Model X.

3) We compare the optimal prices in the two models,

$$p_{LX}^* - p_{LY}^* = \frac{\alpha(\alpha\gamma + \alpha c_{3D} - c_L - c_M)}{2(8+(-5+\alpha)\alpha)} > 0$$

Then,

$$p_{MX}^* - p_{MY}^*$$

$$= \frac{\alpha(2(-4+\alpha)\gamma + (8+(-5+\alpha)\alpha)\delta + 2(-4+\alpha)c_{3D} - (-3+\alpha)c_L - (-3+\alpha)c_M)}{4(8+(-5+\alpha)\alpha)}$$

If $\frac{c_L+c_M}{\alpha\delta} - \gamma < c_{3D} < \frac{-2(-4+\alpha)\gamma-(8+(-5+\alpha)\alpha)\delta+(-3+\alpha)c_L+(-3+\alpha)c_M}{2(-4+\alpha)}$, $p_{MX}^* - p_{MY}^* > 0$

If $1 > c_{3D} > \frac{-2(-4+\alpha)\gamma-(8+(-5+\alpha)\alpha)\delta+(-3+\alpha)c_L+(-3+\alpha)c_M}{2(-4+\alpha)}$, $p_{MX}^* - p_{MY}^* < 0$

$$p_{3DX}^* - p_{3DY}^* = \frac{1}{4(8+(-5+\alpha)\alpha)}(2(8-8\gamma+\alpha(-5+\alpha+3\gamma)) + (-2+\alpha)(8 + (-5+\alpha)\alpha)\delta + 2(-2+\alpha)\alpha c_{3D} + (-4+\alpha)(-3+\alpha)c_L - (4 + (-3+\alpha)\alpha)c_M)$$

$\frac{c_L+c_M}{\alpha\delta} - \gamma < c_{3D} <$

$-\frac{2(8-8\gamma+\alpha(-5+\alpha+3\gamma))+(-2+\alpha)(8+(-5+\alpha)\alpha)\delta+(-4+\alpha)(-3+\alpha)c_L-(4+(-3+\alpha)\alpha)c_M}{2(-2+\alpha)\alpha}$, $p_{3DX}^* - p_{3DY}^* > 0$;

If $1 > c_{3D} > -\frac{2(8-8\gamma+\alpha(-5+\alpha+3\gamma))+(-2+\alpha)(8+(-5+\alpha)\alpha)\delta+(-4+\alpha)(-3+\alpha)c_L-(4+(-3+\alpha)\alpha)c_M}{2(-2+\alpha)\alpha}$,

$p_{3DX}^* - p_{3DY}^* < 0$.

4) We compare the demands in the two models

$$q_{MX}^* - q_{MY}^* = \frac{1}{4\alpha\delta}\left(-\frac{4(-2+\alpha)(\alpha\gamma+\alpha c_{3D}-c_L-c_M)}{(-1+\alpha)(8+(-5+\alpha)\alpha)} + \frac{-2\alpha\delta c_{3D}-(-1+\alpha\delta)(\alpha\delta+c_L)+(1+\alpha\delta)c_M}{-1+\alpha\delta}\right) < 0$$

$$q_{3DX}^* - q_{3DY}^* = \frac{1}{2(-1+\alpha)(8+(-5+\alpha)\alpha)\delta(-1+\alpha\delta)}((8-8\delta+\alpha(-7+\alpha + (5+\alpha)\delta))c_{3D} + (-1+\alpha\delta)(-(8+(-7+\alpha)\alpha)\gamma + (-3+\alpha)(-2 + \alpha)c_L) + (-6+\alpha(5+\alpha(-1+\delta)-7\delta)+8\delta)c_M)$$

Then, we can easily obtain: i) if $0 < \delta < \frac{-8+7\alpha-\alpha^2}{-8+5\alpha+\alpha^2}$, $q_{3DX}^* - q_{3DY}^* < 0$; ii) if $\frac{-8+7\alpha-\alpha^2}{-8+5\alpha+\alpha^2} < \delta < 1$, $q_{3DX}^* - q_{3DY}^* > 0$.

Proof of *PROPOSITION* 6-15.

Under the integrated supply chain, we compare the optimal results of model X and model Y at supply chain level,

1) We compare the integrated supply chain's profit under two model,

$$\prod_X^* SC(p_M, p_{3D}) - \prod_Y^* SC(p_M, p_{3D})$$

$$= \frac{(-1+\delta)c_{3D}^2}{4(-1+\alpha)\delta(-1+\alpha\delta)} - \frac{c_{3D}((-1+\alpha\delta)c_L + (-1+\delta)c_M)}{2(-1+\alpha)\delta(-1+\alpha\delta)}$$

$$+ \frac{1}{4(-1+\alpha)\delta(-1+\alpha\delta)}((-1+\alpha\delta)c_L^2 - 2(-1+\alpha\delta)c_L((-1+\alpha)\delta$$

$$- c_M) - (-1+\delta)((-1+\alpha)\delta(-1+\alpha\delta) - c_M^2))$$

Which is convex in c_{3D}, thus,

$$\frac{\partial \prod_X^* SC(p_M, p_{3D}) - \prod_Y^* SC(p_M, p_{3D})}{\partial c_{3D}} = \frac{(-1+\delta)c_{3D} + c_L + c_M - \delta(\alpha c_L + c_M)}{2(-1+\alpha)\delta(-1+\alpha\delta)} = 0$$

$$c_{3D}^* = \frac{(-1+\alpha\delta)c_L}{-1+\delta} + c_M > \frac{c_L + c_M}{\alpha\delta} - \gamma$$

Therefore, when $c_{3D} = c_{3D}^*$, we can have the unique maximum value of $\prod_X^* SC(p_M, p_{3D}) - \prod_Y^* SC(p_M, p_{3D}) = -\frac{(-1+\delta+c_L)^2}{4(-1+\delta)} > 0$.

Then, set $\prod_X^* SC(p_M, p_{3D}) - \prod_Y^* SC(p_M, p_{3D}) = 0$,

$$c_{3D1} = \frac{(-1+\alpha\delta)c_L - \frac{(-1+\delta+c_L)^2}{\sqrt{K}} + (-1+\delta)c_M}{-1+\delta}$$

$$c_{3D2} = \frac{(-1+\alpha\delta)c_L + \frac{(-1+\delta+c_L)^2}{\sqrt{K}} + (-1+\delta)c_M}{-1+\delta}$$

Where $K = \frac{(-1+\delta+c_L)^2}{(-1+\alpha)\delta(-1+\alpha\delta)}$.

i) If $\frac{-1+c_L-c_L^2+c_M-c_Lc_M}{-1+c_M} < \delta < 1$, and $\frac{c_L+c_M}{\gamma\delta} < \alpha < \frac{-1+\delta+c_L+c_M-\delta c_M}{\delta c_L}$, $c_{3D}^* > 1$, then, $c_{3D2} < 0 < \frac{c_L+c_M}{\alpha\delta} - \gamma < 1 < c_{3D}^* < c_{3D1}$, therefore, we can always have $\prod_X^* SC(p_M, p_{3D}) - \prod_Y^* SC(p_M, p_{3D}) > 0$

ii) If $\frac{c_L+c_M-c_Lc_M-c_M^2}{1-c_L+c_L^2-c_M+c_Lc_M} < \alpha < 1$, and $\frac{c_L+c_M}{\alpha\gamma} < \delta < \frac{-1+c_L+c_M}{-1+\alpha c_L+c_M}$, $c_{3D}^* < 1$, then $0 < \frac{c_L+c_M}{\alpha\delta} - \gamma < c_{3D2} < c_{3D1} < 1$, therefore,

   a. When $\frac{c_L+c_M}{\alpha\delta} - \gamma < c_{3D} < c_{3D2}$, $\prod_X^* SC(p_M, p_{3D}) - \prod_Y^* SC(p_M, p_{3D}) < 0$;
   b. When $c_{3D2} < c_{3D} < c_{3D1}$, $\prod_X^* SC(p_M, p_{3D}) - \prod_Y^* SC(p_M, p_{3D}) > 0$;
   c. When $c_{3D1} < c_{3D} < 1$, $\prod_X^* SC(p_M, p_{3D}) - \prod_Y^* SC(p_M, p_{3D}) < 0$.

2) Now we compare the optimal prices,

$$p_{MX}^* - p_{MY}^* = 0$$

$$p_{3DX}^* - p_{3DY}^* = \frac{1}{2}(1-\delta+c_L)$$

Therefore, if $1 + c_L > \delta$, $p_{3DX}^* - p_{3DY}^* > 0$; if $1 + c_L < \delta$, $p_{3DX}^* - p_{3DY}^* < 0$. Here, because $0 < \delta < 1$, thus, we can always have $p_{3DX}^* - p_{3DY}^* > 0$.

3) We compare the optimal market demand of two product under Model X and Model Y,

$$q_{MX}^* - q_{MY}^* = \frac{(-1+\delta)c_{3D} + c_L + c_M - \delta(\alpha c_L + c_M)}{2(-1+\alpha)\delta(-1+\alpha\delta)} < 0$$

$$q_{3DX}^* - q_{3DY}^* = \frac{-(-1+\delta)c_{3D} + (-1+\alpha\delta)c_L + (-1+\delta)c_M}{2(-1+\alpha)\delta(-1+\alpha\delta)} > 0$$

Proof of *PROPOSITION* 6-16.

Under the decentralized supply chain, we compare the optimal results of model X and model Z,

1) We compare the traditional manufacturer's profit under two models,

$$\prod\nolimits_X^* M(p_M, p_{3D}) - \prod\nolimits_Z^* M(p_M)$$

$$= -\frac{1}{16\alpha\delta(-1+\alpha\delta)}(4\alpha\delta c_{3D}^2 + (-1+\alpha\delta)(\alpha\delta(-4+3\alpha\delta) + 2\alpha\delta c_L - c_L^2) - 2(-1+\alpha\delta)(3\alpha\delta + c_L)c_M + (1+3\alpha\delta)c_M^2 - 8\alpha\delta c_{3D}(1-\alpha\delta + c_M) + \frac{1}{(8+\alpha\delta(-5+\alpha\delta))^2}8(-2(\alpha\beta\delta(-5+\alpha\delta) - 2\alpha\delta c_{3D} + 2c_L + 2c_M)(\alpha\beta\delta(-1+\alpha\delta) + \alpha\delta(-2+\alpha\delta)c_{3D} + (2-\alpha\delta)c_L + (2-\alpha\delta)c_M) + \alpha\beta\delta(8+\alpha\delta(-5+\alpha\delta))((-1+\alpha\delta)(8+\alpha\delta(-5+\alpha\delta) + 2\beta(-4+\alpha\delta)) + (8+\alpha\delta(-7+\alpha\delta))c_{3D} - 6c_L - 6c_M - \alpha\delta(-5+\alpha\delta)(c_L + c_M))))$$

Which is concave in c_{3D},

$$c_{3D1} = \frac{1}{2(64+\alpha\delta(-96+\alpha\delta(49+\alpha\delta(-10+\alpha\delta))))}\Big(-128\beta + 240\alpha\beta\delta - 138\alpha^2\beta\delta^2 + 28\alpha^3\beta\delta^3 - 2\alpha^4\beta\delta^4 + 2\big(8+\alpha\delta(-5+\alpha\delta)\big)^2 - 2\alpha\delta\big(8+\alpha\delta(-5+\alpha\delta)\big)^2 - 32c_L + 16\alpha\delta c_L - 32c_M + 16\alpha\delta c_M + 2\big(8+\alpha\delta(-5+\alpha\delta)\big)^2 c_M - (8+\alpha\delta(-5+\alpha\delta))^2\sqrt{T}\Big)$$

$$c_{3D2} = \frac{1}{2(64 + \alpha\delta(-96 + \alpha\delta(49 + \alpha\delta(-10 + \alpha\delta))))}\big(-128\beta + 240\alpha\beta\delta$$

$$- 138\alpha^2\beta\delta^2 + 28\alpha^3\beta\delta^3 - 2\alpha^4\beta\delta^4 + 2(8 + \alpha\delta(-5 + \alpha\delta))^2$$

$$- 2\alpha\delta(8 + \alpha\delta(-5 + \alpha\delta))^2 - 32c_L + 16\alpha\delta c_L - 32c_M + 16\alpha\delta c_M$$

$$+ 2(8 + \alpha\delta(-5 + \alpha\delta))^2 c_M + (8 + \alpha\delta(-5 + \alpha\delta))^2\sqrt{T}\big)$$

$$T = \frac{1}{(8 + \alpha\delta(-5 + \alpha\delta))^2}((128 + \alpha\delta(-5 + \alpha\delta)(29 + \alpha\delta(-6 + \alpha\delta)))c_L^2 - 2(-1$$

$$+ \alpha\delta)c_L(\alpha\delta(-64 + \alpha\delta(49 + \alpha\delta(-10 + \alpha\delta))) - 4\beta(-40 + \alpha\delta(36$$

$$+ \alpha\delta(-9 + \alpha\delta))) + (64 - \alpha\delta(49 + \alpha\delta(-10 + \alpha\delta)))c_M) + (-1$$

$$+ \alpha\delta)(-32\alpha\beta\delta(-3 + \alpha\delta)(-2 + \alpha\delta) + \alpha^3\delta^3(17 + \alpha\delta(-10 + \alpha\delta))$$

$$+ 4\beta^2(64 + \alpha\delta(-68 + \alpha\delta(23 - 3\alpha\delta))) + c_M(2(16\beta(-3 + \alpha\delta)(-2$$

$$+ \alpha\delta) - \alpha^2\delta^2(17 + \alpha\delta(-10 + \alpha\delta))) + \alpha\delta(17 + \alpha\delta(-10 + \alpha\delta))c_M)))$$

And when

$$\frac{\partial \prod_X^* M(p_M, p_{3D}) - \prod_Z^* M(p_M)}{\partial c_{3D}}$$

$$= -\frac{1}{2(-1 + \alpha\delta)}\Bigg(-1 + \alpha\delta + c_{3D} - c_M$$

$$+ \frac{1}{(8 + \alpha\delta(-5 + \alpha\delta))^2}(\beta(-1 + \alpha\delta)(-64 + \alpha\delta(56 + \alpha\delta(-13 + \alpha\delta)))$$

$$+ 8\alpha\delta(-2 + \alpha\delta)c_{3D} - 8(-2 + \alpha\delta)c_L - 8(-2 + \alpha\delta)c_M)\Bigg) = 0$$

$$c_{3D}^* = \frac{1}{64 + \alpha\delta(-96 + \alpha\delta(49 + \alpha\delta(-10 + \alpha\delta)))}(-(-1 + \alpha\delta)((8 + \alpha\delta(-5 + \alpha\delta))^2$$

$$+ \beta(-64 + \alpha\delta(56 + \alpha\delta(-13 + \alpha\delta)))) + 8(-2 + \alpha\delta)c_L + (48$$

$$+ \alpha\delta(-72 + \alpha\delta(41 + \alpha\delta(-10 + \alpha\delta))))c_M)$$

Gives the unique minimum value. Because $\frac{c_L+c_M}{\alpha\delta} - c_{3D} < \beta < 1$, therefore $0 < c_{3D}^* < 1$, and $\frac{c_L+c_M}{\alpha\delta} - \beta < c_{3D1} < 1 < c_{3D2}$, thus,

$$\prod\nolimits_X^* M(p_M, p_{3D}) - \prod\nolimits_Z^* M(p_M)\,|_{c_{3D}=c_{3D}^*}$$

$$= \frac{1}{16(-1+\alpha\delta)(64+\alpha\delta(-96+\alpha\delta(49+\alpha\delta(-10+\alpha\delta))))}((128 + \alpha\delta(-5+\alpha\delta)(29+\alpha\delta(-6+\alpha\delta)))c_L^2 - 2(-1+\alpha\delta)c_L(\alpha\delta(-64 + \alpha\delta(49+\alpha\delta(-10+\alpha\delta))) - 4\beta(-40+\alpha\delta(36+\alpha\delta(-9+\alpha\delta))) + (64-\alpha\delta(49+\alpha\delta(-10+\alpha\delta)))c_M) + (-1+\alpha\delta)(-32\alpha\beta\delta(-3 + \alpha\delta)(-2+\alpha\delta) + \alpha^3\delta^3(17+\alpha\delta(-10+\alpha\delta)) + 4\beta^2(64+\alpha\delta(-68 + \alpha\delta(23-3\alpha\delta))) + c_M(2(16\beta(-3+\alpha\delta)(-2+\alpha\delta) - \alpha^2\delta^2(17 + \alpha\delta(-10+\alpha\delta))) + \alpha\delta(17+\alpha\delta(-10+\alpha\delta))c_M)))$$

Here,

i) if $\prod_X^* M(p_M, p_{3D}) - \prod_Z^* M(p_M)\,|_{c_{3D}=c_{3D}^*} > 0$, that is $\beta > \beta^*$, then $\prod_X^* M(p_M, p_{3D}) - \prod_Z^* M(p_M) > 0$;

ii) If $\prod_X^* M(p_M, p_{3D}) - \prod_Z^* M(p_M)\,|_{c_{3D}=c_{3D}^*} < 0$, that is $\frac{c_L+c_M}{\alpha\delta} - c_{3D} < \beta < \beta^*$,

   a. then $\frac{c_L+c_M}{\alpha\delta} - \beta < c_{3D} < c_{3D1}$, then $\prod_X^* M(p_M, p_{3D}) - \prod_Z^* M(p_M) > 0$;

   b. $c_{3D1} < c_{3D} < 1$, then $\prod_X^* M(p_M, p_{3D}) - \prod_Z^* M(p_M) < 0$.

Set

$$\prod\nolimits_X^* M(p_M, p_{3D}) - \prod\nolimits_Z^* M(p_M)\,|_{c_{3D}=c_{3D}^*} = 0$$

$$\beta^{*} = \frac{1}{2(-1+\alpha\delta)(-64+\alpha\delta(68+\alpha\delta(-23+3\alpha\delta)))}\big(-8\alpha\delta(-3+\alpha\delta)(-2 + \alpha\delta)(-1+\alpha\delta) + 2(-1+\alpha\delta)(-40+\alpha\delta(36+\alpha\delta(-9+\alpha\delta)))c_L + 8(-3+\alpha\delta)(-2+\alpha\delta)(-1+\alpha\delta)c_M + \sqrt{}((-1+\alpha\delta)(64+\alpha\delta(-96 + \alpha\delta(49+\alpha\delta(-10+\alpha\delta))))((-228+\alpha\delta(219+\alpha\delta(-62+7\alpha\delta)))c_L^2 - 2(-1+\alpha\delta)^2(-4+3\alpha\delta)c_L(\alpha\delta-c_M) + (-1+\alpha\delta)(36+\alpha\delta(-23 + 3\alpha\delta))(-\alpha\delta+c_M)^2))\big)$$

$$\beta^{**} = -\frac{1}{2(-1+\alpha\delta)(-64+\alpha\delta(68+\alpha\delta(-23+3\alpha\delta)))}\big(-8\alpha\delta(-3+\alpha\delta)(-2 + \alpha\delta)(-1+\alpha\delta) + 2(-1+\alpha\delta)(-40+\alpha\delta(36+\alpha\delta(-9+\alpha\delta)))c_L + 8(-3+\alpha\delta)(-2+\alpha\delta)(-1+\alpha\delta)c_M + \sqrt{}((-1+\alpha\delta)(64+\alpha\delta(-96 + \alpha\delta(49+\alpha\delta(-10+\alpha\delta))))((-228+\alpha\delta(219+\alpha\delta(-62+7\alpha\delta)))c_L^2 - 2(-1+\alpha\delta)^2(-4+3\alpha\delta)c_L(\alpha\delta-c_M) + (-1+\alpha\delta)(36+\alpha\delta(-23 + 3\alpha\delta))(-\alpha\delta+c_M)^2))\big)$$

Here, we can easily find out $\beta^{*} > \beta^{**}$ by comparison.

2) Now we compare the logistics vendor's profit,

$$\prod_{X}^{*} L(p_L) - \prod_{Z}^{*} L(p_L, p_{3D})$$

$$= \frac{1}{8}(-2 + 4\beta + \alpha\delta + \frac{8\beta^2(-2 + \alpha\delta)}{8 + \alpha\delta(-5 + \alpha\delta)}$$

$$+ \frac{1}{(-1 + \alpha\delta)(8 + \alpha\delta(-5 + \alpha\delta))}(2(8 + \alpha\delta(-9 + 2\alpha\delta))c_{3D}^2$$

$$+ 4c_{3D}((-1 + \alpha\delta)(8 + \alpha\delta(-5 + \alpha\delta) + \beta(-8 + 3\alpha\delta))$$

$$- (-2 + \alpha\delta)^2 c_L - (-2 + \alpha\delta)^2 c_M) + (c_L + c_M)(-2(-1 + \alpha\delta)(8$$

$$+ \alpha\delta(-5 + \alpha\delta) + 2\beta(-2 + \alpha\delta)) + (5 + \alpha\delta(-4 + \alpha\delta))c_L + (5$$

$$+ \alpha\delta(-4 + \alpha\delta))c_M)))$$

Which is convex in c_{3D},

$$c_{3D1}$$

$$= \frac{1}{2(8 + \alpha\delta(-9 + 2\alpha\delta))}(2(-2 + \alpha\delta)^2 c_L + 2(-2 + \alpha\delta)^2 c_M - (-1 + \alpha\delta)(2\beta(-8$$

$$+ 3\alpha\delta) + (8 + \alpha\delta(-5 + \alpha\delta))(2$$

$$+ \sqrt{2}\sqrt{\frac{\alpha\delta(\alpha\delta + 2\beta(-4 + \beta + 2\alpha\delta)) - (-8\beta + 2\alpha\delta + 4\alpha\beta\delta - c_L - c_M)(c_L + c_M)}{(-1 + \alpha\delta)(8 + \alpha\delta(-5 + \alpha\delta))}})))$$

$$c_{3D2}$$

$$= \frac{1}{2(8 + \alpha\delta(-9 + 2\alpha\delta))}(2(-2 + \alpha\delta)^2 c_L + 2(-2 + \alpha\delta)^2 c_M + (-1 + \alpha\delta)(\beta(16$$

$$- 6\alpha\delta) + (8 + \alpha\delta(-5 + \alpha\delta))(-2$$

$$+ \sqrt{2}\sqrt{\frac{\alpha\delta(\alpha\delta + 2\beta(-4 + \beta + 2\alpha\delta)) - (-8\beta + 2\alpha\delta + 4\alpha\beta\delta - c_L - c_M)(c_L + c_M)}{(-1 + \alpha\delta)(8 + \alpha\delta(-5 + \alpha\delta))}})))$$

If $\frac{\alpha\delta(\alpha\delta+2\beta(-4+\beta+2\alpha\delta))-(-8\beta+2\alpha\delta+4\alpha\beta\delta-c_L-c_M)(c_L+c_M)}{(-1+\alpha\delta)(8+\alpha\delta(-5+\alpha\delta))} < 0$, which is $\alpha\delta\big(\alpha\delta + 2\beta(-4+\beta+2\alpha\delta)\big) - (-8\beta + 2\alpha\delta + 4\alpha\beta\delta - c_L - c_M)(c_L + c_M) > 0$, then there is no real root, then $\prod_X^* L(p_L) - \prod_Z^* L(p_L, p_{3D}) < 0$ is always hold.

If $\frac{\alpha\delta(\alpha\delta+2\beta(-4+\beta+2\alpha\delta))-(-8\beta+2\alpha\delta+4\alpha\beta\delta-c_L-c_M)(c_L+c_M)}{(-1+\alpha\delta)(8+\alpha\delta(-5+\alpha\delta))} > 0$, that is $\alpha\delta\big(\alpha\delta + 2\beta(-4+\beta+2\alpha\delta)\big) - (-8\beta + 2\alpha\delta + 4\alpha\beta\delta - c_L - c_M)(c_L + c_M) < 0$.

Here, we set $\frac{\alpha\delta(\alpha\delta+2\beta(-4+\beta+2\alpha\delta))-(-8\beta+2\alpha\delta+4\alpha\beta\delta-c_L-c_M)(c_L+c_M)}{(-1+\alpha\delta)(8+\alpha\delta(-5+\alpha\delta))} = 0$, we can have

$$\beta^* = -\frac{1}{2\alpha\delta}\Big(2\alpha^2\delta^2 + 4(c_L + c_M) - 2\alpha\delta(2 + c_L + c_M) + \sqrt{2}\sqrt{(8+\alpha\delta(-9+2\alpha\delta))(-\alpha\delta + c_L + c_M)^2}\Big)$$

$$\beta^{**} = \frac{1}{2\alpha\delta}\Big(-2\alpha^2\delta^2 - 4(c_L + c_M) + 2\alpha\delta(2 + c_L + c_M) + \sqrt{2}\sqrt{(8+\alpha\delta(-9+2\alpha\delta))(-\alpha\delta + c_L + c_M)^2}\Big)$$

It is easy to find our $\frac{c_L+c_M}{\alpha\delta} - c_{3D} < \beta^* < 1 < \beta^{**}$, therefore,

when $\beta^* < \beta < 1$, $\alpha\delta\big(\alpha\delta + 2\beta(-4+\beta+2\alpha\delta)\big) - (-8\beta + 2\alpha\delta + 4\alpha\beta\delta - c_L - c_M)(c_L + c_M) > 0$, then $\prod_X^* L(p_L) - \prod_Z^* L(p_L, p_{3D}) < 0$;

when, $\frac{c_L+c_M}{\alpha\delta} - c_{3D} < \beta < \beta^*$, $\alpha\delta\big(\alpha\delta + 2\beta(-4+\beta+2\alpha\delta)\big) - (-8\beta + 2\alpha\delta + 4\alpha\beta\delta - c_L - c_M)(c_L + c_M) < 0$. In this case, we can have $c_{3D1} > c_{3D2}$. And when

$$\frac{\partial \prod_X^* M(p_M, p_{3D}) - \prod_Z^* M(p_M)}{\partial c_{3D}}$$

$$= -\frac{1}{2(-1+\alpha\delta)(8+\alpha\delta(-5+\alpha\delta))}((1-\alpha\delta)(8+\alpha\delta(-5+\alpha\delta)) + \beta(-8+3\alpha\delta)) + (-8+\alpha\delta(9-2\alpha\delta))c_{3D} + (-2+\alpha\delta)^2 c_L + (-2+\alpha\delta)^2 c_M) = 0$$

$$c_{3D}^* = \frac{-(-1+\alpha\delta)(8+\alpha\delta(-5+\alpha\delta)+\beta(-8+3\alpha\delta)) + (-2+\alpha\delta)^2 c_L + (-2+\alpha\delta)^2 c_M}{8+\alpha\delta(-9+2\alpha\delta)}$$

We can have the maximum value of $\prod_X^* L(p_L) - \prod_Z^* L(p_L, p_{3D})$,

$$\prod\nolimits_X^* L(p_L) - \prod\nolimits_Z^* L(p_L, p_{3D})\,|_{c_{3D}=c_{3D}^*} = \frac{-\alpha\delta(\alpha\delta+2\beta(-4+\beta+2\alpha\delta)) + (-8\beta+2\alpha\delta+4\alpha\beta\delta-c_L-c_M)(c_L+c_M)}{8(8+\alpha\delta(-9+2\alpha\delta))} > 0$$

Meanwhile,

$$\prod\nolimits_X^* L(p_L) - \prod\nolimits_Z^* L(p_L, p_{3D})\,|_{c_{3D}=1}$$

$$= \frac{1}{8(-1+\alpha\delta)(8+\alpha\delta(-5+\alpha\delta))}(8\beta^2(-2+\alpha\delta)(-1+\alpha\delta) + 4\alpha\beta\delta(-2+\alpha\delta)(-1+\alpha\delta) + \alpha^2\delta^2(5+\alpha\delta(-4+\alpha\delta)) + (c_L + c_M)(-4\beta(-2+\alpha\delta)(-1+\alpha\delta) - 2\alpha\delta(5+\alpha\delta(-4+\alpha\delta)) + (5 + \alpha\delta(-4+\alpha\delta))c_L + (5+\alpha\delta(-4+\alpha\delta))c_M)) < 0$$

and

$$\prod_X^* L(p_L) - \prod_Z^* L(p_L, p_{3D}) |_{c_{3D}=\frac{c_L+c_M}{\alpha\delta}-\beta}$$

$$= \frac{1}{8\alpha^2\delta^2(-1+\alpha\delta)(8+\alpha\delta(-5+\alpha\delta))}(\alpha^2\delta^2(16+\alpha\delta(-34+2\beta^2 + \alpha\delta(25+\alpha\delta(-8+\alpha\delta)))) - (-2+\alpha\delta)(-1+\alpha\delta)(8+\alpha\delta(-5 + \alpha\delta))(2\alpha\delta - c_L - c_M)(c_L + c_M)) < 0$$

Therefore,

a. $\frac{c_L+c_M}{\alpha\delta} - \beta < c_{3D} < c_{3D2}$ or $c_{3D1} < c_{3D} < 1$, then $\prod_X^* L\,(p_L) - \prod_Y^* L\,(p_L, p_{3D}) < 0$;

b. $c_{3D2} < c_{3D} < c_{3D2}$, then $\prod_X^* L\,(p_L) - \prod_Y^* L\,(p_L, p_{3D}) > 0$.

3) Last, we compare the optimal decisions in following,

$$p_{LX}^* - p_{LZ}^* = \frac{\alpha\delta(4\beta + \alpha\delta c_{3D} - c_L - c_M)}{2(8+\alpha\delta(-5+\alpha\delta))}$$

Then,

if $\beta > Max\left[\frac{1}{4}(-\alpha\delta c_{3D} + c_L + c_M), \frac{c_L+c_M}{\alpha\delta} - c_{3D}\right]$, then $p_{LX}^* - p_{LZ}^* > 0$;

if $\frac{c_L+c_M}{\alpha\delta} - c_{3D} < \beta < Max\left[\frac{1}{4}(-\alpha\delta c_{3D} + c_L + c_M), \frac{c_L+c_M}{\alpha\delta} - c_{3D}\right]$, then $p_{LX}^* - p_{LZ}^* < 0$.We annotate $\beta_1 = \frac{1}{4}(-\alpha\delta c_{3D} + c_L + c_M)$.

$$p_{MX}^* - p_{MZ}^* = \frac{\alpha\delta(8+\alpha\delta(-5+\alpha\delta) + 4\beta(-3+\alpha\delta) + 2(-4+\alpha\delta)c_{3D} + 3c_L + 3c_M - \alpha\delta(c_L+c_M)}{4(8+\alpha\delta(-5+\alpha\delta))}$$

If $\beta > \frac{-8+\alpha\delta(5-\alpha\delta)+(8-2\alpha\delta)c_{3D}+(-3+\alpha\delta)c_L+(-3+\alpha\delta)c_M}{4(-3+\alpha\delta)}$, $p_{MX}^* - p_{MZ}^* > 0$;

If $\beta < \frac{-8+\alpha\delta(5-\alpha\delta)+(8-2\alpha\delta)c_{3D}+(-3+\alpha\delta)c_L+(-3+\alpha\delta)c_M}{4(-3+\alpha\delta)}$, $p_{MX}^* - p_{MZ}^* < 0$.

We annotate $\beta_2 = \frac{-8+\alpha\delta(5-\alpha\delta)+(8-2\alpha\delta)c_{3D}+(-3+\alpha\delta)c_L+(-3+\alpha\delta)c_M}{4(-3+\alpha\delta)}$.

$$p_{3DX}^* - p_{3DZ}^* = \frac{1}{4(8+\alpha\delta(-5+\alpha\delta))}(8\beta(-2+\alpha\delta) + \alpha\delta(8+\alpha\delta(-5+\alpha\delta)) + 2\alpha\delta(-2+\alpha\delta)c_{3D} - 4c_M + (-3+\alpha\delta)((-4+\alpha\delta)c_L - \alpha\delta c_M))$$

If $\beta > Max\left[-\frac{\alpha\delta(8+\alpha\delta(-5+\alpha\delta))+2\alpha\delta(-2+\alpha\delta)c_{3D}-4c_M+(-3+\alpha\delta)((-4+\alpha\delta)c_L-\alpha\delta c_M)}{8(-2+\alpha\delta)}, \frac{c_L+c_M}{\alpha\delta} - c_{3D}\right]$,

$p_{3DX}^* - p_{3DZ}^* > 0$;

$\frac{c_L+c_M}{\alpha\delta} - c_{3D} < \beta <$

$Max\left[-\frac{\alpha\delta(8+\alpha\delta(-5+\alpha\delta))+2\alpha\delta(-2+\alpha\delta)c_{3D}-4c_M+(-3+\alpha\delta)((-4+\alpha\delta)c_L-\alpha\delta c_M)}{8(-2+\alpha\delta)}, \frac{c_L+c_M}{\alpha\delta} - c_{3D}\right]$,

$p_{3DX}^* - p_{3DZ}^* < 0$.

Here, we annotate $\beta_3 = -\frac{\alpha\delta(8+\alpha\delta(-5+\alpha\delta))+2\alpha\delta(-2+\alpha\delta)c_{3D}-4c_M+(-3+\alpha\delta)((-4+\alpha\delta)c_L-\alpha\delta c_M)}{8(-2+\alpha\delta)}$.

$$q_{MX}^* - q_{MZ}^* = -\frac{1}{4(-1+\alpha\delta)(8+\alpha\delta(-5+\alpha\delta))}((-1+\alpha\delta)(8+4\beta+\alpha\delta(-5+\alpha\delta)) + 2(4+\alpha\delta(-3+\alpha\delta))c_{3D} + (-3+\alpha\delta)^2 c_L - (7+\alpha\delta(-4+\alpha\delta))c_M)$$

Then, we can easily obtain:

i) if

$\frac{c_L+c_M}{\alpha\delta} - c_{3D} < \beta <$

$Max\left[-\frac{(-1+\alpha\delta)(8+\alpha\delta(-5+\alpha\delta))+2(4+\alpha\delta(-3+\alpha\delta))c_{3D}+(-3+\alpha\delta)^2c_L-(7+\alpha\delta(-4+\alpha\delta))c_M}{-4+4\alpha\delta}, \frac{c_L+c_M}{\alpha\delta} - c_{3D}\right]$,

$q_{MX}^* - q_{MZ}^* > 0$;

ii) If

$1 > \beta > Max\left[-\frac{(-1+\alpha\delta)(8+\alpha\delta(-5+\alpha\delta))+2(4+\alpha\delta(-3+\alpha\delta))c_{3D}+(-3+\alpha\delta)^2 c_L-(7+\alpha\delta(-4+\alpha\delta))c_M}{-4+4\alpha\delta}, \frac{c_L+c_M}{\alpha\delta} - c_{3D}\right]$, $q^*_{MX} - q^*_{MZ} < 0$.

Then, we annotate

$$\beta_4 = -\frac{(-1+\alpha\delta)(8+\alpha\delta(-5+\alpha\delta))+2(4+\alpha\delta(-3+\alpha\delta))c_{3D}+(-3+\alpha\delta)^2 c_L-(7+\alpha\delta(-4+\alpha\delta))c_M}{-4+4\alpha\delta}.$$

$$q^*_{3DX} - q^*_{3DZ} = \frac{2\alpha\delta c_{3D} + (-3+\alpha\delta)(-2+\alpha\delta)c_L - 2(\beta(-4+\alpha\delta)(-1+\alpha\delta) + c_M)}{2(-1+\alpha\delta)(8+\alpha\delta(-5+\alpha\delta))}$$

So,

i) if $\frac{c_L+c_M}{\alpha\delta} - c_{3D} < \beta < Max\left[\frac{2\alpha\delta c_{3D}+(-3+\alpha\delta)(-2+\alpha\delta)c_L-2c_M}{2(-4+\alpha\delta)(-1+\alpha\delta)}, \frac{c_L+c_M}{\alpha\delta} - c_{3D}\right]$, $q^*_{3DX} - q^*_{3DZ} > 0$;

ii) $1 > \beta > Max\left[\frac{2\alpha\delta c_{3D}+(-3+\alpha\delta)(-2+\alpha\delta)c_L-2c_M}{2(-4+\alpha\delta)(-1+\alpha\delta)}, \frac{c_L+c_M}{\alpha\delta} - c_{3D}\right]$, $q^*_{3DX} - q^*_{3DZ} < 0$.

Last, we annotate $\beta_5 = \frac{2\alpha\delta c_{3D}+(-3+\alpha\delta)(-2+\alpha\delta)c_L-2c_M}{2(-4+\alpha\delta)(-1+\alpha\delta)}$.

Proof of *PROPOSITION* 6-17

Under the integrated supply chain, we compare the optimal results of model X and model Z at supply chain level,

1) We compare the integrated supply chain's profit under two model,

$$\prod\nolimits_X^* SC(p_M, p_{3D}) - \prod\nolimits_Z^* SC(p_M, p_{3D}) = \frac{c_L(2 - 2\alpha\delta - 2c_{3D} + c_L + 2c_M)}{-4 + 4\alpha\delta} < 0$$

Therefore, $\prod_X^* SC(p_M, p_{3D}) - \prod_Z^* SC(p_M, p_{3D}) < 0$ is always hold.

2) We compare the optimal decisions in following,

$$p_{MX}^* - p_{MZ}^* = 0$$

$$p_{3DX}^* - p_{3DZ}^* = \frac{c_L}{2} > 0$$

$$q_{MX}^* - q_{MZ}^* = \frac{c_L}{2 - 2\alpha\delta} > 0$$

$$q_{3DX}^* - q_{3DZ}^* = \frac{c_L}{-2 + 2\alpha\delta} < 0$$

Proof of *PROPOSITION* 6-18.

Under the integrated supply chain, we compare the optimal results of model Y and model Z at supply chain level,

1) We compare the integrated supply chain's profit under two model,

$$\prod\nolimits_Y^* SC(p_M, p_{3D}) - \prod\nolimits_Z^* SC(p_M, p_{3D})$$
$$= \frac{(-1+\delta)((-1+\alpha)\delta(-1+\alpha\delta) - (-c_{3D} + c_L + c_M)^2)}{4(-1+\alpha)\delta(-1+\alpha\delta)}$$

Which is concave in c_{3D}, when

$$\frac{\partial \prod_Y^* SC(p_M, p_{3D}) - \prod_Z^* SC(p_M, p_{3D})}{\partial c_{3D}} = 2(-c_{3D} + c_L + c_M) = 0$$

$$c_{3D}^* = c_L + c_M$$

We can have the unique maximized value of $\prod_Y^* SC(p_M, p_{3D}) - \prod_Z^* SC(p_M, p_{3D}) = \frac{1}{4}(-1+\delta) < 0$. Therefore, we can always have $\prod_Y^* SC(p_M, p_{3D}) - \prod_Z^* SC(p_M, p_{3D}) < 0$.

2) We compare the optimal decisions in following,

$$p_{MY}^* - p_{MZ}^* = 0$$

$$p_{3DY}^* - p_{3DZ}^* = \frac{1}{2}(-1+\delta) < 0$$

$$q_{MY}^* - q_{MZ}^* = -\frac{(-1+\delta)(c_{3D} - c_L - c_M)}{2(-1+\alpha)\delta(-1+\alpha\delta)}$$

$$q_{3DY}^* - q_{3DZ}^* = \frac{(-1+\delta)(c_{3D} - c_L - c_M)}{2(-1+\alpha)\delta(-1+\alpha\delta)}$$

Thus, if $c_{3D} - c_L - c_M > 0$, then $q_{MY}^* - q_{MZ}^* > 0$ and $q_{3DY}^* - q_{3DZ}^* < 0$; if $c_{3D} - c_L - c_M < 0$, then $q_{MY}^* - q_{MZ}^* < 0$ and $q_{3DY}^* - q_{3DZ}^* > 0$.

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