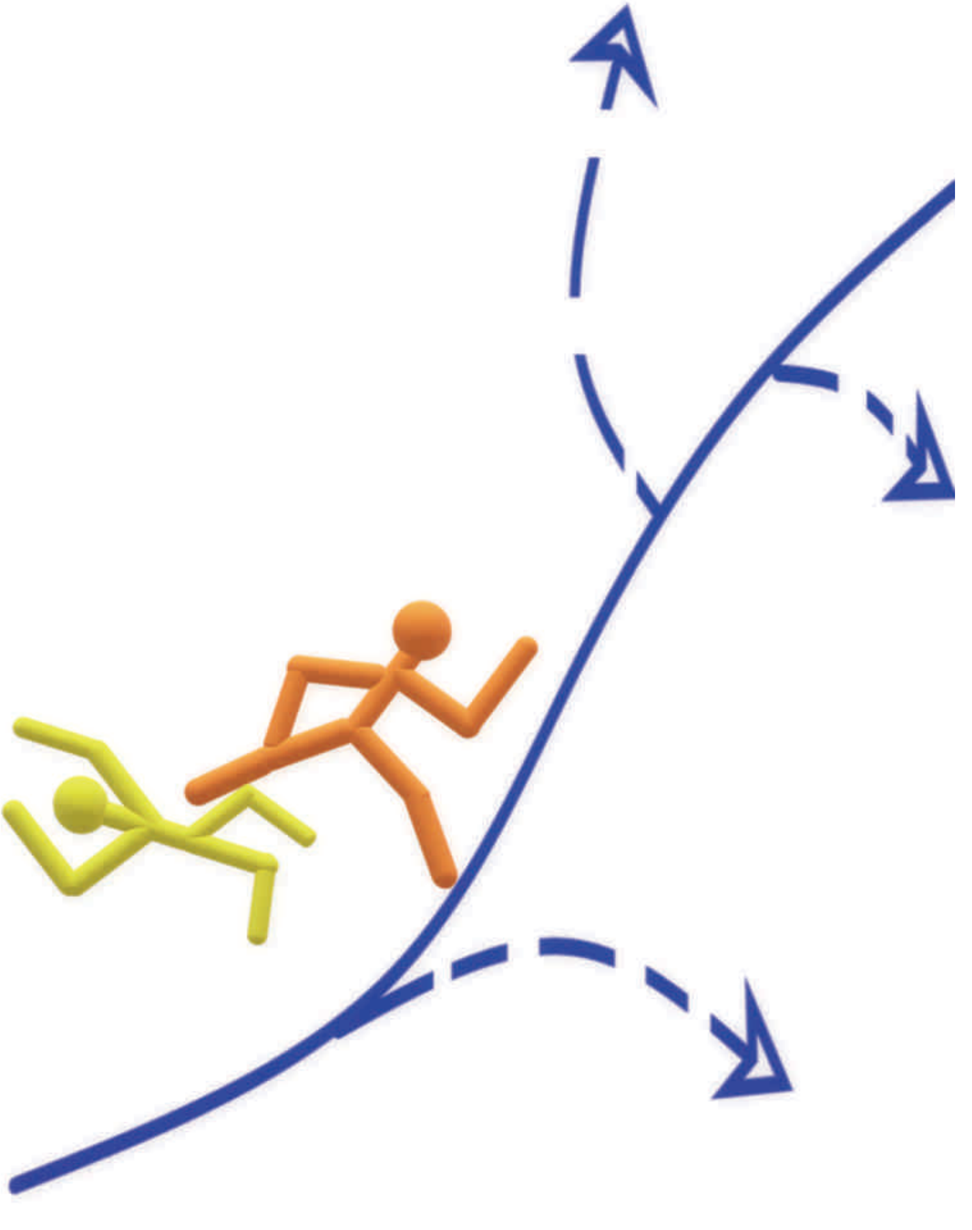
XISHU LI

Dynamic Decision Making under Supply Chain Competition



Dynamic Decision Making under Supply Chain Competition

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Dynamische besluitvorming in supply chains met concurrentie

Thesis

to obtain the degree of Doctor from the
Erasmus University Rotterdam
by command of the
rector magnificus

Prof. dr. R.C.M.E. Engels

and in accordance with the decision of the Doctorate Board.

The public defence shall be held on
Friday 11th January 2019 at 9:30hrs

by

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Erasmus Research Institute of Management – ERIM
The joint research institute of the Rotterdam School of Management (RSM)
and the Erasmus School of Economics (ESE) at the Erasmus University Rotterdam
Internet: www.erim.eur.nl

ERIM Electronic Series Portal: repub.eur.nl/

ERIM PhD Series in Research in Management, 466
ERIM reference number: EPS-2018-ERIM Series 2018-EPS-466-LIS
ISBN 978-90-5892-533-6

Design: PanArt, www.panart.nl

This publication (cover and interior) is printed by Tuijtel on recycled paper, BalanceSilk®
The ink used is produced from renewable resources and alcohol free fountain solution.
Certifications for the paper and the printing production process: Recycle, EU Ecolabel, FSC®, ISO14001.
More info: www.tuijtel.com

Acknowledgments

I grew up as a “fierce" child, according to my parents. I like things which are difficult, energy-consuming, and intense. My father used to say "she likes competition because she likes to win”. But I think what I like most about winning is the process through which I learn how to win. Because the reality is that I have never succeeded at any task at the first. When I really understood how it works and I won, it is also the time to move on to the next challenge.

I believe most of my friends think the reason why I decided to do a Ph.D. is that I like difficult things. "A rebel who is never settled", they would call me that. Indeed, I had been on a zigzag path before I turned 16, which is far away from the path to becoming a scholar. I am lucky to be born in a wealthy family and grow up knowing whatever I do in the future would have little impact on my wealth. I had extremely easy and fun times at school and spent all my summers on the beach. When I turned 16, the expectation my parents had on me was very simple and that is I can stay with them forever, even if I do nothing. My own idea for what I want to become is even simpler: I want to be a nice person. It is also because I am really not sure about what else I can become. I remember one day I had a small piece of reading at hand and it says that at the bottom of a Ph.D. diploma, it writes in Latin: thank you for your contribution to the academia. I am still not sure whether it is true and I would need to check my diploma right after the defense to verify. But at that time when I read this, I felt it so strongly in my heart. It was the first time in my life that I have something I really want: I want to contribute and

I feel extremely honored when I can contribute to a field that has tremendous impacts on human beings life!

The Ph.D. journey was not easy, especially at the beginning. As I said, I have never succeeded at any task at the first. But it is also because of those failures, I have learned what would not work and what would at the next tries. I am extremely lucky to have my supervisor team: Réne de Koster, Rommert Dekker, and Rob Zuidwijk. Sometimes I joked that I should also change my name to Rebecca so that we will have a 4R team, which also fits more the definition of supply chain management. Réne is the first professor of whom I felt afraid. I think many of his master students would agree: he is smart, sharp and direct, which makes lazy students feel intimidated. Unfortunately, I was one of the lazy students at the beginning. Here is a story I would like to share, regarding how I became Réne's Ph.D. student. Réne likes to ask the student's grade for his class when a student contacts him. That's the reason why I never contacted him—because I did not have a good grade. My Ph.D. application was accepted by Rommert and on that day I attended a seminar where I sat right next to Réne. During the seminar, Réne was just being Réne, i.e., asking the speaker many good, sharp and direct questions. I was an amateur in the field and all I was thinking is just "luckily my boss is Rommert". There is always a plot twist in every story. The next day I quickly learned that there is a change in my supervisor team and Réne will be my first supervisor. Now fast forwarding and rewinding my five-year Ph.D. journey, I want to say "THANK GOD, I have Réne!" There have been many times that I felt so frustrated and defeated and I just wanted to leave, but Réne has always been there to help, support and guide me through the difficulties. I am forever grateful to him and I only wish I can be the same supervisor to my students in the future, like the one he has been to me.

I would also like to express my thanks to Rommer Dekker. Because of the great experience working with him during my master thesis, I decided to continue my study at Erasmus and developed my interests in working together with companies in scientific research. So if anyone asks me why I stay in the

Netherlands for so long, I say it is because of the weather (joking!) and also because of Rommert.

I also owe gratitude to Rob Zuidwijk. I always think Rob is almost the perfect supervisor to be added to a team which already consists of Réne and Rommert. They complemented each other in their approach and feedback. I have the most frequent meetings with Rob and because of his detailed feedback, I have grown as an academic. I would also like to thank Suresh Sethi, who is my supervisor during my stay at the University of Texas at Dallas, USA. Suresh is not only a supervisor in academia, he is also a great friend and a mentor. I am very grateful for all his guidance in life.

Besides my supervisors, I would like to thank all my colleagues at the department TOM and at ESE, especially Alp, Kaveh, Arpan, Joydeep, Niels, Francesco, Alberto, Weina, Alex, Joshua, and Sha. Special thanks to Carmen Meesters-Mirasol, Cheryl Blok-Eiting, and Ingrid Waaijer. Without their help, it is impossible for me to finish my Ph.D. journey.

Finally, I am extremely thankful to my boyfriend Ben Haanstra, who is always there to support my decisions and help me deal with all kinds of problems. I cannot express enough how fortunate I am with the unconditional love and support of Ben. Saving the best for the last, I would like to thank my parents. Although what I am doing right now is far different from what they want me to do, I know they are proud of me. Since I am always far away, to them, showing support to me is a sacrifice and I am forever grateful for that.

Contents

Chapter 1

Introduction

Operations management is an area of management concerned with designing and controlling the process of production, which converts material and labor into goods and services, as efficiently as possible to maximize the profit of an organization (Stevenson and Hojati, 2007). Throughout the production process, various types of decisions, such as process design, quality management, capacity planning, facilities planning, production planning, inventory control, and maintenance, are made at strategic, tactical and operational levels. These decisions are complex since firms operate in a dynamic environment where the future is uncertain. To cope with uncertainties, a firm's decisions should take into account different possible future events. In addition to the dynamic environment, competition brings another layer of complexities to a firm's decision making. In a competitive market, firms' decisions interact with each other. For instance, a firm can invest in excessive capacity to bring down the price of a common product, which will affect the competitors' profits. In order to make the right decisions, a firm needs to consider the impact of its decisions on the competitors, their possible responses, and the impact of their decisions on the firm.

This dissertation studies the impact of uncertainty and competition on a firm's decision making in the field of operations management. **First**, I investigate the dynamics of a firm's decisions. **Second**, I investigate how competition changes the dynamics of a firm's decisions. **Chapter 2** provides an overview on dynamic and competitive strategies in operations management. The remainder of this dissertation focuses on three specific decision areas of operations management: **(1)** capacity planning at the strategic and tactic levels (**Chapters 3** and **4**); **(2)** anti-counterfeiting strategies at the tactic level (**Chapter 5**); and **(3)** risk management for long field-life systems at the operational level (**Chapter 6**). **Chapter 7** concludes the dissertation.

Research questions

The main generic research questions can be formulated as follows:

- **how should a firm make its capacity investment decisions in a competitive market, considering the changing demand?**
- **how can a firm compete against counterfeiters in a global supply chain?**
- **how should a firm that purchases parts manage end-of-supply risk of these parts, considering the changing supply and demand?**

Below, I give a detailed description of each chapter (**Chapters 3-6**) in terms of problem definition, methodology and findings.

Chapter 3 studies the research question "**how should competing firms make their long-term capacity investment strategies under demand uncertainty?**" We develop an algorithm to derive full optimal policies in terms of investment timing and size for both the leader and follower firms. Two firms move sequentially in the investment race and a firm's capacity decision interacts with the competitor's current and future capacity. A firm can either plan its investments proactively, taking into account the competitor's possible responses, or respond reactively to the competition. We derive the optimal policy of a firm in the form of an ISD (*Invest*, *Stayput*, *Disinvest*) policy, which is represented by stayput regions. If capacity falls inside such a region, it is optimal to stay put. Otherwise, capacity should be adjusted (either invest or disinvest) to an appropriate point on a region's boundary. A reactive ISD policy contains a unique stayput region, whereas a proactive ISD policy can contain multiple stayput regions, each of which represents a competitive goal towards market share, i.e., a submissive, neutral or aggressive goal. Thus, a proactive competitive strategy can also be called as an SNA (*Submissive*, *Neutral*, *Aggressive*) strategy. We validate our model using detailed data from the container shipping market (2000-2015). Although the investments of shipping lines are often questioned to be irrational, our results show that they are close to the optimal capacity choices determined by proactive competitive strategies. By reviewing the underlying structures of various strategies, we demonstrate that in nearly all cases competing firms can gain more profit and market share by adopting a proactive strategy rather than a reactive one.

Chapter 4, studies the research question "**how should firms launch next-generation products (NGPs), which are quality upgrades to an existing product, in a competitive market?**" Using a game theoretic model, we derive the optimal equilibrium strategy of a firm, which specifies the optimal investment timing in the NGP and also the optimal capacity allocation to the NGP and the existing product. In a competitive market, an early launch gives a firm a leadership position if the competitor chooses to wait, but it also brings risk, since consumer taste is unknown at the early stage and the competitor may launch a better quality product later. Therefore, a firm's optimal investment timing considers the trade-off between demand risk and competition. To measure the impact of demand risk in a market, a firm should measure the correlation between the average consumer taste and the heterogeneity in consumer taste: a strong correlation indicates a large exposure to demand risk. We measure a firm's competitive advantage and disadvantage on a two-dimensional scale, which includes the firm's capacity investment cost advantage over its competitor and the competitor's gain from offering the product quality upgrade. A firm has a *competitive edge* only if its cost advantage exceeds a certain threshold related to its competitor's gain from offering the quality upgrade, and this *edge* can lead the firm to invest earlier than its competitor. We distinguish two non-exclusive situations of a firm: (1) a *stand-still* situation based on the competitive advantage of both firms, and the exposure to demand risk, and (2) a *risky* situation based on the firm's competitive advantage, the other firm's competitive disadvantage and the exposure to demand risk. We derive the optimal investment strategy of a firm in each scenario: in a *stand-still* situation, the firm should invest at the same time as its competitor; in a *risky* situation, the firm should postpone the investment; otherwise, the firm should invest early.

Chapter 5 studies the research question "**how should legitimate OEMs combat counterfeiting in a global supply chain? Should Customs authority help and how?**" To combat counterfeiting, the OEM can either resort to pricing or building a public-private partnership (PPP) with Customs in which the OEM shares supply chain data with Customs to help hinder the entry of counterfeits. Besides detention of counterfeit goods, Customs can be the one who initiates the PPP and thus the OEM can join it with no cost, e.g., cost for building a platform to exchange data. Using a game theoretic framework, we derive the optimal equilibrium strategies of Customs and the OEM, based on their decisions towards the PPP. We consider two types of counterfeiters: non-deceptive and deceptive, where the difference is that consumers cannot distinguish deceptive counterfeits from authentic products at the time of purchase (e.g., counterfeit medications), while they can in the other case (e.g., counterfeit designer bags). Our results show that when combating non-deceptive counterfeiting, the PPP could enable the OEM to increase the price of authentic products and to earn more profit, compared to that without any counterfeit. Compared to the non-deceptive case, we find that the OEM should play a bigger role in initiating the PPP to combat deceptive counterfeiting. The OEM could increase its price when it initiates the PPP and the market seize of the deceptive counterfeiter is decreasing in the price of authentic products in such a situation. In the non-deceptive case, we find that the optimal equilibrium strategy of each player depends on the level of penalty to the counterfeiter and the quality of counterfeits. When the penalty exceeds a certain threshold or the quality of counterfeits drops below a certain threshold, Customs does not have the incentive to initiate the PPP. If the penalty is either too large or too small, the OEM will likely also choose not to initiate the PPP when Customs does not initiate it. One of the reasons why the OEM will likely not initiate the PPP when the penalty is very large is that under such a condition, the counterfeiter will disguise even if the PPP is formed. Lastly, we show that the entry of non-deceptive counterfeits does not always improve consumer welfare. In particular, when the quality of counterfeits exceeds a certain proportion of the quality of authentic products, the OEM initiating the PPP to hinder the entry of counterfeits would actually improve consumer welfare.

Chapter 6 studies the research question "**how should firms of long field-life systems manage end-of-supply risk of parts of their systems?**" Using the proportional hazard model and quantified supply chain condition data, we develop a methodology for firms purchasing spare parts to manage end-of-supply risk, i.e., the risk that the part is no longer supplied. Long field-life systems, such as airplanes, are faced with hazards in the supply of spare parts. If the original manufacturers or suppliers of parts end their supply, this may have large impact on operating costs of firms needing these parts. Existing end-of-supply evaluation methods, e.g., life-cycle models, focus mostly on the downstream supply chain and utilize past sales data to forecast the remaining sales trajectories of parts. These methods are of interest mainly to spare part manufacturers, but not to firms purchasing parts since they have limited information on sales. We focus on the upstream supply chain and propose to use supply chain conditions of parts as indicators of end-of-supply risk. Our methodology is demonstrated using data on about 2,000 spare parts collected from a maintenance repair organization in the aviation industry. Cross-validation results and out-of-sample risk assessments show good performance of the method to identify spare parts with high end-of-supply risk. Further validation is provided by survey results obtained from the maintenance repair organization, which show strong agreement between the firms' and our model's identification of high-risk spare parts.

Chapters 3 and **4** consider both the dynamic and competitive aspects and study their impact on a firm's capacity strategy. In **Chapter 3**, we find that competition isn't always bad for firms. A competitive capacity strategy, which proactively takes into account the possible responses of the competitor as both firms proceed in the investment race, can benefit a firm in the long term. The benefit of competition is also shown in other decision areas, such as new product development. In **Chapter 5**, we find that under certain conditions, the legitimate OEM prefers to compete with the counterfeiter in the market, rather than helping Customs detain counterfeits at the border, since the OEM can benefit from the price and quality competition. It possibly explains why some legitimate manufacturers do not join a public-private partnership with the government to combat counterfeiting. For instance, while there are almost two million active federal trademark registrations and many more copyright registrations that are eligible for enhanced protection against illicit imports, only 32,000 or so have been recorded with US Customs and Border Protection for border enforcement.

In **Chapter 4**, we find that when a firm's competitive advantage over its competitor is not enough to hedge demand risk, it should postpone the investment and invest at the same time as the competitor. Demand risk is only one of many types of risk. In sectors like aerospace, shipping, and defense where firms are focused on sustaining their products for a prolonged period, supply risk of parts of their system components is prominent. In **Chapter 6**, we conduct an applied research on this topic. Although specific end-of-supply risk environments will differ among firms, the methodology can serve all. The crucial condition is to monitor the supply chain and keep track of the relevant supply chain indicators, such as price, lead-time, order cycle time, and throughput, for each part of interest. At any proposed analysis date, the big database can be used to construct a set of end-of-supply risk indicators and calculate risk scores for each part. These scores can be scanned to identify parts at risk and to support proactive order and inventory policies.

Chapter 2

Background on Dynamic & Competitive Strategies

In this chapter, I first provide an overview on dynamic strategies in operations management (OM) (Section 2.1), and then review studies on the impact of competition on dynamic decision making (Section 2.2). Here I focus on survey and literature review papers and give some examples to illustrate a concept or demonstrating the complexity of a problem.

2.1 Dynamic strategies in operations management

One of the most important tasks for any organization is to cope with uncertainties, failing which will result in great losses for a firm. Although a firm cannot always acquire full information required to perform a task, the consideration of uncertainty in decision making may bring a great advance. At the strategic and tactic levels, decisions such as capital investment, facility selection for manufacturing, and new product development should consider possible demand and supply scenarios in the future (Eppen et al., 1989; Karabuk and Wu, 2003; Gupta and Maranas, 2003). Van Mieghem (2003) reviewed the literature on strategic capacity management concerned with determining the sizes, types and timing of capacity adjustments under uncertainty. The objective of dynamic capacity strategies is usually to maximize the expected net present value of the firm, while some recent capacity models incorporate the risk aversion of decision makers and thus the goal is to mitigate risk and improve performance. Snyder (2006) reviewed facility selection models in two types of uncertain decision-making environments: (i) parameters are uncertain, but values are governed by probability distributions that are known by the decision maker; and (ii) parameters are uncertain and no information about probabilities is known. In both environments, the goal of a facility selection model is to find a solution that will perform well under any possible realization of the random parameters. Incorporating uncertainty into decision making at the strategic and tactical levels typically changes decisions and can improve performance and mitigate incentive conflicts e.g., cost-efficiency of production and revenue maximization of sales (Harrison and Van Mieghem, 1999).

At the operational level, decisions such as production and transportation planning, deal with dynamics and stochasticity that are not explicitly addressed at strategic and tactical levels. Mula et al. (2006) provided a detailed review on models for production planning under uncertainty. In addition to demand uncertainty, dynamic production planning models consider system uncertainty, e.g., operation yield uncertainty, production lead time uncertainty, and failure of product systems (Bertrand and Rutten, 1999; Ould-Louly and Dolgui, 2004; Guhlich et al., 2018). SteadieSeifi et al. (2014) reviewed multimodal transportation planning models, in which uncertainties in demand, travel times, and disruption at location or on the routes are crucial elements. These models are remarkably complex since they involve balancing a complicated set of often conflicting objectives of all multimodal operators, carriers and shippers, and the synchronization of operations might fall if uncertainty is ignored. Traditionally, production and transportation planning decisions are made sequentially and independently. However, in today's competitive market, firms have to guarantee the efficiency of their resources and may need to consider production and transportation planning simultaneously (Chandra and Fisher, 1994; Degbotse et al., 2013; Katircioglu et al., 2014). Díaz-Madroñero et al. (2015) reviewed tactical optimization models for integrated production and transport routing planning decisions. Dynamic production routing models integrate all different types of uncertainty inherent to production and routing planning processes and give flexible and valid plans in uncertain environments.

In recent years, postponement strategies have attracted increasing attention as an answer to how firms cope with changing environments (Yang et al., 2004b; Boone et al., 2007). The concept of postponement suggests firms delay activities until the latest possible point in time when more information is available and thus the risk and uncertainty of those activities can be reduced or even eliminated. Activities can be postponed at all phases of a firm's operations (Yang et al., 2004b): at the product development phase, design decisions about less stable portions of the product can be postponed until better information about customer preference is available (Yang et al., 2004a); at the production phase, the point of product differentiation can be postponed until the latest possible point in the supply network (Feitzinger and Lee, 1997; Anupindi and Jiang, 2008); at the logistics phase, the last-leg delivery decisions can also be postponed until a customer places an order (Van Hoek, 2001).

There is an extensive literature on dynamic strategies in operations management and the view on uncertainty has changed from seeing it as a problem to seeing it as an opportunity. For instance, product development postponement provides an opportunity to reduce design lead times and costly redesigns. Production postponement improves forecasting accuracy by shortening the forecasting time horizon and enhances a firm's flexibility and responsiveness in a changing market. Effective dynamic strategies give firms competitive advantages in many aspects such as price/cost, quality, and time to market. Hewlett Packard has reported double-digit savings in supply chain costs by applying postponement in manufacturing and distribution. Similarly, a significant share of the competitive advantage of Dell computers is based on its strategy of mass customization and on the direct-delivery capabilities of postponement. In addition to the consideration of uncertainty, firms should consider competition in their decision making (Van Hoek, 2001). In a competitive market, firms' decisions interact with each other. In order to determine optimal strategies, firms should consider the impact of other firms' decisions on their decisions. Next, we will review literature on the impact of competition on dynamic decision making, with a focus on capacity investment and new product development decisions.

2.2 Impact of competition on dynamic decision making

Competition has been consistently identified as an important force in firms' capacity strategies (Spence, 1977; Porter, 1989; Bashyam, 1996; Smit and Trigeorgis, 2012). Due to the existence of time-to-build, firms usually build their capacity before the demand is known and enter a capacity constrained price competition once the demand is revealed (Bashyam, 1996; Anupindi and Jiang, 2008). Bashyam (1996) found that if the market outlook is either highly optimistic or highly pessimistic, preempting expansion by the rival is a good strategy in the competition. After a preemption race which leads to overcapacity in the industry, firms may coordinate their capacity in the long run through disinvestments, thus there will be little (if any) excess capacity relative to the benchmark of a capacity cartel (Besanko et al., 2010).

In a competitive capacity investment problem where firms may invest either before or after demand is realized at different costs, investment timing trades off flexibility and commitment, and competitive investment strategies focus on interactions between firms and strategic implications of a firm's timing decision. In general, there are two equilibria: in the delay equilibrium, both firms wait to invest until uncertainty is resolved; in the commit-delay equilibrium, one firm acts as a leader and makes a preemptive investment, while the other acts as a follower and waits to invest (Pacheco-de Almeida and Zemsky, 2003). Anderson and Sunny Yang (2015) found that when firms do not have volume flexibility in production, they are most likely to invest at the same time. If there is volume flexibility, then it is more likely that one firm will invest earlier than the other. Capacity and other forms of investment are effective entry deterring variables (Spence, 1977; Dixit, 1980). Huisman and Kort (2015) found that when applying an entry deterrence policy, the incumbent over-invests in capacity in order to delay the investment of the entrant and to suppress the investment size of the entrant. They also showed that when uncertainty increases, the likelihood of deterrence raises.

In addition to capacity investment, new product development should also consider the impact of competition. The choice of product launch time is one of the major reasons for new product success or failure in the competition (Cooper and Kleinschmidt, 1994; Rogers, 2010). A general premise on the new product launch is that the decision to enter the market should be timed to balance the risks of premature entry against the problems of missed opportunity (Cohen et al., 1996). Lilien and Yoon (1990) empirically tested a set of relationship between the market-entry time and the likelihood of success for new industrial products. Based on their results, a potential pioneer in the industry should spend time to build its expertise in R&D, instead of to accelerate its new product entry; a firm who intends to enter the market during the growth stage of the product life cycle should hasten its entry, unless its expertise in R&D can be significantly enhanced by a short delay of entry time; a firm who intends to enter the market during the maturity stage of the product life cycle should enter the market as early as possible. Savin and Terwiesch (2005) developed a model describing the sales trajectories of two new products competing for a limited target market. They found that a firm facing a launch time delay from a competing product might benefit from accelerating its own product launch, as opposed to using the situation to further improve its cost position.

In general, competitive investment strategy under uncertainty involves a trade-off between acting early, benefiting from preemption, and acting late, benefiting from complete information. Firms should analyze this trade-off, taking into consideration the nature of uncertainty, economics in the industry, intensity of competition and a firm's position relative to its competitors. In this thesis, I investigate the dynamics of a firm's competitive strategies in three decision areas: capacity (**Chapters 3** and **4**), anti-counterfeiting (**Chapter 5**), and risk management (**Chapter 6**). In **Chapters 3-6**, I provide detailed literature review on each specific topic.

Chapter 3

Dynamic Capacity Investment under Competition

This chapter is available at SSRN; see Li et al. (2016b).

3.1 Introduction

Capacity investment refers to the change in a firm's stocks of various processing resources over time (Van Mieghem, 2003). Firms face a number of challenges in such decisions, since capital assets are costly, an investment is usually irreversible, and future rewards are uncertain. Since a discrepancy between a firm's capacity and demand results in inefficiency and losses, either through under-utilized resources or unfulfilled demand, the goal of capacity planning is often to minimize this discrepancy in a profitable way. However, doing this is not always possible when firms compete in quantity and in the long run (Del Sol and Ghemawat, 1999). In a competitive market where dominant firms exist and product price fluctuates with these firms' capacity, decisions of one firm directly impact those of the other firms, currently and in the future. Investment strategies that ignore competition can have fundamental problems, as they either tend to recommend waiting too long before making an investment, or underestimate the likely countermoves of the other dominant firms towards the firm's investment decision. Without a proper theory, investment decisions in a competitive market can lack guidance.

The container shipping market, where the shipping service price is controlled by a small number of liner operators through their capacity[1], is a good example of a competitive market. Over the past few years, we have observed a striking investment race among shipping firms for fleet capacity: the world fleet capacity in fully cellular containerships increased by over 56.9% between 2010 and 2017 (Barnard, 2010; Alphaliner, 2017). However, in stark contrast to the enormous increase in fleet capacity, the shipping industry has had a difficult ride since the 2008 global recession (Barnato, 2015). The battle of survival for shipping firms can only be partially attributed to the crisis or to buying too many ships before the crisis started, in anticipation of continued growth. The situtation was aggrevated by post-crisis investment cascades. Except Maersk's Emma, all Ultra Large Container Vessels[2] were ordered after 2008 (Wikipedia, 2016b). For example, in 2011 CMA-CGM increased the capacity option of its three on-order vessels by 15.7% (CMA-CGM, 2011) and this capacity record only stood for a short while. In the same year, Maersk spent $3.8 billion to build 20 Triple-E-class vessels, causing the size of the largest containership to instantly rise by another 14.2% (Macguire, 2013).

These large investments during the market downturn cannot be explained by generic investment frameworks. *First*, the investments are not supported by demand. Market economy theories recommend firms to order more new ships when they expect demand to outpace supply growth (Olhager et al., 2001; Van Mieghem, 2003). However, the continuing recession in Europe and the slowdown in China led firms to downgrade their demand growth forecast from 9%-13% before the crisis to 3%-5% afterwards (Drewry, 2005, 2014).

[1] By June 2017, the top 10 shipping lines controlled over 73.8% of the world container fleet (Alphaliner, 2017).

[2] Container vessels are distinguished into seven major size categories and the category of Ultra Large Container Vessel includes container vessels with a capacity of 14,501 TEU and higher (Wikipedia, 2016a).

Second, the competition for vessel size cannot be justified by economies of scale. Larger vessels are more cost efficient as they result in lower unit costs in many categories, e.g., operating cost and building cost (Cullinane and Khanna, 2000). However, as the gap between world fleet capacity and trade volume increased to over 144% between 2005 and 2014 (Søndergaard and Eismark, 2012), the advantage of economy-of-scale cannot always be realized. In fact, carriers face more losses if they sail large vessels with insufficient cargo. *Third*, the outcome of these investments in the container shipping market does not meet the general investment expectation, which is to boost profit. Instead, these investments cause high volatility in freight rate and losses in profits (UNCTAD, 2012, 2013, 2014). For instance, after CMA-CGM's Marco Polo vessels and Maersk's Triple-E-class were ordered, the spot rates in the Asia-Europe market hit rock bottom, dropping from an average value of $1789 per TEU in 2010 to $450 per TEU in December 2011 (Odell, 2012; UNCTAD, 2013). Consequently, in 2011 many carriers suffered huge losses and depleted their cash reserves (Sanders, 2012).

However, these post-crisis investments clearly have a competitive feature. Having faced a market downturn since 2008, leading carriers chose not to lay off capacity in order to mitigate declining freight rates. Instead, they further deflated rates by ordering more vessels, resulting in lower profits and suppressed capacity for competitors (Søndergaard and Eismark, 2012). Without careful planning, even firms with a strong financial position had difficulties surviving. Hanjin, the world's seventh-largest shipping line, which had increased its fleet size nearly twofold between 2009 and 2013, but in turn had caused its debt-to-equity ratio to rise from 155% to 452%, filed for bankruptcy in 2016 (Wei, 2017). Besides the shipping industry, other oligopolistic markets have also shown similar investment races. For instance, in the semiconductor industry, manufacturers invest aggressively in capacity during market downturns (Ghemawat, 2009).

Obviously, competitive capacity investment is risky for any firm as the future is uncertain. One way to reduce the risk is to divide the investment project into several sub-projects and execute them in phases. This allows firms to respond to market changes more easily. Because capital assets have long lifetimes, investment decisions that are made in earlier phases influence decision making in the future. A long-term investment strategy should address the optimal timing and size of capacity adjustments. Capturing the optimal investment timing in a competitive market requires firms to balance the financial risk of investing and the competitive risk of not investing. Once-in-a-cycle delays can create a lasting competitive disadvantage in a multi-round investment race. Moreover, competition does not necessarily drive a firm to build the maximum possible capacity. More is not always better, which has been demonstrated, for example, by the lack of success of the Airbus 380.

An investment strategy, which helps firms survive and thrive in the competition, should achieve an "elusive" balance between being too defensive and being too aggressive (Gulati et al., 2010). However, little research has focused on the optimal structure of such a competitive investment strategy, in which firms' investment decisions timely respond to each other and to demand. Our study fills this gap by investigating optimal long-term investment strategies of two firms moving sequentially in a competitive market where 1) uncertainty exists in the exogenous demand growth; 2) a firm's decision interacts with the opponent's current and future decisions; and 3) a firm's objective in each period is to maximize the expected value of its long-term plan by adapting it to the evolving market.

We contribute to research and practice as follows. *First*, we contribute to the literature by providing a theory that can explain the competitive investment phenomena observed in practice. Current models do not fully explain these phenomena. *Second*, we explicitly take the competition effect into account by developing an algorithm which derives all stayput intervals for both the leader and the follower in their optimal policies. Each interval is part of the optimal solution set of a firm and has a competitive meaning, taking into account the impact of the competitor's responses on the firm's current and future rewards. *Third*, we allow a firm to choose either a proactive or a reactive strategy, and develop methods to efficiently derive the optimal policy in each case. By revealing the underlying structures of capacity strategies, our methods show the advantages of adopting a proactive strategy. *Fourth*, we derive full optimal policies in terms of investment timing and size. Existing research either focuses on timing only or studies investment in a single-shot game. *Fifth*, we validate our model using detailed data from the container shipping market over a timespan of 16 years (2000-2015) and show that the investment decisions computed by our model are consistent with what happened in practice. Thus, the investments of the leading liner operators, which are often questioned to be irrational, follow a competitive structure. *Last*, we provide a practical guideline with four steps on how to achieve an effective competitive investment strategy.

3.2 Related literature

The literature on strategic capacity investment is mostly concerned with strategically determining the timing and size of buying or selling additional capacity under uncertainty (see Van Mieghem, 2003 and Chevalier-Roignant et al., 2011 for a detailed literature review). Models that study the optimal capacity type often consider a single-period problem where a firm sells two products and has the option to invest in two types of resources: flexible vs dedicated (Van Mieghem, 1998; Goyal and Netessine, 2007). A flexible resource can produce either product, but require higher investment costs compared to dedicated resources. These models study the impact of capacity characteristics and demand correction of the two products on the optimal capacity strategy. Since our focus is on the competition effect on a long-term investment strategy, we limit this review to models that consider only a single type of capacity resources.

Brennan et al. (2000) address the three stages in the development of capacity models: (1) *static* models, (2) *dynamic* models, and (3) *combined real options and game-theoretic* models. As *combined real options and game-theoretic* models also study investment dynamics, they can be considered as a stream within *dynamic* models. *Static* models investigate the optimal locations and sizes of capacity in a processing network for a single or for multiple decision makers in a stationary environment where there is no managerial flexibility to cope with market changes (Bish and Wang, 2004; Van Mieghem, 2007). It collapses the problem to a single initial capacity investment where the optimal capacity remains constant over time. This category of capacity models adopts queuing (Lederer and Li, 1997; Cachon and Harker, 2002) and newsvendor network formulations (Van Mieghem and Rudi, 2002; Netessine et al., 2002; Kulkarni et al., 2004). While losing dynamics in capacity decisions, some models extend the single-period solution to a situation with dynamic independent and identically distributed (i.i.d.) demand and hence investigate dynamics in inventory (Van Mieghem and Rudi, 2002). *Static* models that involve multiple players often study coordination between "vertical" players such as manufacturers and retailers (Cachon and Lariviere, 1999; Armony and Plambeck, 2005; Plambeck and Taylor, 2005; Caldentey and Haugh, 2006), or competition between "horizontal" players (Lederer and Li, 1997; Van Mieghem and Dada, 1999) who supply a common market. Two main aspects considered in these multi-player *static* models are supply network partitioning and information asymmetry. Although these models consider firm interaction, they are still restricted to a stationary setting, emphasizing the optimal capacity size.

Dynamic models allow time-dependent investments to respond to the resolution of uncertainty. They emphasize the timing of capacity adjustment in a single-shot or a long-term game and derive a structured policy for investments at different time points (Burnetas and Gilbert, 2001; Angelus and Porteus, 2002; Narongwanich et al., 2002; Ryan, 2004; Huh and Roundy, 2005; Huh et al., 2006). Some noted approaches in this category are decision-tree analysis, dynamic programming, control theory, and real options approach. Often, optimal investment dynamics follow an ISD (invest, stayput and disinvest) policy, which is characterized by a continuation region: if current capacity falls in this region, it is optimal to stay put; otherwise, it should be adjusted to an appropriate point on the region's boundary (Eberly and Van Mieghem, 1997). Although traditional *dynamic* models have been refined over time to incorporate many real-world features, such as hedging, they fail to consider competitive interactions between firms' capacity, which limits their applications in a competitive setting. Our work is built on Eberly and Van Mieghem (1997)'s ISD method, and we extend their method to incorporate the competition effect on investments.

Our model belongs to the most recent development of *dynamic* models, i.e., *combined real options and game-theoretic* models (Chevalier-Roignant et al., 2011), which involve several decision makers and an uncertain market. In these models, firms condition their decisions not only on the resolution of exogenous uncertainty, but also on the (re)actions of competitors. The focus is on determining the investment timing of players and explaining competitive behavior. The most widely used method is the "option games" approach (Ferreira et al., 2009). Most models consider two types of players only (i.e., leader vs. follower) or n players moving simultaneously, while only a few incorporate a third player (Bouis et al., 2009). There are two major types of *combined real options and game-theoretic* models. The first studies a single-shot investment with lumpy capacity (Dixit, 1994; Hoppe, 2000; Murto, 2004; Pawlina and Kort, 2006; Thijssen et al., 2006; Swinney et al., 2011). Investment is viewed as an optimal stopping problem, focusing on finding the demand values at which capacity should be adjusted to maximize the expected reward. The second allows multiple rounds of investments and explores an optimal capacity strategy that contains a sequence of decisions. Most models in this category focus on incremental capacity expansion (Grenadier, 2002; Aguerrevere, 2003, 2009), while a few investigate repeated lumpy investment decisions (Novy-Marx, 2007). Numerical results of a multi-round investment problem can be derived using stochastic dynamic programming and Monte Carlo simulation (Murto et al., 2004). For analytical results, control theory is used to derive equilibrium investment strategies in a Nash framework. The key feature is that each firm determines its optimal capacity strategy while taking its competitors' strategies as given.

Research that examines dynamic competitive investments is an emerging trend in the literature of capacity models. So far they have been applied mostly in financial studies and have some limitations. First, most studies specify a fixed capacity size as the action available to a firm and use the real options approach to determine only the timing of taking this particular action. Second, current studies have been limited to simultaneous investment strategies and are considered as "open-loop" strategies in the sense that there is no feedback from the investment of any firm to the investment of any other firm, neither in the same period nor in the next ones (Back and Paulsen, 2009). Although "open-loop" strategies are mathematically tractable, they are dynamically inconsistent as decisions are derived at the initial time, without accounting for the state evolution beyond that time. We contribute to the extant literature by introducing sequential feedback strategies, modeled by a Stackelberg game, where all firms respond to the investment of any other firm like a Stackelberg follower. When using feedback strategies, firms have information on their competitors' current capacity and react to capacity perturbations through their own investments. Moreover, we allow the size of an investment to be determined by the optimal policy and hence study more complete features of a capacity strategy, i.e., timing and size. Table 3.1 gives an overview of some existing capacity models and our model.

3.3 The model

The notations used in our model are listed in Table 3.2. To illustrate the model, consider the following example: two firms (l and f) sell a homogeneous product (e.g., shipping service) in an oligopolistic market within a finite time horizon $\Gamma = \{1, \cdots, T\}$, assuming capacity is instantaneously adjustable and investment is partially irreversible. Throughout the entire timespan, firm l is the leader and firm f is the follower. For $t \in \Gamma$ and $j \in \{l, f\}$, let k_{tj} represent firm j's capacity level in period t and let the finite set $\mathscr{K}_{tj} \subseteq \mathbb{R}_{\geq 0}$ denote the

Table 3.1: Overview of some existing capacity models and our model

Capacity models	Examples	Multi-round	Investment decisions		Firm interaction		
						horizontal	
			timing	*size*	*vertical*	*simultaneous*	*sequential*
Static	Netessine et al., 2002			✓			
	Kulkarni et al., 2004			✓			
	Van Mieghem and Rudi, 2002	✓		✓			
	Plambeck and Taylor, 2005			✓	✓		
	Caldentey and Haugh, 2006			✓	✓		
	Lederer and Li, 1997			✓		✓	
	Van Mieghem, and Dada, 1999			✓		✓	
Dynamic	Eberly and Van Mieghem, 1997	✓	✓	✓			
	Ryan, 2004	✓	✓	✓			
	Huh et al., 2006	✓	✓	✓			
	Dixit, 1994		✓				✓
	Hoppe, 2000		✓				✓
	Pawlina and Kort, 2006		✓				✓
	Thijssen et al., 2006		✓				✓
	Swinney et al., 2011		✓			✓	
	Grenadier, 2002	✓	✓			✓	
	Aguerrevere, 2003, 2009	✓	✓			✓	
	Our research	✓	✓	✓			✓

set of available capacity choices, i.e., $k_{tj} \in \mathscr{K}_{tj}$. The origin and the end of $\mathscr{K}_{tj}$ are denoted as k_{tj_o} and k_{tj_e}: $k_{tj_o} = \inf \mathscr{K}_{tj}$ and $k_{tj_e} = \sup \mathscr{K}_{tj}$. The initial capacity of the two players are k_{0l} and k_{0f}. At the beginning of each period $t \in \Gamma$, the leader first changes its capacity from k_{t-1l} to k_{tl}. The follower then observes k_{tl} and changes its capacity from k_{t-1f} to k_{tf}.

The optimal capacity in each period is determined such that the value of a firm's long-term strategy, which is a sequence of actions from the current one to the one at the end of Γ, is maximized. Therefore, the capacity decision is based on the demand, supply, and investment cost information then available to the firm and on its assessment of the uncertain future. Let $\omega_\tau \in \Theta$ represent the (expected) demand at the beginning of period τ, where $\Theta \subseteq \mathbb{R}$ is the set of demand values. Exogenous uncertainty exists in ω_τ, $\forall \tau > t$, and it possesses a Markov property. We denote the transition probability function of demand as $Pr : \Theta \times \Theta \times \Gamma \to [0, 1]$. The conditional transition probability is $\Pr\{\omega_{t+1} = x_{t+1} \mid \omega_t = x_t\} = Pr(x_t, x_{t+1}, t)$, independent of x_{t_0} $\forall t_0 < t$. Thus, the demand information relevant to the capacity decision in period t contains the current demand, i.e., ω_t, and the transition probability.

The supply information comprises both firms' capacity levels, available capacity choices, capacity utilization parameters, and utilization cost functions in the current period. Let time t, demand value ω_t, and firms' capacity k_{tj} (or k_{t-1j}) define the state of the system. Denote the state space by $\Omega = \mathscr{K}_{tl}(or \mathscr{K}_{t-1f}) \times \mathscr{K}_{tf}(or \mathscr{K}_{t-1l}) \times \Theta \times \Gamma$. At the beginning of period t, the leader observes state $\mathbf{Y}_{tl} = (k_{t-1l}, k_{t-1f}, \omega_t, t) \in \Omega$ and decides k_{tl}. The follower then observes state $\mathbf{Y}_{tf} = (k_{tl}, k_{t-1f}, \omega_t, t) \in \Omega$ and decides k_{tf}. Hereinafter, we omit the time variable t in state vectors. After capacity decisions, the two firms engage in a single-period production competition which takes the form of a Cournot competition. Thus, the optimal production quantities can be found by allowing firms to set their production simultaneously to maximize their own operating profit of the current period. It is worth mentioning that production decisions only affect the current period, whereas capacity decisions influence firms permanently (see also *Murto et al., 2004*).

We denote firm j's production quantity in period t as q_{tj} and it is determined by a function of the state $(k_{tl}, k_{tf}, \omega_t)$, i.e., $q_{tj} = Q_{tj}(k_{tl}, k_{tf}, \omega_t)$. The total production quantity in period t is $q_t = \sum_{j\in\{l,f\}} Q_{tj}(k_{tl}, k_{tf}, \omega_t)$. Given the total production quantity and the demand of period t, the price of the homogeneous product is given by an inverse demand function: $p_t = P_t(q_t, \omega_t)$. As q_t can be represented as a function of the state $(k_{tl}, k_{tf}, \omega_t)$, we can write the price function in the same manner, i.e., $P_t(k_{tl}, k_{tf}, \omega_t)$. Given the production quantity and capacity, the production cost of firm j in period t is denoted as h_{tj} and is given by a cost function: $h_{tj} = H_{tj}(q_{tj}, k_{tj})$. Let a_{tj} denote the capacity utilization parameter, which represents the capacity usage per produced unit of firm j in period t. Firm j's operating profit in period t is given in equation (3.1). Since the marginal profit of an investment is usually non-increasing, we assume that a firm's operating profit is concave in its capacity decision, given a fixed capacity of the opponent (see Assumption 3.1). Examples of operating profit functions that satisfy Assumption 3.1 include those associated with the market-clearing price or isoelastic prices.

$$\begin{aligned} &\pi_{tj}(k_{tl}, k_{tf}, \omega_t) = p_t q_{tj} - h_{tj}, \qquad \forall t \in \Gamma \\ &s.t. \qquad a_{tj} q_{tj} \leq k_{tj} \end{aligned} \tag{3.1}$$

Assumption 3.1. *For any given and fixed capacity of the opponent* $k_{ti} \in \mathscr{K}_{ti}\,(i \neq j)$ *and for each* $\omega_t \in \Theta$*, firm* j*'s operating profit function* $\pi_{tj}(k_{ti}, \cdot, \omega_t)$ *is concave in its own decision* k_{tj}*.*

In addition to the demand and supply information, which are used for determining the profit of each period, the investment cost information is also used in the capacity decision. This includes the discount rate δ and both firms' marginal investment costs and marginal disinvestment revenues in period t, i.e., c_{tj} and r_{tj}. It may seem strict to assume that firms know each other's cost parameters, and above-mentioned capacity choices, capacity utilization parameters, and utilization cost functions. However, in the shipping industry, such parameters are published by market observers such as *Drewry* in their annual reports on container census and on carrier financials (Drewry, 2015a,b). Since shipping firms as well as firms in other industries often use current investment costs for future planning, we assume that both players consider $\mathscr{K}_{\tau j} = \mathscr{K}_{tj}$, $a_{\tau j} = a_{tj}$, $H_{\tau j} = H_{tj}$, $c_{\tau j} = c_{tj}$, and $r_{\tau j} = r_{tj}$, $\forall \tau > t$. This assumption is also in line with existing dynamic capacity models, which only allow univariate uncertainty (e.g., demand uncertainty). We define the investment cost function of firm j in period t as a kinked piece-wise linear function: $C_{tj}(k_{tj}) = c_{tj} \times (k_{tj} - k_{t-1j})^+ - r_{tj} \times (k_{t-1j} - k_{tj})^+$, where $(x)^+$ denotes $\max\{0, x\}$. As purchasing capital assets or technology is partially irreversible, we make the following assumption on the investment cost parameters c_{tj}, r_{tj} and δ:

Assumption 3.2. *Capacity investment is costly to reverse as $c_{tj} > r_{tj}$. In addition, the present value of a unit of used capacity cannot be higher than a new unit, i.e., $c_{tj} \geqslant \delta^{\tau - t} r_{\tau j}$ for each $\tau \in \{t, \cdots, T\}$, where $\delta > 0$ is the single-period discount factor.*

At the end of Γ, the salvage value of firm j is determined by the function $F_j(k_{Tl}, k_{Tf}, \omega_{T+1})$. Analogous to the operating profit function, we assume that a firm's salvage value is concave in its final capacity, given a fixed final capacity of the opponent (see Assumption 3.3).

Assumption 3.3. *For any given and fixed capacity of the opponent $k_{Ti} \in \mathscr{K}_{Ti} (i \neq j)$ and for each $\omega_{T+1} \in \Theta$, firm j's salvage value function $F_j(k_{Ti}, \cdot, \omega_{T+1})$ is concave in its own capacity k_{Tj}.*

3.4 Optimal value functions

3.4.1 Follower's value function

Let $\mathbf{K}_{tj} = (k_{tj}, k_{t+1j}, \cdots, k_{Tj})$ denote firm j's investment strategy vector from period t to the end of Γ and $\mathcal{K}_{tj}$ denote the set of all investment strategy vectors, i.e., $\mathbf{K}_{tj} \in \mathcal{K}_{tj}$. Given the state $\mathbf{Y}_{tf} = (k_{tl}, k_{t-1f}, \omega_t)$, $\mathbf{K}_{t+1l}$ and $\mathbf{K}_{tf}$,

Parameter	Description
Γ	set of time periods
k_{tj}	firm j's capacity in period t
$\mathscr{K}_{tj}$	set of capacity choices available to firm j in period t
k_{tj_o}, k_{tj_e}	origin and end of the capacity space $\mathscr{K}_{tj}$
$\mathbf{K}_{tj}$	firm j's investment strategy vector from period t to the end of Γ
$\mathcal{K}_{tj}$	set of all investment strategy vectors $\mathbf{K}_{tj}$
ω_t	demand indicator of period t
Θ	set of demand realizations
Pr	transition probability function of the demand
$\mathbf{Y}_{tj}$	state vector observed by firm j at the beginning of period t
q_{tj}, Q_{tj}	firm j's production quantity and production quantity function in period t
q_t	total production quantity of the product in period t
p_t, P_t	product price and price function in period t
h_{tj}, H_{tj}	firm j's production cost and production cost function in period t
a_{tj}	firm j's capacity utilization parameter in period t
π_{tj}	firm j's operating profit function in period t
c_{tj}, r_{tj}	firm j's marginal investment cost and marginal disinvestment revenue in period t
C_{tj}	firm j's investment cost function in period t
δ	single-period discount factor
F_j	firm j's salvage value function
V_{tj}, V^*_{tj}	firm j's value function and optimal value function at the beginning of period t
S_{tj}	firm j's stayput region in period t
k^L_{tj}, K^L_{tj}	lowerbound and lowerbound function of firm j's stayput region in period t
k^H_{tj}, K^H_{tj}	upperbound and upperbound function of firm j's stayput region in period t

Table 3.2: Model parameters

the follower's expected net present value (NPV), conditioned on the demand at the beginning of period t, is:

$$V_{tf}(k_{tl}, k_{t-1f}, \omega_t, \mathbf{K}_{t+1l}, \mathbf{K}_{tf}) =$$
$$E\left[\sum_{\tau=t}^{T} \delta^{\tau-t}(\pi_{\tau f}(k_{\tau l}, k_{\tau f}, \omega_\tau) - C_{\tau f}(k_{\tau f})) + \delta^{T+1-t} F_f(k_{Tl}, k_{Tf}, \omega_{T+1}) \mid \omega_t\right] \tag{3.2}$$

Here $\mathbf{K}_{t+1l}$ is the follower's opinion of the leader's future strategy. In order to derive a structured optimal strategy, we assume that for each $k_{\tau f}$ in $\mathbf{K}_{tf}$, a value of $k_{\tau+1l}$ is decided according to a rule and this rule is consistent for each $\tau \in \{t, \cdots, T-1\}$. The follower can either have a reactive rule, assuming $k_{\tau+1l} = k_{tl}$, or proactively calculate $k_{\tau+1l}$ as a response of the leader to the follower's action, $k_{\tau f}$. All existing oligopoly capacity models that study interaction between two firms' investments (e.g., Grenadier (2002); Novy-Marx (2007)) implicitly assume that both players know ex ante the opponent's exact response to the player's own strategy. This assumption may hold true for the leader, as it can exert some control over the market and thus knows the follower's possible responses. However, the same assumption is not always applicable to the follower in a multi-round game. We relax the optimality assumption and consider two situations where the follower's proactive thinking is effective and ineffective, respectively. These two situations can also be thought of as: the follower has full information or has incorrect information on the leader's future strategy.

After specifying the rule, we can omit $\mathbf{K}_{t+1l}$ in the follower's value function, i.e., $V_{tf}(k_{tl}, k_{t-1f}, \omega_t, \mathbf{K}_{tf})$. The follower's optimal value function at the beginning of period t is:

$$V^*_{tf}(k_{tl}, k_{t-1f}, \omega_t) = \sup_{\mathbf{K}_{tf} \in \mathcal{K}_{tf}} V_{tf}(k_{tl}, k_{t-1f}, \omega_t, \mathbf{K}_{tf}) \tag{3.3}$$

3.4.2 Leader's value function

The leader can either adopt a reactive strategy or plan its investments proactively, considering the follower's responses. We assume that in the proactive cases, the leader has full information on the follower's responses as part of the first mover advantage. Full information includes the follower's opinion of the leader's future strategy. Given the state $\mathbf{Y}_{tl} = (k_{t-1l}, k_{t-1f}, \omega_t)$, $\mathbf{K}_{tl}$ and $\mathbf{K}_{tf}$, the leader's expected NPV, conditioned on the demand at the beginning of period t, is:

$$V_{tl}(k_{t-1l}, k_{t-1f}, \omega_t, \mathbf{K}_{tl}, \mathbf{K}_{tf}) = \\ E\left[\sum_{\tau=t}^{T} \delta^{\tau-t}(\pi_{\tau l}(k_{\tau l}, k_{\tau f}, \omega_\tau) - C_{\tau l}(k_{\tau l})) + \delta^{T+1-t}F_l(k_{Tl}, k_{Tf}, \omega_{T+1}) \mid \omega_t\right] \tag{3.4}$$

If the leader adopts the reactive strategy, it assumes $\mathscr{K}_{tf} = \mathscr{K}_{t-1f}$ and $k_{\tau f} = k_{t-1f} \in \mathscr{K}_{t-1f}$, $\forall \tau \in \{t, \cdots, T\}$ in $\mathbf{K}_{tf}$. A proactive leader knows the exact response of the follower, obtaining $k_{\tau f}$ from the vector $\mathbf{K}^*_{\tau f}$ which is determined by $V^*_{\tau f}(k_{\tau l}, k_{\tau-1f}, \omega_\tau)$. After specifying the strategy, we can omit $\mathbf{K}_{tf}$ in the leader's value function. The leader's optimal value function at the beginning of period t is:

$$V^*_{tl}(k_{t-1l}, k_{t-1f}, \omega_t) = \sup_{\mathbf{K}_{tl} \in \mathcal{K}_{tl}} V_{tl}(k_{t-1l}, k_{t-1f}, \omega_t, \mathbf{K}_{tl}) \tag{3.5}$$

Mixing the two players' proactive or reactive strategies, as well as the effectiveness of a proactive strategy, we consider four cases. Case (a) *stayput*: the leader is proactive, while the follower reacts to the competition by assuming that the leader will stay put in the next period, i.e., $k_{\tau l} = k_{tl}$, for all $\tau \in \{t+1, \cdots, T\}$ in equation (3.2). Case (b) *adversarial*: both players are proactive, however, the follower has incorrect information on the leader's strategy and assumes that the leader is adversarial, i.e., $k_{\tau l} = \arg\min_{k \in \mathscr{K}_{\tau l}} V^*_{\tau f}(k, k_{\tau-1f}, \omega_\tau)$, for all $\tau \in \{t+1, \cdots, T\}$ in equation (3.2). Case (c) *optimal*: both players are proactive, and the follower has full information on the leader's optimal strategy, i.e., $k_{\tau l} = \arg\max_{k \in \mathscr{K}_{\tau l}} V^*_{\tau l}(k_{\tau-1l}, k_{\tau-1f}, \omega_\tau)$, for all $\tau \in \{t+1, \cdots, T\}$ in equation (3.2). Case (d) *reactive*: both players are reactive by assuming that the other player will stay put in the next period. A case in which the leader is reactive and the follower is proactive is not mentioned here, as it is identical to case (a) with a delayed starting point (i.e., the follower moves first). We denote cases (c) and (d) as symmetric cases since both players adopt the same approach and have the same amount of information on each other's strategy, whereas cases (a) and (b) are asymmetric as the situations are different for the two players. In any proactive case, equations (3.3) and (3.5) suffer the curse of dimensionality. Below, we use recursive optimality equations to get the optimal value and derive an ISD policy which determines the optimal action of each period.

3.4.3 Recursive optimality equations

The value of a long-term strategy comprises the value of the current action and the value of future actions. According to Bellman's principle of optimality, V_{tj} (equations (3.3) and (3.5)) satisfy the recursive optimality equations below.
At the end of the time horizon Γ (or at the beginning of period $T+1$), firm j's salvage value associated with the state $\mathbf{Y}_{T+1j} = (k_{Tl}, k_{Tf}, \omega_{T+1})$ is:

$$V^*_{T+1j}(k_{Tl}, k_{Tf}, \omega_{T+1}) = F_j(k_{Tl}, k_{Tf}, \omega_{T+1}) \tag{3.6}$$

At the beginning of each period $t \in \Gamma$, the follower's optimal value function associated with the state $\mathbf{Y}_{tf} = (k_{tl}, k_{t-1f}, \omega_t)$ is:

$$V^*_{tf}(k_{tl}, k_{t-1f}, \omega_t) = \sup_{k_{tf} \in \mathscr{K}_{tf}} \left\{ \pi_{tf}(k_{tl}, k_{tf}, \omega_t) - C_{tf}(k_{tf}) + \delta E[V^*_{t+1f}(k_{t+1l}, k_{tf}, \omega_{t+1}) \mid \omega_t] \right\} \tag{3.7}$$

where k_{t+1l} depends on the follower's strategy, for example, whether it is case (a) or (c).
At the beginning of each period $t \in \Gamma$, the leader's optimal value function associated with the state $\mathbf{Y}_{tl} = (k_{t-1l}, k_{t-1f}, \omega_t)$ is:

$$V^*_{tl}(k_{t-1l}, k_{t-1f}, \omega_t) = \sup_{k_{tl} \in \mathscr{K}_{tl}} \left\{ \pi_{tl}(k_{tl}, k_{tf}, \omega_t) - C_{tl}(k_{tl}) + \delta E[V^*_{t+1l}(k_{tl}, k_{tf}, \omega_{t+1}) \mid \omega_t] \right\} \tag{3.8}$$

where k_{tf} depends on the type of the leader's strategy, for example, whether it is case (c) or (d).

Without specifying the case here, we define a function G_{tj} (see equations (3.9) and (3.10)) as firm j's expected NPV evaluated in period t, given that its capacity has been adjusted to k_{tj} and an optimal follow-up investment strategy will be implemented (i.e., $V^*_{t+1j}(\cdot)$).

$$G_{tf}(k_{tl}, k_{tf}, \omega_t) = \pi_{tf}(k_{tl}, k_{tf}, \omega_t) + \delta E[V^*_{t+1f}(k_{t+1l}, k_{tf}, \omega_{t+1}) \mid \omega_t] \tag{3.9}$$

$$G_{tl}(k_{tl}, k_{t-1f}, \omega_t) = \pi_{tl}(k_{tl}, k_{tf}, \omega_t) + \delta E[V^*_{t+1l}(k_{tl}, k_{tf}, \omega_{t+1}) \mid \omega_t] \tag{3.10}$$

Substituting G_{tf} into equation (3.7) and G_{tl} into equation (3.8), the optimization problems of the follower and the leader in period t equal the ones in equations (3.11) and (3.12), respectively.

$$V^*_{tf}(k_{tl}, k_{t-1f}, \omega_t) = \sup_{k_{tf} \in \mathscr{K}_{tf}} \left\{ G_{tf}(k_{tl}, k_{tf}, \omega_t) + r_{tf} \times (k_{t-1f} - k_{tf})^+ - c_{tf} \times (k_{tf} - k_{t-1f})^+ \right\} \tag{3.11}$$

$$V^*_{tl}(k_{t-1l}, k_{t-1f}, \omega_t) = \sup_{k_{tl} \in \mathscr{K}_{tl}} \left\{ G_{tl}(k_{tl}, k_{t-1f}, \omega_t) + r_{tl} \times (k_{t-1l} - k_{tl})^+ - c_{tl} \times (k_{tl} - k_{t-1l})^+ \right\} \tag{3.12}$$

Eberly and Van Mieghem (1997) solve the optimization problem for a single-firm case. They show that if the optimal value function V^* is strictly concave, the optimal policy (also called ISD policy) can be represented in the form of a unique stayput region, which is a continuum of optimal solutions to the investment problem. The boundaries of the stayput region define the decision rule for investments in each period: if capacity falls within the boundaries (i.e., inside the stayput region), it is optimal not to adjust capacity; otherwise, capacity should be adjusted to an appropriate point on the region's boundary. Extending their method to a two-firm setting, we derive the reactive and proactive ISD policies, respectively, for a firm in the competition.

3.5 Reactive ISD policy

If a firm adopts a reactive strategy, it observes the latest action of the opponent and plans its capacity accordingly, assuming that its opponent will stay at the current capacity for the rest of the timespan. Under Assumptions 3.1, 3.2, and 3.3, we show in Proposition 3.1 that a player's optimal value function in each period is concave in its capacity decision if it adopts the reactive strategy (e.g., the follower in case (a) and both players in case (d)). This allows us to efficiently find an optimal solution to the investment problem. Proofs to all Corollaries, Propositions, and Theorems are listed in Appendix A. In Theorem 3.1, we present firm j's ISD policy in period t in the case where the optimal value function V_{tj}^* is jointly concave in (k_{t-1j}, k_{tj}) for any given $k_{ti} \in \mathscr{K}_{ti}$ and for each $\omega_t \in \Theta$. Thus, a firm's reactive ISD policy takes the same form as in Theorem 3.1 and is a function of the opponent's latest observed action.

Proposition 3.1. *Under Assumptions 3.1, 3.2, and 3.3, if firm j adopts the reactive strategy, the optimal value function V_{tj}^* is jointly concave in (k_{t-1j}, k_{tj}) for any given current capacity of the opponent $k_{ti} \in \mathscr{K}_{ti}$ or $k_{t-1i} \in \mathscr{K}_{t-1i}$ $(i \neq j)$ and for each $\omega_t \in \Theta$.*

Theorem 3.1. *Given the current capacity of the opponent $k_{ti} \in \mathscr{K}_{ti}$ $(i \neq j)$ and $\omega_t \in \Theta$, if firm j's optimal value function V_{tj}^* is jointly concave in (k_{t-1j}, k_{tj}) and there exists a unique solution to the optimization problem in equation* (3.11) *if $j = f$ or in equation* (3.12) *if $j = l$, then the solution is an ISD policy that is characterized by the following lowerbound and upperbound functions:*

$$K_{tj}^L(k_{ti}, \omega_t) = \sup\left\{\{k_{tj_o}\} \cup \{k_{tj} : \frac{\nabla_- G_{tj}(k_{ti}, k_{tj}, \omega_t)}{\nabla k_{tj}} \geq c_{tj}, \quad k_{tj} \in \mathscr{K}_{tj}\}\right\} \tag{3.13}$$

$$K_{tj}^H(k_{ti}, \omega_t) = \inf\left\{\{k_{tj_e}\} \cup \{k_{tj} : \frac{\nabla_+ G_{tj}(k_{ti}, k_{tj}, \omega_t)}{\nabla k_{tj}} \leq r_{tj}, \quad k_{tj} \in \mathscr{K}_{tj}\}\right\} \tag{3.14}$$

Corollary 3.1. *Let k_{tj}^L and k_{tj}^H denote the lowerbound and upperbound computed by the two boundary functions in Theorem 3.1, i.e., $k_{tj}^L = K_{tj}^L(k_{ti}, \omega_t)$ and $k_{tj}^H = K_{tj}^H(k_{ti}, \omega_t)$: $k_{tj}^L \leq k_{tj}^H$.*

In Theorem 3.1, $\frac{\nabla_- G_{tj}(k_{ti}, k_{tj}, \omega_t)}{\nabla k_{tj}}$ is the infimum of all left-sided difference quotients of the function $G_{tj}(k_{ti}, k_{tj}, \omega_t)$ at the point k_{tj}, and $\frac{\nabla_+ G_{tj}(k_{ti}, k_{tj}, \omega_t)}{\nabla k_{tj}}$ is the supremum of all right-sided difference quotients of the function $G_{tj}(k_{ti}, k_{tj}, \omega_t)$

at the point k_{tj}, i.e., $\frac{G(k_{ti},x,\omega_t)-G(k_{ti},k_{tj},\omega_t)}{x-k_{tj}} \geq \frac{\nabla_- G(k_{ti},k_{tj},\omega_t)}{\nabla k_{tj}}$ for all $x < k_{tj}$, and $\frac{G(k_{ti},y,\omega_t)-G(k_{ti},k_{tj},\omega_t)}{y-k_{tj}} \leq \frac{\nabla_+ G(k_{ti},k_{tj},\omega_t)}{\nabla k_{tj}}$ for all $y > k_{tj}$, where x, y and k_{tj} are in the domain of G. Thus, $\frac{\nabla_- G_{tj}(k_{ti},k_{tj},\omega_t)}{\nabla k_{tj}}$ and $\frac{\nabla_+ G_{tj}(k_{ti},k_{tj},\omega_t)}{\nabla k_{tj}}$ can be seen as firm j's (minimal) marginal value of investment and (maximal) marginal value of disinvestment at capacity k_{tj}. The ISD policy defined in Theorem 3.1 is characterized by two boundaries which are determined by marginal values of investment and disinvestment. In Corollary 3.1, we prove that one boundary is always lower than or equal to the other boundary. Therefore, such an ISD policy can be presented as a stayput region $S_{tj}(k_{ti},\omega_t) \subset \mathbb{R}_{\geq 0}$, of which the (minimal) marginal value of investment equals c_{tj} at the lowerbound k_{tj}^L and the (maximal) marginal value of disinvestment equals r_{tj} at the upperbound k_{tj}^H (see Property 3.1). With a discrete capacity space, the stayput region is a subset containing a finite number of values in the interval $[k_{tj}^L, k_{tj}^H]$. The concavity of V_{tj}^* indicates that capacity which is outside of $S_{tj}(k_{ti},\omega_t)$ should be adjusted to the closest boundary of $S_{tj}(k_{ti},\omega_t)$.

Property 3.1. *For each $k_{ti} \in \mathscr{K}_{ti}$ $(i \neq j)$ and for each $\omega_t \in \Theta$, the ISD policy defined in Theorem 3.1 can be written as a stayput region $S_{tj}(k_{ti},\omega_t) \subset \mathbb{R}_{\geq 0}$, where:*

$$S_{tj}(k_{ti},\omega_t) = [k_{tj}^L, k_{tj}^H] = \left\{ k_{tj} : \, r_{tj} \leq \frac{\nabla_+ G_{tj}(k_{ti},k_{tj},\omega_t)}{\nabla k_{tj}} \wedge \frac{\nabla_- G_{tj}(k_{ti},k_{tj},\omega_t)}{\nabla k_{tj}} \leq c_{tj}, \quad k_{tj} \in \mathscr{K}_{tj} \right\} \tag{3.15}$$

In period t, firm j's decision rule indicated by the reactive ISD policy $S_{tj}(k_{ti},\omega_t)$ is as follows:

- *if $k_{t-1j} \in S_{tj}(k_{ti},\omega_t)$, no adjustment should be made, i.e., $k_{tj} = k_{t-1j}$;*
- *if $k_{t-1j} \notin S_{tj}(k_{ti},\omega_t)$ and $k_{t-1j} < K_{tj}^L(k_{ti},\omega_t)$, an investment should be made such that the new capacity hits the boundary of $S_{tj}(k_{ti},\omega_t)$ at the lower side, i.e., $k_{tj} = K_{tj}^L(k_{ti},\omega_t)$;*

- *if* $k_{t-1j} \notin S_{tj}(k_{ti}, \omega_t)$ *and* $k_{t-1j} > K^H_{tj}(k_{ti}, \omega_t)$*, a disinvestment should be made such that the new capacity hits the boundary of* $S_{tj}(k_{ti}, \omega_t)$ *at the higher side, i.e.,* $k_{tj} = K^H_{tj}(k_{ti}, \omega_t)$*.*

3.6 Proactive ISD policy

If firm j adopts a proactive strategy, the optimal value function V^*_{tj}, as well as the expected NPV function G_{tj}, may not be concave in k_{tj}. Non-concavity of the optimization problem arises from the fact that a proactive firm strategically plans its investments, considering the opponent's potential response strategy, which non-monotonously influences the firm's own present and future value. A firm's proactive ISD policy considers multiple competitive goals towards the opponent's future capacity growth and thus contains multiple disjoint stayput intervals. The number and size of stayput intervals determine the strategic responsiveness of a firm's ISD policy to the opponent's strategy: the more intervals and the shorter each interval is, the more responsive an ISD policy is. We first reduce the dynamic long-term problem to a single-shot investment and derive the leader's proactive ISD policy in closed form. Using similar logic, we then develop an algorithm to derive the proactive ISD policy for a long-term setting and a discrete capacity space.

3.6.1 Single-shot proactive investment

In the single-shot setting, the leader has full information on the follower's response strategy and proactively plans its investment, while the follower responds reactively. Satisfying Assumptions 3.1 and 3.3, we use a linear form for the price function and for the salvage value function: $p_t = \alpha\omega_t - k_{tl} - k_{tf}$, and $F_j(k_{Tl}, k_{Tf}, \omega_{T+1}) = (\alpha\omega_{T+1} - k_{Tl} - k_{Tf}) \times k_{Tj}$. For simplicity, we set the capacity utilization parameter $a_{tj} = 1$ and the production cost $h_{tj} = 0$. In addition, we use the same cost parameters values for both players: $c_{tl} = c_{tf} = c$ and $r_{tl} = r_{tf} = r$. We set $c > r$, which satisfies Assumption 3.2, and set the capacity space as $\mathscr{K}_{tj} = \mathbb{R}_{\geq 0}$.

According to Proposition 3.1 and Theorem 3.1, the follower's value function is concave in k_{1f} and the follower's ISD policy contains a single stayput interval, of which the boundaries are determined by functions of k_{1l}. Set $\omega = \frac{\alpha(\omega_1+\delta E[\omega_2])}{2(1+\delta)}$, the follower's optimal action is given in equation (3.16) and can also be simply seen as a function of the leader's first move:

$$k_{1f} = K_{1f}(k_{1l}) = \begin{cases} k_{1f}^{L} = \omega - \frac{c}{2(1+\delta)} - \frac{k_{1l}}{2} & \textit{if } k_{0f} < \omega - \frac{c}{2(1+\delta)} - \frac{k_{1l}}{2} \\ k_{0f} & \textit{if } \omega - \frac{c}{2(1+\delta)} - \frac{k_{1l}}{2} \leq k_{of} \leq \omega - \frac{r}{2(1+\delta)} - \frac{k_{1l}}{2} \\ k_{1f}^{H} = \omega - \frac{r}{2(1+\delta)} - \frac{k_{1l}}{2} & \textit{if } k_{of} > \omega - \frac{r}{2(1+\delta)} - \frac{k_{1l}}{2} \end{cases} \tag{3.16}$$

The leader takes three steps in the decision making process to maximize its value function $V_{1l} = k_{1l} \times (\alpha\omega_1 + \delta\alpha E[\omega_2] - k_{1l}(1+\delta) - k_{1f}(1+\delta)) - c \times (k_{1l} - k_{0l})^{+} + r \times (k_{0l} - k_{1l})^{+}$. **First**, the leader identifies its available capacity choices for different competitive goals based on the follower's response. According to equation (3.16), the leader's decision k_{1l} belongs to one of the three mutually exclusive and complementary ranges: (1) $k_{1l} \leq 2\omega - \frac{c}{1+\delta} - 2k_{0f}$; (2) k_{1l} : $2\omega - \frac{c}{1+\delta} - 2k_{0f} \leq k_{1l} \leq 2\omega - \frac{r}{1+\delta} - 2k_{0f}$; (3) $k_{1l} \geq 2\omega - \frac{r}{1+\delta} - 2k_{0f}$. If the leader chooses any action from each of the three ranges, the follower's reaction is to invest, stay put, and disinvest, respectively, while the magnitude of the follower's decision depends on the exact value of k_{1l}. We refer to these ranges as the capacity range for a *submissive*, *neutral*, or *aggressive* competitive goal. We call this an SNA (*Submissive, Neutral, Aggresive*) strategy.

After dividing the capacity space, the leader's **second** step is to determine the optimal decision interval for each competitive goal. Substituting the corresponding response of the follower into the leader's value function in each competitive goal range, V_{1l} in that capacity range is concave in k_{1l}. Thus, the leader's stayput interval associated with a fixed response of the follower can be derived using Theorem 3.1 and by comparing the interval boundaries and the capacity range boundaries. A stayput interval exists for a competitive goal if at least one interval boundary is within the range. We denote the stayput interval for competitive goal x as S_x and the interval boundaries as $k_o^{S_x}$ and $k_e^{S_x}$, i.e., $S_x = [k_o^{S_x}, k_e^{S_x}]$. The detailed stayput interval for each competitive goal is given below:

1. In the *submissive* goal range (S) with $k_{1l} \leq 2\omega - \frac{c}{1+\delta} - 2k_{0f}$, the follower's response is to invest $k_{1f} = k_{1f}^L = \omega - \frac{c}{2(1+\delta)} - \frac{k_{1l}}{2}$. If $k_{0f} \leq \frac{\omega}{2} - \frac{c}{4(1+\delta)}$, the stayput interval for this goal is $S_S = [k_o^{S_S}, k_e^{S_S}] = \big[\omega - \frac{c}{2(1+\delta)}, \min\{\omega + \frac{c-2r}{2(1+\delta)}, 2\omega - \frac{c}{1+\delta} - 2k_{0f}\}\big]$. If $k_{0f} > \frac{\omega}{2} - \frac{c}{4(1+\delta)}$, no stayput interval exists for this goal. This means that the leader's SNA strategy may not trigger the follower to invest, if the follower's current capacity is large or the investment unit cost is high.

2. In the *neutral* goal range (N) with $k_{1l} : 2\omega - \frac{c}{1+\delta} - 2k_{0f} \leq k_{1l} \leq 2\omega - \frac{r}{1+\delta} - 2k_{0f}$, the follower's response is to stay put $k_{1f} = k_{0f}$. If $\frac{2\omega}{3} + \frac{r-2c}{3(1+\delta)} \leq k_{0f} \leq \frac{2\omega}{3} + \frac{c-2r}{3(1+\delta)}$, the stayput interval for this goal is $S_N = [k_o^{S_N}, k_e^{S_N}] = \big[\max\{\omega - \frac{c}{2(1+\delta)} - \frac{k_{0f}}{2}, 2\omega - \frac{c}{1+\delta} - 2k_{0f}\}, \min\{\omega - \frac{r}{2(1+\delta)} - \frac{k_{0f}}{2}, 2\omega - \frac{r}{1+\delta} - 2k_{0f}\}\big]$. If $k_{0f} > \frac{2\omega}{3} + \frac{c-2r}{3(1+\delta)}$ or $k_{0f} < \frac{2\omega}{3} + \frac{r-2c}{3(1+\delta)}$, then no stayput interval exists for this goal. This means that the leader's SNA strategy will keep the follower stay at its current capacity, only if the follower's current capacity is within a certain range, determined by the level of investment irreversibility.

3. In the *aggressive* goal range (A) with $k_{1l} \geq 2\omega - \frac{r}{1+\delta} - 2k_{0f}$, the follower's response is to disinvest $k_{1f} = \omega - \frac{r}{2(1+\delta)} - \frac{k_{1l}}{2}$. If $k_{0f} \geq \frac{\omega}{2} - \frac{r}{4(1+\delta)}$, the stayput interval for this goal is $S_A = [k_o^{S_A}, k_e^{S_A}] = \big[\max\{\omega + \frac{r-2c}{2(1+\delta)}, 2\omega - \frac{r}{1+\delta} - 2k_{0f}\}, \omega - \frac{r}{2(1+\delta)}\big]$. If $k_{0f} < \frac{\omega}{2} - \frac{r}{4(1+\delta)}$, then no stayput interval exists for this goal. This means that the leader's SNA strategy may not trigger the follower to disinvest, if the follower's current capacity is small or the disinvestment unit price is low.

If the leader's current capacity k_{0l} is within S_S, S_N or S_A, the value of adjusting to another competitive goal range may be higher than the value of staying put, considering that the follower may respond differently. Therefore, the leader's **third** step is to obtain the decision intervals that are optimal for all competitive goals by comparing the values of switching to different competitive goals. Based on Theorem 3.1, the leader has more value staying put than adjusting to any other point within the interval if the current capacity is in a stayput interval. Therefore, we can compare two competitive goals by comparing the value of staying at one interval and the value of adjusting to either the lowerbound or upperbound of the other interval. Using the lowerbound as an example, the minimal difference between the value of sticking to a competitive goal and the value of adjusting to any other goal is $J(k) = k(\alpha\omega_1 + \delta\alpha E[\omega_2] - k(1+\delta) - K_{1f}(k)\cdot(1+\delta)) - \max_{y\neq x}\left\{k_o^{S_y}(\alpha\omega_1 + \delta\alpha E[\omega_2] - k_o^{S_y}(1+\delta) - K_{1f}(k_o^{S_y})\cdot(1+\delta)) + c\times(k_o^{S_y} - k)^+ - r\times(k - k_o^{S_y})^+\right\}$. The value of staying at a final optimal point should be larger than the value of adjusting, i.e., $J(k) > 0$ if k is a final optimal point. It is easy to prove that $J(k)$ is concave in k, $\forall k \in S_x$. Hence, there exists a single interval $S_x^{'} \subset S_x$ satisfying $J(k) > 0$, $\forall k \in S_x^{'}$. $S_x^{'}$ is the final stayput interval in competitive goal range x, which is optimal for all goals.

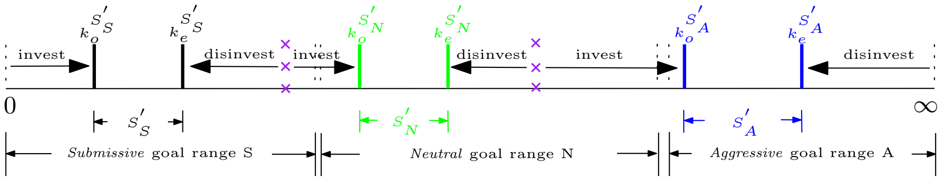


Figure 3.1: Example of the leader's ISD policy in the single-shot game

Depending on the parameters values, some competitive goals may not have a stayput interval, or intervals for two adjacent goals may be connected to each other. For this single-shot investment, the leader's ISD policy has up to three separate stayput intervals. After the three steps, the value of staying outside any final stayput interval is smaller than the value of adjusting to an interval boundary. If the current capacity falls within a stayput interval, the value of staying put is larger than the value of adjusting to any other point. Therefore, a proactive ISD policy with multiple stayput intervals assigns a non-stayput capacity value to the closest boundary of a close-by stayput interval. We call this a Multi-ISD decision rule.

For capacity values that are on one side of all stayput intervals, there is only one close-by interval, thus the optimal decision is to either invest or disinvest to hit the closest interval boundary. For non-stayput capacity values that fall between two consecutive intervals, the decision to which interval the current capacity should be adjusted depends on the investment costs and the values of two adjacent competitive goals. The difference between the values of adjusting a non-stayput point $k \in (k_e^{S_x^{'}}, k_o^{S_y^{'}})$ to one of the two adjacent goals (x and y) is monotonously decreasing (or increasing) in k. Thus, there exists an investment threshold $k_{0l}^{xy} \in [k_e^{S_x^{'}}, k_o^{S_y^{'}}]$ such that the optimal decision for all $k_{0l} \in (k_o^{S_x^{'}}, k_{0l}^{xy})$ is to disinvest to hit the upperbound of $S_x^{'}$, and the optimal decision for all $k_{0l} \in (k_{0l}^{xy}, k_e^{S_y^{'}})$ is to invest to hit the lowerbound of $S_y^{'}$. If $k_{0l}^{xy} \in (k_e^{S_x^{'}}, k_o^{S_y^{'}})$ and $k_{0l} = k_{0l}^{xy}$, adjusting k_{0l} to either boundary yields the same value. Figure 3.1 gives an example of the leader's ISD policy, where the first, second, and third stayput intervals are marked in black, green, and blue, respectively, and the investment thresholds are presented by purple crosses. The black lines with an arrow on one side indicate the optimal action for a non-stayput point.

The leader's ISD policy is illustrated by the number, sizes, and positions of stayput intervals, as well as the investment threshold between two consecutive intervals. The number of intervals indicates the availability of various competitive goals: the more intervals, the more goals the leader's policy contains. A small interval indicates a small range of optimal decisions, considering a specific goal and the follower's response, and suggests a high probability that the current capacity will be outside the interval and should be adjusted to an interval boundary, i.e., it is beneficial for a firm to change its capacity to trigger a specific response of the opponent. Therefore, an ISD policy with many small intervals implies that the investment strategy is highly responsive to the opponent's strategy. In the single-shot game, the leader has at most seven decisions: investment and disinvestment for each competitive goal (2×3) and stayput at the current capacity. Extending the game to a two-period setting, a proactive follower decides its optimal action in the first period taking into account the leader's reaction k_{2l}, which is decided based on the follower's response k_{2f}. By backwards induction, the leader's decision k_{2l} takes the same form as k_{1l} in the single-shot game. Therefore, there are seven different values of k_{2l}, and the follower can have seven competitive goals in the first period, thus potentially having seven stayput intervals. In a long-term setting, the number of stayput intervals increases exponentially, and the computation is intensive since an interval can exist for each fixed sequence of the other player's responses. Below, we develop an efficient algorithm to derive the optimal long-term proactive ISD policy.

3.6.2 Long-term proactive investment

In a long-term investment, a proactive player j expects its action k_{tj} to influence the other player i's optimal value $V_{ti}^*(k_{tj}, k_{t-1i}, \omega_t)$, i.e., $\frac{\nabla V_{ti}^*(k_{tj}, k_{t-1i}, \omega_t)}{\nabla k_{tj}} \neq 0$. Therefore, it strategically chooses k_{tj} to influence the opponent's upcoming investments, $k_{ti}, \cdots, k_{Ti}$, with the purpose of maximizing its own value V_{tj}. Note that a proactive follower $(j = f)$ perceives $\frac{\nabla V_{t+1l}^*(k_{tl}, k_{tf}, \omega_{t+1})}{\nabla k_{tf}} \neq 0$, and thus its action k_{tf} influences the leader's future capacity that starts from the next period, $k_{t+1l}, \cdots, k_{Tl}$. For simplicity, we do not distinguish the notations for the two players. In a long-term setting, the follower in period t can be considered as the "leader" in period $t + 1$. Two proactive players can be different in the effectiveness of their proactive strategies. For example, a player may not have complete information on the other player's strategy, and thus its proactive strategy may be less effective than that of the player who has full information.

We develop a *Decomposition Algorithm* to compute firm j's proactive ISD policy in period t. The mechanism of this type of algorithm is to "divide and conquer" (see also Groenevelt (1991)). Following similar logic as in Section

3.6.1, our *Decomposition Algorithm* contains three steps. The **first** step identifies a unique range that contains the stayput region. We exclude capacity values that fall outside this range from the final solution set. Next, we identify all *terminals*, which are the transition points between two different immediate responses of the opponent either in the current period t or in the next period $t+1$. Then we divide the range into separate *terminal intervals*, each of which ends at a *terminal*, and thus each *terminal interval* corresponds to a fixed immediate response of the other player. Within the same interval, firm j can still influence the opponent's later capacity by choosing different k_{tj}. The **second** step determines the stayput intervals in each *terminal interval* separately through two sequential *rolling capacity procedures*. The **third** step eliminates the capacity values that are not optimal to the optimization problem from each stayput interval, considering actions in other *terminal intervals*. Below, we elaborate on the three steps.

Step 1. Given the capacity space $\mathscr{K}_{tj} = [k_{tj_o}, k_{tj_e}]$, the range of the stayput region computed in the first step is denoted as $S^r_{[k_{tj_o}, k_{tj_e}]}$, and the final stayput region in the third step is denoted as $S_{[k_{tj_o}, k_{tj_e}]}$. To solve firm j's optimization problem in equation (3.11) or (3.12), we use the two boundary functions (equations (3.13) and (3.14)) in Theorem 3.1 to identify the range: $S^r_{[k_{tj_o}, k_{tj_e}]} = [k^L_{tj}, k^H_{tj}]$. Since G_{tj} is not necessarily concave, k^L_{tj} is not guaranteed to be smaller than or equal to k^H_{tj}. In Proposition 3.2, we show that the stayput region $S_{[k_{tj_o}, k_{tj_e}]}$ is completely contained in the range $S^r_{[k_{tj_o}, k_{tj_e}]}$. Therefore, if there exists a solution to the optimization problem, then $k^L_{tj} \leq k^H_{tj}$ (i.e., $S_{[k_{tj_o}, k_{tj_e}]} \subseteq S^r_{[k_{tj_o}, k_{tj_e}]} \neq \emptyset$). Such a condition is guaranteed if the capacity space $\mathscr{K}_{tj}$ is nonempty and closed. Hereinafter, we assume the existence of an optimal solution k_{tj} (not necessarily unique). In Proposition 3, we show that the boundaries of the range $S^r_{[k_{tj_o}, k_{tj_e}]}$ are contained in the final solution set: $k^L_{tj}, k^H_{tj} \in S_{[k_{tj_o}, k_{tj_e}]}$.

Proposition 3.2. $S_{[k_{tj_o}, k_{tj_e}]} \subseteq S^r_{[k_{tj_o}, k_{tj_e}]} = [k^L_{tj}, k^H_{tj}]$.

Proposition 3.3. k^L_{tj} *and* k^H_{tj} *are the lowerbound and the upperbound of*

$S_{[k_{tjo},k_{tje}]}$.

Let the function $K_{ti}(k_{tj})$ represent the opponent firm i's optimal action k_{ti}, which depends on its stayput region S_{ti} that is a function of k_{tj}. We identify all *terminals* in $S^r_{[k_{tjo},k_{tje}]}$ sequentially. Denote the start of the nth *terminal interval* as I^n_o and the nth *terminal* as I^n_e. The nth *terminal interval* is then $[I^n_o, I^n_e]$. The first *terminal interval* starts with the origin of $S^r_{[k_{tjo},k_{tje}]}$, i.e., $I^1_o = k^L_{tj}$. For $n \geq 1$ and $k \in S^r_{[k_{tjo},k_{tje}]}$: if there exists $\triangle k = \inf\{k' : k < k' \in S^r_{[k_{tjo},k_{tje}]}\}$ satisfying $K_{ti}(k) \neq K_{ti}(\triangle k)$, the nth *terminal* is set as $I^n_e = \inf\{k : K_{ti}(k) \neq K_{ti}(\triangle k), I^n_o \leq k \in S^r_{[k_{tjo},k_{tje}]}\}$; Otherwise, $I^n_e = k^H_{tj}$. If $I^1_e \neq k^H_{tj}$, the $n+1$th *terminal interval* starts with the smallest possible value after I^n_e in $S^r_{[k_{tjo},k_{tje}]}$: $I^{n+1}_o = \triangle I^n_e = \inf\{k : I^n_e < k \in S^r_{[k_{tjo},k_{tje}]}\}$. The searching process for *terminals* is continued until $I^n_e = k^H_{tj}$. In the first step, we assume that N *terminals* are identified in $S^r_{[k_{lo},k_{le}]}$ and the range is thus divided into N *terminal intervals.*

Step 2. Given a subset $\mathscr{K} = [k_o, k_e]$, where k_o and k_e are the origin and the end, and $k_i \in \mathscr{K}$, denote $\triangle k_i$ as the smallest possible value after k_i in $\mathscr{K}$ and $\triangle^- k_i$ as the largest possible value before k_i in $\mathscr{K}$: $\triangle k_i = \inf\{k : k_i < k \in \mathscr{K}\}$ and $\triangle^- k_i = \sup\{k : k_i > k \in \mathscr{K}\}$. If $k_i = k_e$, set $\triangle k_i = k_e$, and if $k_i = k_o$, set $\triangle^- k_i = k_o$. The two *rolling capacity procedures* eliminate non-optimal values in an interval through sequentially iterations. Below, we define the two rolling procedures in $\mathscr{K}$:

Rolling up procedure in $\mathscr{K}$ Starting with the origin k_o, the first iteration interval is set as $\mathscr{K}_1 := [k_o, k_o]$. Denote the ith iteration interval as $\mathscr{K}_i = [k_o, k_i]$, $\forall i \geq 1$. At the $i+1$th iteration, we extend the previous interval $\mathscr{K}_i$ by adding the smallest possible value after k_i to the right end of the iteration interval, i.e., $k_{i+1} = \triangle k_i$, until $k_{i+1} = k_e$. Given each iteration interval $\mathscr{K}_i = [k_o, k_i]$, we identify the upperbound of the range $S^r_{[k_o,k_i]}$ using the upperbound function (equation (3.14)) in Theorem 3.1: if k_i is not the upperbound of $S^r_{[k_o,k_i]}$, eliminate k_i from $\mathscr{K}$; otherwise, keep k_i.

Rolling down procedure in $\mathscr{K}$ Starting with the end k_e, the first iteration interval is set as $\mathscr{K}_1 := [k_e, k_e]$. Denote the ith iteration interval as $\mathscr{K}_i = [k_i, k_e]$, $\forall i \geq 1$. At the $i+1$th iteration, we extend the previous iteration interval $\mathscr{K}_i$ by adding the largest possible value before k_i to the left end of the iteration interval, i.e., $k_{i+1} = \triangle^{-} k_i$, until $k_{i+1} = k_o$.**??** Given each iteration interval $\mathscr{K}_i = [k_i, k_e]$, we identify the lowerbound of the range $S^r_{[k_i,k_e]}$ using the lowerbound function (equation (3.13)) in Theorem 3.1: if k_i is not the lowerbound of $S^r_{[k_i,k_e]}$, eliminate k_i from $\mathscr{K}$; otherwise, keep k_i.

In each *terminal interval* $[I^n_o, I^n_e]$ obtained from **Step 1**, we first implement the *rolling up procedure*. Starting with the origin I^n_o, this procedure is finished once the iteration reaches the end I^n_e. Next, we implement the *rolling down procedure* in the remaining set. Starting with the end point in the set, this procedure is finished once the iteration reaches the origin of the set. In Proposition 3.4, we show that the remaining capacity values after the two sequential *rolling capacity procedures* compose the stayput region in the nth *terminal interval* $[I^n_o, I^n_e]$. We denote it as S_n and denote the origin and the end of S_n as $k^{s_n}_o$ and $k^{s_n}_e$: $S_n = [k^{s_n}_o, k^{s_n}_e]$.

Proposition 3.4. *The rolling up and rolling down procedures eliminate all non-stayput capacity values from the interval* $[I^n_o, I^n_e]$.

Step 3. For a capacity $k \in S_n$, if the value of the objective function in equation (3.11) or (3.12) can be improved by adjusting k to another stayput region $S_{i \neq n}$, then k is a non-stayput value in the leader's capacity space $[k_{tj_o}, k_{tj_e}]$, i.e., $k \notin S_{[k_{tj_o}, k_{tj_e}]}$. Proposition 3.5 shows that whether $k \in S_{[k_{tj_o}, k_{tj_e}]}$ can be efficiently determined by comparing k with the upperbounds of S_i, $\forall i = 1, \cdots, n-1$, and with the lowerbounds of S_i, $\forall i = n+1, \cdots, N$. Thus, in order to eliminate all non-stayput values from S_n, $\forall n = 1, \cdots, N$, we apply the *rolling up procedure* in $[k^{s_i}_e, k^{s_n}_e]$, $\forall i = 1, \cdots, n-1$ (see black solid lines in Figure 3.2), and apply the *rolling down procedure* in $[k^{s_n}_o, k^{s_i}_o]$, $\forall i = n+1, \cdots, N$ (see black dashed lines in Figure 3.2). For each

$i = 1, \cdots, n-1$, the ith *rolling up procedure* starts with the first iteration interval $[k_e^{s_i}, k_o^{s_n}]$ and stops at the jth iteration if $k_j \in S^r_{[k_e^{s_i}, k_j]}$, where $[k_e^{s_i}, k_j]$ is the jth iteration interval. For each $i = n+1, \cdots, N$, the $(i-n)$th *rolling down procedure* starts with the first iteration interval as $[k_e^{s_n}, k_o^{s_i}]$ and stops at the jth iteration if $k_j \in S^r_{[k_j, k_o^{s_i}]}$, where $[k_j, k_o^{s_i}]$ is the jth iteration interval. Proposition 3.6 shows that these two stopping rules are sufficient for eliminating all non-stayput points in S_n. After cross-interval comparisons, the remaining capacity values in each S_n compose the final stayput region. We represent the stayput region in firm j's ISD policy in period t as a function of the opponent's immediate response policy, which is determined by its stayput region in period t. In Theorem 3.2, we outline the decomposition method for computing proactive ISD policies.

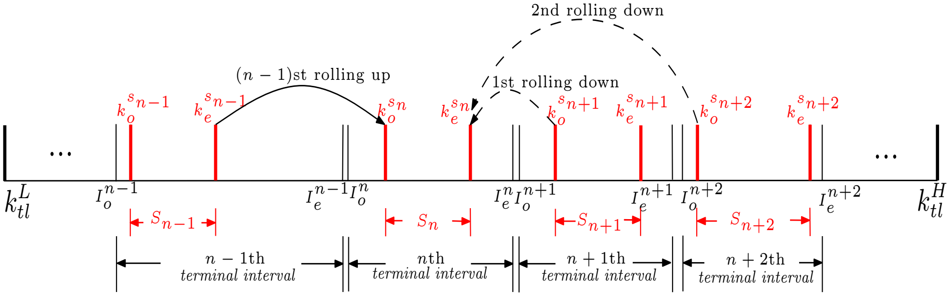


Figure 3.2: Illustration of the cross-interval comparison

Proposition 3.5. *Given the stayput region in the ith terminal interval,* $S_i = [k_o^{s_i}, k_e^{s_i}]$*, if there exists a capacity value* $k_1 > k_e^{s_i}$ *satisfying* $k_1 \in S^r_{[k_e^{s_i}, k_1]}$ *(or* $k_1 < k_o^{s_i}$ *satisfying* $k_1 \in S^r_{[k_1, k_o^{s_i}]}$*), then* $k_1 \in S_{[k_2, k_1]}$ *(or* $k_1 \in S_{[k_1, k_2]}$*),* $\forall k_2 \in S_i$*.*

Proposition 3.6. *Given the stayput region in the ith terminal interval,* S_i*, if there exists* $k_1 \in S_i$ *and* $k_0 < k_1$ *such that* $k_1 \in S^r_{[k_0, k_1]}$ *(or exists* $k_0 > k_1$ *such that* $k_1 \in S^r_{[k_1, k_0]}$*), then* $k_2 \in S_{[k_0, k_2]}$*,* $\forall k_2 : k_1 < k_2 \in S_i$ *(or* $k_2 \in S_{[k_2, k_0]}$*,* $\forall k_2 : k_1 > k_2 \in S_i$*).*

Theorem 3.2. *Given* S_{ti}*,* $k_{t-1i} \in \mathscr{K}_{t-1i}$ *(*$i \neq j$*), and* $\omega_t \in \Theta$*, the solution to firm j's optimization problem in period t (see equation* (3.11) *or* (3.12)*) can be* *represented in the form of an ISD policy. The stayput region $S_{tj}(S_{ti}, k_{t-i}, \omega_t)$, can be derived by the Decomposition Algorithm.*

Decomposition Alg. for computing firm j's stayput region in period t

1. Compute the range of the stayput region using equations (3.13) and (3.14): $S^r_{[k_{tjo}, k_{tje}]} = [k^L_{tj}, k^H_{tj}]$. Next, identify *terminals* in the range $S^r_{[k_{tjo}, k_{tje}]}$ and divide the range into separate *terminal intervals.* Assume that there are N *terminals* and the range is divided into N *terminal intervals.*

2. Use two sequential *rolling capacity procedures* to search for the optimal solution set in each *terminal interval.* Denote the stayput region in the nth *terminal interval* as S_n.

3. Eliminate all non-stayput values from S_n, $\forall n = 1, \cdots, N$, through cross-interval comparisons.

The remaining capacity values constitute firm j's stayput region in period t, which is denoted as $S_{tj}(S_{ti}, \omega_t)$ $(i \neq j)$.

In Proposition 3.7, we prove that the decision rule indicated by an ISD policy with multiple separate stayput intervals assigns a non-stayput capacity value to the closest boundary of a close-by stayput interval. For a non-stayput capacity that falls between two consecutive stayput intervals, Corollary 3.2 presents a decision rule which uses an investment threshold. This investment threshold can be identified through a binary search.

Proposition 3.7. *Given $k_{t-1j} = k$ and $k \notin S_{tj}(S_{ti}, k_{t-1i}, \omega_t)$ $(i \neq j)$, if the optimal investment policy indicated by $S_{tj}(S_{ti}, \omega_t)$ assigns $k_{tj} = b$, then no stayput values exist in the interval $[k, b)$, $\forall k < b$, or in the interval $(b, k]$, $\forall k > b$. In other words, the interval $[k, b)$ or $(b, k] \nsubseteq S_{tj}(S_{ti}, k_{t-1i}, \omega_t)$.*

Corollary 3.2. *Given two consecutive stayput intervals, $[k^{L1}, k^{H1}]$ and $[k^{L2}, k^{H2}]$, there exists an investment threshold k, $k^{H1} \leq k \leq k^{L2}$, such that the optimal* *investment policy assigns all capacity in* (k^{H1}, k) *to be adjusted downwards to the upperbound of the lower stayput interval (i.e.,* k^{H1}*) and assigns all capacity in* (k, k^{L2}) *to be adjusted upwards to the lowerbound of the higher stayput interval (i.e.,* k^{L2}*). If* $k^{H1} < k < k^{L2}$*, there is no difference between adjusting* k *to the closet boundary of either close-by interval.*

3.7 Case study on the container shipping market

We first use data from the container shipping market to determine the optimal ISD investment strategies for a leader and a follower in all four cases, i.e., (a) *stayput*, (b) *adversarial*, (c) *optimal*, and (d) *reactive*. We then compare the results with the two players' capacity investments in practice. Second, we reveal the underlying structures of the capacity strategies in the four cases and compare the advantages of the strategies. Last, based on our results, we draw several implications for investors in a competitive market.

3.7.1 Optimal ISD investment strategies in the container shipping market

We use the demand and supply data of the container shipping market over a timespan of 16 years (2000-2015). To avoid the border effect in a long-term strategy, we extend the timespan to 2017, i.e., $\Gamma = \{1, \cdots, 18\}$. Maersk and MSC, which are ranked as the first and second liner operators based on their fleet capacity (Alphaliner, 2017), are chosen as the leader and the follower. At the beginning of each year, firms observe the current demand and predict the demand growth of this year. In order to mitigate the risk, a demand forecast consists of several future scenarios with different probabilities, each of which takes into account the forecast error to a varying degree. We use a categorical distribution as an approximation of a normal distribution to represent the demand scenario forecast. At the beginning of 2000, the first observed demand ω_1 is set as 1. For each $t \in \Gamma$, ω_{t+1} evolves according to the transition rule in equation 3.17: The transition probabilities, pr, are taken from the Z-score

$$\omega_{t+1} = \begin{cases} \omega_t \times (1 + \mu_t + 2\sigma_t) & with\ pr = 2.28\% \\ \omega_t \times (1 + \mu_t + \sigma_t) & with\ pr = 13.59\% \\ \omega_t \times (1 + \mu_t) & with\ pr = 68.26\% \\ \omega_t \times (1 + \mu_t - \sigma_t) & with\ pr = 13.59\% \\ \omega_t \times (1 + \mu_t - 2\sigma_t) & with\ pr = 2.28\% \end{cases} \quad (3.17)$$

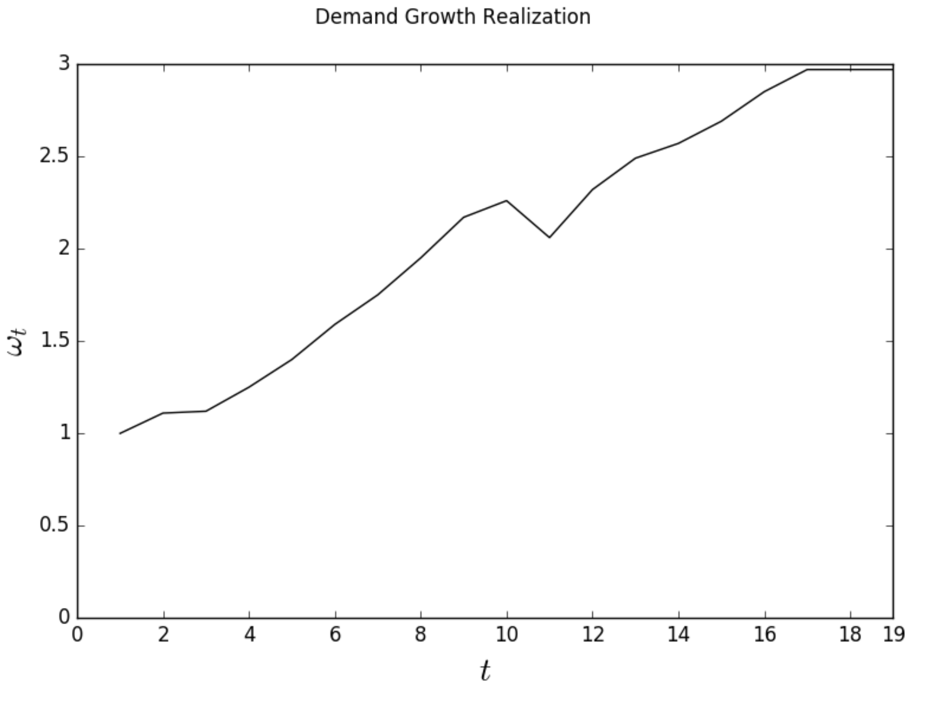


Figure 3.3: Realized demand growth path $\mu_t^{'}$

table. μ_t is the forecast of the demand growth of period t and σ_t is the forecast error in period t, which is the average discrepancy between all previous forecasts μ_τ and the realized demand growths μ'_τ, $\forall \tau = 1, \cdots, t-1$. We use a forecast deviation in the container shipping market of 5% as the first forecast error σ_1. The values of μ_t and μ'_t are the average values based on the two half-yearly *Clarkson Shipping Review and Outlook* reports. We use the same forecast of 2015 for the artificial years 2016 and 2017, i.e., $\mu_{18} = \mu_{17} = \mu_{16}$, and assume a zero demand growth in 2016 and 2017, i.e., $\mu'_{18} = \mu'_{17} = \mu'_{16}$. (Clarkson Research Services, 2000-2015b, 2000-2015a). Figure 3.3 shows the demand growths in practice, i.e., $\mu'_1, \cdots, \mu'_{18}$.

We keep supply and investment cost parameters constant throughout the entire timespan. In each period, we present the capacity choices available to both firms as discrete market share values, and thus capacity decisions can be interpreted as changes in firms' respective market shares. An upper limit of 19 is set to both firms' capacity spaces, due to the fact that an operator's market share (based on its fleet capacity) has never exceeded 19% to date (Alphaliner, 2017). Both firms have the same set of capacity choices: $\mathscr{K}_{tl} = \mathscr{K}_{tf} = \{0, 1, \cdots, 19\}$, $\forall t \in \Gamma$. In period $t \in \{1, \cdots, 15\}$ (i.e., 2000-2014), the realized capacity k'_{tj} of Maersk and MSC are the end-of-year capacity, which is extracted from the yearly *UNCTAD Review of Maritime Transport* report (UNCTAD, 2001-2015). We obtain the two liners's realized capacity at the end of 2015 from Alphaliner (2015). At the beginning of 2000, the market shares of Maersk and MSC were around 12% and 5%, i.e., $k_{0l} = k'_{0l} = 12$ and $k_{0f} = k'_{0f} = 5$ (UNCTAD, 2000).

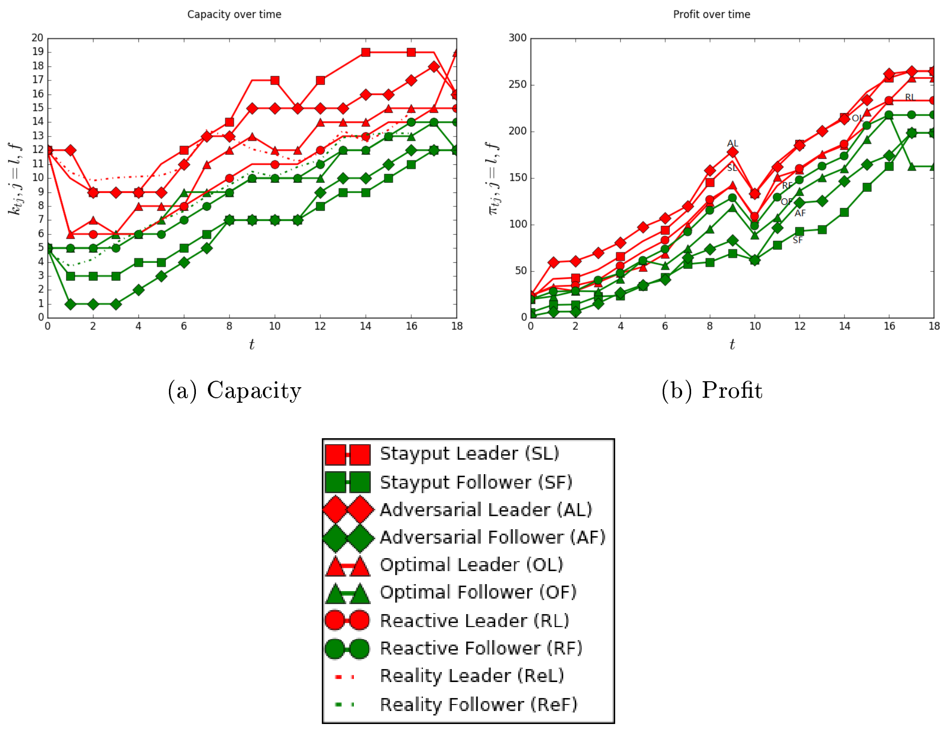
For simplicity, we assume that in each period $t \in \Gamma$, both firms' capacity utilization parameters equal 1, i.e., $a_{tj} = 1$, and utilization cost functions $H_{tj}(\cdot)$ take the following form: if $a_{tj}q_{tj} \leq k_{tj}$, $H_{tj}(q_{tj}, k_{tj}) = 0$; otherwise, $H_{tj}(q_{tj}, k_{tj}) = \infty$. Since the freight rate fluctuates heavily with capacity investments of dominant firms in the shipping market, we use a linear market-clearing price: $q_{tj} = k_{tj}$ and $p_t = P_t(k_{tl}, k_{tf}, \omega_t) = \alpha \cdot \omega_t - k_{tl} - k_{tf}$, $\forall t \in \Gamma$. $\alpha > 0$ is a given market parameter, representing the marginal impact of demand on price. We determine the value of α using the historical freight rates (dollars per TEU), demand and supply data (both in thousand TEUs) on the three major liner trade routes, i.e., transpacific, Europe-Asia, and transatlantic. Using the linear market-clearing price, the marginal demand impact on freight rate ranged from 1.2 to 2.1 on the three routes at the beginning of 2000 (UNCTAD, 2001). We choose the average value of 1.5 as the marginal demand effect. However, since we use single-digit demand values (e.g., $\omega_1 = 1$) and double-digit capacity choices (e.g., $k_{0l} = 12$), we scale the marginal demand effect by multiplying it by 10 and thus set $\alpha = 15$. As $a_{tj} = 1$ and $q_{tj} = k_{tj}$, $H_{tj}(q_{tj}, k_{tj}) = 0$. Therefore, firm j's operating profit function is: $\pi_{tj}(k_{tl}, k_{tf}, \omega_t) = (\alpha \cdot \omega_t - k_{tl} - k_{tf}) \times k_{tj}$, $\forall t \in \Gamma$. We use the same form for the salvage value function, i.e., $F_j(k_{Tl}, k_{Tf}, \omega_{T+1}) = (\alpha \cdot \omega_{T+1} - k_{Tl} - k_{Tf}) \times k_{Tj}$. Assumptions 3.1 and 3.3 are satisfied with these functions. In addition, as $p_t < 0$ is possible, a firm can have negative profits for a period. This is consistent with the common practice in the shipping industry, i.e., in order to remain active in the market, shipping lines continue to operate even if they are facing a loss. With this profit function, the product price p_t can be seen as the marginal profit of a unit capacity. A firm benefits from all its capacity if the marginal profit of a unit capacity is positive, and suffers losses from all its capacity if the marginal profit is negative, i.e., if market supply exceeds demand.

Based on the vessel prices in *Maersk's container market weekly report* (Maersk, 2015), which states that the average second-hand vessel price is $\$4,837$ per TEU and the average newbuilding vessel price is $\$10,741$ per TEU, we set both firms' investment cost parameters as $c_{tl} = c_{tf} = 10.7$ and $r_{tl} = r_{tf} = 4.8$, $\forall t \in \Gamma$. Notice that these are not the prices of changing 1% market share, however, the difference between c and r represents the investment irreversibility level in the container shipping market. We adopt a discount rate of 0.89 as this value is frequently used by shipping firms to calculate the present value of future earnings (Gullaksen, 2012; Greenwood and Hanson, 2013).

We compute the leader's and the follower's optimal value functions (see equations (3.7) and (3.8)) using a backward induction method and in ech period we determine a firm's optimal capacity based on its current capacity and the corresponding ISD policy as discussed in Sections 3.5 and 3.6. Using the same demand path as shown in Figure 3.3, the two players' optimal capacity and profits in the four cases are presented in Figure 3.4. In Figure 3.4a, the red dashed line represents the leader's (Maersk) realized capacity, while the green dashed line represents the follower's (MSC) realized capacity. The figure shows that the realized capacity of the two liner operators is matched by different competitive strategies from the booming economy phase ($t \leq 8$) to the (post-)crisis phase ($8 \leq t \leq 16$). During the first either periods, the leader's realized capacity (ReL) is close to AL in terms of value and adjustment pattern. Although the values of the follower's realized capacity (ReF) are close to RF and OF, the adjustment pattern of ReF is more similar to AF. The deviation between the values of AF and ReF results from the difference in the first period. During the later either periods, the realized capacity of the two players is matched by OL and OF (or RL and RF) in terms of value and adjustment pattern. At the end of 2015 ($t = 16$), the capacity of the two liner operators grew by 22.5% and 164%, respectively, reaching market shares of 14.7% and 13.2% (Alphaliner, 2015), which are best matched by OL and OF. While the dominant players followed their respective competitive strategies, other players were squeezed out of the market. Søndergaard and Eismark (2012) reported that a large-scale consolidation in the shipping industry between 2004 and 2011, e.g., the top five operators increased their total market share by 9.5%.

3.7.2 Underlying structures of the ISD strategies

Figure 3.5 shows the underlying structures of investment strategies in the four cases. Abbreviations are used to refer to a player in a specific case, e.g., the leader (L) in the *stayput* case (S) is abbreviated as SL and the follower (F) in the *stayput* case (S) is abbreviated as SF. The black, green, and



(a) Capacity

(b) Profit

Figure 3.4: Optimal capacity and profit of leader and follower

blue boxes indicate the first, second, and third stayput intervals, respectively. The purple crosses indicate the investment threshold between two consecutive intervals. Note that all investment thresholds are located at a boundary of a stayput interval in our example. According to Corollary 3.2, capacity below the threshold should be adjusted downward to the upperbound of the lower interval, and capacity above the threshold should be adjusted upward to the lowerbound of the upper interval. In this example, only AL at $t = 12$ has a third interval, and all the second and third intervals contain only one value, thus showing as a single line. In each subfigure, the red solid line depicts the optimal capacity of the leader and the follower in the corresponding case (same as the optimal capacity in Figure 3.4a). Taking subfigure (a) SL as an example, at the beginning of period 4 with $k_{3l} = 9$, the leader's stayput region in this period contains two intervals: $\{9, 9\}$ and $\{11, 11\}$, with a threshold at 11. Hence, it is optimal for the leader to stay put at its current capacity, i.e., $k_{4l} = 9$. If $k_{3l} = 10$, the optimal decision in period 4 is then $k^*_{4l} = 11$.

As discussed in previous sections, proactive thinking leads a player (e.g., *SL*) to have separate stayput intervals that correspond to the opponent's responses. An ISD policy with multiple short intervals is highly responsive to the opponent's strategy. In Figure 3.5, comparing subfigure (a)-(d) with (e)-(h), the leader has more and shorter stayput intervals in each period than the follower. The difference between the two players' stayput intervals is especially obvious in the asymmetric cases (comparing case (a) with (e) and comparing case (b) with (f)), where the leader possesses either a higher level of proactive thinking (case (a)) or more effective proactive thinking (case b). In our example of demand paths and investment costs, a more proactive planning clearly brings benefits: in the asymmetric cases, the leader (*SL* and AL) holds more capacity than the follower (*SF* and AF) in each period. Here higher capacity leads to more profits (see Figure 3.4b). By adopting a proactive strategy, the leader has more capacity and profits in any proactive case (*SL*, AL and *OL*), than in the reactive case (*RL*). It also means that the leader's first mover advantage is amplified only when adopting a proactive strategy in a long-term investment race.

Figure 3.4a shows that the follower benefits from responding proactively to the leader's proactive strategy. If we compare the capacity of *OF* and AF with the capacity of *SF*, we see that *OF* acquires a higher capacity than *SF*, and the capacity of AF gradually surpasses the capacity of *SF* starting from $t = 8$. Compared to *SF*, *OF* has multiple stayput intervals due to its proactive thinking (see Figure 3.5), which lead to a higher capacity. In the *adversarial* case where the follower has inaccurate information on the leader's strategy, the follower still benefits from proactive thinking as it constrains the leader's strategy. Figure 3.5 shows that AL has larger intervals than *SL*, indicating that the strategic responsiveness of AL is restrained. It also explains why AL has lower capacity than *SL* (see Figure 3.4a).

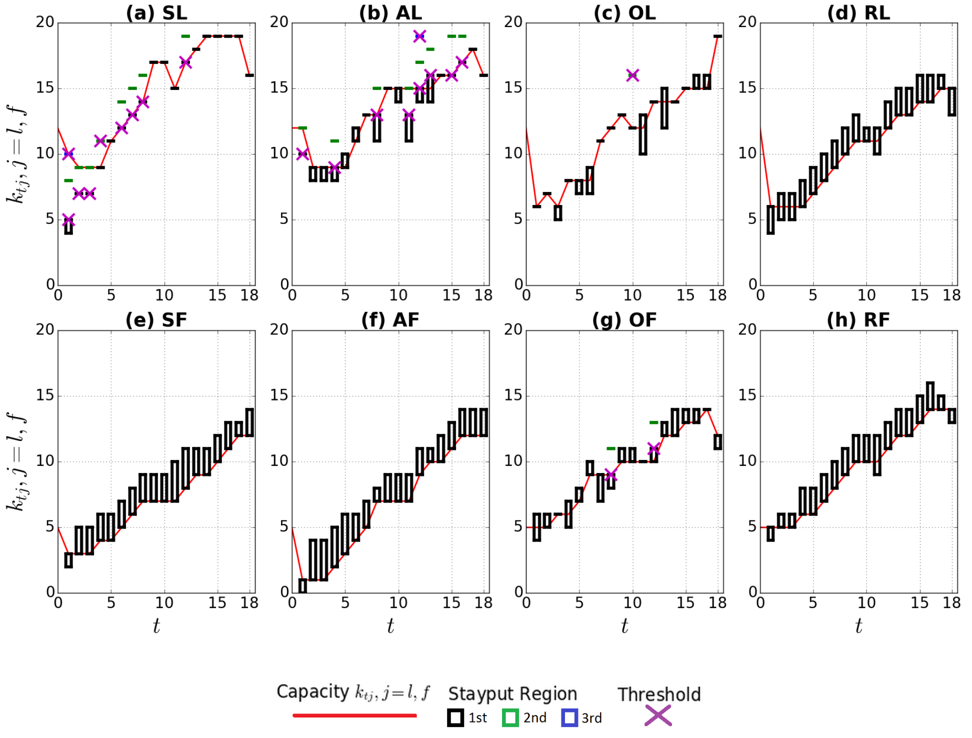


Figure 3.5: Stayput region of leader and follower

3.7.3 Managerial insights

It is crucial to act first in the competition as the first entrant usually gains a competitive advantage through control of resources. However, our case study shows that the key to success in a long-term investment race is to collect as much information as possible on the competitor's strategy and plan investments proactively. Using the real industry data, we show that the leader can gain up to 20.2% more profits in 18 years when adopting a proactive strategy (SL, AL, and OL), compared to when both players are reactive in the competition (RL). The follower can gain 30% more profits if it responds proactively to the leader's proactive strategy (OF) rather than being reactive (SF). Even in the case where the follower has inaccurate information about the leader's strategy, the follower can still gain approximately 3.6% more profits by acting proactively (AF). Therefore, a general recommendation for competing firms is to ***act proactively at the earliest opportunity and to make this visible in the competition***. The essence of a proactive strategy is for a firm to realize that its actions can influence other firms' future plans. Regardless of how accurately the firm knows its impact, if it is able to convey the message that its strategy considers its rivals' potential responses, then the proactive strategy serves as a credible threat. This may alter rivals' expectations of the firm's future actions, and thereby induce them to take favorable actions, or deter them from making harmful moves. Our method provides a useful tool for both leader and follower firms to plan their long-term capacity investments under competition. Based on our results, we formulate the following four steps for achieving an effective competitive investment strategy.

1. ***Find the most relevant competitor.*** The relevance of a competitor is judged based on the impact of its capacity decisions on the product price. In the example of the container shipping industry, a liner operator's most relevant competitor is the shipping line that operates on the same routes and has a similar fleet size.

2. ***Set the competitive goal(s).*** A competitive goal is a firm's vision on how its action will interact with the competitor's future capacity growth. In general, there are three types of competitive goals: *submissive*, *neutral* and *aggressive*. An appropriate competitive goal is set based on the current market situation, i.e., demand (growth), the competitor's capacity and costs. Our single-shot analysis shows that a high level of investment irreversibility leads to a *neutral* goal, and that a low demand value or high capacity level of the competitor suggest a more *aggressive* goal. If the market is highly volatile, a firm should always make plans for several feasible goals, which helps it cope better with the rapidly changing market.

3. ***Identify good investment options for each competitive goal.*** Based on the investment costs and the competitor's current capacity, a firm can

identify good investment options for each competitive goal. Notice that a good option for a specific goal may not exist. For instance, if the competitor's current capacity is small or if the disinvestment unit price is low, it may not be beneficial for the firm to choose any investment option which is suitable to an *aggressive* goal.

4. ***Find the best option by comparing options that are close to the current capacity.*** An optimal ISD policy directs a firm's current capacity to a close-by interval. This implies that when considering the best investment plan, a firm should first evaluate the competitive goal and investment options that are easy to reach from the current position, and later decide how much further it can use its competitive strength based on the current investment costs. The approach of comparing close plans is sensible as there could still be sizable economies to be gained from adjusting the plan slightly, while overextending is highly risky.

Different from a perfect market where investments are solely driven by a firm's current capacity, demand and investment costs, dynamics in a competitive market challenges firms to evaluate their options from a competitive point of view. This means that a firm should consider the value of an action in terms of the value of the opponent's response, i.e., whether it is beneficial to take a certain action to trigger a specific response. This may lead to some non-obvious decisions in practice. For instance, ***holding more assets in the competition may trigger investments, while having fewer assets may trigger disinvestments.*** In some market positions, investing to reach a higher market share can put off rivals' future investments and lead to a higher profit. In this situation, the optimal decision is to invest, even if the current capacity is high. With a lower market share, it may be better to stay at the current capacity or even fall back since the amount of investment required to hold back rivals' investments may be so large that the plan is unrewarding.

3.8 Conclusion

We study a competitive capacity investment problem under demand uncertainty and derive the optimal strategy in the form of an ISD policy. Different from the majority of oligopoly capacity models in the literature, which focus on a single-shot investment or timing of investment decisions only, we investigate a long-term problem where two firms sequentially adjust their capacity in each period to respond to each other's decisions. Our focus is on the impact of competition on the dynamics and attributes of a long-term strategy. Moreover, by allowing flexible capacity choices, our optimal strategy determines both the timing of capacity adjustments and the size of an optimal investment. A firm can either proactively or reactively plan its investments. We derive the reactive ISD policy in closed form and develop the *Decomposition Algorithm* to efficiently compute the proactive ISD policy in a long-term setting.

We illustrate the optimal ISD investment strategies using long-term detailed data from the container shipping market. Our results show that the realized investments, which are questioned to be irrational decisions, followed a competitive structure. In addition, firms' overinvestments during a market downturn are also shown to be optimal according to their long-term strategies. The 2008 global recession was the turning point when shipping lines, especially follower firms, changed their investment strategies. Our results show that although both leader and follower firms adopted proactive strategies, the follower had inaccurate information on the leader's strategy before 2008. Since 2008, the follower's proactive strategy utilizes full information on the leader's future investments. An explanation could be that market downturns attract extra attention on the leader's moves, making the leader's strategy transparent to the follower. In our case study, the leader generally performs better than the follower in terms of capacity and profit, and the leader enhances its first mover advantage by adopting a proactive rather than a reactive competitive strategy. The follower's best response to the leader's proactive strategy is also to be proactive. The reason why a proactive strategy brings more benefits in a long run is because it gives a firm strategic responsiveness to the opponent's strategy. Despite the effectiveness of a firm's proactive strategy, the firm can benefit from proactive thinking since it also restrains the responsiveness of the opponent's strategy.

Our results provide insights into the structure of an optimal competitive investment policy. We show that in a competitive investment environment, the optimal proactive player deploys an SNA strategy, considering various competitive goals (*submissive*, *netural*, *aggresive*). Therefore, a proactive ISD policy can contain multiple separate stayput intervals, leading to a Multi-ISD decision rule. We discover the core of a competitive strategy by revealing the meanings behind different stayput intervals. Investment in practice is complex. The competition often involves more than two firms, and a third player can adopt either a leader, follower, or mixed strategy. A direction for future research is to investigate the optimal policy of the third player. Moreover, firms can learn from previous experience and update their information on the competitors' strategies, and thus their own strategies or the opponent's strategy may change as time proceeds. Future research should address the optimal structure of an evolving competitive investment strategy.

Chapter 4

Launching Next-Generation Products (NGP) in a Competitive Market

4.1 Introduction

The business environment today is characterized by increasing product variety and diversity in consumer taste. Successful product differentiation can generate a firm profit as the firm can cater better consumer wishes. Quality is often the most distinct characteristic which differentiates a product from other products. Therefore, an effective differentiation strategy of a firm is to provide a better version of an existing product in terms of quality. We refer to this quality upgrade as a next-generation product (NGP). Christensen and Raynor (2003) and Christensen et al. (2004) referred to NGP as a *sustaining innovation*: *"a new product that is better in the eyes of a firm's existing customers"*. An NGP does not create new markets but only extends existing ones with better values, allowing firms to compete against improved products of other firms. An example of an NGP is the Intel Core i7 relative to the Intel Core i5, where the new faster generation of processor is more attractive to most consumers. The improvements in an NGP can be incremental advances or major breakthroughs. Successive generations of a product can also be introduced by different firms and the firm which satisfies consumer needs at the right time can detract the market from the competitors (Schmidt and Druehl, 2008).

An NGP launch is a challenging and complex process. Research shows that 40% of product transitions have failed, and some have led to company failure (Lee, 2002). Since consumers always desire a better product, an NGP directly competes against a firm's own existing product and cannibalizes it, starting at the high end of the market and diffusing downwards. The success of an NGP depends on its quality and whether enough consumers appreciate a better quality product and are willing to pay a sufficiently higher price. Quality can only improve over time and consumer taste is highly uncertain until the very late stage of a new product development project. However, postponing a product launch can lead to lost sales. Cohen et al. (1996) showed that companies can lose 33% profit if they ship products six months late. In the history of NGP launches, "bad timing" is often mentioned as one of the main reasons for NGP failure. For example, Microsoft Zune failed to compete with Apple iPod mainly because it was launched five years later than iPod (Manjoo, 2012), whereas Microsoft SPOT Watch failed to compete with Apple Watch because it was launched too early (Nguyen, 2016). HTC First (also known as the Facebook phone) lost the battle against Samsung Galaxy S4 and market researchers attribute this defeat to its launch timing, which is the same time as Samsung (Cheng, 2013). Our research investigates the optimal NGP launch timing, considering both consumer interest and firm competition.

We investigate two main capacity decisions of two competing firms during an NGP launch: (1) *when to build capacity for the NGP* and (2) *how to optimally allocate the total available capacity to the two products*. The first decision aims to balance the risks of premature entry (investing too early) and the problems of missed opportunities (investing too late). Since the two products differ along an evolutionary feature, i.e., quality, they share the same production resource and the second capacity question is essentially a capacity mix problem. In contrast to a standard product portfolio problem, in which trade-offs besides costs do not necessarily occur when building capacity for a product, a capacity mix problem requires a firm to divide a single resource among different products. Here the trade-off is internal: allocating more capacity to the NGP means less capacity for the existing product. For instance, during the launch of a new iPhone series, Apple gradually changes the existing production lines that are used for previous iPhone series into manufacturing the new series and eventually discontinues the aging series (Smith, 2016). As pricing strategies depend on the available capacity of each product in the portfolio, the capacity mix problem directly affects a firm's total profit.

We focus on the impact of a two-dimensional competition on a firm's optimal timing for an NGP launch and the subsequent optimal capacity. The **first** dimension of competition is the *internal competition* between the NGP and the existing product. For instance, due to consumer utility for product quality and price, launching "too much" capacity of a far-advanced NGP may jeopardize a currently profitable product and decrease the price of the NGP. In an ideal situation, a firm delays investment until consumer taste is clear and then allocates its capacity to the two products. The **second** dimension of competition, which is the *external competition* between the two firms for their own total profit, makes waiting risky. In the duopoly, the early-moving firm may have the first-mover advantage. However, as consumer taste becomes clearer over time and the quality could also improve later, the first-mover faces two potential risks. (1) If the first-mover concentrated its capacity on the product which later turns out to be less-favored by consumers than expected, the late-comer can then seize the opportunity and reserve more capacity for the favored product. (2) If product quality improved since the first-mover's investment, the late-comer can provide a better quality NGP which outperforms the NGP of the first-mover, and can thus exclusively capture the highest-value consumer segment.

Our research extends both the literature on *new product development* by incorporating the competition between the two firms and the literature on *capacity competition* by considering evolutionary product innovation. In addition, we consider both demand uncertainty at the early stage and a potential product quality upgrade at the late stage in the NGP launch decision. We integrate these aspects of the NGP launch decision and show how it impacts the dimensionality of the decision space and the outcomes. Our findings contribute to both theory and practice in three ways. **First**, in a competitive market with demand uncertainty, a firm's optimal timing for an NGP launch should consider the trade-off between demand risk and competition. To measure the impact of demand risk in a specific market, a firm should measure the correlation between the average consumer taste and the density of consumer taste. A strong correlation indicates a large exposure to demand risk in the market. **Second**, a firm's competitive advantage and disadvantage can be evaluated based on a two-dimensional scale. The first dimension measures its competitor's gain from offering the quality upgrade, and the second dimension measures the firm's investment cost advantage over its competitor. A firm has a *competitive edge* only if its cost advantage exceeds a certain threshold related to its competitor's gain from offering the quality upgrade, and this *edge* can lead the firm to invest earlier than its competitor. **Third**, we distinguish two non-exclusive situations of a firm: (1) a *stand-still* situation based on both firms' competitive advantage and the exposure to demand risk, and (2) a *risky* situation based on the firm's competitive advantage, the other firm's competitive disadvantage, and the exposure to demand risk. We derive the optimal investment strategy of the firm in each scenario: in a *stand-still* situation, the firm should invest at the same time as its competitor; in a *risky* situation, the firm should postpone the investment; otherwise, the firm should invest early.

4.2 Related literature

Our model belongs to strategical and tactical capacity investment models. It is related to the extensive operations literature on this topic; see the comprehensive review by Van Mieghem (2003). In addition, our work is closely related to the economics literature on market entry timing and product portfolio determination, and to the strategic management literature on new product development.

At the strategic level, competitive capacity planning focuses on the capacity investment timing of competing firms and on the trade-off between commitment and flexibility. Each firm has an incentive to delay its investment until it receives more precise information about the profitability of the market, but if it does so it risks being preempted by its rival (Weeds, 2002; Pacheco-de Almeida and Zemsky, 2003). Such a trade-off can lead two ex-ante identical firms to asymmetric equilibria, in which one firm chooses a preemptive strategy and the other follows a flexible, wait-and-see strategy (Maggi, 1996). Swinney et al. (2011) analyzed the capacity investment timing decisions of two competing firms with different objectives: a start-up whose goal is to maximize the probability of survival, and an established firm whose goal is to maximize expected profits. They found that when demand uncertainty is high and costs do not decline too severely over time, the start-up firm takes the leadership and invests in capacity first, while the established firm follows. Models in this research stream consider a single product and focus on the competition between firms for the product. However, a high degree of product diversity has become the norm across all industries in recent years since companies have found that offering a diverse product portfolio is essential for remaining competitive. Thus, competitive capacity planning models should not only consider the competition between firms but also the trade-off between products.

At the tactical level, competitive capacity planning focuses on capacity expansion tactics related to the operational aspects of competing firms. Anupindi and Jiang (2008) studied the effect of production postponement on two competing firms' capacity and pricing decisions, which are taken both ex-ante and ex-post demand realization. They found flexibility in production benefits both the firm and its customers by allowing the firm to increase capacity and by keeping the price in a narrower range. Some existing tactical capacity models consider a collection of products in a competitive market. For example, Anand and Girotra (2007) and Kouvelis and Tian (2014) analyzed the value of delayed differentiation for a two-product portfolio problem in a competitive market and demonstrated that the strategic effects can significantly diminish the value of a production postponement strategy. These models study a product mix problem, in which products compete for a finite set of resources but do not consider the competition between products due to consumer-driven substitution.

The literature on market entry timing typically considers the choice of introducing an incrementally better, safe, new product early or a superior, yet highly risky, product later. Bhaskaran and Ramachandran (2011) studied the technology performance vs. time-to-market trade-off in a competitive setting, where two firms select technologies and invest in improving the success probability of the riskier advanced technology if they decide to pursue it. Kirshner et al. (2017) investigated a firm's optimal timing of upgrades for a durable product in the presence of stochastic technology advancements. They derived the optimal upgrade strategy as a threshold policy based on the level of pent-up demand for their next-generation product. These studies focused on R&D investment rather than on a firm's capacity investment. In contrast to studies on product improvement and the introduction of improved products, researchers have also studied market entry from the low end through a low-cost and low-quality version of the existing product. Pun and DeYong (2017) studied how a manufacturer competes with a copycat who may enter the market later by providing a low-cost version of the manufacturer's product. They found that customers' strategic behaviors may negatively affect the copycat's profit. Groznik and Heese (2010) studied store brand introductions by two competing retailers who sell a national brand product. They found that under a law that prohibits price discrimination, both retailers prefer a store brand introduction by the competitor. The existing models on market entry timing focus on the competition between firms which infiltrate different ends of the market. However, they do not consider the competition between firms in both low and high ends of the market or the optimal allocation of their resources in these two market segments.

The literature on product portfolio studies the optimal inventory levels and assortment for products under demand substitution. A number of papers study such problems under stockout-based substitution, which means that customers may substitute a similar product for their first-choice product if it is out of stock (Smith and Agrawal, 2000; Mahajan and Van Ryzin, 2001; Netessine and Rudi, 2003; Honhon et al., 2010). Another stream of research on product portfolio employs choice models and captures customer behavior explicitly (Gaur and Honhon, 2006; Rusmevichientong et al., 2010, 2014). For instance, Talluri and Van Ryzin (2004) studied a product assortment problem, in which the probability of purchase for each product depends on the set of products offered. Lacourbe et al. (2009) examined the optimal product portfolio for a monopolist firm in a market where consumers exhibit vertical differentiation for product quality and horizontal differentiation for product feature. The majority of existing product portfolio models only examine a single-firm case and thus neglect the strategic effect on firms' product portfolio choices.

Selecting the right products to develop and managing risk in the development process are critical challenges in new product development (NPD) and have received considerable attention in the strategic management literature on NPD. Christensen and Bower (1996) differentiated two types of product innovation, i.e., *sustaining* and *disruptive innovation*, and used an example of the disk drive industry to show that leading firms were successful in developing *sustaining innovation*, whereas entrant firms were successful in developing *disruptive innovation*. Uncertainty is endemic to NPD in demand forecast and performance of the new product. Ahmadi and Wang (1999) provided optimal policies for allocating resources across various development phases to control risk.

The aforementioned models on new product launch consider either the competition between two firms (in a market segment or at different ends of a market) or the competition between two products of a firm. However, they do not investigate the impact of both dimensions of competition on a firm's launch decision. In the competition, missed sales opportunity for either the existing product or the NGP can be reaped by the competitor. The interaction between the two dimensions of competition affects a firm's NGP launch decision, different from the impact of each dimension of competition separately. Our research considers the competition between two firms in both low and high ends of the market. The second limitation is that the existing models consider either the trade-off between time-to-market and demand risk or the trade-off between time-to-market and product quality. In practice, both trade-offs exist and affect a firm's timing decision. Our research fills the gap by considering an NGP launch problem in a competitive market with two investment stages: consumer tastes are uncertain at the early stage and the product quality may improve at the late stage.

4.3 The model

Two competing firms (indexed as x and y) sell a series of products in a market where consumers recognize each product by its quality and price only. We focus on evolutionary product innovation and capacity competition between firms, rather than on a consumer's brand choice behavior. At the very beginning, both firms sell a basic product which we denote as product B. As time proceeds, both firms have the option to launch an advanced version of the basic product, i.e., an NGP, which we denote as product A. We denote quality level and price of product j as $S^j > 0$ and p^j, $j = B, A$. By the definition of an NGP, product A has a higher quality compared to product B, i.e., $\triangle S = S^A - S^B > 0$. We adopt a standard vertical product differentiation demand model in which all consumers prefer better quality products, but differ in their willingness to pay for the quality. That is to say, consumers have unanimous assessment of the relative quality of different products, but have heterogeneous taste for the same product. For instance, consumers agree that airline business class is better than economy class, but differ in how much better they perceive it (and thus how much more they are willing to pay). This demand structure resembles a form of consumer-driven substitution since consumers may be induced to substitute a product for another product by a pricing strategy.

We assume that a consumer's taste t follows a uniform distribution on the interval $[0, \theta]$, where θ is the highest consumer taste and $\theta > 0$. For the purpose of analytical tractability, the uniform distribution is widely used to model consumer taste, e.g., see Shi et al. (2013). Market research has demonstrated that two indexes are critical when characterizing a market and developing a product: the average consumer taste, and the density of consumer taste which indicates heterogeneity in consumer taste (Keane and Wasi, 2013; Shi et al., 2013). Given $t \sim U[0, \theta]$, $\frac{\theta}{2}$ is the average consumer taste and $\frac{1}{\theta}$ is the density of consumer taste. To capture the uncertainty in both indexes[3], we model the highest consumer taste θ as a continuous random variable with positive support $[\theta_l, \theta_u]$, known distribution function F, mean $\overline{\theta}$ (the expected average consumer taste is then $\frac{\overline{\theta}}{2}$) and variance σ_θ^2. Given a consumer taste $\widehat{t}$, the consumer utility (surplus) of buying product j with quality level S^j and price p^j is then $u^j = \widehat{t}S^j - p^j$. If a consumer does not buy any product, his utility is zero. Each consumer purchases at most one unit of a product, based on the principle of maximizing his individual utility. Along the interval of consumer taste $[0, \theta]$, we derive two thresholds, t^B and t^A, at which a consumer is indifferent between buying the basic product and not buying any product, and between buying the NGP and the basic product, respectively. In other words, $t^B S^B - p^B = 0$ and $t^A S^A - p^A = t^A S^B - p^B$. The total number of consumers is N, which is assumed to be larger than the sum of the two firms' total capacity. Let d^j denote the number of consumers who purchase product

[3] If a consumer's taste follows a distribution other than a uniform distribution, we can model the average consumer taste and the density of consumer taste as two stochastic variables, each having a distribution function with known parameters.

$j = B, A$, and let d^0 denote the number of consumers who do not purchase any product, respectively. Solving for t^B and t^A, we find the following three segments of consumers in Figure 4.1.

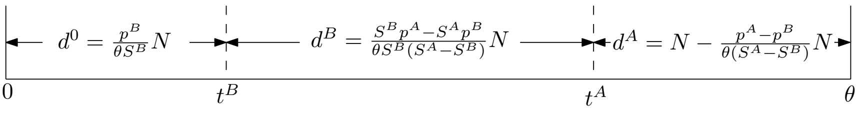


Figure 4.1: Three segments of consumers

According to equations of d^B and d^A in Figure 4.1, as the density of consumer taste $\frac{1}{\theta}$ increases, the number of consumers who purchase the basic product increases, and the number of consumers who purchase the NGP decreases. The sequence of events is depicted in Figure 4.2. Both firms decide their own investment timing and the optimal capacity of each product. We assume that each firm can invest in the NGP at only one of two times: either early or late. We also assume that early investment is well before product launch and that consumer taste in the NGP is still uncertain at that point, i.e., θ is not yet realized. In contrast, late investment is sufficiently close to product launch so that all uncertainty in θ is eliminated. We refer to this initial stage when both firms decide their own investment timing as the *investment timing game* and refer to later stages when firms allocate capacity to the two products at their own chosen investment time as the *capacity subgame*. There are four possible pure strategy outcomes to the *investment timing game*: both firms invest early, both firms wait until the late stage, and the two asymmetric outcomes in which one firm invests early and the other firm invests late. The abbreviations used to refer to the outcomes to the *investment timing game* are depicted in Table 4.1. We assume that firms' timing decisions are credible and irreversible. Capacity investments in the *capacity subgame* are also irreversible.

Denote the capacity of firm i for product j as k_i^j, $i = x, y$ and $j = A, B$. We refer to the competitor of firm i as firm $-i$, $-i = x, y$. Denote the total

	Firm y early	Firm y late
Firm x early	(E, E)	(E, L)
Firm x late	(L, E)	(L, L)

Table 4.1: The four possible strategies in the *investment timing game*

available capacity of firm i as k_i, i.e., $k_i = \sum_j k_i^j$, which is given and fixed throughout the whole game. At the beginning of the *capacity subgame*, the total capacity of each firm is reserved exclusively for the basic product. Thus, firm i's capacity mix problem can be interpreted to determine the optimal capacity of the NGP, i.e., k_i^{*A}, and the capacity of the basic product is then $k_i^{*B} = k_i - k_i^{*A}$. Note that firms can also decide not to launch the NGP, i.e., $k_i^{*A} = 0$ or not to keep the basic product, i.e., $k_i^{*A} = k_i$. We assume that capacity decisions are publicly observable. If firm i invests early and firm $-i$ invests late, then firm $-i$ observes firm i's capacity level of the NGP at the late stage before deciding its own capacity level. A firm's total investment cost is linear in its amount of capacity reserved for the NGP. Define firm i's investment cost function as $C_i(k_i^A) = c_i^A k_i^A$, where $c_i^A > 0$ is firm i's cost for one unit capacity of the NGP. We assume that the unit cost is quadratic in quality level: $c_i^A = \epsilon_i (S^A)^2$, where $\epsilon_i > 0$ and $2\epsilon_i S^A$ is firm i's marginal cost of quality. It means that the unit investment cost increases at an increasing rate as quality is improving.

After the capacity decisions, the price p^j of product j is jointly set by the two firms based on a capacity clearance pricing strategy. That is, the price p^j is set in order to sell all available capacity of product j. Joint capacity clearing pricing is commonly used when modeling capacity competition between firms, e.g., see Swinney et al. (2011). Denote the total capacity of product j as k^j: $k^j = \sum_i k_i^j$. $\sum_i k_i = \sum_j k^j < N$. Setting $d^j = k^j$ in equations d^B and d^A

and solving for p^j, we find:

$$p^B = \frac{\theta}{N} S^B(N - k^B - k^A) = \frac{\theta}{N} S^B(N - k_i - k_{-i}) \tag{4.1}$$

$$p^A = \frac{\theta}{N}(NS^A - S^A k^A - S^B k^B) = \frac{\theta}{N}\Big(NS^A - \triangle S(k_i^A + k_{-i}^A) - S^B(k_i + k_{-i})\Big) \tag{4.2}$$

According to equations (4.1) and (4.2), both the price of the basic product and the price of the NGP are increasing in θ and decreasing in a firm's NGP capacity k_i^A. Note that in the case where $k_i^A = k_{-i}^A = 0$, the price of the NGP still exists: $p^A = \theta S^A - \frac{\theta}{N} S^B(k_i + k_{-i}) > 0$. It means, if the quality of a product is known to consumers, a price exists for this product even if it is (temporarily) unavailable in the market.

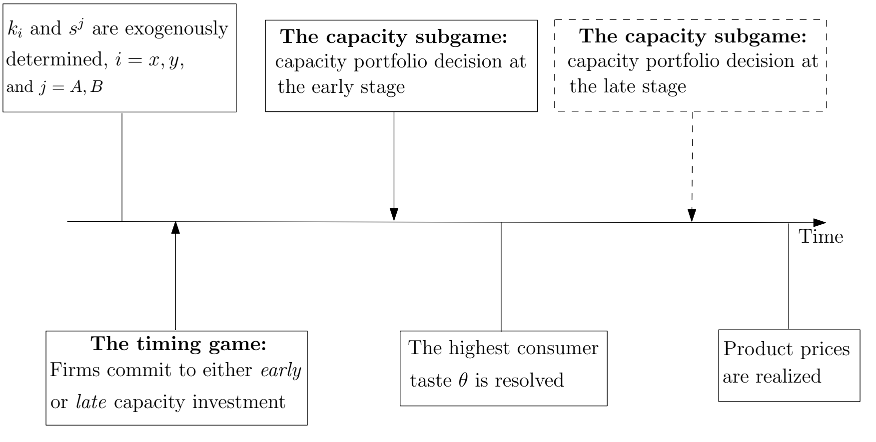


Figure 4.2: The sequence of events for both firms

Since excess capacity is costly, we assume that firms produce up to their maximum capacity or build the least capacity that they plan to use. In addition, the production cost can be considered as a fraction of the investment cost. Thus, we assume the unit production cost is zero in our model. Let $\pi_i(k_i^A, k_{-i}^A, \theta)$ denote firm i's profit function:

$$\pi_i(k_i^A, k_{-i}^A, \theta) = \sum_j p^j k_i^j - c_i^A k_i^A = p^B(k_i - k_i^A) + p^A k_i^A - c_i^A k_i^A \tag{4.3}$$

Substituting p^B and p^A (equations (4.1) and (4.2)) into equation (4.3), firm i's profit function with given $\widehat{k^A_{-i}}$ is: $\pi_i(k_i^A, \widehat{k^A_{-i}}, \theta) = \frac{\theta}{N} S^B k_i(N - k_i - k_{-i}) + \frac{\theta}{N} \triangle S(N - \widehat{k^A_{-i}} - k_i^A)k_i^A - c_i^A k_i^A$, which is concave in its own capacity k_i^A. Setting $\frac{\partial \pi_i(k_i^A, \widehat{k^A_{-i}}, \theta)}{\partial k_i^A} = 0$ and solving for k_i^A, firm i's best response function is $R_i(\widehat{k^A_{-i}}) = \frac{N}{2} - \frac{\widehat{k^A_{-i}}}{2} - \frac{c_i^A}{2\theta \triangle S} N$. We derive a sufficient condition on a firm's total available capacity k_i, which ensures it is sufficiently large for the firm to respond to any decision of the other firm for any given realization of θ: $k_i \geq \max_{\theta, \widehat{k^A_{-i}}} R_i(\widehat{k^A_{-i}}) = \frac{N}{2}(1 - \frac{c_i^A}{\theta_u \triangle S})$. To make our results interpretable, we assume that a firm's best response function $R_i(\widehat{k^A_{-i}})$ specifies a non-negative capacity decision for any given realization of θ, and refer to this assumption as the *non-negativity* assumption:

$$\min_{\theta} R_i(\widehat{k^A_{-i}}) = \min_{\theta}\{\frac{N}{2} - \frac{\widehat{k^A_{-i}}}{2} - \frac{c_i^A}{2\theta \triangle S} N\} = \frac{N}{2} - \frac{\widehat{k^A_{-i}}}{2} - \frac{c_i^A}{2\theta_l \triangle S} N \geq 0 \tag{4.4}$$

Existing capacity models and NPD research widely assume there is no constraint on the total amount of capacity a firm can build, e.g., see Swinney et al. (2011). Models considering a resource constraint study ex-post production decisions under fixed capacity. Our model considers a resource constraint by investigating the optimal capacity allocation to the two products for a fixed total capacity. In contrast to the first assumption, the *non-negativity* assumption is not innocent. In Section 4.4.3, we relax this assumption and consider a wide range of scenarios, in which it is possible for θ to be low such that $\frac{N}{2} - \frac{\widehat{k^A_{-i}}}{2} - \frac{c_i^A}{2\theta \triangle S} N < 0$. In this situation, the early firm can make a loss if it invested in the NGP, whereas the late firm can avoid losses by deciding not to invest. Under the *non-negativity* assumption, $k_i^{*A} = 0$ only if $R_i(\widehat{k^A_{-i}}) = 0$. Without the *non-negativity* assumption, the decision not to invest results from the fact that $R_i(\widehat{k^A_{-i}}) < 0$ (i.e., $\pi_i(k_i^A, \cdot) < \pi_i(0, \cdot)$, $\forall k_i^A > 0$). A firm's timing decision should include the possibility that if the firm itself or its rival waits, the optimal decision after observing θ would be not to invest to avoid losses. Although the possible strategies in the *investment timing game* will not change (see Table 4.1), relaxing the *non-negativity* assumption would lead to five special outcomes which would influence a firm's investment timing decision: (E, LN), (LN, E), (L, LN), (LN, L), and (LN, LN), where LN is the abbreviation for the decision not to invest at the late stage.

In the *capacity subgame*, both firms decide their own capacity of the NGP to maximize their own (expected) profit. Given the competitor's capacity $\widehat{k^A_{-i}}$, firm i's optimal expected profit from early capacity investment is:

$$\mathbb{E}_e[\pi_i^*(k_i^A, \widehat{k^A_{-i}}, \theta)] = \max_{k_i^A \geq 0} \mathbb{E}\Big[\frac{\theta}{N} S^B k_i(N - k_i - k_{-i}) + \frac{\theta}{N} \triangle S(N - \widehat{k^A_{-i}} - k_i^A)k_i^A - c_i^A k_i^A\Big] \tag{4.5}$$

If firm i invests late, it observes the realization of θ, and then decides on k_i^A to maximize $\pi_i(k_i^A, \widehat{k^A_{-i}}, \theta)$. Given the competitor's capacity $\widehat{k^A_{-i}}$, at the phase of the *investment timing game*, firm i's optimal ex-ante expected profit from late capacity investment is:

$$\mathbb{E}_l[\pi_i^*(k_i^A, \widehat{k^A_{-i}}, \theta)] = \mathbb{E}\Big[\max_{k_i^A \geq 0} \Big(\frac{\theta}{N} S^B k_i(N - k_i - k_{-i}) + \frac{\theta}{N} \triangle S(N - \widehat{k^A_{-i}} - k_i^A)k_i^A - c_i^A k_i^A\Big)\Big] \tag{4.6}$$

Lemma 4.1 lists the optimal profit and optimal ex-ante profit of a monopolist from the early and late investments. Comparing the optimal (ex-ante) profits, the optimal investment timing of a monopolist depends on the value of $1 - \mathbb{E}(\frac{1}{\theta})\mathbb{E}(\theta)$, which is the covariance between the average consumer taste $\frac{\theta}{2}$ and the density of consumer taste $\frac{1}{\theta}$: $Cov(\frac{\theta}{2}, \frac{1}{\theta}) = 1 - \mathbb{E}(\theta)\mathbb{E}(\frac{1}{\theta})$. Note that $\mathbb{E}(\frac{1}{\theta})$ is also the inverse of the harmonic mean[4] of the highest consumer taste θ and $\mathbb{E}(\frac{1}{\theta}) > \frac{1}{\mathbb{E}(\theta)}$. Thus, $Cov(\frac{\theta}{2}, \frac{1}{\theta}) < 0$. Since the total number of purchasing consumers is fixed, i.e., $N - d^0 = \sum_i k_i$, and assuming fixed product prices

[4]The harmonic mean is the reciprocal of the arithmetic mean of the reciprocals. For example, the harmonic mean of 1, 2, and 4 is $\frac{1}{\frac{1}{3}(\frac{1}{1}+\frac{1}{2}+\frac{1}{4})}$.

p^B and p^A, the number of consumers who switch from purchasing the basic product to the NGP is decreasing in the density of consumer taste $\frac{1}{\theta}$. The prices of both products are increasing in the average consumer taste $\frac{\theta}{2}$. When uncertainty exists in the average consumer taste and in the density of consumer taste, both of which influence a firm's profit, the correlation between them indicates the exposure to demand risk in a market. The stronger[5] the correlation, the higher the exposure, since if one index has an extreme value, the other index will also have an extreme value when the two indexes are highly related. We refer to the exposure to demand risk as:

$$r = -Cov(\frac{\theta}{2}, \frac{1}{\theta}) \tag{4.7}$$

Lemma 4.1. *If a monopolist with a total capacity k_m and unit investment cost c_m^A for the NGP decides to invest at the early stage, its optimal NGP capacity is $k_{m|e}^{*A} = \frac{N}{2} - \frac{c_m^A}{2\overline{\theta}\triangle S}N$ and its optimal profit is $\mathbb{E}_e[\Pi_m^*(k_m^A, \theta)] = \frac{\overline{\theta}}{N}S^B k_m(N-k_m) + \frac{\overline{\theta}\triangle S - c_m^A}{2} \times (\frac{N}{2} - \frac{c_m^A}{2\overline{\theta}\triangle S}N)$. If it decides to invest at the late stage, its optimal NGP capacity is $k_{m|l}^{*A} = \frac{N}{2} - \frac{c_m^A}{2\theta\triangle S}N$, and its optimal ex-ante profit is $\mathbb{E}_l[\Pi_m^*(k_m^A, \theta)] = \frac{\overline{\theta}}{N}S^B k_m(N-k_m) + \frac{\overline{\theta}\triangle S - c_m^A}{2} \times (\frac{N}{2} - \frac{c_m^A}{2\triangle S}N\mathbb{E}(\frac{1}{\theta}))$.*

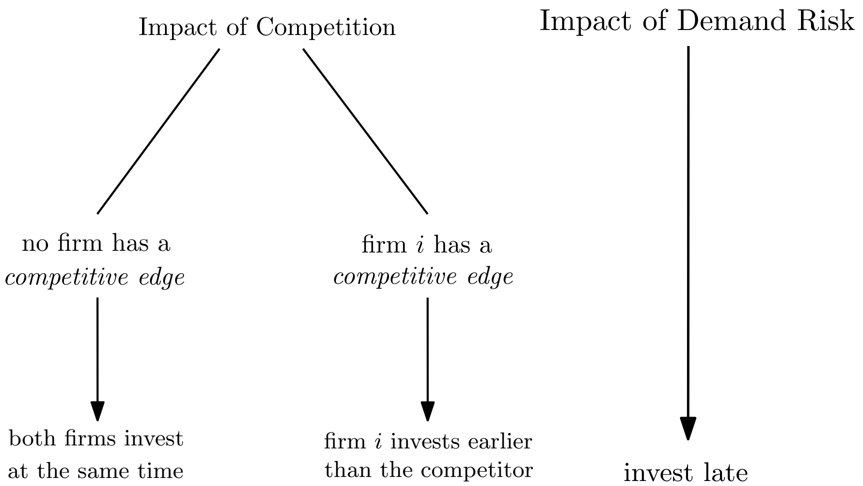
In Proposition 4.1, we derive the optimal investment timing of a monopolist. Because of uncertainty, i.e., $r > 0$, and no competition pressure, a monopolist will always postpone its investment until uncertainty is resolved (see Figure 4.3b). A similar result can also be found in Maggi (1996) for a single-product investment problem.

Proposition 4.1. *A monopolist will always invest late.*

4.4 Optimal investment timing in the competition

In this section, we investigate the optimal investment timing of two competing firms. In the competition, a firm decides whether to invest early or wait by

[5] Given σ_θ and $\sigma_{\frac{1}{\theta}}$, the strength of the correlation can then be illustrated by the coefficient of correlation $\rho = \frac{Cov}{\sigma_\theta \sigma_{\frac{1}{\theta}}}$.



(a) Duopoly without uncertainty (b) Monopoly under uncertainty

Figure 4.3: Impact of competition and demand risk on a firm's optimal investment timing

evaluating the impact of demand risk, which is based on the exposure to demand risk and on the first-mover advantage in the competition. In the following four lemmas, we analyze the equilibrium strategy to each of the four *capacity subgames* depicted in Table 4.1. According to Lemma 4.3, a firm that invests late may have a higher NGP capacity than its competitor who invests early, depending on the realization of the highest consumer taste θ, and the cost difference between the two firms.

Lemma 4.2. *If both firms invest early, i.e., (E, E), then the equilibrium capacity is $k_i^{*A} = \frac{N}{3}+\frac{c_{-i}^A-2c_i^A}{3\bar{\theta}\triangle S}N$, and the equilibrium expected profit is $\mathbb{E}_e[\pi_i^*(k_i^A, k_{-i}^{*A}, \theta)] = \frac{\bar{\theta}}{N}S^B k_i(N-k_i-k_{-i}) + (\frac{N}{3}+\frac{c_{-i}^A-2c_i^A}{3\bar{\theta}\triangle S}N)(\frac{\bar{\theta}\triangle S}{3}+\frac{c_{-i}^A-2c_i^A}{3})$, $\forall i = x, y$.*

Lemma 4.3. *If firm i invests early and firm $-i$ invests late, i.e., (E, L) or (L, E), then the equilibrium capacity is $k_i^{*A} = \frac{N}{2}+\frac{c_{-i}^A-2c_i^A}{2\bar{\theta}\triangle S}N$ and $k_{-i}^{*A} = \frac{N}{4}+\frac{2c_i^A-c_{-i}^A}{4\bar{\theta}\triangle S}N - \frac{c_{-i}^A}{2\theta\triangle S}N$. The equilibrium expected profits are $\mathbb{E}_e[\pi_i^*(k_i^A, k_{-i}^{*A}, \theta)] =$*

$\frac{\overline{\theta}}{N}S^B k_i(N-k_i-k_{-i})+(\frac{N}{2}+\frac{c_{-i}^A-2c_i^A}{2\overline{\theta}\triangle S}N)(\frac{\overline{\theta}\triangle S}{4}+\frac{c_{-i}^A-2c_i^A}{4})$ *and* $\mathbb{E}_l[\pi_{-i}^*(k_{-i}^A, k_i^{*A}, \theta)] = \frac{\overline{\theta}}{N}S^B k_{-i}(N - k_i - k_{-i}) + \frac{\overline{\theta}\triangle S}{16}N - \frac{c_{-i}^A}{4}N + (2c_i^A - c_{-i}^A)(\frac{N}{8} + \frac{2c_i^A-5c_{-i}^A}{16\overline{\theta}\triangle S}N) + \frac{(c_{-i}^A)^2}{4\triangle S}N\mathbb{E}(\frac{1}{\theta})$.

Lemma 4.4. *If both firms invest late, i.e.,* (L, L)*, then the equilibrium capacity is* $k_i^{*A} = \frac{N}{3}+\frac{c_{-i}^A-2c_i^A}{3\theta\triangle S}N$*, and the equilibrium expected profit is* $\mathbb{E}_l[\pi_i^*(k_i^A, k_{-i}^{*A}, \theta)] = \frac{\overline{\theta}}{N}S^B k_i(N - k_i - k_{-i}) + \frac{\overline{\theta}\triangle S}{9}N + \frac{2}{9}N(c_{-i}^A - 2c_i^A) + \frac{(c_{-i}^A-2c_i^A)^2}{9\triangle S}N\mathbb{E}(\frac{1}{\theta})$*,* $\forall i = x, y$*.*

To decide the optimal NGP capacity k_i^{*A}, firm i needs to balance price premium $p^A - p^B$ with the marginal profit loss of capacity extension $c_i^A - \frac{\partial p^A}{\partial k_i^A}k_i^{*A}$: $p^A - p^B = c_i^A - \frac{\partial p^A}{\partial k_i^A}k_i^{*A}$ (substituting equations (4.1), (4.2), and $\frac{\partial p^A}{\partial k_i^A} = -\frac{\theta\triangle S}{N}$ into the best response function $R_i(\widehat{k_{-i}^A})$). In the equilibrium where both firms invest at the same time, the marginal profit loss of both companies are the same. We define index M_i in equation (4.8) to represent the expected marginal profit loss of firm i due to price elasticity at the equilibrium. In the equilibrium strategy (E, E), the optimal NGP capacity of firm i is $k_i^{*A} = \frac{N}{\overline{\theta}\triangle S}M_i$ and $M_i + c_i^A = p^A - p^B$. Index M_i considers two dimensions of competition: the first dimension of measurement is the firm's gain from offering the quality upgrade, i.e., $\overline{\theta} \triangle S - c_i^A$, and the second dimension of measurement is the firm's cost disadvantage, i.e., $c_i^A - c_{-i}^A$. Bounded by the *non-negativity* assumption in equation (4.4), $M_i > 0$.

$$M_i = \frac{\overline{\theta} \triangle S - c_i^A - (c_i^A - c_{-i}^A)}{3} > 0 \tag{4.8}$$

In equation (4.9), we derive a condition which ensures that a firm's (ex-ante) expected optimal NGP capacity is non-negative, i.e., $E[k_i^{*A}] \geq 0$. This condition is a necessary condition for the *non-negativity* assumption in equation (4.4). The closed-form results in Sections 4.4 and 4.5 only hold under the *non-negativity* assumption in equation (4.4). The equilibrium results in Figure 4.5 are therefore bounded by the necessary condition in equation (4.9). In Section 4.4.3, we relax the *non-negativity* assumption and investigate a firm's optimal investment timing under a wide range of scenarios (See closed-form results in Appendix B). In Section 4.4.1 below, we first investigate a firm's optimal investment timing in the competition with no demand uncertainty, then in Section 4.4.2 we incorporate uncertainty.

$$\overline{\theta} \triangle S \geq \max\{2c_{-i}^{A} \times (1+r) + c_{-i}^{A} - 2c_{i}^{A}, (2c_{-i}^{A} - c_{i}^{A}) \times (1+r), \forall i = x, y\} \tag{4.9}$$

4.4.1 Optimal competitive investment timing with no uncertainty

To compare with the analysis in Section 4.4.2, we assume that the highest consumer taste is $\overline{\theta}$ when no uncertainty exists. Comparing a firm's marginal profit loss M_i and its cost disadvantage $c_i^A - c_{-i}^A$, Theorem 4.1 illustrates the equilibria of two competing firms to a *timing game* with no demand uncertainty. The results show that the equilibrium strategy (L, L) will not exist in such a situation. Obviously, when no uncertainty exists in the market, there is no incentive for both firms to wait. With no demand uncertainty, a firm's optimal investment timing depends only on the impact of competition.

Theorem 4.1. *In the competition with no demand uncertainty, the following pure strategy equilibria to the investment timing game exist:*

1. *If* $M_i > \frac{1}{7}(c_i^A - c_{-i}^A)$, $\forall i = x, y$, *then both firms invest early, i.e.,* (E, E).
2. *If* $M_{-i} \leq \frac{1}{7}(c_{-i}^A - c_i^A)$, *then firm* i *invests early and firm* $-i$ *invests late.*

Based on Theorem 4.1, we define two types of competition impact in equations (4.10) and (4.11), based on which firm has a *competitive edge*. The equilibrium strategy of the two firms then depends on the type of competition impact: if neither firm has a *competitive edge*, both firms invest at the same time; if firm i has a *competitive edge*, it invests earlier than the competitor. Figure 4.3a presents the flowchart for determining the optimal investment timing of a firm in the competition with no demand uncertainty. The two types of competition impact are exclusive and cover the entire parameter space which satisfies the *non-negativity* assumption in equation (4.4). If firm i has a *competitive edge*, the other firm $-i$ has: $(c_i^A - c_{-i}^A) < 0 \leq \frac{7(\bar{\theta}\triangle S - c_{-i}^A)}{17}$, thus $M_i > \frac{1}{7}(c_i^A - c_{-i}^A)$, which implies that firm $-i$ does not have a *competitive edge*.

$$\text{If } M_i > \frac{1}{7}(c_i^A - c_{-i}^A) \quad \forall i = x, y, \quad \textit{no firm has a competitive edge} \tag{4.10}$$

$$\text{If } M_{-i} \leq \frac{1}{7}(c_{-i}^A - c_i^A), \quad \textit{firm } i \textit{ has a competitive edge} \tag{4.11}$$

As shown in equation (4.11), a cost advantage does not directly translate into a *competitive edge*. A firm has a *competitive edge* only if its cost advantage $c_{-i}^A - c_i^A$ exceeds a certain threshold related to its competitor's marginal profit loss M_{-i}. Since index M_i can also be interpreted as the two dimensions of competition, the definition in equation (4.11) means that only when a firm's cost advantage exceeds a certain threshold related to its competitor's gain from offering the quality upgrade, the firm has a *competitive edge*. Index M_{-i} also indicates the degree of firm i's competitive advantage regardless of whether it has a *competitive edge* according to equation (4.11): a smaller value of M_{-i} indicates a larger competitive advantage. By the same token, we evaluate the degree of firm i's competitive disadvantage by the value of $M_{-i} - \frac{1}{7}(c_{-i}^A - c_i^A)$: a larger value of $M_{-i} - \frac{1}{7}(c_{-i}^A - c_i^A)$ indicates a larger competitive disadvantage. Given fixed $\bar{\theta} \triangle S$ and c_i^A, the value of M_{-i} negatively influences the value of M_i and the value of $M_i - \frac{1}{7}(c_i^A - c_{-i}^A)$. In other words, if a firm has a small competitive advantage, the competitor will have a small competitive disadvantage, and vice versa.

4.4.2 Optimal competitive investment timing under uncertainty

If there is uncertainty in the highest consumer taste θ at the phase of the *timing* game, a firm decides its optimal investment timing by evaluating the competitive advantage M_{-i} and disadvantage $M_{-i} - \frac{1}{7}(c_{-i}^A - c_i^A)$ of both firms and the impact of demand risk r. Using the results in Lemmas 4.2 to 4.4

and comparing a firm's profit in different equilibrium strategies, Theorem 4.2 describes all the possible equilibria of two competing firms to the *timing game*.

Theorem 4.2. *The following pure strategy equilibria to the investment timing game exist:*

1. *If* $M_{-i} \times \Big(M_i - \frac{1}{7}(c_i^A - c_{-i}^A)\Big) > \frac{4}{7}r \times \Big(c_i^A\Big)^2$, $\forall i = x, y$, *then both firms invest early, i.e.,* (E, E).
2. *If* $\Big(M_i\Big)^2 > \frac{8}{9}r \times \Big(c_{-i}^A - 2c_i^A\Big)^2$ *and* $M_i \times \Big(M_{-i} - \frac{1}{7}(c_{-i}^A - c_i^A)\Big) \leq \frac{4}{7}r \times \Big(c_{-i}^A\Big)^2$, *then firm* i *invests early and firm* $-i$ *invests late, i.e.,* (E, L) *or* (L, E).
3. *If* $\Big(M_{-i}\Big)^2 \leq \frac{8}{9}r \times \Big(c_i^A - 2c_{-i}^A\Big)^2$, $\forall i = x, y$, *then both firms invest late, i.e.,* (L, L).

In Theorem 4.2, we notice that the equilibrium regions are not exhaustive in covering the parameter space, nor are they mutually exclusive. In all, there are seven potential equilibrium regions to the *timing game*: one region for each pure strategy equilibrium (E, E), (E, L), (L, E), (L, L); one region in which (E, E) and (L, L) are both possible; one region in which (E, L) and (L, E) are both possible; and one region in which no equilibria exist. It may also be the case that some regions do not exist, depending on the parameter values.

According to the condition of each equilibrium strategy in Theorem 4.2, if no firm is expected to have a *competitive edge* (see equation (4.10)), the optimal equilibrium strategy could be any of the four strategies. If firm i is expected to have a *competitive edge*, i.e., $M_{-i} < \frac{1}{7}(c_{-i}^A - c_i^A)$ (see equation (4.11) and thus $\Big(M_{-i} - \frac{1}{7}(c_{-i}^A - c_i^A)\Big) \times M_i < 0$, the equilibrium strategy (E, E) will not exist, but the optimal equilibrium strategy could be any of the other three, i.e., (E, L), (L, E), or (L, L). This indicates that if there is demand uncertainty, evaluating the type of competition impact alone is not enough to determine the optimal investment timing of a firm. Based on a firm's competitive advantage and disadvantage i.e., M_i and $M_i - \frac{1}{7}(c_i^A - c_{-i}^A)$, and the impact of demand risk, which is is measured by the exposure to demand risk, i.e., r, and the investment cost or the cost difference between the two firms, i.e., c_i^A or $c_{-i}^A - 2c_i^A$, we identify the following two situations:

$$\textit{If } M_i \leq \frac{2}{3}\sqrt{2r} \times |c_{-i}^A - 2c_i^A| \quad \forall i = x, y, \qquad \textit{both firms are in a stand-still situation} \tag{4.12}$$

$$\textit{If } M_{-i} \times \left(M_i - \frac{1}{7}(c_i^A - c_{-i}^A)\right) \leq \frac{4}{7}r \times (c_i^A)^2, \qquad \textit{firm } i \textit{ is in a risky situation} \tag{4.13}$$

The two situations defined above are non-exclusive to each other, which means that a firm can be in a *stand-still* situation as well as in a *risky* situation. In addition, both firms can be in a *risky* situation and a firm can be in neither situation. A *stand-still* situation is evaluated based on both firms' competitive advantage and the exposure to demand risk. A *risky* situation is evaluated based on a firm's competitive advantage, the other firm's competitive disadvantage, and the exposure to demand risk. If there is a large exposure to demand risk, (i.e., a large value of r), a firm would be in both a *stand-still* situation and a *risky* situation, indicating that its competitive advantage is insufficient to hedge the impact of demand risk. Both firms would be in a *stand-still* situation if the values of M_i and M_{-i} are comparable, i.e., the two firms are expected to have similar competitive advantage. If the competitor is expected to have a *competitive edge* according to the criterion in equation (4.10), then firm i is in a *risky* situation. If the competitor does not have a *competitive edge*, firm i can still be in a *risky* situation if the values of M_{-i} and $M_i - \frac{1}{7}(c_i^A - c_{-i}^A)$ are comparable, i.e., firm i's competitive advantage is comparable to the other firm's competitive disadvantage.

Based on Theorem 2 and the conditions defined in equations (4.12) and (4.13), we present a flowchart in Figure 4.4 showing how to determine the optimal equilibrium strategy of the two firms competing under demand uncertainty. For instance, in a market where no firm is expected to have a *competitive edge* and both firms are in a *stand-still* situation, if any firm is in

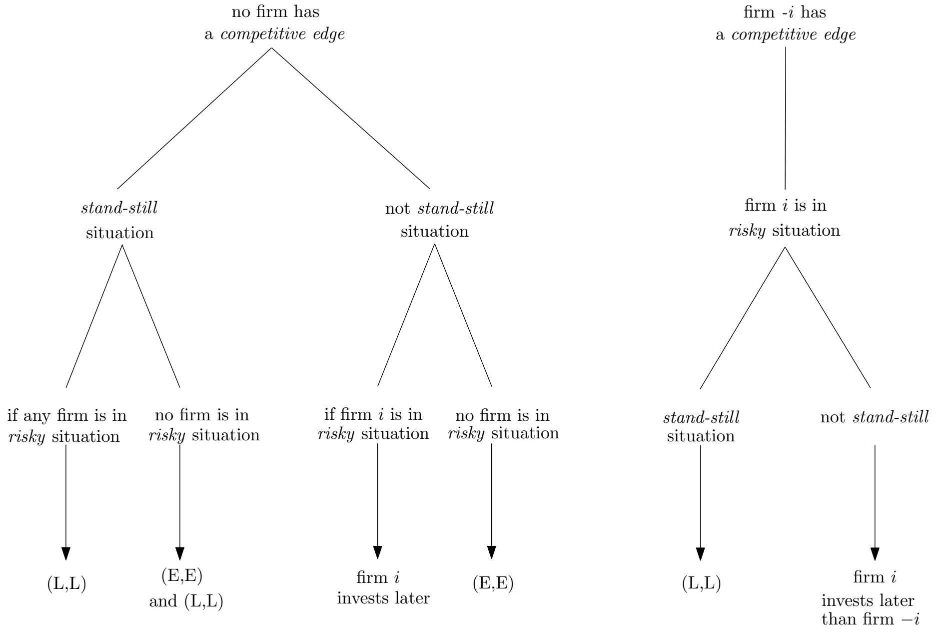


Figure 4.4: The optimal equilibrium strategy in the competition with demand uncertainty

a *risky* situation, they will both invest late, i.e., (L, L); otherwise, they will invest at the same time, i.e., both (E, E) and (L, L) can exist. According to the flowchart, the optimal investment timing of a firm depends on its situation:

- If the firm is in a *stand-still* situation, it should invest at the same time as its competitor;
- If the firm is in a *risky* situation, it should postpone its investment;
- If the firm is in neither *stand-still* nor *risky* situation, the firm should invest early.

Figure 4.5 shows an example of the equilibrium regions described in Theorem 4.2. The specification of parameters is listed in the box. Set $\gamma = \frac{\epsilon_y}{\epsilon_x}$, indicating the cost ratio between firm y and firm x. The x-axis represents the value of γ: when $\gamma < 1$, the low-cost firm is firm y; when $\gamma > 1$, the low-cost

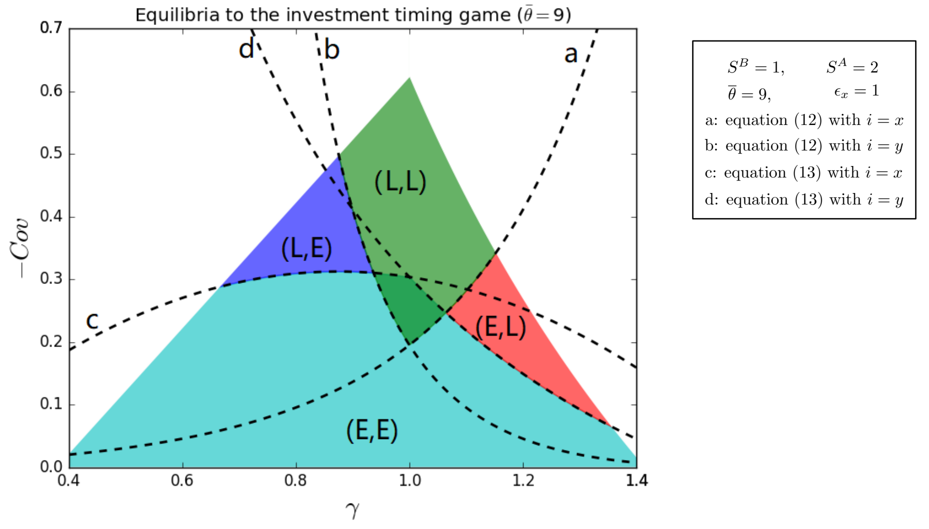


Figure 4.5: Equilibria to the *investment timing game*

firm is firm x. The y-axis represents the value of r, i.e., the exposure to demand risk. Given γ, we only depict equilibrium regions in an example of the parameter space where the value of r meets the assumption in equation (4.9). The white area in Figure 4.5 is the area where the assumption is not met. The regions of equilibrium strategies (E, E), (E, L), (L, E), and (L, L) are colored in cyan (light blue), red, blue, and green, respectively. The area colored in gradient green is a mix-strategy region of (E, E) and (L, L). Equations (4.12) and (4.13) are shown as the dashed line $a - d$ (see details in the specification box). We validate the decision rule in the flowchart: (1) the area above the dashed lines a and b is where both firms are in a *stand-still* situation, thus they should invest at the same time; (2) the area above the dashed line c is where firm x is in a *risky* situation, thus it should wait; (3) the area above the dashed line d is where firm y is in a *risky* situation, thus it should wait; (4) the area below the dashed lines a and c is where firm x is in neither situation, thus it should invest early; (5) the area below the dashed lines b and d is where firm y is in neither situation, thus it should invest early.

4.4.3 Optimal competitive investment timing without the *non-negativity* assumption

Without the *non-negativity* assumption in equation (4.4), firm i that invests late will choose not to launch the NGP if its best response to the other firm's capacity $\widehat{k^A_{-i}}$ and the realized θ is negative, i.e., $\frac{N}{2} - \frac{\widehat{k^A_{-i}}}{2} - \frac{c_i^A}{2\theta\triangle S}N < 0$. Therefore, if any firm decides to invest late, both firms need to consider the probability that the late firm will not invest. This decision not to invest should be considered differently from the optimal capacity using the best response function $R_i(\widehat{k^A_{-i}})$. In Appendix B, we present the analysis for the *investment timing game* without the *non-negativity* assumption. The main results in Sections 4.4.1 and 4.4.2 still hold, e.g., a firm's optimal competitive investment timing depends on the trade-off between the impact of demand risk and the impact of competition, which is evaluated based on the two dimensions of competition. Relaxing the *non-negativity* assumption causes a higher probability that the realized consumer taste will be unfavorable to a launch decision, thus, more likely that both firms will wait until the uncertainty is resolved.

4.5 When quality of the NGP may improve later

In this section, we incorporate another feature of an NGP launch, that is, a firm that invests late may launch an NGP with a better quality than the NGP of a firm that invest early. We refer to the improved NGP as A^+ and $j = B, A, A^+$. We consider the scenario where NGPs are provided by a third-party institute, e.g., a research lab, and the R&D process is independent of the capacity decisions of the two firms. We assume that with probability pr, the quality of the NGP will improve to S^{A^+} ($> S^A$) at the late stage; with probability $1 - pr$, the quality remains S^A. Thus, if a firm decides to wait, it may receive an NGP with quality S^{A^+} to invest and launch to the market. The sequence of both firms' timing and capacity decisions remains the same. The summary can be found in Figure 4.6. Compared to the previous sequence of events (see Figure 4.2), the differences in the new timeline are colored in red. The potential quality improvement does not influence the two firms' capacity and profit outcomes if both decide to invest early. Thus, the equilibrium capacity and expected profits of the two firms in the subgame (E, E) are the same as in Lemma 4.2. In (E, L) and (L, E): with probability pr, three products with quality levels S^B, S^A, and S^{A^+}, exist; with probability $1 - pr$, only the basic product and the NGP with quality level S^A exist. In the subgame (L,L): with probability pr, the basic product and the NGP with quality level S^{A^+} exist; with probability $1 - pr$, the basic product and the NGP with quality level S^A exist.

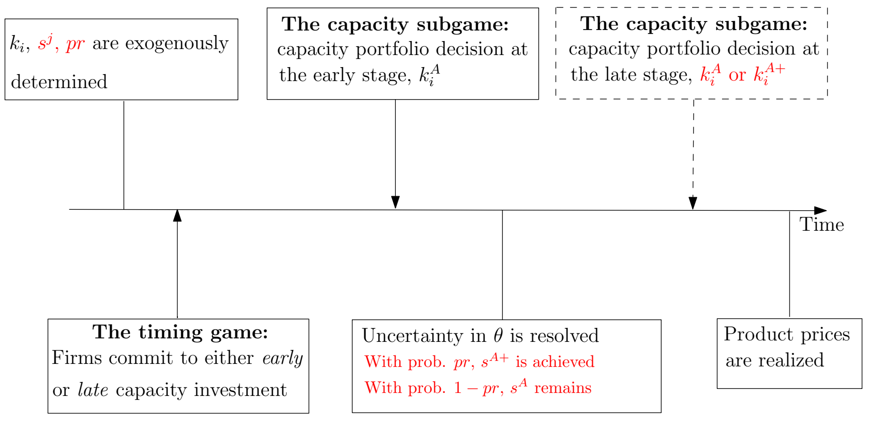


Figure 4.6: The sequence of events

Set $\triangle S^+ = S^{A^+} - S^A$ and $S = \triangle S + \triangle S^+$. Proposition 4.2 characterizes the optimal investment timing of a monopolist. The impact of demand risk is measured by $r \times \left((1 - pr)(c_m^A)^2 + \frac{\triangle S}{S} pr(c_m^{A^+})^2\right)$, where $(1 - pr)(c_m^A)^2 + \frac{\triangle S}{S} pr(c_m^{A^+})^2$ indicates the expected investment cost of the NGP. Different from the previous result where a monopolist will always postpone its investment until the uncertainty is resolved (see Proposition 4.1), when product quality could improve later, there are some situations where a monopolist is better off investing early. This is because the unit investment cost is convex in product quality, i.e., $c_i^j = \epsilon_i (S^j)^2$. If $\triangle S^+$ is very large, offering the NGP with quality S^A may be better than offering one with S^{A^+}. $pr \times \Big(\frac{\triangle S}{S} c_m^{A^+} (\overline{\theta} S - c_m^{A^+}) - c_m^A (\overline{\theta} \triangle S - c_m^A) - \overline{\theta} \triangle S \big(\overline{\theta} \triangle S^+ - (c_m^{A^+} - c_m^A) \big) \Big)$ represents the expected loss due to launching the A^+ instead of A. Thus, the economic interpretation of a monopolist's optimal investment timing is: a monopolist should invest early if and only if the expected loss exceeds the impact of demand risk due to launching a more advanced NGP.

Proposition 4.2. *For a monopolist with unit investment costs c_m^A and $c_m^{A^+}$ for A and A^+: if $r \times \Big((1-pr)(c_m^A)^2 + \frac{\triangle S}{S} pr (c_m^{A^+})^2 \Big) < pr \times \Big(\frac{\triangle S}{S} c_m^{A^+} (\overline{\theta} S - c_m^{A^+}) - c_m^A (\overline{\theta} \triangle S - c_m^A) - \overline{\theta} \triangle S \big(\overline{\theta} \triangle S^+ - (c_m^{A^+} - c_m^A) \big) \Big)$, it will invest early; otherwise, it will invest late.*

Lemma 4.5. *If firm i invests early and firm $-i$ invests late, i.e., (E, L) or (L, E), then the equilibrium capacity is $k_i^{*A} = \frac{N}{2\overline{\theta}(\triangle S + \frac{\triangle S \triangle S^+}{S} pr)} \times M_i^{AorA^+}$ and $k_{-i}^{*A} = \frac{N}{2} - \frac{c_{-i}^A N}{2\theta \triangle S} - \frac{k_i^{*A}}{2}$ or $k_{-i}^{*A^+} = \frac{N}{2} - \frac{c_{-i}^{A^+} N}{2\theta S} - \frac{\triangle S k_i^{*A}}{2S}$. The equilibrium expected profits are $\mathbb{E}_e[\pi_i^*(k_i^A, k_{-i}^{*Aor*A^+}, \theta)] = \frac{\overline{\theta}}{N} S^B k_i (N - k_i - k_{-i}) + \frac{(M_i^{AorA^+})^2 Ns}{8\overline{\theta} \triangle S (s + \triangle S^+ pr)}$ and $\mathbb{E}_l[\pi_{-i}^*(k_{-i}^{AorA^+}, k_i^{*A}, \theta)] = \frac{\overline{\theta}}{N} S^B k_{-i} (N - k_i - k_{-i}) + \frac{N}{4} \mathbb{E}(\frac{1}{\theta}) [\frac{1}{\triangle S} (1-pr)(c_{-i}^A)^2 + \frac{1}{S} pr (c_{-i}^{A^+})^2] + (1-pr) \frac{N}{\overline{\theta} \triangle S} (\frac{\overline{\theta} \triangle S}{2} - \frac{M_i^{AorA^+}}{4(1 + \frac{\triangle S^+}{S} pr)})(\frac{\overline{\theta} \triangle S}{2} - \frac{M_i^{AorA^+}}{4(1 + \frac{\triangle S^+}{S} pr)} - c_{-i}^A) + pr \frac{N}{\overline{\theta} S} (\frac{\overline{\theta} S}{2} - \frac{M_i^{AorA^+}}{4(1 + \frac{\triangle S^+}{S} pr)})(\frac{\overline{\theta} S}{2} - \frac{M_i^{AorA^+}}{4(1 + \frac{\triangle S^+}{S} pr)} - c_{-i}^{A^+})$.*

Lemma 4.6. *If both firms invest late, i.e., (L, L), then the equilibrium capacity is $k_i^{*A} = \frac{N}{3} + \frac{c_{-i}^A - 2c_i^A}{3\theta \triangle S} N$ or $k_i^{*A^+} = \frac{N}{3} + \frac{c_{-i}^{A^+} - 2c_i^{A^+}}{3\theta S} N$, and the equilibrium expected profit is $\mathbb{E}_l[\pi_i^*(k_i^{AorA^+}, k_{-i}^{*Aor*A^+}, \theta)] = \frac{\overline{\theta}}{N} S^B k_i (N - k_i - k_{-i}) + \frac{N\overline{\theta}}{9}(\triangle S + pr \triangle S^+) + \frac{2}{9} N \Big((1-pr)(c_{-i}^A - 2c_i^A) + pr (c_{-i}^{A^+} - 2c_i^{A^+}) \Big) + \frac{N}{9} \Big(\frac{1}{\triangle S} (1-pr)(c_{-i}^A - 2c_i^A)^2 + \frac{1}{S} pr (c_{-i}^{A^+} - 2c_i^{A^+})^2 \Big) \mathbb{E}(\frac{1}{\theta})$, $\forall i = x, y$.*

Lemmas 4.5 and 4.6 describe the equilibrium capacity and expected profits of the two firms in the subgames (E, L), (L, E), and (L, L). Similar to M_i (see equation (4.8)), we define index $M_i^{AorA^+}$ for the situation when firm i invests early and the competitor waits (thus, the investment cost of firm $-i$

considers the probability of launching A^+).

$$M_i^{AorA^+} = \overline{\theta} \triangle S - c_i^A - (c_i^A - (1-pr)c_{-i}^A - \frac{\triangle S}{S} prc_{-i}^{A^+}) \tag{4.14}$$

To ensure that the expected optimal NGP capacity of both firms in the four subgames is non-negative, we make the following assumptions, which are also the necessary conditions of the *non-negativity* assumption in equation (4.4):

$$\begin{aligned}\overline{\theta} \triangle S \geq \max\{&2c_i^A - (1-pr)c_{-i}^A - \frac{\triangle S}{S} prc_{-i}^{A^+}, (2c_{-i}^A - c_i^A)(1+r),\\ &c_{-i}^A(1+r) + \frac{M_i^{AorA^+}}{2(1+\frac{\triangle S^+}{S}pr)}, \forall i = x, y\}\end{aligned} \tag{4.15}$$

$$\overline{\theta} S \geq \max\{(2c_{-i}^{A^+} - c_i^{A^+})(1+r), c_{-i}^{A^+}(1+r) + \frac{M_i^{AorA^+}}{2(1+\frac{\triangle S^+}{S}pr)}, \forall i = x, y\} \tag{4.16}$$

Set $c_i^{AorA^+} = (1-pr)(c_i^A)^2 + \frac{\triangle S}{S}pr(c_i^{A^+})^2$ and $c_{-i,i}^{AorA^+} = (1-pr)(2c_i^A - c_{-i}^A)^2 + \frac{\triangle S}{S}pr(2c_i^{A^+} - c_{-i}^{A^+})^2$. $r \times c_i^{AorA^+}$ measures the impact of demand risk on firm i, and $r \times c_{-i,i}^{AorA^+}$ represents the impact of demand risk on firm i considering the cost difference between the two firms. Theorem 4.3 describes all the possible equilibria of two competing firms to the *investment timing game*. Following a similar manner as in equations (4.12) and (4.13), we can also define different types of situations of a firm, based on the impact of demand risk, M_{-i} and $M_{-i}^{AorA^+}$. Then the optimal investment timing of a firm depends on its situation. Figure 4.7 presents an example of the equilibrium strategy regions described in Theorem 4.3. The specification of parameters is listed in the box. Compared to the results in Figure 4.5, adding the trade-off between time-to-market and quality upgrade does not change the majority of our previous observations, but only expands the region of the equilibrium strategy (L, L). This result is obvious since potential quality improvement at the late stage makes waiting more appealing to both firms.

Theorem 4.3. *The following pure strategy equilibria to the investment timing game with potential quality improvement exist:*

1. *If* $(1+r)\times c_i^{AorA^+} \leq \frac{4}{9}M_{-i}^2 - (1-pr)(\overline{\theta}\triangle S - \frac{M_{-i}^{AorA^+}}{2(1+\frac{\triangle S^+}{S}pr)})(\overline{\theta}\triangle S - \frac{M_{-i}^{AorA^+}}{2(1+\frac{\triangle S^+}{S}pr)} - 2c_i^A) - \frac{\triangle S}{S}pr(\overline{\theta}S - \frac{M_{-i}^{AorA^+}}{2(1+\frac{\triangle S^+}{S}pr)})(\overline{\theta}S - \frac{M_{-i}^{AorA^+}}{2(1+\frac{\triangle S^+}{S}pr)} - 2c_i^{A^+})$, $\forall i = x, y$, *then both firms invest early, i.e.,* (E,E).

2. *If* $(1+r)\times c_{-i}^{AorA^+} \geq \frac{4}{9}M_i^2 - (1-pr)(\overline{\theta}\triangle S - \frac{M_i^{AorA^+}}{2(1+\frac{\triangle S^+}{S}pr)})(\overline{\theta}\triangle S - \frac{M_i^{AorA^+}}{2(1+\frac{\triangle S^+}{S}pr)} - 2c_{-i}^A) - \frac{\triangle S}{S}pr(\overline{\theta}S - \frac{M_i^{AorA^+}}{2(1+\frac{\triangle S^+}{S}pr)})(\overline{\theta}S - \frac{M_i^{AorA^+}}{2(1+\frac{\triangle S^+}{S}pr)} - 2c_{-i}^{A^+})$ *and* $(1+r)\times c_{-i,i}^{AorA^+} \leq \frac{9}{8}\times\frac{(M_i^{AorA^+})^2}{1+\frac{\triangle S^+}{S}pr} + \overline{\theta}\triangle S\Big((1-pr)(\overline{\theta}\triangle S - 2M_{-i}) + pr(\overline{\theta}S - 2M_{-i}^{A^+})\Big)$, *then firm* i *invests early and firm* $-i$ *invests late, i.e.,* (E,L) *or* (L,E).

3. *If* $(1+r)\times c_{-i,i}^{AorA^+} \geq \frac{9}{8}\times\frac{(M_i^{AorA^+})^2}{1+\frac{\triangle S^+}{S}pr} + \overline{\theta}\triangle S\Big((1-pr)(\overline{\theta}\triangle S - 2M_{-i}) + pr(\overline{\theta}S - 2M_{-i}^{A^+})\Big)$, $\forall i = x, y$, *then both firms invest late, i.e.,* (L,L).

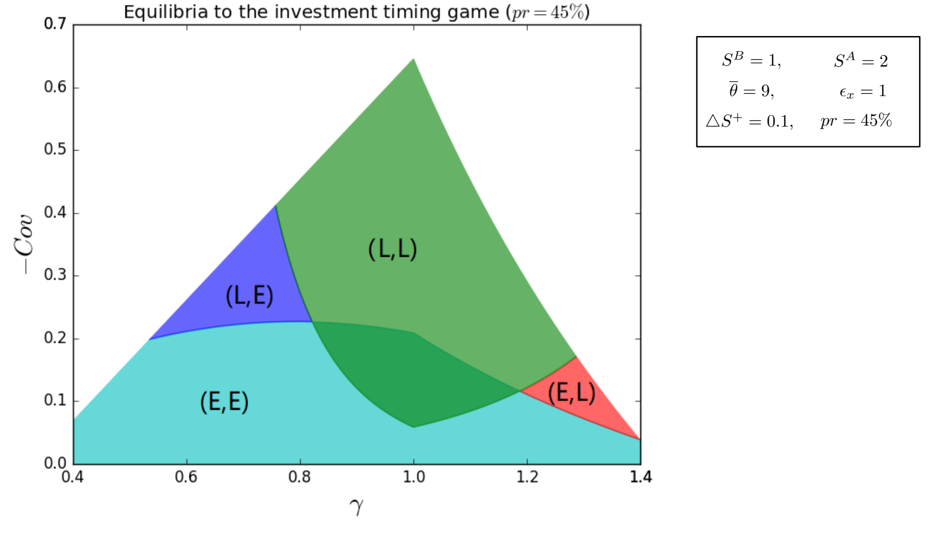


Figure 4.7: Equilibria to the *investment timing game* with potential quality improvement

Managerial insights

A firm launching an NGP in a competitive market faces two major challenges. Because consumers have varied and often uncertain tastes in a market, a firm's first challenge is therefore to evaluate the risk associated with demand uncertainty for the NGP. To characterize a target market, companies should carry out market research to measure the following two indexes: the average consumer taste and the density of consumer taste. A high density of consumer taste indicates that few consumers will switch from purchasing the basic product to the NGP, whereas a high average consumer taste indicates that firms can ask high prices for both the basic product and the NGP. When consumer tastes are uncertain and the two consumer taste indexes are stochastic, our results show that the firm should evaluate the exposure to demand risk, which is measured by the correlation between the average consumer taste and the density of consumer taste. The stronger the correlation, the higher the exposure, since if one index has an extreme value, the other index will also have an extreme value when the two indexes are highly related. Thus, it indicates a large exposure to demand risk and a large impact of demand risk on firms in the market. Although, in practice it is not straightforward to measure the correlation, it may be measured based on realized consumer data from previous product launches in the same market.

If exposure to demand risk is large, firms should postpone their investments until the uncertainty is resolved. However, a firm may hold a cost advantage over its competitor. Our results show that a firm can use this cost advantage to mitigate the impact of demand risk and thus invest earlier than its competitor, benefiting from the first-mover advantage. The second challenge a firm faces during an NGP launch is to evaluate to what extent its cost advantage can be transferred into an advantage in the competition. We show that a firm's competitive advantage and disadvantage can be measured based on the competitor's gain from offering the quality upgrade and its cost advantage over the competitor. A firm has a *competitive edge* only if its cost advantage exceeds a certain threshold related to its competitor's gain from offering the quality upgrade, and this *Edge* can lead the firm to invest earlier. To decide the optimal investment timing, a firm needs to consider the competitive advantage and disadvantage of both firms. If the competitor has a *competitive edge*, the firm will be in a *risky* situation and the best strategy is to wait. In a market where no firm has a *competitive edge*, if a firm's competitive advantage is comparable to the other firm's competitive disadvantage, the firm would still be in a *risky* situation and thus it should wait. If both firms have similar competitive advantage, they would be in a *stand-still* situation and the best strategy is to invest at the same time as its competitor. If none of the above holds, i.e., a firm is in neither a *stand-still* nor *risky* situation, the best strategy is to invest early.

Table 4.2 lists three examples of failed NGPs. The first example is Microsoft Zune, which is considered to be one of the decade's 10 biggest tech launch failures. It was launched in 2006, but never passed the single-digit market share in music players before it was discontinued in 2011 (McIntyre, 2009). There is little evidence that Zune was of low quality. In fact, its users enjoyed the interface and audio quality just as much as, if not more than the rival product, i.e., Apple iPod. Microsoft attributed the failure of Zune to bad timing i.e., launching five years later than iPod. Microsoft had access to as much hardware development expertise as any company in the world and the capital to support a massive marketing budget for any new product. In hindsight, Microsoft and Apple were in a *stand-still* situation at that time and Microsoft's optimal investment timing should have been at the same time as Apple's. It is worth comparing what Microsoft experienced with Zune to the wrest between Windows PCs and Apple's Mac. As the two firms follow each other's new model launches closely, the outcome of this battle is still undetermined. The second example of a failed NGP is HTC first, which is also known as the first Facebook phone (Cheng, 2013). In the market of smartphones, Facebook did not have much advantage compared to other flagship phone manufacturers. In hindsight, Facebook was in a risky situation at the

Table 4.2: Examples of failed NGPs and hindsight

Failed NGP	Competitor's NGP (which succeeded)	Timing of Launch (comp. competitor)	Exposure to Demand Risk	Impact of Competition	Competitive Situation	Optimal Investing Timing
Microsoft Zune	Apple iPod	Later	Moderate	No firm has a competitive edge	*Stand-still*	Same time as the competitor
Facebook phone	Samsung Galaxy S4	Nearly the same time	Moderate	The competitor has a competitive edge	*Risky*	Late
Microsoft SPOT	Apple Watch	Earlier	Large	No firm has a competitive edge	*Stand-still* and *Risky*	Same time as the competitor and late

time and should have waited, instead of launching at nearly the same time as Samsung. The third example is Microsoft SPOT Watch which was launched too early (Nguyen, 2016). Consumers were not ready to embrace the concept of a smartwatch at that time. The realized average consumer taste was too low and the consumer taste density was too high, both leading to a flopped product. In hindsight, the exposure to demand risk was large when SPOT was launched, and Microsoft was in both a *stand-still* and a *risky* situation. Therefore, Microsoft should have waited, launching at the same time as the competitor.

In addition to bad timing, there are many other reasons, such as quality failure, why an NGP could fail. However, in order to avoid bad timing, a firm must identify the type of competitive situation it is in, based on the exposure to demand risk and the impact of competition.

4.6 Conclusion

We study an NGP launch problem for two firms competing in the same market. The challenges of an early NGP launch include imperfect information on consumer preference and immature R&D results, therefore bearing the risk of insufficient demand for the NGP. However, an early launch promises leadership benefits if the other firm chooses to wait and invests later. A late launch bears the risk of becoming the market follower, but the firm benefits from complete demand information and from the possibility of improved product quality and hence the follower could provide a superior version of the leader's next-generation product. Our results show that the optimal NGP investment timing of a firm depends on the impact of demand risk and the impact of competition. The former depends on the exposure to demand risk, which is measured by the correlation between the average consumer taste and the density of consumer taste. The latter depends on the competition between the two products and the competition between the two firms. In addition to demand risk and competition, there are many other factors which can influence the success of a product launch. For example, the strategic behavior of consumers may lead a firm to postpone its new product launch. Moreover, our research considers a situation where the new product is provided by a third party. In practice, the new product is often owned by a firm who launches it later. The firm can then decide whether to license the technology to the competitor, which will influence the optimal NGP investment strategies of both firms. Future research should take into account the existence of strategic consumers and the possibility of technology licensing between firms.

Chapter 5

Combating Strategic Cross-Border (CB) Counterfeiters: ***Public and/or Private Responsibility?***

5.1 Introduction

In today's business world, firms often find themselves in the thick of competition. While healthy competition encourages firms to improve the quality of goods and services they sell and create a wider choice for consumers, vicious competition such as counterfeiting harms both legitimate business and consumers. Counterfeiting in its broadest sense is defined as "*any manufacturing of a product which so closely imitates the appearance of the product of another to mislead a consumer that it is the product of another*" (Vithlani, 1998). The key elements of this definition are if the product is similar and if there is deception of the consumer. Although it is difficult to obtain accurate statistics on counterfeiting because of the clandestine nature, it is widely agreed that counterfeiting has become a prevalent issue in industries such as clothing, pharmaceutical, and spare-parts industries (Lewis, 2009; Stevenson and Busby, 2015; Frontier Economics, 2016). According to a governmental report prepared for the Business Action to Stop Counterfeiting and Piracy and the International Trademark Association, the value of international and domestic trade in counterfeit and pirated goods in 2013 was estimated to be $710 -$917 billion (Frontier Economics, 2016).

Not only counterfeiting hurts reputation and profitability of legitimate firms, but it also exposes unsuspecting consumers to ineffective and dangerous products. The World Health Organization (WHO) estimates that counterfeits comprise 10-30% of drug sales in some developing countries and some have estimated that one out of every hundred pharmaceuticals in the United States is counterfeit (Teresko, 2008; Lewis, 2009; Frontier Economics, 2016). According to the WHO, 1 million people die each year as a result of taking counterfeit medicines (Więcławski, 2018).

Almost 70% of all counterfeits seized worldwide come from China (Turnage, 2013) and other low-wage countries where intellectual property (IP) protection is weak (Zimmerman and Chaudhry, 2009; Cai et al., 2010). It is difficult to obstruct counterfeiting activities in those countries due to cultural and political reasons, however, it would be a plausible solution to hinder the entrance of counterfeits into final markets. Customs, as the entry point of shipments of products to a market, plays a prominent role in fighting against counterfeiting. In 2016, EU Customs seized over 41 million fake goods at EU borders (European Commission, 2017). Unfortunately, Customs cannot solve the problem on its own. The effectiveness of the Customs act against counterfeiting depends on the information shared by the rights holders. If firms make their supply chain and product related information visible to Customs, it could be effortless for Customs to thwart counterfeit products (Vithlani, 1998). In recent years, we have seen a number of public-private partnerships (PPP), in which information is shared between governmental authorities and private enterprises, being formed to combat counterfeiting at the borders. A good example is the cooperation agreement between the British American Tobacco

(BAT) and the European Commission (EC) (BAT, 2010). This agreement involves a $200 million investment of BAT in sharing intelligence, providing expanded support and implementing far-reaching product-tracking procedures to help EC and the law enforcement authorities of the Member States tackle illicit tobacco trade (European Commission, 2010). In 2016, Alibaba formed a task force together with the Chinese government, in which legitimate brands can work proactively by tipping off the police and e-commerce firms to counterfeiters (Chen et al., 2018). A PPP can also be initiated and funded by governmental authorities. For example, in 2011 the World Customs Organization (WCO) developed the Interface Public Member (IPM) platform, i.e., an online platform where rights holders can communicate brand operational data to Customs officers, facilitating the identification of counterfeit goods. This tool is currently freely used by one third of the WCO Members (WCO, 2015). Another example is the enforcement database (EDB), which is initiated by the European Union Intellectual Property Office. Any IP rights holder can be part of it by entering information about their products into the database, and it then becomes available to enforcement authorities and helps them identify counterfeits and take actions.

Enabling information sharing between different parties requires infrastructure, which can be costly to build. For instance, firms can adopt blockchain technology to enable Customs and related supply chain parties to exchange and store information in encrypted format, however it requires the entire supply chain to revolutionize the information system. Therefore, an important question is ***when forming a PPP as an anti-counterfeiting strategy, which party should be responsible for the investment in the information sharing infrastructure?*** Should it be the legitimate OEM as it benefits from removing counterfeits from the market, or the government as the existence of counterfeits will bring societal challenges? In addition to the PPP, legitimate firms can also resort to pricing to compete against counterfeiters in the market. Our paper investigates the question ***how should a legitimate firm combat counterfeiting.*** Should it join (or initiate) the

PPP or rely solely on pricing? To address these questions, we consider two types of counterfeits: non-deceptive and deceptive, where the difference is that consumers can distinguish non-deceptive counterfeits from authentic products at the time of purchase, while they cannot in the other case. Non-deceptive counterfeits compete with authentic products on price and quality, whereas deceptive counterfeits infiltrate the licit distribution channel of legitimate firms and are sold as authentic products at the same price. We study the impact of the type of counterfeits on a firm's anti-counterfeiting strategy, as well as the strategy of the government.

We model the problem as a multi-stage game with three players, i.e., Customs, a legitimate OEM, and a counterfeiter. In the game, Customs decides whether to initiate a PPP, i.e., whether to invest in the public-private information-sharing mechanism, the OEM decides whether to join the PPP if Customs has initiated it or initiate it if needed, and the counterfeiter decides whether to disguise the nature of its shipments to escape the detection by Customs. Deriving the optimal equilibrium strategy to the game, we **first** show that compared to the situation without any counterfeit, the existence of non-deceptive counterfeits could lead the OEM to increase the price of authentic products and earn more profit if the PPP is formed. However, when Customs does not bear the costs of information sharing, initiating the PPP by the OEM on its own will lead the counterfeiter to increase its price and even potentially capture a higher market share than the OEM. It possibly explains why some legitimate manufacturers do not join such a partnership with the government to combat counterfeiting. For instance, while there are almost two million active federal trademark registrations and many more copyright registrations that are eligible for enhanced protection against illicit imports, only 32,000 or so have been recorded with US Customs and Border Protection for border enforcement (Botts, 2014).

Second, we find that in the non-deceptive case, the optimal equilibrium strategy of each player depends on the damage to the society, the penalty to the counterfeiter and the quality of counterfeits. When the damage to the society is below a certain threshold defined as a function of the penalty to the counterfeiter and the quality of counterfeits, Customs does not have the incentive to initiate the PPP either because the penalty can already serve as an effective counterfeiting deterrence tool or because the damage to the society when a counterfeit enters the market is minor. The government plays an important role in initiating the partnership with private enterprises in the fight against non-deceptive counterfeiter. Because if Customs does not initiate the PPP, the OEM will likely also choose not to initiate it, especially when the penalty is either very large or very small. When the penalty is small, the counterfeiter can still provide a low-price product even after paying the penalty. Thus, to maintain a competitive price of authentic product, the OEM may choose not to invest in the PPP. Besides the reason that large penalty is effective in deterring the entry of counterfeits, another reason why the OEM will likely not initiate the PPP when the penalty is large is that under such a condition, the counterfeiter will disguise even if the PPP is formed.

Third, we find that the OEM should play a bigger role in initiating the PPP to combat deceptive counterfeiting, compared to his role in the non-deceptive case. The OEM could choose a higher price than that without any counterfeit only if it initiates the PPP, and the market seize of the deceptive counterfeiter is decreasing in the price of authentic products in such a situation. **Lastly**, we show that, unlike what the literature suggests, the entry of non-deceptive counterfeits does not always improve consumer surplus. In particular, when the quality of counterfeits exceeds a certain proportion of the quality of authentic products, it could be better for consumers if the OEM initiates the PPP to hinder the entry of counterfeits. In the deceptive case, which party initiates the PPP could yield different outcomes in terms of consumer welfare: it could be better for consumers if Customs initiates the PPP, compared to the situation where the OEM initiates the PPP. In addition, when the quality of counterfeits is sufficiently low, it is better for consumers if the PPP is formed.

The remainder of this paper is organized as follows: Section 5.2 presents a literature review in related areas; In Section 5.3, we describe the detention process of counterfeits at Customs and the PPP model between Customs and the legitimate OEM; In Sections 5.4, we present the analysis for the multi-stage model in the non-deceptive case; In Section 5.5, we explore the situation when the counterfeiter is being deceptive and present results which are different from the non-deceptive case. Finally, we conclude our research in Section 5.6.

5.2 Related literature

Our paper relates to three streams of literature: the industrial organization literature on entry deterrence, the marketing literature on consumer behavior towards counterfeiting, and the operations literature on a firm's anti-counterfeiting strategies, and on the competition between brand-name products and other alternatives.

Entry-deterrence models study the effect of the incumbent's investment-level decisions, e.g., pricing and advertising selections, on the entrant's profit (Srinivasan, 1991; Wilson, 1992) and the impact of the entrant's entry strategies on the incumbent's profit (Balachander, 2001). For the incumbent, the most commonly used strategy to deter a profitable entry is pricing. For instance, Bagwell (2007) considered whether a privately informed incumbent can deter profitable entry by pricing below the monopoly price and increasing its level of advertising. He showed that profitable entry may be deterred if the incumbent knows about the entrant's cost type and whether the entrant is long- or short-termism. For the entrant, product quality is one of the most important factors that determines the success of its entry. Balachander (2001) considered a market with an incumbent, whose quality is known to consumers, and an entrant, whose quality is unknown to consumers. The entrant signals its quality to consumers through warranty. They showed that signaling behavior leads to an outcome where the less reliable product may carry the longer warranty, which is consistent with the empirical phenomenon. Using a game-theoretic model, Gao et al. (2016) considered a situation where the entrant is a copycat, whose products show physical resemblance to genuine products of the incumbent. They showed that copycats with a high physical resemblance but low product quality are more likely to successfully enter the market by defying the pricing deterrence of the incumbent. To a certain extent, a counterfeiter is an entrant to an existing market. Our research relates to entry-deterrence models in the sense that we study the effect of the legitimate manufacturer's pricing on the counterfeiter's entry and the impact of the quality of counterfeits on the manufacturer's optimal anti-counterfeiting strategy. The existing entry-deterrence models see the entrant as a regular competitor of the incumbent, and ignore legal aspects of the market entry. However, these aspects are crucial in the case where the entrant free rides on the incumbent's investments in research and product development to offer a comparable product at a cheaper price. Our research considers legal aspects of counterfeiting and investigates anti-counterfeiting strategies which rely on government acts.

The marketing literature on counterfeiting focuses on the demand side of counterfeits. Often through empirical studies, they try to answer the question why consumers purchase counterfeits (e.g., Hoon Ang et al. (2001); Eisend and Schuchert-Güler (2006); Qian and Xie (2013)). Using results from a consumer survey, Prendergast et al. (2002) found that quality is an important factor to consumers who are apt to buy pirated goods and thus suggested brand manufacturers ensure that there are significant differences between the authentic product and the counterfeit. Using data from Chinese shoe companies, Qian (2014) examines how counterfeits of various qualities affect the consumer's purchase decision. The study showed that fake products can benefit a manufacturer of high-quality products during the early stage of brand development, while a manufacturer of low-quality products would be severely affected by the existence of a counterfeiter. These marketing studies focus on non-deceptive counterfeits, which consumers can distinguish from authentic products at the time of purchase. The root of the non-deceptive counterfeiting problem stems from the willingness of consumers to purchase fakes (Prendergast et al., 2002), thus the goal of this stream of research is to provide implications to policy makers and legitimate manufacturers regarding how to educate consumers not to purchase fakes. Our research considers both the non-deceptive and deceptive counterfeits, and we investigate how legitimate manufacturers can resort to operations strategies to fight against each type of counterfeits.

The operations literature links the counterfeiting risk to operations issues such as supplier involvement in new product development (Handfield et al., 1999; Parker et al., 2008), off-shore outsourcing (Choi et al., 2004; Chopra and Sodhi, 2004), and relocation of a firm's operations (Klassen and Whybark, 1994). The majority of the existing research on managing the counterfeiting risk is conceptual and descriptive (e.g., Haley (2003); Christopher and Peck (2004)). They provide frameworks for fighting against counterfeiting, usually based on case studies (e.g., Staake and Fleisch (2008a)). Research on strategic implications of a firm's decisions in the presence of counterfeits is still lacking.

Our research is mostly related to the operations models on the competition between high-quality (high-cost) brand-name products and low-quality (low-cost) alternatives provided by another seller. These alternatives can be a store-brand version of the manufacturer's product (Heese, 2010; Groznik and Heese, 2010) or a copycat product that resembles physical attributes of the genuine branded product (Grossman and Shapiro, 1986, 1988; Pun and DeYong, 2017). Similar to the entry-deterrence models in the industrial organization literature, these operations models consider the competition between brand-name products and alternatives as a regular price and quality competition, and focus on the interactions among supply chain partners. The role of the government in fighting against counterfeiting is usually ignored. Stevenson and Busby (2015) identified strategies employed by counterfeiters in their exploitation of legitimate supply chains. Their empirical results suggested that counter-measures for increasing the resilience of supply chains must involve actors both within and outside the supply chains and the counterfeiting risk is more controllable with suitable governance arrangements. Another limitation in the majority of the existing anti-counterfeiting operations models is that they consider only non-deceptive counterfeits, and ignore the fundamental difference between non-deceptive and deceptive counterfeits. Therefore, the anti-counterfeiting strategies they recommend may only be effective for one type of counterfeits.

Our model is closely related to the work of Cho et al. (2015), which examined the effectiveness of anti-counterfeiting strategies against two types of counterfeits: non-deceptive counterfeits which are sold in an illicit channel, and deceptive counterfeits which infiltrate a licit distributor. They found that strategies such as reducing price or improving quality, which are effective against non-deceptive counterfeits, do not work well against deceptive ones. Like other operations models on counterfeiting, their research considers counterfeiting as a problem of the legitimate OEM only and focuses on the interaction between the manufacturer and the retailer. In reality, the effects of counterfeiting are felt throughout the society. Thus, responses to the problem should come from all levels, including both legislators and companies. Current practices have also demonstrated the effectiveness of a public-private partnership in fighting against counterfeiting. Our research fills the gap in the literature by considering a partnership between Customs and the legitimate OEM as an anti-counterfeiting strategy. We consider both non-deceptive and deceptive counterfeits, and study the conditions under which the OEM should resort to the partnership to combat different types of counterfeits and the role of the government in the fight against counterfeiting.

5.3 The public-private partnership (PPP) model

In a global supply chain, all shipments have to pass through Customs inspection before reaching final consumers. Once a shipment arrives at Customs, it will undergo a primary inquiry which is based on processing shipment related data, including manifest documents, bill of lading, etc (CBP, 2013). Customs can use intelligence from a number of sources, e.g., data provided by private enterprises, to perform cargo examinations more selectively and identify high-risk shipments more efficiently (CBP, 2017). We model a public-private partnership (PPP) as an information-sharing platform where the legitimate OEM shares IP related information with Customs to assist it in identifying and detaining counterfeit shipments. This platform can be initiated by either Customs or the OEM. Whether the PPP will be successfully formed depends on whether it is initiated and whether the OEM joins, i.e., sharing data with Customs on the platform.

We model the decisions of Customs and the OEM towards the PPP as follows. Customs decides whether to initiate the PPP, i.e., investing in the information-sharing mechanism. We denote this decision as α: $\alpha \in \{0, 1\}$, where $\alpha = 1$ indicates that Customs will bear the costs of information sharing (similar to the IPM and the EDB examples), and $\alpha = 0$ otherwise. The OEM decides whether to join the PPP (or initiate it if needed). We denote this decision as κ: $\kappa \in \{0, 1\}$, where $\kappa = 1$ indicates that the OEM decides to join (or initiate) the PPP, and $\kappa = 0$ otherwise. If $\alpha = 0$ and $\kappa = 1$, it is the OEM who initiates the PPP, i.e., bearing the costs of information sharing (similar to the BAT and the Alibaba examples). Note that regardless of the value of κ, if $\alpha = 1$, Customs will bear the costs of initiating the PPP. However, if $\alpha = 1$ and $\kappa = 0$, the PPP is not effective since the OEM decides not to join. Thus, $\kappa = 1$ is a necessary and sufficient condition for the PPP to be formed. The total investment in the PPP, i.e., annual costs of information sharing, can be averaged on the annual production quantity of authentic products. Thus, we assume that it costs C_o per unit of authentic product to share information between Customs and the OEM.

The counterfeiter can disguise the nature of its shipments to escape the detection by Customs. For example, the counterfeiter can use free-trade zones (FTZ) to sanitize shipping documents in a way that it disguises the original point of manufacture (United Nations, 2018). Another example is that rather than using cheap ocean-going vessel shipping, counterfeiters can use more expensive postal service, mailing in small packages in target countries, to limit traceability and the size of a seizure if intercepted (Elings, 2017). We denote the counterfeiter's decision on whether to disguise as e_c: $e_c \in \{0, 1\}$, where $e_c = 1$ indicates that the counterfeiter decides to disguise, and $e_c = 0$ otherwise. Disguise effort such as using postal service costs a fee per unit of counterfeit product. Thus, we assume that it costs the counterfeiter C_c per unit of counterfeit product to disguise. Throughout the paper, we use subscripts, o and c, to represent whether the notation applies to legitimate OEM/authentic product or counterfeiter/counterfeit. In addition, $c \in \{n, d\}$, where n and d represent the non-deceptive and deceptive counterfeiter, respectively.

As intuition dictates, the likelihood of a counterfeit product being detected when passing through Customs is increasing in the amount of information shared between Customs and the OEM, but decreasing in the counterfeiter's disguise effort. We assume that if the PPP is not formed, Customs will be unaware of the existence of counterfeits in the market and will not stop any shipments on the suspicion of being a counterfeit. Moreover, the detection probability is increasing in the rigorousness of the inspection process, but decreasing in the effectiveness of the counterfeiter's disguise effort. If the inspection process is not sufficiently rigorous, more counterfeits may escape. Some disguise effort such as producing in a specific FTZ might be more effective than others such as forging a bill of lading, in the sense that it makes it more difficult for Customs to detect counterfeits. We use the following function to model the detection, red-flagging, probability, meeting all the previously mentioned properties:

$$\mathbb{P}_c^r(\kappa, e_c) = \mathbb{P}\{\textit{red flag}|\textit{counterfeit}\} = (\beta_1 - \beta_2 e_c)\kappa \tag{5.1}$$

where $1 - \beta_1$ represents the probability of not detecting a counterfeit (type II error of the inspection process) and β_2 captures the effect factor of the counterfeiter's disguise effort. We set $0 < \beta_1 - \beta_2 < 1$, $0 < \beta_1 < 1$, and $0 < \beta_2 < 1$. The red-flagging function means that even if the PPP is formed and the counterfeiter does not disguise, a portion of counterfeits, i.e., $1 - \beta_1$, will be leaked to the market due to type II error of the inspection process. If the counterfeiter exerts effort to disguise, more but not all counterfeits, i.e., $1-\beta_1+\beta_2$, will pass Customs inspection without raising a red flag. Additionally, we assume that the detention probability of authentic products (type I error of the inspection process) is negligible and thus set to zero, i.e., $\mathbb{P}_o^r(\kappa, e_c) = \mathbb{P}\{red\ flag|authentic\} = 0$.

Denote the market shares of authentic products and counterfeits as m_o and m_c. The total production quantity of authentic products therefore equals m_o, and the total production quantity of counterfeits is $\frac{m_c}{1-\mathbb{P}_c^r(\kappa,e_c)}$. If a counterfeit is detected and detained at Customs, a penalty, L_f, is charged on the counterfeiter. In practice, if an OEM shares information and files an IP watch notice with Customs then Customs will inform her if a shipment suspicious of violating OEM's IP rights is detected. In this case, the OEM has to pay the Customs' inspection cost for services such as examining the samples, providing evidences, etc. (Schwab et al., 2017). The inspection fee usually runs from \$80 to \$1000 per container, whereas the penalty for importing counterfeit goods can amount to twice the manufacturer's suggested retail price of genuine goods (Flexport, 2018), which can easily exceed a million dollars. In addition, this inspection fee is negligible compared to the investment in the PPP. Thus, for the sake of brevity, we assume that the inspection fee is zero. For the same reason, we also set the production costs of the OEM and the counterfeiter to zero. For the OEM, having a non-zero production cost will not affect its optimal decisions (i.e., p_o^* and κ^*) structurally since Customs inspection does not influence shipments of authentic products. For the counterfeiter, the detention by Customs would cost extra production costs if it is not zero, in addition to the penalty. However, the counterfeiter's production cost is usually much smaller than the penalty since the counterfeiter uses cheap labor and technologies in substandard working conditions and often avoids paying taxes.

As a governmental agency, Customs is responsible for the safety and security of the society, and therefore we assume that if a counterfeit escapes the detection by Customs, it imposes a cost L_e to Customs, representing the cost to the society. Although it is difficult to quantify this cost L_e in practice, it is clear that different types of counterfeits result in different emotional responses from the public and trigger different actions of government. For instance, deceptive counterfeit medications can cause deaths of patients, and the government reacts strongly to this type of counterfeiting due to salience of the issue, whereas non-deceptive counterfeit handbags only harm business and the government may take mild countermeasures. Incorporating the cost of counterfeits to the society in our model allows us to identify the optimal strategy of Customs in different situations. Table 5.1 summarizes the notation used in our model.

Notation	Description
α	decision of Customs on whether to initiate the PPP
κ	decision of the OEM on whether to join (or initiate) the PPP
e_c, $c \in \{n, d\}$	decision of the non-deceptive or deceptive counterfeiter on whether to disguise
C_o	information-sharing cost per unit of authentic product
C_c, $c \in \{n, d\}$	disguise-effort cost per unit of non-deceptive or deceptive counterfeit
$\mathbb{P}_c^r(\kappa, e_c)$, $c \in \{n, d\}$	probability function that a product will be red flagged, given that it is a non-deceptive or deceptive counterfeit
β_1	indicator of inspection rigorousness at Customs
β_2	effect factor of the counterfeiter's disguise effort
L_f	penalty to the counterfeiter if a counterfeit is found
L_e	cost to the society if a counterfeit is leaked to the market
q_c, $c \in \{n, d\}$	quality of non-deceptive or deceptive counterfeits
t	taste of a consumer
t^n	taste of the consumer who is indifferent between purchasing the non-deceptive counterfeit and not purchasing any product
t^o	taste of the consumer who is indifferent between purchasing the authentic product and the non-deceptive counterfeit
p_o, p_c, $c \in \{n, d\}$	prices of authentic products and non-deceptive or deceptive counterfeits
m_o, m_c, $c \in \{n, d\}$	market shares of authentic products and non-deceptive or deceptive counterfeits
s	market seize of the deceptive counterfeiter
S	infiltration cost per unit of deceptive counterfeits

Table 5.1: Model specification

5.4 Combating non-deceptive counterfeits

We first consider non-deceptive counterfeits, i.e., the type of counterfeits which consumers can distinguish from authentic products at the time of purchase. Non-deceptive counterfeits usually have an inferior observable quality and are offered at a price which is remarkably lower than the authentic product. Similar to any other competitor's products, once non-deceptive counterfeits are leaked to the market, they compete with authentic products on price and quality. Denote the quality and the price of non-deceptive counterfeits or authentic products as q_i and p_i, $i \in \{n, o\}$, where $0 < q_n < q_o$. For simplicity, we set the quality of authentic products to one, i.e., $q_o = 1$.

Consumers have heterogeneous tastes, which we assume to follow a uniform distribution on the interval $[0, 1]$. All consumers prefer a high quality product, but a consumer with a higher taste is willing to pay more for it. Given the price p_i and quality q_i of every product, a consumer with taste t purchases at most one product based on the principle of maximization of his/her individual utility: $\max\limits_{i \in \{0,n,o\}} \{tq_i - p_i\}$, where $tq_0 - p_0 = 0$ if the consumer chooses not to buy any product, i.e., $i = 0$. The market is divided into three segments (see Figure 5.1): the first (right) segment consists of consumers who buy authentic products; the second (middle) segment contains consumers purchasing counterfeits; and the third (left) segment contains consumers who are not buying any products. The consumer, who is indifferent between purchasing the authentic product and the counterfeit, has the taste $t^o = \frac{p_o - p_n}{1 - q_n}$, which solves $t^o - p_o = t^o q_n - p_n$. Similarly, the consumer, who is indifferent between purchasing the counterfeit and not purchasing any product, has the taste $t^n = \frac{p_n}{q_n}$. Assuming the total number of consumers in the market to one and solving $\sum_{i \in \{n,o\}} m_i = 1 - \frac{p_n}{q_n}$, we list the market shares of counterfeits and authentic products, i.e., m_n and m_o, in Figure 5.1.

Although the competition between the non-deceptive counterfeiter and the legitimate OEM is analogous to a duopoly in a vertically differentiated market, it is not the same because the counterfeiter bears legal risks associated with

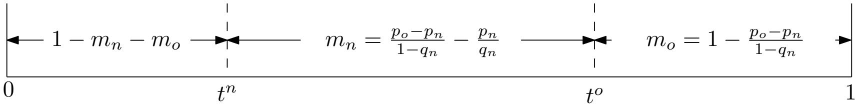


Figure 5.1: Three segments of consumers (non-deceptive case)

counterfeiting and thus the OEM can utilize the help from the government to fight against the counterfeiter. We model the interaction between Customs, the OEM, and the counterfeiter using a three-stage model (see the timeline of events in Figure 5.2). Since decisions of governmental authorities are usually announced in advance of firms' decisions in practice, we assume that at the first stage, Customs decides whether to initiate the PPP, i.e., α. At the second stage, the OEM and the counterfeiter observe the decision of Customs. Then, the OEM decides whether to join the PPP (or initiate it if needed), i.e., κ, while the counterfeiter decides whether to disguise, i.e., e_n. The red-flagging probability of counterfeit shipments is then realized (see equation (5.1)). At the third stage, both the OEM and the counterfeiter learn the red-flagging probability and simultaneously set their own market-clearing price, i.e., p_o and p_n. In Sections 5.4.1-5.4.2, we solve the game backwards, starting with the Bertrand price competition at the third stage.

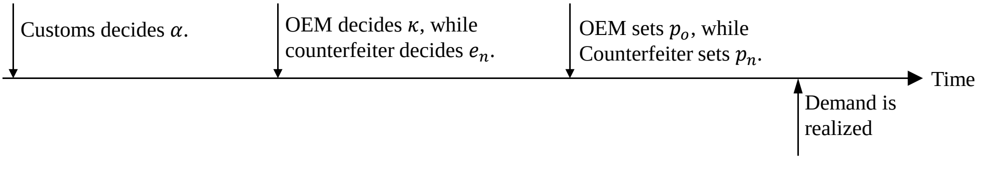


Figure 5.2: Timing of events and decisions (non-deceptive case)

5.4.1 Bertrand price competition in each subgame (κ, e_n)

At the third stage, the OEM and the non-deceptive counterfeiter observe the decision of Customs from the first stage, i.e., α, and each other's decision from the second stage, i.e., κ and e_n. Then, they set their own price, following a Bertrand price competition. The OEM's profit function is as follows:

$$\max_{p_o} \Pi_o = \big(p_o - C_o(1-\alpha)\kappa\big)m_o \tag{5.2}$$

$p_o m_o$ calculates the OEM's revenue, and $C_o(1-\alpha)\kappa m_o$ calculates the OEM's investment in the PPP. Similarly, the profit function of the non-deceptive counterfeiter is:

$$\max_{p_n} \Pi_n = (p_n - \frac{C_n e_n}{1-\mathbb{P}_n^r(\kappa, e_n)})m_n - \frac{\mathbb{P}_n^r(\kappa, e_n)}{1-\mathbb{P}_n^r(\kappa, e_n)} L_f m_n \tag{5.3}$$

The first term $(p_n - \frac{C_n e_n}{1-\mathbb{P}_n^r(\kappa,e_n)})m_n$ calculates the counterfeiter's revenue after paying for disguise effort and the second term $\frac{\mathbb{P}_n^r(\kappa,e_n)}{1-\mathbb{P}_n^r(\kappa,e_n)} L_f m_n$ calculates the penalty that the non-deceptive counterfeiter incurs due to the detention by Customs.

Lemma 5.1. *At the third stage, there exist unique optimal prices of authentic products and non-deceptive counterfeits, i.e., p_o^* and p_n^*, which are derived by substituting the OEM's optimal response function $\mathbb{R}_o(p_n)$ into the counterfeiter's optimal response function $\mathbb{R}_n(p_o)$; $\mathbb{R}_o(p_n)$ and $\mathbb{R}_n(p_o)$ satisfy the first-order derivative conditions: $(\frac{\partial \Pi_o}{\partial p_o}) \mid_{p_o=\mathbb{R}_o(p_n)} = 0$ and $(\frac{\partial \Pi_n}{\partial p_n}) \mid_{p_n=\mathbb{R}_n(p_o)} = 0$.*

According to Lemma 5.1, unique optimal prices of authentic products and non-deceptive counterfeits exist in each subgame (κ, e_n). The optimal market shares of non-deceptive counterfeits and authentic products, i.e., m_n^* and m_o^*, are derived by substituting the optimal prices, i.e., p_n^* and p_o^*, into m_n and m_o (see equations in Figure 5.1). To avoid trivial solutions, we assume that the optimal prices specified in Lemma 5.1 are larger or equal to a player's total cost (i.e., investment cost for the OEM and the sum of disguise cost and penalty for the non-deceptive counterfeiter), and thus the resulting optimal market shares satisfy: $0 \leq m_n^* \leq 1$, $0 \leq m_o^* \leq 1$ and $m_n^* + m_o^* \leq 1$. It requires that parameters e.g., q_n and L_f, are bounded such that $\frac{p_n^*}{q_n} \leq p_o^* \leq 1 - q_n + p_n^*$. The optimal profits of the OEM and the non-deceptive counterfeiter are derived by substituting p_o^* and m_o^* into Π_o (see equation (5.2)) and substituting p_n^* and m_n^* into Π_n (see equations (5.3)).

5.4.2 Optimal equilibrium strategy of the three players

The optimal equilibrium strategies at the second stage can be derived by comparing each player's profit in different subgames. At the first stage, Customs decides whether to initiate the PPP, considering the optimal responses, i.e., the optimal equilibrium strategies of the OEM and the non-deceptive counterfeiter from the second stage. The optimization problem of Customs is as follows:

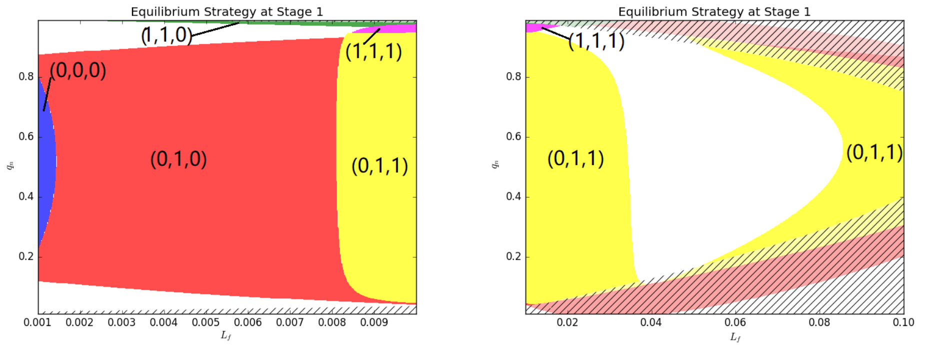
$$\max_{\alpha \in \{0,1\}} \Pi_b = \left(\frac{\mathbb{P}_n^r(\kappa^*, e_n^*)}{1 - \mathbb{P}_n^r(\kappa^*, e_n^*)} L_f - L_e\right) m_n - C_o \alpha \kappa^* m_o \tag{5.4}$$

$\frac{\mathbb{P}_n^r(\kappa^*, e_n^*)}{1 - \mathbb{P}_n^r(\kappa^*, e_n^*)} L_f m_n$ calculates the penalty collected by Customs, $L_e m_n$ calculates the damage to the society because of the leaked non-deceptive counterfeits, and $C_o \alpha \kappa^* m_o$ calculates the investment in the PPP paid by Customs.

Comparing each player's profit in different strategy, we derive five Nash equilibrium strategies $(\alpha^*, \kappa^*, e_n^*)$ to the complete game in Proposition 5.1. The conditions under which each equilibrium strategy exists is specified in Appendix A. Because we assume that Customs will be unaware of the existence of counterfeits in the market if the PPP is not formed (see equation 5.1), the strategy where the PPP is not formed but the counterfeiter disguises, i.e., $(\alpha^*, \kappa^*, e_n^*) = (-, 0, 1)$, is a dominated strategy since the counterfeiter is always better off in the equilibrium strategy $(-, 0, 0)$ than in $(-, 0, 1)$. The strategy where Customs initiates the PPP but the OEM does not join, i.e., $(\alpha^*, \kappa^*, e_n^*) = (1, 0, -)$, is also a dominated strategy since Customs is always better off in the equilibrium strategy $(0, 0, -)$ than in $(1, 0, -)$. According to the conditions of each equilibrium strategy (see Appendix A), except that $(0, 0, 0)$ and $(0, 1, 1)$ may overlap, any two equilibrium strategies are mutually exclusive.

Proposition 5.1. *Based on the optimal decision of Customs, α^*, the OEM's optimal (response) decision, κ^*, and the non-deceptive counterfeiter's optimal (response) decision e_n^*, the following five Nash equilibrium strategies exist at the first stage:*

$$(\alpha^*, \kappa^*, e_n^*) = \begin{cases} (0,0,0) & \textit{OEM resorts to pricing only} \\ (0,1,0) & \textit{OEM initiates the PPP \& counterfeiter does not disguise} \\ (1,1,0) & \textit{Customs initiates the PPP \& counterfeiter does not disguise} \\ (0,1,1) & \textit{OEM initiates the PPP \& counterfeiter disguises} \\ (1,1,1) & \textit{Customs initiates the PPP \& counterfeiter disguises} \end{cases} \tag{5.5}$$



(a) $L_f \in [0.001, 0.01]$ (b) $L_f \in [0.01, 0.1]$

Figure 5.3: Equilibrium strategy region at the first stage, non-deceptive case ($C_n = 0.004$, $C_o = 0.009$, $L_e = 0.13$, $\beta_1 = 0.6$, $\beta_2 = 0.1$)

Figure 5.3 shows two examples of the optimal equilibrium strategies. The equilibriums $(0,0,0)$, $(0,1,0)$, $(1,1,0)$, $(0,1,1)$, and $(1,1,1)$ are colored in blue, red, green, yellow, and magenta, respectively. In each example, we observe that the five equilibriums do not cover the entire parameter space. Areas where no equilibrium exists remain as white. In addition, areas where the non-triviality assumptions are not met are marked with shade and are not considered.

Proposition 5.2 illustrates the conditions under which Customs will not initiate the PPP: Customs will not bear the costs of setting up an information sharing mechanism if either the quality of non-deceptive counterfeits, q_n, or the cost to the society, L_e, drops below a certain threshold.

Proposition 5.2. *In the non-deceptive case, Customs will not initiate the PPP, i.e., neither the equilibrium strategy* $(1,1,0)$ *nor* $(1,1,1)$ *exists at the first stage, if either of the following conditions hold:*

- $q_n \leq 1 - \frac{1}{2}\max\{L_e - \frac{2\beta_1}{1-\beta_1}L_f, L_e - \frac{2(\beta_1-\beta_2)}{1-\beta_1+\beta_2}L_f - \frac{C_n}{1-\beta_1+\beta_2}\}$,
- $L_e \leq \frac{\beta_1-\beta_2}{1-\beta_1+\beta_2}L_f$.

Regardless of the quality of non-deceptive counterfeits, if the damage of counterfeits to the society without the PPP is smaller than the least amount of penalty with the PPP, i.e., $L_e \leq \frac{\beta_1-\beta_2}{1-\beta_1+\beta_2}L_f$, then there is no incentive for Customs to initiate the PPP. This is either because the damage to the society will be trivial even if a counterfeit escapes Customs inspection or because the penalty alone serves as an effective counterfeiting deterrence tool. If this condition does not hold, i.e., $L_e > \frac{\beta_1-\beta_2}{1-\beta_1+\beta_2}L_f$, Customs will still decide not to initiate the PPP when the quality of counterfeits q_n is low such that $q_n \leq 1 - \frac{1}{2}\max\{L_e - \frac{2\beta_1}{1-\beta_1}L_f, L_e - \frac{2(\beta_1-\beta_2)}{1-\beta_1+\beta_2}L_f - \frac{C_n}{1-\beta_1+\beta_2}\}$. This is because when q_n is low (and L_f is small), only a small amount of consumers will buy low-quality counterfeits and the societal impact would be limited. In addition, the OEM can win the competition against low-quality counterfeits in the market through pricing. In Figure 3, we observe that the equilibrium strategies where Customs initiates the PPP, i.e., $(1,1,0)$ or $(1,1,1)$, only appear in the top-right part of Figure 5.3a and in the top-left part of Figure 5.3b. It indicates that Customs will likely initiate the PPP when q_n is high. This result also signifies that the higher the quality of counterfeits, the more important the role of the government becomes in the fight against non-deceptive counterfeiting.

In Proposition 5.3, we show that if Customs does not initiate the PPP, the OEM will possibly also choose not to initiate it when L_f is either too large or too small. In the two examples in Figure 5.3, the equilibrium strategy where the PPP is not formed, i.e, $(0,0,0)$, only appears in the left part of Figure 5.3a, i.e., when L_f is small.

Proposition 5.3. *Set* $\mathbb{G}(L_f) = \Pi^*_{o|(0,0,0)} - \Pi_{o|(0,1,0)}$. *In the presence of a non-deceptive counterfeiter, there exist two thresholds for* L_f*, i.e., the lowerbound* $L_f^{lo} = \max\{0, \arg\min_{L_f}\{\mathbb{G}(L_f) = 0\}\}$*, and the upperbound* $L_f^{uo} = \max\{0, \arg\max_{L_f}\{\mathbb{G}(L_f) = 0\}\}$ *such that when* $L_f^{lo} < L_f < L_f^{uo}$*, the outcome where the PPP is not formed will never happen, i.e., the equilibrium strategy* $(0,0,0)$ *will not exist at the first stage.*

When L_f is small, the non-deceptive counterfeiter can still provide a low-price product even after paying the penalty. Thus, to maintain a competitive price of authentic product, the OEM may choose not to initiate the PPP since it will incur extra cost that will be carried over to the selling price. This result is consistent with the empirical phenomenon: in countries where the legal consequence of counterfeiting is mild, legitimate OEMs rarely take the initiative in forming a partnership with the government to combat counterfeiting since there lacks force to prevent a recurrence of the counterfeiting problem (KPMG, 2005). In general, non-deceptive counterfeiters' loss from Customs detention is small because many of them are small workshops selling products through street vendors or Internet sites and when they get caught, they tend to close their stores temporarily to avoid penalty (Cho et al., 2015). Therefore, Proposition 5.3 also indicates that the government should play a bigger role in initiating the PPP to combat non-deceptive counterfeits because the OEM will likely not take the initiative in such a situation.

Same reason as Customs, when the penalty is large, there is no incentive for the OEM to initiate the PPP since large penalty is effective in deterring the entry of counterfeits. According to Proposition 5.4, another reason why the OEM will likely not initiate the PPP when L_f is very large is that under such a condition, the non-deceptive counterfeiter will disguise even if the PPP is formed. In Figure 5.3, we observe that the equilibrium strategies where the counterfeiter disguises, i.e., $(0, 1, 1)$ and $(1, 1, 1)$, only appears in the right part of Figure 5.3a and covers the entire space where an equilibrium strategy exists in 5.3b. It shows that the non-deceptive counterfeiter would disguise if L_f is large. This result is reasonable since the counterfeiter will disguise to avoid paying penalty if the penalty is high. It also shows that the government should not rely solely on penalty to combat counterfeiting since it may result in undesirable counteraction.

Proposition 5.4. *Set* $\mathbb{H}(L_f) = \Pi^*_{n|(\overline{\alpha},1,0)} - \Pi^*_{n|(\overline{\alpha},1,1)}$, *where* $\overline{\alpha}$ *is the given decision of Customs. In the presence of a non-deceptive counterfeiter, suppose the PPP is formed, there exist a threshold for* L_f, *i.e.,* $L_f^{uc} = \arg\max_{L_f}\{\mathbb{H}(L_f) = 0\}$, *such that if* $L_f > L_f^{uc}$, *the counterfeiter will disguise, i.e.,* $e_n^* = 1$.

5.4.3 Effectiveness of the anti-counterfeiting strategies

We first examine the impact of the OEM's anti-counterfeiting strategies by comparing the OEM's price and profit with and without non-deceptive counterfeiter. Proposition 5.5 shows that compared to the situation without any counterfeit, the existence of non-deceptive counterfeits could lead the OEM to earn more profit if the PPP is formed. To combat counterfeiting, initiating or joining the PPP would allow the OEM to choose a higher price than that without any counterfeit, and thus the OEM could earn more profit; However, without the PPP, the OEM's only anti-counterfeiting strategy is pricing and to remain competitive, he should lower its price.

Proposition 5.5. *To combat the non-deceptive counterfeiter:*

1. *the OEM should choose a lower price than that without any counterfeit, if the PPP is not formed;*

2. *the OEM should choose a higher price than that without any counterfeit, if the PPP is formed and* $\frac{3}{2}q_n - 2(1-\overline{\alpha})C_o \leq \min\{\frac{\beta_1}{1-\beta_1}L_f, \frac{\beta_1-\beta_2}{1-\beta_1+\beta_2}L_f +$

$\frac{C_n}{1-\beta_1+\beta_2}\}$, *where* $\overline{\alpha}$ *is the given decision of Customs;*

3. *compared to the situation without any counterfeit, the OEM earns more profit if the PPP is formed; without the PPP, the OEM earns less profit than that without any counterfeit.*

According to Proposition 5.5.2, if the PPP is formed, it is more likely for the OEM to increase its price when the quality of non-deceptive counterfeits is low. Existing literature on counterfeiting has demonstrated similar results: the existence of non-deceptive counterfeits can benefit a manufacturer of high-quality products (Qian, 2014). Here we show that this benefit can be realized through the combined PPP and pricing strategy.

Next, we examine the effectiveness of the OEM's anti-counterfeiting strategies by comparing the market share and price of authentic products with those of non-deceptive counterfeits. Proposition 5.6 shows that when only using pricing to combat counterfeiting, the OEM captures a higher market share than the non-deceptive counterfeiter. Thus, it is guaranteed that the OEM will earn more profit than the counterfeiter since the price of authentic products is always higher than that of counterfeits. When the PPP is formed, under certain conditions[6] related to the quality of non-deceptive counterfeits, the counterfeiter may capture a higher market share than the OEM. When the counterfeiter captures a higher market share, it is possible that it also earns more profits than the OEM. These results are stated in Proposition 5.6 .

Proposition 5.6. *To combat the non-deceptive counterfeiter:*

1. *when only using pricing, the OEM captures a higher market share than the counterfeiter;*

2. *with the PPP, the OEM captures a higher market share than the counterfeiter if Customs initiates the PPP; if the OEM initiates the PPP,*

[6]For the sake of brevity, these conditions are only stated in Proposition 5.5 in the appendix.

under certain conditions related to the quality of counterfeit product, the market share of counterfeiter may exceed the market share of the OEM;

3. *when Customs decides not to initiate the PPP, the OEM's investment in the PPP will result in an increase in both prices of authentic and counterfeit product, i.e.,* $\min\{p^*_{o|(0,1,0)}, p^*_{o|(0,1,1)}\} > p^*_{o|(0,0,0)}$ *and* $\min\{p^*_{n|(0,1,0)}, p^*_{n|(0,1,1)}\} > p^*_{n|(0,0,0)}$*;*

4. *when* $(\frac{\beta_1}{1-\beta_1} - \frac{\beta_1-\beta_2}{1-\beta_1+\beta_2})L_f < \frac{C_n}{1-\beta_1+\beta_2}$*, the non-deceptive counterfeiter's disguise effort will result in an increase in the price of authentic product, i.e.,* $p^*_{o|(\overline{\alpha},1,1)} > p^*_{o|(\overline{\alpha},1,0)}$*, where* $\overline{\alpha}$ *is the given decision of Customs.*

When Customs does not bear the costs of information sharing, initiating the PPP by the OEM on its own will lead to an increase in the price of non-deceptive counterfeits. Proposition 5.6.1-5.6.3 possibly explain why some legitimate manufacturers do not form a partnership with Customs to combat non-deceptive counterfeits: it may lead the counterfeiter to increase its price compared to the situation where the PPP is not formed, capture a higher market share than the OEM, and earn more profits than the OEM. When Customs initiates the PPP, the OEM will capture a higher market share than the counterfeiter and thus it is guaranteed that the OEM will gain more profits. It again signifies the importance of the government in initiating the PPP to combat non-deceptive counterfeits. Lastly, in Proposition 5.6.4, we show that when the penalty saved due to disguise effort is smaller than the cost of exerting disguise effort, i.e., $(\frac{\beta_1}{1-\beta_1} - \frac{\beta_1-\beta_2}{1-\beta_1+\beta_2})L_f < \frac{C_n}{1-\beta_1+\beta_2}$, the counterfeiter's disguise effort will lead to an increase in the price of authentic products since the counterfeiter will increase its selling price to cover the cost in this situation and thus the OEM can also increase the price of authentic products.

Last, we investigate the impact of anti-counterfeiting strategies on consumer welfare. We define consumer welfare when no counterfeit exists as $CS_o = \int_p^1 (t-p)dt$, where p is the price of authentic products in a market with no counterfeits. Using the first order condition we have optimal p equal to $\frac{1}{2}$. Similarly, we define consumer welfare in a market where non-deceptive counterfeits coexist with authentic products as follows:

$$CS_n = \int_{t^n}^{t^o} (tq_n - p_n)dt + \int_{t^o}^{1} (t - p_o)dt \tag{5.6}$$

where $t^o = \frac{p_o - p_n}{1 - q_n}$ and $t^n = \frac{p_n}{q_n}$ (see Figure 5.1). The first term of CS_n represents the surplus of those consumers who purchase the non-deceptive counterfeit; the second term represents the surplus of those consumers who purchase the authentic product. Considering the chances that non-deceptive counterfeits do not reach the market due to Customs detention, we define ECS_n as the expected consumer welfare as follows:

$$ECS_n = (1 - \mathbb{P}_n^r(\kappa, e_n))CS_n + \mathbb{P}_n^r(\kappa, e_n)CS_o \tag{5.7}$$

The same definitions of consumer welfare and expected consumer welfare are used in Cho et al. (2015). It is conventional wisdom that the entry of non-deceptive counterfeits would improve consumer surplus since the presence of counterfeits will enable consumers with a lower taste to gain access to the counterfeit product at a lower price, instead of the authentic product which they may be unable to afford or unwilling to buy (Gao et al., 2016).

In Proposition 5.7.1, we show that when the quality of non-deceptive counterfeits exceeds a certain threshold, the expected consumer welfare is decreasing in the quality regardless of which anti-counterfeiting strategy the OEM adopts. It is because, in this situation, more consumers with a lower taste will end up with buying nothing. However, we show in Proposition 5.7.2 and 3 that when the quality of counterfeiters exceeds a certain proportion of the quality of authentic products, the OEM's establishing the PPP to hinder the entry of counterfeits could improve the expected consumer welfare compared to a situation where a PPP is not formed.

Proposition 5.7. *The following results on the expected consumer welfare ECS_n hold:*

1. *In each strategy (α, κ, e_n), there exists a unique $q^*_{n|(\alpha,\kappa,e_n)}$ such that the expected consumer welfare $ECS_{n|(\alpha,\kappa,e_n)}$ is decreasing as q_n is exceeding $q^*_{n|(\alpha,\kappa,e_n)}$.*

2. *A necessary condition for ECS_n to be higher in the situation where the PPP is formed than that without the PPP is when the PPP is initiated by the OEM and $q_n > \frac{1}{2}$.*
3. *A sufficient condition for ECS_n to be higher in the situation where the PPP is not formed than that with the PPP is when $q_n < \frac{1}{3}$.*

Figure 5.4 shows an example of the consumer welfare in the five strategies (see the dash lines). In this example, consumer welfare is the highest when the PPP is not formed, i.e., in the strategy $(0, 0, 0)$, until the quality of counterfeits exceeds 0.65. It verifies Proposition 5.7.2. The solid line in Figure 5.4 is the consumer welfare which corresponds to the optimal equilibrium strategy, given the value of q_n. In this example, when the quality of counterfeits is above 0.65, the optimal equilibrium strategy, i.e., $(0, 0, 0)$, does not yield the highest consumer welfare, compared to other strategies. Earlier work, such as Cho et al. (2015), has also shown that strategies which improve the profit of the OEM may hurt consumer welfare. Therefore, the government and firms should carefully consider a trade-off among different objectives in implementing an anti-counterfeiting strategy.

So far, we have investigated in the non-deceptive case, the impact of the penalty L_f and the quality of counterfeits q_n on the optimal strategies of Customs and the OEM, and the impact of different anti-counterfeiting strategies on the market shares and prices of authentic products and counterfeits, and on consumer welfare. Next, we explore the situation when counterfeits are deceptive, i.e., the type of counterfeits which consumers cannot distinguish from authentic products, to see whether results will deviate from those in the non-deceptive case.

5.5 Combating deceptive counterfeits

We assume that shipment inspection and detention at Customs is the same for both non-deceptive and deceptive counterfeits. The difference between the two cases lies in the final market: consumers cannot distinguish deceptive

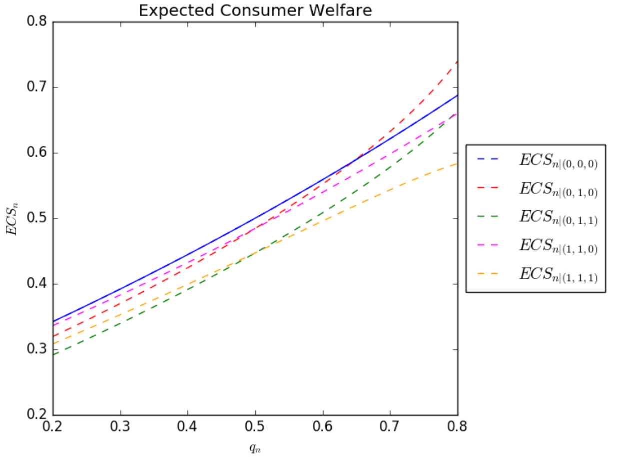


Figure 5.4: Expected consumer welfare, non-deceptive case ($C_o = 0.09$, $C_n = 0.04$, $L_f = 0.01$, $\beta_1 = 0.06$, $\beta_2 = 0.01$)

counterfeits from authentic products at the time of purchase, whereas they can in the case of non-deceptive counterfeits. Using the same licit distribution channel, deceptive counterfeits are sold as authentic products, commanding the same price (Fang, 2014; Stevenson and Busby, 2015). With the presence of non-deceptive counterfeit products, some consumers may downgrade the perceived quality for all products in the market if they believe they may have paid unfair price for counterfeits (Akerlof, 1978; Cho et al., 2015). This downgraded perceived quality for authentic products is a form of damage to brand image and this type of consumers is referred to as proactive consumers in the literature of deceptive counterfeits (e.g., see Cho et al. (2015)). Proactive consumers take into account the likelihood of receiving deceptive counterfeits unknowingly, and thus perceive the quality of any product in the market as a weighted average of the quality of authentic products and deceptive counterfeits: $(1 - \xi)q_o + \xi q_d$, where ξ denotes the consumer's expectation about the fraction of deceptive counterfeits in the market. Non-proactive consumers do not consider the likelihood of purchasing counterfeit at legitimate stores and thus perceive the quality of any product in the market as $q_o = 1$. We denote the portion of proactive consumers among all consumers as λ, $0 \leq \lambda \leq 1$.

In each consumer group (proactive or non-proactive), consumers either purchase a product or not. The market thus only consists of two segments. Denote the total number of consumers who purchase as D. Among those consumers who purchase a product, a fraction s of them receive deceptive counterfeits unknowingly. Thus, the market share of counterfeits is $m_d = sD$, and the market share of authentic products is the portion of consumers who purchase and receive authentic products, i.e., $m_o = (1 - s)D$. We assume that consumers are rational and thus the proactive consumers' expectation on the fraction of deceptive counterfeits equals the fraction of all consumers who make purchases and receive counterfeits: $\xi = s$. This notion of rational expectations equilibrium is also used in Cho et al. (2015). Given the price of authentic products p_o, which is also the price of deceptive counterfeits, the total number of consumers who purchase is:

$$D = \lambda(1 - \frac{p_o}{1 - s + sq_d}) + (1 - \lambda)(1 - p_o) \qquad (5.8)$$

The total number of purchasing consumers D is decreasing in the portion of proactive consumers λ (see equation (5.8)). The interaction among Customs, the OEM, and the deceptive counterfeiter still takes place through three stages (see Figure 5.5). At the first stage, Customs decides whether to initiate the PPP, i.e., α. At the second stage, the OEM and the deceptive counterfeiter observe the decision of Customs, and then decide whether to join the PPP (or initiate it if needed), i.e., κ, and whether to disguise, i.e., e_d, respectively. At the third stage, the OEM decides the price of authentic products p_o. The deceptive counterfeiter observes p_o and then decides s, i.e., the portion of the market which the counterfeiter will seize from the OEM. In practice, deceptive counterfeits often target products which are long established and in high demand. Thus, the price of authentic products are observed by the deceptive counterfeiter before it plans its market seize. Our sequential setting at the third stage resembles the reality in the deceptive case. The price p_o is still a market-clearing price, i.e., the production quantity of authentic products equals the total number of consumers who purchase, i.e., $m_o + m_d = D$.

In order to sell counterfeits in the market, the deceptive counterfeiter needs to pay for infiltrating the distribution channel, for example, paying bribes, and share profit with the licit distributor (Staake and Fleisch, 2008b). We assume that the infiltration cost is increasing in the market seize of the counterfeiter, i.e., s and it costs S per unit of counterfeits. The lost profit due to profit sharing with the licit distributor is also increasing in the market share of counterfeits because the more counterfeits the distributor decides to sell among all products sold through the same channel, the more profit of the counterfeiter will be asked to shift to the distributor. A similar way of modeling the deceptive counterfeiter's costs has been used in Cho et al. (2015).

When deceptive counterfeits exist, the OEM will lose part of the market, due to either damage to brand image if proactive consumers exist or breach in the licit distribution channel. It is different from the competition with the non-deceptive counterfeiter, which leads the OEM to capture higher-end consumer segments and potentially earn more than that without any counterfeit (see Proposition 5.5). Below we solve the three-stage game backwards, same as in the non-deceptive case, and bring up results which deviate from those in the non-deceptive case.

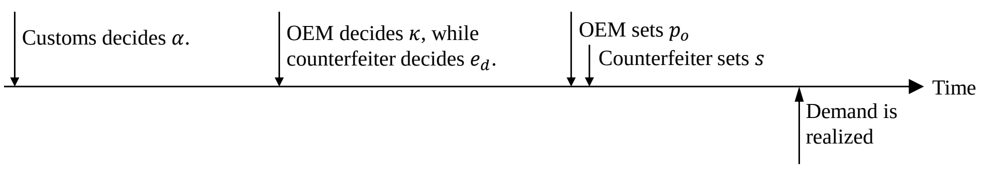


Figure 5.5: Timing of events and decisions (deceptive case)

5.5.1 Optimal price(s) and unique optimal market seize in each subgame (κ, e_d)

Given decisions from the first and second stages, i.e., α, κ, and e_d (thus, given $\mathbb{P}^r_d(\kappa, e_d)$), the OEM first decides the optimal price p^*_o and then deceptive counterfeiter decides the optimal market seize s^*. At the third stage, the optimization problems of the OEM and the deceptive counterfeiter are:

$$\max_{p_o} \Pi_o = (p_o - C_o(1-\alpha)\kappa)m_o \tag{5.9}$$

$$\max_{s} \Pi_d = (1-s)(\overline{p_o} - \frac{C_d e_d}{1-\mathbb{P}^r_d(\kappa, e_d)} - \frac{\mathbb{P}^r_d(\kappa, e_d)}{1-\mathbb{P}^r_d(\kappa, e_d)} L_f)m_d - sS \tag{5.10}$$

The OEM's problem in equation (5.9) is the same as in the non-deceptive case (see equation (5.2)). In the deceptive counterfeiter's problem in equation (5.10): in the first term, $(\overline{p_o} - \frac{C_d e_d}{1-\mathbb{P}^r_d(\kappa,e_d)} - \frac{\mathbb{P}^r_d(\kappa,e_d)}{1-\mathbb{P}^r_d(\kappa,e_d)} L_f)m_d$ calculates the revenue after paying for disguise effort and the penalty imposed by Customs due to detention, and $(1-s)$ is the counterfeiter's share in the profit-sharing agreement with the licit distributor; and the second term sS calculates the infiltration cost.

Previously we showed that there exists a unique optimal price of authentic products when the OEM competes with the non-deceptive counterfeiter. When the counterfeiter is deceptive in a market with no proactive consumers, i.e., $\lambda = 0$, Lemma 5.2.1 shows that there may exist more than one optimal price of authentic products, while there exists a unique optimal market seize of the deceptive counterfeiter. For the general case, i.e., $\lambda \in [0,1]$, we show in Lemma 5.2.2 that if certain conditions are met, there exists a unique optimal market seize of the deceptive counterfeiter. while there may exist multiple optimal prices of authentic products. Set $C = \frac{\mathbb{P}^r_d(\kappa,e_d)}{1-\mathbb{P}^r_d(\kappa,e_d)} L_f + \frac{C_d e_d}{1-\mathbb{P}^r_d(\kappa,e_d)}$, which represents the counterfeiter's cost, including both penalty and disguise effort.

Lemma 5.2. *In the presence of a deceptive counterfeiter:*

1. *when no consumer is proactive (i.e., $\lambda = 0$), the deceptive counterfeiter's optimal market seize is: if $p^*_{o|\lambda=0} < C$, $s^*_{\lambda=0} = 0$; otherwise, $s^* =$*

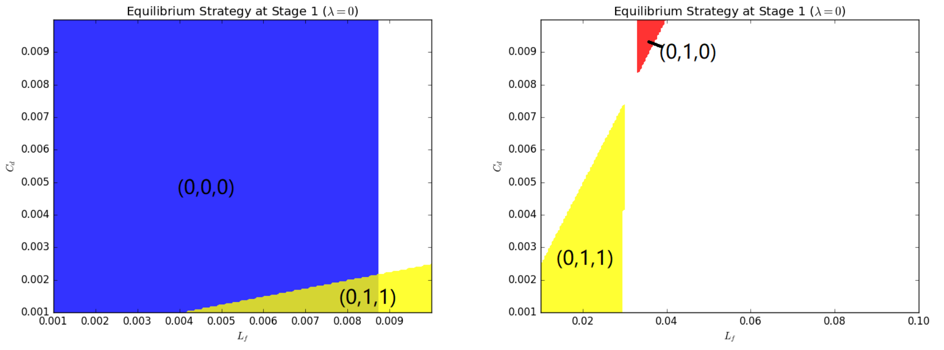
$\frac{1}{2} - \frac{S}{2(p_o^*-C)(1-p_o^*)}$,. *The optimal price(s) for authentic products is* $p_o^* = \arg\max_{p_o} \Pi_o = (p_o - C_o(1-\alpha)\kappa)(\frac{1-p_o}{2} + \frac{S}{2(p_o-C)})$.

2. *for* $\lambda \in [0,1]$, *if* $p_o^* < (1 - s^* + s^* q_d)^2$, *there exists a unique market seize* s^* *of the deceptive counterfeiter, which solves* $\frac{\partial \Pi_d}{\partial s} = 0$. *The optimal price(s) of authentic product is* $p_o^* = \arg\max_{p_o} \Pi_o$.

The optimal profits of the OEM and the deceptive counterfeiter in each subgame can be computed by substituting the optimal price(s) and the optimal market seize into equations (5.9) and (5.10). The optimal equilibrium strategies at the second stage can be computed by comparing each player's profit in different subgames. At the first stage, the optimization problem of Customs is the same as the one in the non-deceptive case (see equation (5.4)). There are five Nash equilibrium strategies to the full game, which are the same ones as in the non-deceptive case (see Proposition 5.1). Figure 5.6 show two examples of the optimal equilibrium strategies to the full game in the deceptive case with no proactive consumers, i.e., $\lambda = 0$. In the two examples, the OEM initiates the PPP when the penalty to the counterfeiter, i.e., L_f, is large, and the disguise cost, i.e., C_d, is small. Because the optimal price(s) of authentic products at the third stage do not have closed forms, the closed-form expressions for the conditions of each equilibrium strategy cannot be obtained. Thus, it is analytically intractable to prove the impact of parameter values on the equilibrium strategy, like what we did in the non-deceptive case. Our focus is then to generate insights on the effectiveness of the anti-counterfeiting strategies in the deceptive case.

5.5.2 Effectiveness of the anti-counterfeiting strategies

According to Proposition 5.8 , if the OEM initiates the PPP to combat deceptive counterfeits in a market with no proactive consumers and the investment in the PPP is larger than the counterfeiter's cost (including both penalty and disguise cost), the OEM should choose a higher price than that without any counterfeit. When the PPP is not formed or when Customs initiates the PPP,



(a) $L_f \in [0.001, 0.01]$ (b) $L_f \in [0.01, 0.1]$

Figure 5.6: Equilibrium strategy region at the first stage, deceptive case ($C_o = 0.009$, $L_e = 0.13$, $\beta_1 = 0.6$, $\beta_2 = 0.1$, $S = 0.05$)

the OEM should lower its price. This finding is different from the one in the non-deceptive case, where the OEM could increase its price when it either initiates or joins the PPP (see Proposition 5.5.2). The importance of considering the type of counterfeits in the OEM's optimal anti-counterfeiting strategy is also discussed in Cho et al. (2015). They found that in a game with a brand-name OEM, a potential counterfeiter, and a distributor, the OEM should lower its price in the non-deceptive case, but increase its price in the deceptive case, in which no consumers are proactive. Our results are in line with their finding and we show that when combating deceptive counterfeiting, the OEM's initiative in the PPP could enable the OEM to increase its selling price.

Proposition 5.8. *In a market where no consumer is proactive, i.e., $\lambda = 0$, to combat the deceptive counterfeiter:*

1. *the OEM should choose a lower price than that without any counterfeit, if the PPP is initiated by Customs or if the PPP is not formed;*

2. *the OEM should choose a higher price than that without any counterfeit, if the PPP is initiated by the OEM and $C < C_o$.*

Increasing the price of authentic products does not always reduce the deceptive counterfeiter's market share since it increases the counterfeiter's margin from selling deceptive counterfeits (Cho et al., 2015). Thus, in implementing this pricing strategy one should carefully consider the trade-offs. When part of deceptive counterfeits would get detained at the border before they reach the market, because of the penalty imposed by Customs and the disguise cost (if incurred), the counterfeiter's optimal market seize is decreasing in the price of authentic products once it exceeds a certain threshold. In Lemma 5.3, we show that if the PPP is initiated by Customs or if the PPP is not formed, the optimal market seize of the deceptive counterfeiter is increasing in the price of authentic products, and if the PPP is initiated by the OEM, the optimal market seize is decreasing in the price of authentic products. On the one hand, this result explains the results in Proposition 5.8, i.e., when the PPP is initiated by Customs or when the PPP is not formed, the OEM chooses a lower price than that when the PPP is initiated by the OEM and $C < C_o$ so that the deceptive counterfeiter's market seize is constrained. On the other hand, it signifies the importance of private enterprises in initiating the partnership with the government in the fight against deceptive counterfeiting. When the OEM initiates the PPP, it could choose a higher price and the counterfeiter's market seize is decreasing in the price of authentic products in such a situation.

Lemma 5.3. *In the presence of a deceptive counterfeiter, when no consumer is proactive, i.e.,* $\lambda = 0$*:*

- *if the PPP is initiated by Customs or if the PPP is not formed, the optimal market seize of the deceptive counterfeiter* s^* *is increasing in the price of authentic products* p_o*;*

- *if the PPP is initiated by the OEM and* $C < C_o$*, the optimal market seize of the deceptive counterfeiter* s^* *is decreasing in the price of authentic products* p_o*.*

Lastly, we investigate the impact of anti-counterfeiting strategies on consumer welfare in the deceptive case. We define CS_d as consumer welfare in a market where deceptive counterfeits coexist with authentic products as follows:

$$CS_d = s\int_{\overline{\theta}}^{1}(\theta q_d - p_o)d\theta + (1-s)\int_{\overline{\theta}}^{1}(\theta - p_o)d\theta \tag{5.11}$$

where $\overline{\theta} = \frac{\lambda p_o}{(1-s)+sq_d} + (1-\lambda)p_o$. The first term of CS_d represents the surplus of those consumers who are cheated and receive the deceptive counterfeit, and the second term represents the surplus of those consumers who purchase and receive the brand-name product.

Considering the chances that counterfeits do not reach the market due to detention by Customs, we define ECS_d as the expected consumer welfare when the counterfeiter is deceptive, as follows:

$$ECS_d = (1 - \mathbb{P}_d^r(\kappa, e_d))CS_n + \mathbb{P}_d^r(\kappa, e_d)CS_o \tag{5.12}$$

When no proactive consumers exist in the market, we show in Proposition 5.9 that Customs initiating the PPP would lead to a higher consumer welfare than that if the OEM initiates the PPP. In addition, when the quality of deceptive counterfeits is sufficiently low, it is better for consumers if the PPP is formed, than that if the PPP is not formed. These results are different from those in the non-deceptive case, where forming the PPP would increase the consumer welfare only if the OEM initiates the PPP, and not forming the PPP is better for consumers when the quality of non-deceptive counterfeits is low (see Proposition 5.7). These differences again demonstrate the importance of differentiating the two types of counterfeits when deciding the right anti-counterfeiting strategy.

Proposition 5.9. *In a market where no consumer is proactive, i.e.,* $\lambda = 0$*:*

- *given the same disguise effort of the deceptive counterfeiter, the expected consumer welfare* ECS_d *is higher if the PPP is initiated by Customs, than that if the PPP is initiated by the OEM and* $C < C_o$*;*

- *if the quality of deceptive counterfeits is sufficiently low, the expected consumer welfare ECS_d is higher if the PPP is formed, than that if the PPP is not formed.*

5.6 Conclusion

Counterfeiting has damaging impacts on both business and the society. We study how the government and private enterprises can build a partnership to combat counterfeiting. More specifically, we investigate which party should initiate the partnership, i.e., investing in the information-sharing infrastructure, and the optimal anti-counterfeiting strategy of each party in different situations. We consider two types of counterfeits, i.e., non-deceptive and deceptive counterfeits. Our results show that the existence of non-deceptive counterfeits is not always bad to the OEM, if it chooses the right strategy. Compared to the situation without any counterfeit, if the OEM either joins or initiates the partnership with Customs, in the presence of a non-deceptive counterfeiter, it might increase the price of authentic products and earn more profit.

However, forming the partnership with Customs to combat non-deceptive counterfeiter does not bring the OEM benefits in all aspects. When Customs does not initiate the partnership, especially in the situation where the quality of counterfeits is high, initiating it by the OEM on its own will lead the counterfeiting to increase the price of counterfeits and even potentially capture a higher market share than the OEM. It possibly explains why in practice some legitimate firms do not join such a partnership with the government. We show that if Customs initiates the PPP, it is guaranteed that the OEM will earn more profit than the counterfeiter. We also show that the government should play a bigger role in initiating the PPP when the penalty to the non-deceptive counterfeiter is small, because the OEM will likely not take the initiative in such a situation. Our results signify the importance of the government in initiating the partnership with enterprises to combat non-deceptive counterfeiting, especially when the quality of counterfeits is high and the penalty to the counterfeiter is small.

Compared to the non-deceptive case, we found that private enterprises should play a bigger role in initiating the partnership with the government in the fight against deceptive counterfeiting. The OEM could set a higher price than that without any counterfeit only if it initiates the PPP, and the market seize of the deceptive counterfeiter is decreasing in the price of authentic products in such a situation. Our results also demonstrate the importance of differentiating the two types of counterfeits when deciding the right anti-counterfeiting strategy.

Despite investigative powers of Customs, fighting counterfeit products at ports of entry is still a case of limited resources targeted far too late in the supply chain to make a significant impact on the problem. For this reason, firms should recognize that relying solely on Customs is a poor strategy. In today's business environment, combating counterfeiting requires firms to consider all aspects of a global supply chain, e.g., production, distribution and sales, and use all resources at disposal, e.g., help from governmental agencies or business associations. Future research could consider a similar partnership model as an anti-counterfeiting strategy in other phases of a global supply chain, e.g., in the manufacturing phase. In addition, future research could study the most effective supply chain phase to form such a partnership, e.g., should it be in the upstream supply chain phases or phases where products are closer to the final market.

Chapter 6

Assessing End-of-Supply Risk of Spare Parts Using the Proportional Hazard Model (PHM)

This chapter was accepted by *Decision Sciences* in 2016 (Volume 47, Issue 2); see Li et al. (2016a).

6.1 Introduction

In sectors like aerospace, shipping, and defense, manufacturers and customers are focused on sustaining their products for prolonged periods. This is due to the high costs and long time horizons associated with new product development. As a result, the lifecycle of systems in these sectors often spans over 20, 30, or even more than 40 years (Rojo et al., 2010). One of the main problems that these long field-life systems face during their lifetime is that parts of their system components are not supplied anymore. The procurement life of components, especially of electronic parts, is usually significantly shorter than the lifetime of the overall systems that they are built into, which poses great challenges of maintainability and sustainability (Bartels et al., 2012). For long field-life systems, lifecycle mismatch between the system and its components has become one of the main costs. For instance, end-of-supply of spare parts for United States Navy systems has been estimated to cost up to 750 million dollars per year (Adams, 2005).

The main causes for ending supply of spare parts are technological developments and demand falls. Consequences can be mitigated by predicting, assessing, and actively managing end-of-supply risk. In this way, companies can decide to keep larger stock of parts that face ending supply but remain crucial for current business. Threat advisory systems for ending supply are very valuable, because it can be very expensive to find proper replacements at short notice (Craighead et al., 2007). Therefore, evaluating end-of-supply risk of spare parts is the key factor in proactive management and strategic lifecycle planning for systems with long field-life.

This article describes a methodology to assess end-of-supply risk of spare parts using quantified upstream supply chain conditions. The methodology is developed from the perspective of purchasing firms, that is, firms that purchase parts, especially firms of long field-life systems. Such firms typically have only very limited access to the downstream supply chain information that is available to the parts manufacturers, such as parts sales data to perform lifecycle analysis. Indicators of end-of-supply risk are derived from information on the flow of spare parts from suppliers to downstream companies in the supply chain. Both demand and supply side factors are considered from the company perspective, as is common in the supply chain literature (Craighead et al., 2007). The aim is to develop indicators for ending supply of spare parts and to quantify the associated supply risks in order to assist organizations in their inventory management and in using long field-life products more effectively. Four supply chain indicators are taken into account, that is, price and lead time that represent risks originating at the supply side, and cycle time and throughput that represent risks from the demand side. The methodology is demonstrated on data collected from a maintenance and repair organization (MRO) in the aviation industry. The results show that our methodology based on up-stream supply information available to purchasing firms provides them with a helpful tool to reduce the risk of unforeseen ending supply of spare parts that are essential for their operation. Moreover, the joint incorporation of several risk indicators provides substantial gains over approaches based on a single risk indicator, stressing the importance of the joint analysis of big data.

The rest of this chapter is organized as follows. Section 6.2 reviews current methods for predicting end-of-supply and presents the research hypotheses. Section 6.3 presents the methodology for assessing end-of-supply risk and the type of data required for this analysis, and Section 6.4 illustrates the methodology and evaluates its performance, both in-sample and out-of-sample. Last, Section 6.5 provides discussions and conclusions.

6.2 Literature and research hypotheses

This section gives a brief review of literature related to end-of-supply risk. Previous studies mostly focus on manufacturers and supply factors, whereas the current study considers end-of-supply risk from the perspective of purchasing firms. After identifying potentially relevant supply and demand factors, four hypotheses are formulated to assist purchasing firms of spare parts in their timely detection of increased end-of-supply risk.

For purchasing firms, possibly the most straightforward way of assessing end-of-supply risk is to simply ask the part manufacturers when supply will be discontinued. Sandborn et al. (2011) refer to a survey conducted for electronic parts showing considerable inaccuracies in the procurement lifetime reported by manufacturers. As manufacturers realize that revealing their procurement outlook can lead to self-fulfilling prophecies, they may be hesitant to share their views with customers. Zsidisin et al. (2000) conclude from interviews with purchasing professionals that firms are inclined to form single sourcing alliances with suppliers to reduce costs. Supply risk might be mitigated by multiple sourcing, but this is often not possible for highly specialized parts. Solomon et al. (2000) predict a part's lifecycle stage and the remaining time until supply ends from part sales curves. Application of such lifecycle models is limited to part manufacturers, because part purchasing firms largely lack the required sales information. Sandborn et al. (2011) present a methodology based on failure times, assuming that past failure trends can be extrapolated to the future. In cases where products have short lifecycles because of continuing innovations, Meixell and Wu (2001) propose the use of leading indicators for advance warning of major demand changes. As an example, for a given cluster of products, some products may provide advance indication of demand patterns for the rest of the cluster (Wu et al., 2006). Leading indicator methods usually predict demand patterns from two to eight months ahead, making them unsuitable for long field-life systems that have much longer planning horizons. Further, several authors have expressed concerns on neglected information in end-of-supply forecasting (Sandborn et al., 2007, 2011), as current methods mainly focus on sales data and technological characteristics of parts whereas supply chain conditions are usually ignored.

In our study, we consider supply loss of spare parts used by maintenance firms in out-of production high-capital equipment, such as ageing aircraft. When an aircraft type is still in production, it is relatively easy and profitable to produce aircraft-specific spare parts by increasing lot sizes in production runs. When production of the aircraft stops, it becomes much more difficult to produce such parts because of high set-up costs, hence requiring substantial lot sizes. With further aging of the aircraft type, the install base (number in use) will decline, and abandoned aircraft can be dismantled for spare parts (Kennedy et al., 2002). This all leads to less frequent sales and smaller order quantities for the manufacturer of such parts. To compensate for the set-up costs, the manufacturer will often wait to combine several customer orders into a larger lot size. The manufacturer may also concentrate on other parts for newer planes, so that replacement orders for old parts get lower priority. As a result, lead times tend to increase and to show more fluctuations (Chopra and Sodhi, 2004; Bogataj and Bogataj, 2007; Blackhurst et al., 2008). Further, because production becomes less profitable, the manufacturer may change prices to keep his production economical (Zsidisin et al., 2004; Blackhurst et al., 2008).

In addition to the above supply-related risk indicators, other relevant indicators stem from the demand side. From a supply chain perspective, supply and demand risks describe directions of potential disruptive effects (Jüttner, 2005) that are often interconnected (Chopra and Sodhi, 2004). Demand risk has been discussed by Johnson (2001), Cattani and Souza (2003), and Solomon et al. (2000), among others. End-of-supply risk may be related to demand patterns, in particular, cycle time and throughput. When seen from the perspective of a purchasing firm, these demand data pertain to the firm itself and are generally unavailable for other firms. Still, the demand patterns of this single firm may have predictive power for end-of-supply risk, for example, if the firm is itself a major purchaser or if its demand trends are shared by other firms. Cycle time is defined as the period between successive orders. Longer order intervals for a part might lead to a higher probability of supply failure since it may represent the underlying market trend of this part. Further, for parts with long cycle time, the purchasing firm gets no update on the availability of the part over long periods of time, thereby increasing the risk that supply of the part has meanwhile been ended. Throughput is defined as order quantity divided by the cycle time. Throughput tends to decrease when a part reaches the end of its lifecycle.

Summarizing, we formulate the following four research hypotheses on end-of-supply risk indicators, that is, factors that indicate the risk that manufacturers stop production of parts. This risk becomes larger if

- the lead-time increases;
- the price increases;
- the cycle time increases;

- the throughput decreases.

If the above hypotheses hold true, the managerial implication is that companies buying spare parts can assess end-of-supply risk from studying their purchasing records. The main aim of this article is to propose a methodology incorporating combined information on the above risk indicators in order to provide practical tools for firms in their management of end-of-supply risk of spare parts.

6.3 Methodology

This section discusses the spare part data used in the empirical analysis and the statistical model to express end-of-supply risk in terms of four groups of risk indicators: lead time, price, cycle time, and throughput.

Spare Part Data

The data are collected from an MRO in the aviation industry. The MRO acts as intermediary between its clients, the owners of aircraft, and its suppliers, the parts manufacturers. The main interest of the MRO lies in high quality support by guaranteed delivery of all parts that their clients need for the continued operation of their systems. The aircraft maintained by this MRO are composed of more than thirty thousand parts. Many of the aircraft are already out of production and have entered the last phase of their lifecycles. The MRO needs to pay close attention to supply problems, as it increasingly operates under performance-based contracts that make part availability even more critical. Further, unavailability of spare parts may lead to abandonment of the aircraft with large loss for the MRO. In order to achieve the availability targets for long field-life systems, it is necessary to have high enough stocks for spare parts. Being farseeing and proactive about end-of-supply risk is critical to maintain fully capable products and systems and to satisfy customers.

The data have been collected from databases maintained by the technical support group of the MRO. We will use the terminology of the MRO and call a part obsolete if it is no longer supplied and healthy if its supply continues. One of the databases of the MRO is the obsolescence database, which contains the part number, obsolescence date, reason of obsolescence, and its solution, for all parts of which supply ended during the observation interval between May 2006 and June 2013. The considered parts consist of vendor parts, as firm specific parts are easier to monitor whereas the supply risk of vendor parts is much more uncertain. Each time the MRO receives an end-of-supply notification from a supplier, the cause of ending their supply is requested. Manufacturers may discontinue a product due to unavailability of a critical part. If the part in question is revealed by the supplier, the MRO adds the number of the obsolete part, instead of the higher assembly (module), to the database. In total, the database contains 700 obsolete parts, with obsolescence dates ranging from October 2006 to March 2013. A total of 7767 higher assemblies are linked to these parts.

The MRO also has a procurement database, which contains purchase histories of parts from May 2006 until June 2013. In principle, each time a part is purchased, the date of the purchase order is registered, together with the price, quantity, and supplier information. The delivery date is added to the database when the MRO receives the part. The database was scanned for doubtful and irrelevant purchase data, and the following types of purchases were excluded: canceled orders (199), purchases from once-only suppliers (709), internal deliveries (474), missing delivery date (32), single purchases (182), and purchases after obsolescence date (1015). After excluding these purchase data, a total of 180 obsolete parts remain for analysis, most of which are piece parts whereas others are registered as higher assemblies because the supplier did not reveal the part causing end-of-supply. The parts are clustered in four groups according to functionality criteria provided by the MRO: airframe components, electronics parts, interior parts, and other parts such as engine and mechanical parts. The idea behind this classification is that the dynamics of supply chain characteristics may differ among these four clusters.

As the methodology intends to distinguish obsolete from healthy parts, data on healthy parts are also considered. Even though a large number of parts have not been indicated as obsolete yet, most of them were not purchased during the analysis period (2006-2013). Purchase data satisfying the inclusion criteria discussed above for obsolete parts are available for in total 1910 healthy parts. From this subset, 186 healthy parts were randomly selected such that each of the following criteria were met: the parts have been purchased in 2012 or 2013; they have constant suppliers in the procurement database; they have not yet been declared obsolete by their suppliers; and the number of parts in the healthy and obsolete groups are comparable within each of the four clusters.

Table 6.1 gives an overview of the 180 obsolete and 186 healthy parts used to construct a statistical model for end-of-supply risk. The purpose is to relate differences in procurement lifetimes between obsolete and healthy parts to underlying supply and demand risk indicators. The procurement lifetime of an obsolete part is defined as the time between the obsolescence date and the first purchase date. For healthy parts, the procurement lifetime is right-censored, as it is defined as the time between the analysis date (July 1 of 2013) and the first purchase date. The lifetimes are censored, because all parts were introduced before the start of the analysis period (May 2006). Comparison-of-means ANOVA tests show no significant differences in mean lifetimes for the four parts clusters, neither for healthy parts (p-value 0.26) nor for obsolete parts (p-value 0.87). The time span of the study is slightly more than seven years, which is too short to show the longer lifetimes of airframe components and interior parts as compared to electronics parts.

End-of-Supply Risk Indicators

The procurement database can be used to construct various variables related to the risk indicators discussed before, that is, price, lead time, cycle time, and throughput. Discussions with MRO personnel provided motivation to consider 13 risk factors in total. This subsection first discusses the definition

		Percentage Shares			Mean Life Time (Days)		
Parts	Sample	All	Healthy	Obsolete	All	Healthy	Obsolete
Airframe	23	6.28	2.73	3.55	1750	2552	1133
Electronic	59	16.12	8.20	7.92	1868	2514	1200
Interior	12	3.28	1.91	1.37	1940	2539	1102
Other	272	74.32	37.98	36.34	1820	2503	1107
All	366	100	50.82	49.18	1828	2509	1124

Table notes:

- Sample contains 186 healthy parts and 180 obsolete parts.
- The cluster of other parts includes, among others, engine and mechanical parts, fuel systems, hydraulics, pneumatics, and landing gears.

Table 6.1: Four clusters of parts

of each risk factor, followed by comparisons between the groups of obsolete and healthy parts.

The risk factors can be defined by using the following notation for each given part. The number of purchases of this part in the database is denoted by n. The i-th purchase ($i = 1, \cdots, n$) has purchase date t_i (measured in days), price p_i, order quantity q_i, and lead time l_i. The last (n-th) observation refers to the last purchase before the obsolescence date (d_o) for obsolete parts and to the last purchase before the analysis date (d_a) for healthy parts. The time interval between two successive purchase dates is denoted by $c_i = t_i \breve{} t_{i-1}$ ($i = 2, \cdots, n$). If the values of a risk indicator vary over time, the corresponding risk factor is defined either as an average over time or in terms of the total change over time. This way of measurement is motivated by the fact that there are long periods without purchases, so that a detailed analysis of purchase patterns over time is not well possible.

The three price factors are defined as price change $PRC = (p_n \breve{} p_1)/p_1$, price change over time $PRCT = PRC/(t_n \breve{} t_1)$, and annual relative price increase $PRAI = -1 + (p_n/p_1)^{365/(t_n \breve{} t_1)}$. If parts are purchased from different countries, prices are converted to euros by means of the currency rate at the purchase date. Prices are deflated by an annual inflation rate of 2 percent, corresponding roughly to the average inflation rate over the observation period. Cycle time factors are the average cycle time CTA (the sample mean of $c_2, \cdots, c_n$), the change in cycle time $CTC = (c_n ˘ c_2)/c_2$, and the order interval since the last purchase ($OILP$, measured in years), defined by $OILP = (d_0 ˘ t_n)/365$ for obsolete parts and $OILP = (d_a ˘ t_n)/365$ for healthy parts. The throughput factors are average throughput TPA (the sample mean of $q_2/c_2, \cdots, q_n/c_n$), and throughput change $TPC = (q_n/c_n ˘ q_2/c_2)/(q_2/c_2)$. Lead time factors include average lead time LTA (the sample mean of $l_1, \cdots, l_n$), change in lead time $LTC = (l_n ˘ l_1)/l_1$, and change in lead time over time $LTCT = LTC/(t_n ˘ t_1)$. Two other lead time factors are obtained by comparing the most recent lead time of each part to its longest lead time in the database (l_{max}): last versus longest $LTLvL = (l_{max} ˘ l_n)/l_n$, and the corresponding value over time $LTLvLT = LTLvL/c_L$ where c_L is the time interval between the last (n-th) purchase date and the purchase date for which the lead time was the longest of all. The motivation for the latter factor is that supply disruptions in the far past are less harmful than recent ones.

A diagnostic test of the descriptive power of the above risk factors is obtained by comparing mean levels between the groups of obsolete and healthy parts. The results in Table 6.2 show that, at the 5% significance level, five of the 13 factors differ significantly: CTA and $OILP$ for cycle time, TPA for throughput, and LTA and $LTCT$ for lead time. As compared to the healthy group, parts in the obsolete group have higher cycle time, longer order interval since last purchase, longer and more steeply increasing lead time, and smaller throughput, in correspondence with our hypotheses. Although obsolete parts have higher and more steeply increasing prices than healthy parts, the differences in mean price levels are not significant due to large price variations caused by product heterogeneity. Price differences remain insignificant also when considered separately per cluster of products.

Correlations between pairs of risk factors are small between groups (price, cycle time, throughput, and lead time), and in some cases large within these groups. The three price factors are highly correlated (the correlations are 0.98, 0.95, and 0.90), and the group of five lead time factors show two high correlations (0.98 and 0.66). Between different groups of risk factors, the highest correlations are those between TPA and CTC (0.62) and between ALT and the three price variables (0.38, 0.37, and 0.35). Apart from the mentioned 9 correlations, all other 69 pairs of risk factors have correlation below 0.20. For example, the maximal correlation with other factors is 0.13 for average cycle time (CTA) and 0.18 for the order interval since last purchase ($OILP$). The various risk factors seem to measure different supply chain characteristics, so that their combination may improve risk assessments.

Proportional Hazard Model (PHM)

The various risk factors can be taken into consideration jointly by means of the proportional hazard model (PHM), introduced by Cox (1972). This model is widely used in condition-based maintenance (Scarf, 1997), as it provides condition-specific predictions of failure probabilities over time. For instance, Jardine et al. (1987) proposed using PHM to combine aircraft engine-failure data with metal concentration measurements of the engine oil. The standard PHM specification uses fixed covariates, meaning that the value of each risk factor is constant over time, and otherwise the PHM is called time-dependent (Cox, 1972). The analysis of end-of-supply risk of spare parts in this article employs standard PHM, because the value of each considered risk factor (summarized in Table 6.2) is determined at the analysis date, either as sample average or as change over the full observation period or over a sub-period. The practical interpretation of this choice is that risk evaluation is considered a task to be performed at a chosen evaluation date rather than a continuous on-line task.

The core of PHM is the hazard function, which is defined as follows. Let T be the failure time of a given part, which is considered as a random variable as this time is not known a priori. At any given time instant (t), the hazard

		Healthy Parts		Obsolete Parts		
Covariate	Acronym	Mean	St. Dev.	Mean	St. Dev.	P-value
Price						
change	PRC	0.513	1.002	0.956	5.014	0.247
change over time (×100)	PRCT	0.022	0.043	0.316	2.321	0.092
annual increase	PRAI	0.051	0.076	11.890	99.705	0.113
Cycle Time						
average/100	CTA	1.273	1.007	2.444	2.526	0.000
change/100	CTC	0.179	0.965	0.108	0.608	0.403
order interval last purchase	OILP	0.520	0.325	1.168	1.137	0.000
Throughput						
average/100	TPA	1.570	8.774	0.026	0.135	0.017
change/100	TPC	0.132	1.550	0.662	7.703	0.367
Lead Time						
average/100	LTA	0.389	0.229	0.695	0.706	0.000
change/100	LTC	0.008	0.027	0.077	0.538	0.089
change over time (×100)	LTCT	0.037	0.117	3.470	18.897	0.016
last vs longest/100	LTLvL	0.049	0.067	0.390	3.137	0.147
last vs longest over time	LTLvLT	0.005	0.011	0.270	2.808	0.207

Table notes:

- Sample contains 186 healthy parts and 180 obsolete parts.
- The factors for cycle time, throughput, and lead time are all measured in days, except for the order interval since last purchase (OILP) that is measured in years.
- Some factors are rescaled to prevent very small or very large coefficients.
- The p-value is for the t-test of equal means in the two groups (healthy and obsolete), not assuming equal variances in the two groups (as the latter hypothesis is rejected for each variable).

Table 6.2: Supply risk factors in groups of healthy and obsolete parts

rate $h(t)$ is the marginal probability rate for the part becoming obsolete in an infinitesimally small time period between t and $t + \delta$, given that it is still available at time t, so

$$h(t) = lim_{\delta \downarrow 0} Prob(t < T < t + \delta)/(\delta \times Prob(T > t)) \tag{6.1}$$

A hazard rate implies the associated survival function $S(t) = Prob(T > t) = \exp(˘ \int_0^t h(s)ds)$, and end-of-life occurs in the time interval $a \leq T \leq b$ with probability $S(b)˘S(a)$. For obsolete parts, the procurement lifetime is defined as $T = d_o˘d_1$, where d_o is the obsolescence date and d_1 is the first purchase date. For d_1, one sometimes uses the date on which the original manufacturer introduced the part (Sandborn et al., 2011), but this date is generally unknown to the MRO or customer in the upstream supply chain and their first purchases may fall far behind introduction dates. Further, as is usual in survival analysis, the observed life times of healthy parts are right-censored, as the failure date is known only to fall beyond the analysis date. For healthy parts, the (right-censored) lifetime is defined as $T = d_a˘d_1$, where d_a is the analysis date.

In PHM, the hazard rate is expressed as the product of the baseline hazard $h_0(t)$, which depends on time only, and a positive function $f(x, \beta)$ that involves the risk factors (x) and their effects (β), so that $h(t) = f(x, \beta) \times h_0(t)$. By far the most widely used specification is the exponential one, which in case of k risk factors gives

$$h(t) = \exp(\beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_k x_k) \times h_0(t) \tag{6.2}$$

If risk factor j increases by one unit, the hazard rate is multiplied by $\exp(\beta_j)$, and the relative effect of an increase by one percent is equal to $\exp(\beta_j x_j/100)˘1$. Further, as $\log(h(t)) = \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_k x_k + \log(h0(t))$, it follows that

$$\beta_j = \partial \log(h(t))/\partial x_j = (\partial h(t)/\partial x_j)/h(t) \tag{6.3}$$

This means that the marginal effect on the hazard rate of an increase in the j-th risk factor is equal to $\beta_j \times h(t)$, so that this effect is proportional to the hazard rate $h(t)$. Higher levels of a risk factor increase (decrease) end-of-supply risk if they have a positive (negative) coefficient.

The data used in estimation consists of the life time durations, which are right-censored for healthy parts, and the part-specific values of the risk factors that are included in the model. If the baseline hazard is expressed in parametric form, the resulting PHM in (6.2) becomes fully parametric, allowing estimation by maximum likelihood (ML). In many cases, however, the baseline specification is ambiguous. The inconsistency resulting from incorrect baseline specification can be prevented by leaving the baseline hazard unspecified and estimating the resulting semi-parametric model by means of the partial likelihood approach suggested by Cox (1975). This method has the advantage of providing consistent estimates of the coefficients $(\beta_1, \beta_2, \cdots, \beta_k)$ in (6.2) and their standard errors, irrespective of the baseline hazard, at the expense of some loss of efficiency as compared to ML in a correctly specified fully parametric model (Kumar and Klefsjö, 1994; Newby, 1994). In many applications, this expense well outweighs the risk of wrong estimates and wrong standard errors resulting from applying ML in a wrongly specified model. If all parts in the dataset have different obsolescence dates, the partial likelihood estimates are obtained by maximizing (Cox, 1975)

$$L(\beta_1, \beta_2, \cdots, \beta_k) = \prod_{i=1}^{n} \frac{\exp(\beta' x_i)}{\sum_{j \in H(i)} \exp(\beta' x_j)} \tag{6.4}$$

Here $\beta' x_i = \beta_1 x_{1i} + \beta_2 x_{2i} + \cdots + \beta_k x_{ki}$, where $x_i = (x_{1i}, x_{2i}, \cdots, x_{ki})$ are the scores on the k risk factors for the i-th part, n is the total number of obsolete parts, and $H(i)$ is the set of parts that are not (yet) obsolete at the time just before the i-th part becomes obsolete. If the obsolescence date of the i-th part is t_i, then $H(i)$ contains all parts that are still healthy at the end of the observation period and all parts that become obsolete between time t_i and the end of the observation period. For each obsolescence time t_i, the fraction in (6.4) can be interpreted as the probability that it is the i-th part that fails, given that some part does become obsolete at the time t_i, and given the set of parts that has already become obsolete before time t_i. A similar expression can be derived in case some of the obsolescence times coincide (Breslow, 1974). The partial likelihood estimator is consistent and asymptotically normally distributed with standard errors computed similar to ML, replacing the full likelihood by the partial likelihood. A backward stepwise approach is followed for models containing several risk factors, starting with all risk factors and reducing the model step-by-step by deleting the least significant factor until all remaining factors are significant (at 5% level). For the resulting model, each omitted factor is considered once again, and if any is significant, it is added to the set of included factors. After final selection of the included risk factors, the resulting PHM is estimated by maximizing the partial likelihood (Kalbfleisch and Prentice, 2011). As was discussed before, correlations between the four groups of risk indicators (price, lead time, cycle time, and throughput) are small, which simplifies coefficient interpretation (Kobbacy et al., 1997).

Once the parameters $(\beta_1, \beta_2, \cdots, \beta_k)$ have been estimated, the baseline hazard can be estimated by means of non-parametric procedures (Breslow, 1974). In order to estimate the probability of ending supply of a part during a given time interval, parametric approximations of the baseline hazard may be needed, and the Weibull distribution is a popular choice. For the empirical application of this article, the statistical package SPSS was used, which has a wide range of facilities for testing the model and for selecting explanatory variables.

The dataset used to estimate the hazard models consists of the set of 366 parts summarized in Table 6.1. In this dataset, about 50 percent of the parts become obsolete somewhere during the observation period, and the final value of the survival probability $S(d_a)$ at the analysis date will therefore be close to 0.5. As the set of 186 healthy parts included in the analysis is only a small part of all healthy parts that are relevant for the MRO, the levels of the survival function $S(t)$ and of the baseline hazard rate $h_0(t)$ do not have a direct interpretation. What matters most is the effect of each risk factor on the hazard rate, that is, the sign and size of the parameters $(\beta_1, \beta_2, \cdots, \beta_k)$, and the ranking of the survival probabilities $S(d_a)$ of the various parts. Note that these parameters and rankings are not affected by the baseline hazard, because of the chosen structure of the PHM (see equation (6.2)) and the partial likelihood method of estimation.

6.4 Results

Estimation Results

Kaplan-Meier survival plots of the four spare parts clusters are shown in Figure 6.1. In the figure, label 1 is for 23 airframe parts (long dashed line), 2 is for 59 electronic parts (short dashed line), 3 is for 12 interior parts (shaded tiny dashed line), and 4 is for 272 other parts (continuous line). These plots do not indicate any noticeable lifetime differences between different clusters over the observation period, which is in line with the ANOVA results for mean lifetime discussed before. In all models, possible cluster effects were always investigated by including cluster dummies, and as none of these cluster effects were found significant they are not be reported here.

The upper part of Table 6.3 shows the results obtained by including a single risk factor in the PHM. The column 'Effect' shows the percentage increase in the hazard rate if the factor increases by one percent from its mean value, with value equal to $100(\exp(b \times m/100)$˘$1)$, where m is the sample mean of the factor and b is its coefficient. Nine out of the 13 considered risk factors are individually significant (at 5% level), with largest size effect for average throughput. The set of significant factors closely resembles the set of factors with significantly different means between the sets of obsolete and healthy parts in Table 6.2: the results coincide for all cycle time and throughput factors, for two out of three price variables, and for two out of five lead time factors. All significant factors have the expected sign, with larger end-of-supply risk for higher price, longer lead time, longer cycle time, and smaller throughput. These results confirm our research hypotheses.

The lower part of Table 6.3 shows the PHM with multiple factors, obtained by the backward stepwise strategy starting with all nine individually significant factors. The resulting model contains six risk factors: average cycle time, order interval since last purchase, average throughput, and three lead time factors. In this multifactor PHM, none of the three price variables has significant additional explanatory power, neither individually, nor jointly. The effect sizes of the included risk factors are roughly similar to those obtained for the single-factor models, owing to the small correlations between most of the risk factors. The results for lead time, cycle time, and throughput confirm again our research hypotheses.

Several tests are performed to check the assumptions underlying the multiple-factor model of Table 6.3. Schoenfeld's residuals (Schoenfeld, 1982) do not show any systematic patterns over time, and Cox-Snell residuals provide no indication for risk factor transformations.

Cross-Validation Results

In order to evaluate how the PHM performs in out-of-sample prediction, stratified five-fold cross-validation is performed. The 180 obsolete parts and 186 healthy parts are partitioned into five disjoint sets of nearly equal size, each containing roughly the same proportions of obsolete and healthy parts. Subsequently, five rounds of training and validation are performed. In each round, the model is estimated from data of four of the subsets (the training set, with 292 or 293 parts), using the same backward stepwise PHM model selection strategy and baseline estimation procedures as discussed before, and the other subset (with 73 or 74 parts) is hold out for validation. All five rounds resulted in the same set of six significant risk factors that were also obtained for the full dataset in Table 6.3, also with roughly similar coefficients. In predicting end-of-supply risk for each validation set, all parts in the validation set are considered healthy on the date of analysis, as this is the relevant situation in actual out-of-sample prediction where the status (healthy or obsolete) of the predicted parts is still unknown. Therefore, for obsolete parts in the validation set, the lifetime is adjusted accordingly. The order interval

Covariates	Mean	Coeff.	St. Error	P-value	Sign.	Effect (%)
Single Factor						
PRC	0.731	0.024	0.017	0.142	No	0.018
PRCT(×100)	0.166	0.062	0.031	0.042	Yes	0.012
PRAI	5.874	0.001	0.001	0.071	No	0.008
CTA/100	1.849	0.118	0.025	0.000	Yes	0.218
CTC/100	0.144	-0.132	0.139	0.345	No	-0.019
OILP	0.839	0.327	0.060	0.000	Yes	0.275
TPA/100	0.811	-2.388	0.771	0.002	Yes	-1.918
TPC/100	0.392	0.012	0.010	0.222	No	0.005
LTA/100	0.539	0.682	0.101	0.000	Yes	0.368
LTC/100	0.042	0.427	0.118	0.000	Yes	0.018
LTCT(×100)	1.725	0.034	0.005	0.000	Yes	0.058
LTLvL/100	0.217	0.102	0.023	0.000	Yes	0.022
LTLvLT	0.136	0.106	0.026	0.000	Yes	0.014
Multiple Factors						
CTA/100	1.849	0.086	0.029	0.003	Yes	0.160
OILP	0.839	0.308	0.062	0.000	Yes	0.259
TPA/100	0.811	-1.877	0.698	0.007	Yes	-1.511
LTA/100	0.539	0.486	0.111	0.000	Yes	0.262
LTCT(×100)	1.725	0.033	0.005	0.000	Yes	0.056
LTLvLT	0.136	0.129	0.026	0.000	Yes	0.018

Table notes:

- ‘Mean’ is the sample mean of the factor.
- ‘Sign.’ shows whether the factor effect is significant or not at the 5% level.
- ‘Effect (%)’ shows the percentage increase of the hazard rate if the risk factor increases by one percent from its mean.

Table 6.3: Estimated PHMs for single and multiple factors

since the last purchase ($OILP$) is not adjusted; if the ‘healthy part’ formula $OILP = (d_a{}^{\smile}t_n)/365$ were used also for obsolete parts, instead of the ‘obsolete part’ formula $OILP = (d_0{}^{\smile}t_n)/365$, then this risk factor would be artificially enlarged for parts with obsolescence date d_0 that falls far before the analysis date d_a.

Table 6.4 shows the cross-validation results, both for each single-factor model (averaged over the five validation sets) and for the multiple-factor model (for each individual validation set, and averaged). The average survival probability over the sample is approximately 50 percent, and high (low) end-of-supply risk is defined as survival probability below 0.3 (above 0.7). These probabilities are partly based on the baseline hazard, and it is also of interest to consider the set of spare parts that carry the highest end-of-supply risk, as this set does not depend on the baseline hazard. Table 6.4 shows the results for the 25 spare parts in the validation set (of 73 or 74 parts) that have the highest end-of-supply risk as predicted from the training set.

The outcomes show that the multiple-factor PHM provides substantial improvements over the single-factor models. For the top-25 risky parts, the multiple-factor model has an average hit rate over the five validation sets of more than 80 percent (20.2 correct and 4.8 false alarms). Averaged over the nine significant single-factor models of Table 6.3, the average hit rate is below 50 percent (11.4 correct and 13.6 false alarms). The best performing single-factor models are those with average cycle time and order interval since last purchase (with hit rates slightly below 60 percent). The multiple-factor model also provides more reliable results for spare parts with low survival probabilities ($0 \leq S \leq 0.3$), as the single-factor models provide very few predictions in this class (maximal average of 5.0 for LTA). For risky parts with predicted survival probability below 0.3, nearly all parts identified by the multiple-factor model are actually obsolete (on average 12.6 out of 13.2, hit rate 95 percent). For non-risky parts with predicted survival probability above 0.7, the hit rate is 68 percent (6.8 out of 10).

The overall conclusion is that the combination of various types of risk indicators (lead time, cycle time, and throughput) provides considerably more reliable out-of-sample end-of-supply assessments as compared to methods based on a single supply chain indicator.

Out-of-Sample Risk Assessment and MRO Survey

The models and cross-validation results described before are all based on a set of 386 parts, of which 186 are healthy and 180 have become obsolete during the observation interval. The multiple-factor model can be used to estimate the end-of-supply risk of any other part for which the relevant supply chain information is available. The available procurement database contains this information for 1724 other parts that were not included in the set of 386 parts considered before. At the date of analysis (July 1 of 2013), all these parts had a healthy status in the database in the sense that these parts were not registered as being obsolete.

In order to evaluate prediction accuracy, the MRO asked its procurement department to answer a list of survey questions measuring supply disruption risk for parts. This survey was originally developed by Ellis et al. (2010), who found that technological uncertainty, market thinness, item customization, and item importance influence buyers' perceptions of overall supply disruption risk. The survey consists of 20 questions (all measured on a seven-point scale from low to high risk) on eight items, details of which are provided in the Appendix C. The completion time for the questionnaire ranges from 25 to 40 minutes (Ellis et al., 2010). It is therefore infeasible to implement this survey-based risk assessment for all purchased parts, whereas our model-based risk score for each part can be obtained directly from the supply chain database. The MRO answered the survey for a selection of 60 out of the 1724 parts. These 60 parts are obtained by random selection of 30 out of the 60 most risky parts and also 30 out of the 60 least risky parts, identified by respectively the 60 smallest and the 60 largest values of the estimated survival probabilities $S(d_a)$ at the analysis date. The average survival probability is 0.017 for the 30 selected high-risk parts and 1.000 for the 30 selected low-risk parts. The MRO

	Top-25 Risk			High Risk: $0 \leq S \leq 0.3$			Low Risk: $0.7 < S \leq 1$		
	Mean	Obs.	Hea.	Mean	Obs.	Hea.	Mean	Obs.	Hea.
Single factor									
PRCT	0.441	9.8	15.2	0.000	0.4	0	0.764	1.2	0
CTA	0.392	14.8	10.2	0.183	2.8	0.8	0.788	1.4	0
OILP	0.375	14.2	10.8	0.204	4.8	0	0.752	2.8	0
TPA	0.407	11.0	14.0	—	0	0	0.909	1.8	6.6
LTA	0.348	14.0	11.0	0.168	4.8	0.2	0.768	2.4	0
LTC	0.444	9.4	15.6	0.000	0.2	0	0.816	0.6	0
LTCT	0.431	10.2	14.8	0.000	1.0	0	0.796	0.8	0
LTLvL	0.440	9.4	15.6	0.126	0.6	0	0.786	1.0	0
LTLvLT	0.440	9.8	15.2	0.097	0.6	0	0.784	1.0	0
Average	0.413	11.4	13.6	0.097	1.7	0.1	0.796	1.4	0.7
Multiple factors									
Set 1	0.302	19	6	0.166	11	0	0.817	6	8
Set 2	0.239	20	5	0.166	14	1	0.900	3	3
Set 3	0.225	23	2	0.137	13	1	0.853	1	6
Set 4	0.215	21	4	0.141	15	1	0.960	2	7
Set 5	0.308	18	7	0.191	10	0	0.890	4	10
Average	0.258	20.2	4.8	0.161	12.6	0.6	0.884	3.2	6.8

Table notes:

- ‘Mean’ shows mean probability S that spare part is still healthy (at the moment of analysis).
- ‘Obs.’ and ‘Hea.’show the mean number of respectively obsolete and healthy parts.
- The results for single-factor models are averages over five validation sets, and the row ‘Average’ is the average over these nine factors. The results for the multiple-factor model are shown both for each validation set and as average over these five validation sets.

Table 6.4: Cross-validation results for single and multiple factor PHMs

personnel were kept uninformed on the risk status of the part to guarantee their independent risk evaluation.

Ellis et al. (2010) found that the question on overall disruption risk is a very informative one. The 30 surveys for the high-risk parts have an average score of overall supply disruption risk of 5.8 (standard error 0.3), which is significantly larger than the average score of 1.8 (standard error 0.2) for the 30 low-risk parts (the t-test for equal means has p-value below 0.0005). This single survey question is very informative on disruption risk, as 26 out of the 30 high-risk parts have a score of 5 or higher on this question, and 28 out of the 30 low-risk parts have a score of 2 or lower. The three survey questions on the probability of supply disruption are almost equally informative, with mean scores of 5.8 for high-risk parts and 2.1 for low-risk parts. Other questions are less informative, with mean scores for high-risk and low-risk parts of respectively 4.6 and 4.2 for item customization, 2.5 and 2.1 for technological uncertainty, 2.3 and 1.4 for item importance, 4.3 and 3.5 for market thinness, 1.9 and 1.3 for magnitude of supply disruption, and 1.8 and 1.2 for search for alternative source of supply. Still, all of these questions have a higher average risk score for high-risk parts than for low-risk parts. These results show that the model identification of (extreme) high and low risk parts is in accordance with the MRO expert opinions. Later on, the MRO found that supply of 21 out of the 30 estimated high-risk parts had actually already been ended. Further, the MRO stated that four of the remaining nine parts are very suspicious indeed. The model therefore showed strong out-of-sample predictive power for parts with high end-of-supply risk. In addition, 29 of the 30 estimated low-risk parts turned out to be healthy, whereas one of these parts was judged by the MRO to be at risk.

Implementation at MRO

The MRO used to follow a reactive policy, contacting manufacturers after finding out that supply of parts had ended. This strategy has recently been transformed into a proactive one, by implementing the PHM with multiple factors shown in Table 6.3 as a user-friendly interface tool for risk evaluation. The procurement database of the MRO is updated on a weekly basis and contains information on about half a million parts. Every week, the MRO employs the tool to assess the end-of-supply risk of parts, and it contacts manufacturers of parts with high risk. In this way, the MRO is able to manage end-of-supply risk in a structured and proactive way.

6.5 Discussion

Implications

Sufficient availability of spare parts is crucial for prolonged maintenance of long field-life systems. Firms that purchase spare parts often have limited insight in the future production plans of spare part suppliers and therefore need to resort to the supply chain information that is available to them in their buyer's role. Potential indicators for end-of-supply risk are increasing prices, longer lead times, longer cycle times, and smaller throughput volumes. Price and lead time capture uncertainty from the supplier side, whereas cycle time and throughput represent demand risk, for example, if the firm is itself a major purchaser or if its demand trends are shared by other firms. Detailed registration of information on price, lead time, cycle time, and throughput volume for all parts of the maintained systems provides a big database that can be exploited to support order and inventory policies of firms purchasing spare parts. In particular, when the supply chain indicators show high end-of-supply risk of a part, firms can contact their supplier for further information and they can try to build up sufficient inventory for the risky part. By this kind of proactive management, these firms may prevent high adjustment costs and dissatisfaction of system owners because of failure to comply with contracted maintenance.

The various end-of-supply risk indicators obtained from the database are incorporated in an integrated methodology for risk assessment by means of the PHM. This model provides a hazard rate function, that is, for each part and at each moment in time it gives the marginal increase in the end-of-supply probability. This methodology is applied to an MRO in the aviation industry handling over thirty thousand parts. The database of this MRO contains relevant purchase information only for a limited number of parts, leaving a set of about 2,000 parts available for analysis. The end-of-supply risk of parts is modeled in terms of the information available at the analysis date. For this MRO, significant supply-chain risk indicators are throughput, cycle time, and lead time, whereas price and part cluster were not found to have additional predictive power. Higher end-of-supply risk is associated with smaller throughput, longer average cycle time between successive orders, longer periods since the last order in the database, longer average or recent lead times, and steeper increase in lead time. The PHM tool is employed to identify sets of parts with high end-of-supply risk. Cross-validation results and out-of-sample predictions show that the proposed methodology performs very well in identifying risky parts, with hit rates (correct identification of end-of-supply) of 95 percent in cross-validation and 70-80 percent out-of-sample. The last result is obtained by comparing model predictions of highest and lowest risk parts with evaluations made by the MRO by means of a survey asking for the perceived disruption risk for each part.

The joint incorporation of various supply chain indicators provides a substantially better risk assessment than methods based on a single indicator, confirming the value of big data analysis as the various indicators measure different risk dimensions.

Although specific end-of-supply risk environments will differ among firms purchasing spare parts, the methodology can serve all. The crucial condition is that the firm keeps track of the relevant supply chain indicators for each part of interest. At any proposed analysis date, the big database can be used to construct a set of end-of-supply risk indicators and the PHM can be estimated from these data. The resulting risk scores for each part can be scanned to identify parts at risk and to support proactive order and inventory policies.

Limitations and Conclusions

The methodology presented in this article can be applied in general for MRO's keeping detailed purchasing data records, but the specific outcomes will depend on the industrial sector. For long field-life systems, purchase data need to be registered over long periods. The observation period of this study covers slightly more than seven years, which is relatively short as compared to the lifetime of the considered systems. Another limitation of the analysis is that the risk factors are measured at the analysis date, either as averages or in terms of first and last available purchase information, thereby neglecting the fact that supply chain characteristics may show considerable variation within the observation period. These limitations can be mitigated by more detailed recording of purchase histories over longer periods to allow the use of more advanced risk assessment models, including PHM with time-varying covariates (Cox, 1972), proportional intensity models (Vlok et al., 2004), hidden Markov models (Bunks et al., 2000), models using delay-time concepts (Wang, 2002), and stochastic process models (Wang et al., 2000).

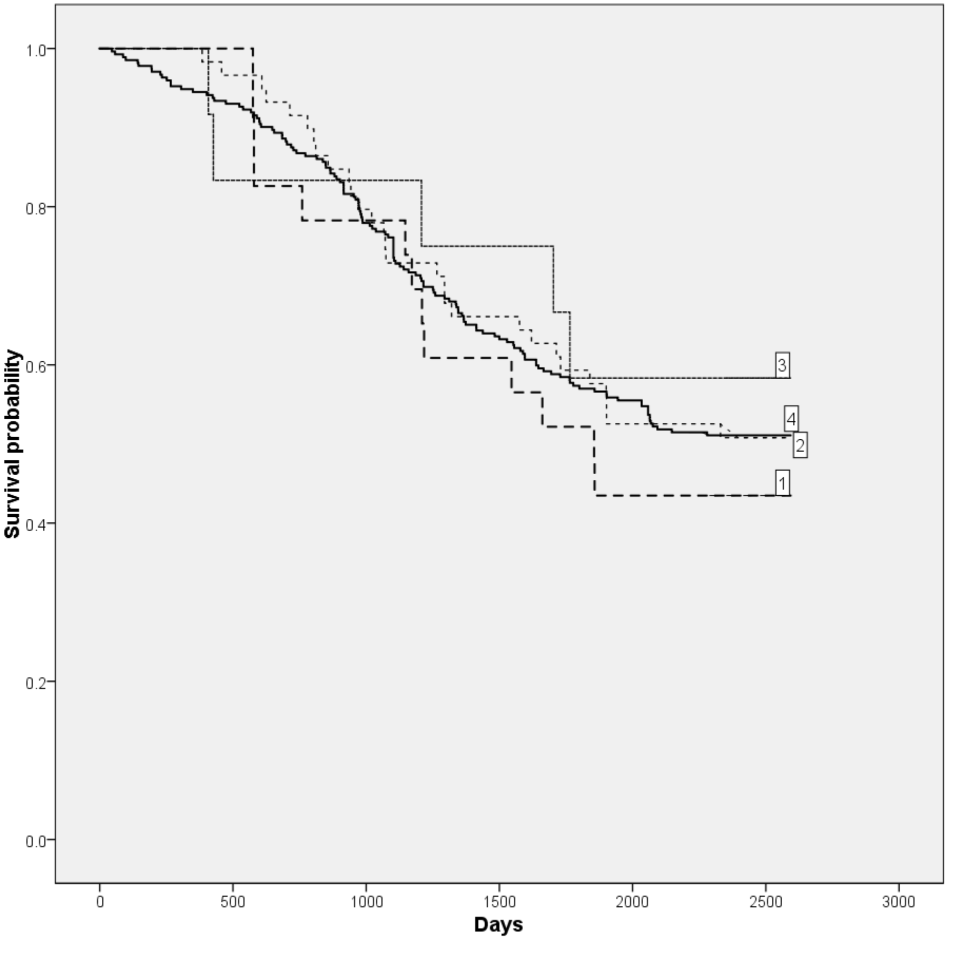


Figure 6.1: Kaplan-Meier survival plots of four spare part clusters

Chapter 7

Conclusion

Uncertainty exists in every aspect of a firm's operations. Underestimating it can lead to strategies that neither defend a company against the threats nor take advantage of the opportunities that higher levels of uncertainty provide. Making systematically sound decisions under uncertainty does not require a firm to predict all possible future scenarios, but to develop a policy according to which it adapts its decisions to future changes. With the right insights and strategies, firms can turn uncertainty from a liability to a leverage point. In addition to uncertainty, competition also shapes a firm's strategy. While one sometimes hears business executives complaining to the contrary, competition in an industry is not bad luck. The existence of competing products can lead a firm to earn more profits by capturing higher-value consumer segments. In my dissertation (**Chapters 3-6**), I study the optimal dynamic operations strategies in the competition and I focus on three specific decisions in four phases of a firm's operations. First, I start with the question how much capacity should a firm build in a competitive market with changing demand. Then, I move to the next phase where a firm decides the optimal launch timing for its next-generation product and the optimal capacity allocation. After the product launch phase, I look at vicious competition, i.e., the counterfeiting issue, in the market and study how should a firm combat different types of counterfeiting. Lastly, I study risk management for long field-life systems in the operations phase. Below, I summarize the main findings and contributions in each chapter.

Chapter 3. Dynamic Capacity Investment under Competition

This chapter studied optimal long-term investment strategies under competition. We developed an algorithm to derive full optimal policies in terms of investment timing and size for both the leader and follower firms. Our model was validated using detailed date from the container shipping market (2000-2015). Although the investments of shipping lines are often questioned to be irrational, our results showed that they are close to the optimal capacity choices determined by our proactive competitive strategies. We contributed to the literature by providing a theory that can explain the competitive investment phenomena observed in practice, which are not fully explained by current models. We contributed to practice by providing a practical guideline with four steps on how to achieve an effective competitive investment strategy.

Chapter 4. Launching Next-Generation Products (NGP) in a Competitive Market

This chapter studied two main capacity decisions of two competing firms during an NGP launch: (1) when to build capacity for the NGP, and (2) how to optimally allocate the total capacity to the NGP and the existing product. Our research extended both the literature on new product development by incorporating the competition between the two firms and the literature on capacity competition by considering evolutionary product innovation. In addition, we considered both demand uncertainty at the early stage and a potential product quality upgrade at the later stage in the NGP launch decision. Our findings contributed to both theory and practice by showing how to measure demand risk and competitive (dis)advantage of a firm during the NGP launch. In addition, we showed how to distinguish the competitive situation of a firm based on advantage and disadvantage of both firms and demand risk. A firm's optimal launch timing depends on its competitive situation.

Chapter 5. Combating Strategic Cross-Border Counterfeiters

This chapter studied optimal anti-counterfeiting strategies of a legitimate

OEM in a global supply chain. To combat counterfeiting, the OEM can either resort to pricing or building a public-private partnership (PPP) with Customs in which the OEM helps Customs hinder the entry of counterfeits. Customs can also be the one who initiates the PPP and thus the OEM can join it with no cost. Using a game theoretic framework, we derive the optimal equilibrium strategies of Customs and the OEM. We considered two types of counterfeiting: non-deceptive and deceptive counterfeiting. We showed that the existence of non-deceptive counterfeits is not always bad to the OEM, if it chooses the right strategy. Compared to the situation without any counterfeit, if the OEM either joins or initiates the PPP with Customs, it could increase the price of authentic products and earn more profit. Compared to the non-deceptive case, we found that private enterprises should play a bigger role in initiating the PPP in the fight against deceptive counterfeiting. The OEM could choose a higher price than that without any counterfeit, only if the OEM initiates the PPP, and the market seize of the deceptive counterfeiter is decreasing in the price of authentic products in such a situation.

Chapter 6. Assessing End-of-Supply Risk of Spare Parts Using the Proportional Hazard Model (PHM)

This chapter studied end-of-supply risk management of parts of long field-life systems. End-of-supply risk is the risk that a part is no long supplied. Long field-life systems, such as airplanes, are faced with hazards in the supply of spare parts. Using the proportional hazard model and quantified supply chain condition data, we develop a methodology for firms purchasing spare parts to manage end-of-supply risk. Our methodology was validated using data on about 2,000 spare parts collected from a maintenance repair organization in the aviation industry. Cross-validation results and out-of-sample risk assessments show good performance of the method to identify spare parts with high end-of-supply risk. Further validation was provided by survey results obtained from the maintenance repair organization, which show strong agreement between the firms' and our model's identification of high-risk spare parts.

When planning capacity, a firm should make a long-term plan which consists of a sequence of capacity decisions and a policy according to which it changes its capacity to adapt to the demand changes and to respond to the competitor's capacity. When determining the new product launch timing, a firm should consider both the competition between the new product and the existing one, and the competition between firms for the two products. The optimal product launch timing depends on the competitive situation a firm is in. When determining the optimal anti-counterfeiting strategy, a firm should take into account the type of counterfeiting in decision making because the competition mechanics is different. When assessing risk for long field-life systems, a firm should monitor its supply chain and develop supply chain indicators to proactively identify parts at risk. In Appendix D, I state my contributions in each chapter of this dissertation (**Chapters 3-6**).

Dynamic decision making under competition is a broad area which requires extensive research. Future research should focus on the interaction between dynamic and competitive strategies, e.g., how can a firm utilize its competitive advantage to hedge against demand uncertainty, and the impact of a combined strategy on a firm's operations.

Appendix A

Proofs to all Corollaries, Lemmas Propositions, and Theorems

Proposition 3.1. *Under Assumptions 1,2, and 3, if firm j adopts the reactive strategy, the optimal value function* V_{tj}^* *is jointly concave in* (k_{t-1j}, k_{tj}) *for any given current capacity of the opponent* $k_{ti} \in \mathscr{K}_{ti}$ *or* $k_{t-1i} \in \mathscr{K}_{t-1i}$ $(i \neq j)$ *and for each* $\omega_t \in \Theta$*.*

Proof. Follow the reasoning of *Theorem 1 from Eberly and Van Mieghem (1997): satisfying Assumptions 1, 2, and 3, they show by induction and a concavity preservation lemma that a single firm's optimal value function* $V_t(k_{t-1}, \omega_t)$ *is jointly concave in* (k_{t-1}, k_t) *for each* $\omega_t \in \Theta$*. In the reactive case with a given capacity of the opponent,* $k_{\tau i}$ *which is invariant for all* $\tau > t$*, firm j's optimal value function* $V_{tj}^*(k_{ti}, k_{t-1j}, \omega_t)$ *is jointly concave in* (k_{t-1j}, k_{tj}) *for each* $\omega_t \in \Theta$*.* □

Theorem 3.1. *Given the current capacity of the opponent* $k_{ti} \in \mathscr{K}_{ti}$ $(i \neq j)$ *and* $\omega_t \in \Theta$*, if firm j's optimal value function* V_{tj}^* *is jointly concave in* (k_{t-1j}, k_{tj}) *and there exists a unique solution to the optimization problem in* *equation* (3.11) *if* $j = f$ *or in equation* (3.12) *if* $j = l$*, then the solution is an ISD policy that is characterized by the following lowerbound and upperbound functions:*

$$K_{tj}^{L}(k_{ti}, \omega_t) = \sup\left\{\{k_{tj_o}\} \cup \{k_{tj} : \frac{\nabla_- G_{tj}(k_{ti}, k_{tj}, \omega_t)}{\nabla k_{tj}} \geq c_{tj}, \quad k_{tj} \in \mathscr{K}_{tj}\}\right\} \tag{3.13}$$

$$K_{tj}^{H}(k_{ti}, \omega_t) = \inf\left\{\{k_{tj_e}\} \cup \{k_{tj} : \frac{\nabla_+ G_{tj}(k_{ti}, k_{tj}, \omega_t)}{\nabla k_{tj}} \leq r_{tj}, \quad k_{tj} \in \mathscr{K}_{tj}\}\right\} \tag{3.14}$$

Proof. If firm j's optimization problem V_{tj}^* is jointly concave in (k_{t-1j}, k_{tj}) for any given $k_{ti} \in \mathscr{K}_{ti}$ and for each $\omega_t \in \Theta$, the function $G_{tj}(k_{ti}, k_{tj}, \omega_t)$ is concave in k_{tj} under Assumption 3.1, as a sum of concave functions is concave. The rest of the theorem then follows the reasoning of *Theorem 2* in Eberly and Van Mieghem (1997). □

Corollary 3.1. *Let* k_{tj}^L *and* k_{tj}^H *denote the lowerbound and upperbound computed by the two boundary functions in Theorem 3.1, i.e.,* $k_{tj}^L = K_{tj}^L(k_{ti}, \omega_t)$ *and* $k_{tj}^H = K_{tj}^H(k_{ti}, \omega_t)$*:* $k_{tj}^L \leq k_{tj}^H$*.*

Proof. Under Assumption 3.2, which specifies $c_{tj} > r_{tj}$, and concavity of the optimization problem in equation (3.11) or (3.12), it guarantees that $k_{tj}^L \leq k_{tj}^H$. □

Proposition 3.2. $S_{[k_{tj_o}, k_{tj_e}]} \subseteq S^r_{[k_{tj_o}, k_{tj_e}]} = [k_{tj}^L, k_{tj}^H]$.

Proof. We write $G_{tj}(k)$ to represent the expected NPV function $G_{tj}(k_{ti}, k_{tj} = k, \omega_t)$ (see equations (9) and (10)). According to equations (13) and (14), $\frac{\nabla_- G_{tj}(k_{tj}^L)}{\nabla k_{tj}^L} \geq c_{tj}$ and $\frac{\nabla_+ G_{tj}(k_{tj}^H)}{\nabla k_{tj}^H} \leq r_{tj}$. Thus, $\frac{G_{tj}(k) - G_{tj}(k_{tj}^L)}{k - k_{tj}^L} \geq \frac{\nabla_- G_{tj}(k_{tj}^L)}{\nabla k_{tj}^L} \geq c_{tj}$, $\forall k < k_{tj}^L$, and $\frac{G_{tj}(k) - G_{tj}(k_{tj}^H)}{k - k_{tj}^H} \leq \frac{\nabla_+ G_{tj}(k_{tj}^H)}{\nabla k_{tj}^H} \leq r_{tj}$, $\forall k > k_{tj}^H$. This means that if the current capacity is smaller than k_{tj}^L or larger than k_{tj}^H, the optimal decision is to adjust it to maximize the value of the objective function in equation (11) or (12). If $k_{tj}^L > k_{tj}^H$, $S_{[k_{tj_o}, k_{tj_e}]} = [k_{tj}^L, k_{tj}^H] = \emptyset$; if $k_{tj}^L \leq k_{tj}^H$, $S_{[k_{tj_o}, k_{tj_e}]} \subseteq [k_{tj}^L, k_{tj}^H] \neq \emptyset$. In conclusion, $S_{[k_{tj_o}, k_{tj_e}]} \subseteq S^r_{[k_{tj_o}, k_{tj_e}]} = [k_{tj}^L, k_{tj}^H]$. □

Proposition 3.3. *k_{tj}^L and k_{tj}^H are the lowerbound and the upperbound of $S_{[k_{tjo},k_{tje}]}$.*

Proof. Assume there exists $k_1 = \inf\{k : \frac{G_{tj}(k_{tj}^L)-G_{tj}(k)}{k_{tj}^L-k} \geq c_{tj}, \quad k > k_{tj}^L\}$ and $k_2 = \sup\{k : \frac{G_{tj}(k_{tj}^H)-G_{tj}(k)}{k_{tj}^H-k} \leq r_{tj}, \quad k < k_{tj}^H\}$. Thus: $\frac{G_{tj}(k_{tj}^L)-G_{tj}(k_1)}{k_{tj}^L-k_1} \geq c_{tj}$, $\frac{G_{tj}(k_{tj}^L)-G_{tj}(k)}{k_{tj}^L-k} < c_{tj}$, $\forall k : k_{tj}^L < k < k_1$; and $\frac{G_{tj}(k_{tj}^H)-G_{tj}(k_2)}{k_{tj}^H-k_2} \leq r_{tj}$, $\frac{G_{tj}(k_{tj}^H)-G_{tj}(k)}{k_{tj}^H-k} > r_{tj}$, $\forall k : k_2 < k < k_{tj}^H$. According to equations (13) and (14), $\frac{G_{tj}(k)-G_{tj}(k_{tj}^L)}{k-k_{tj}^L} \geq \frac{\nabla_- G_{tj}(k_{tj}^L)}{\nabla k_{tj}^L} \geq c_{tj}$, $\forall k < k_{tj}^L$, and $\frac{G_{tj}(k)-G_{tj}(k_{tj}^H)}{k-k_{tj}^H} \leq \frac{\nabla_+ G_{tj}(k_{tj}^H)}{\nabla k_{tj}^H} \leq r_{tj}$, $\forall k > k_{tj}^H$. Adding the inequalities, we get the following: $\frac{G_{tj}(k)-G_{tj}(k_1)}{k-k_1} > c_{tj}$, $\forall k : k_{tj}^L < k < k_1$, and $\frac{G_{tj}(k)-G_{tj}(k_2)}{k-k_2} < r_{tj}$, $\forall k : k_2 < k < k_{tj}^H$; $\frac{G_{tj}(k)-G_{tj}(k_1)}{k-k_1} \geq c_{tj}$, $\forall k < k_{tj}^L$, and $\frac{G_{tj}(k)-G_{tj}(k_2)}{k-k_2} \leq r_{tj}$, $\forall k > k_{tj}^H$. Hence, $\frac{G_{tj}(k)-G_{tj}(k_1)}{k-k_1} \geq c_{tj}$, $\forall k < k_1$, and $\frac{G_{tj}(k)-G_{tj}(k_1)}{k-k_1} \leq r_{tj}$, $\forall k > k_2$.

According to the definitions of k_{tj}^L and k_{tj}^H (see equations (13) and (14)), the marginal values at $k_1$and k_2 are: $\frac{\nabla_- G_{tj}(k_1)}{\nabla k_1} < c_{tj}$ and $\frac{\nabla_+ G_{tj}(k_2)}{\nabla k_2} > r_{tj}$. This contradicts the claim $\frac{G_{tj}(k)-G_{tj}(k_1)}{k-k_1} \geq c_{tj}$, $\forall k < k_1$, and $\frac{G_{tj}(k)-G_{tj}(k_1)}{k-k_1} \leq r_{tj}$, $\forall k > k_2$. $k_1 > k_{tj}^L$ and $k_2 < k_{tj}^H$ such that $\frac{G_{tj}(k_{tj}^L)-G_{tj}(k_1)}{k_{tj}^L-k_1} \geq c_{tj}$ and $\frac{G_{tj}(k_{tj}^H)-G_{tj}(k_2)}{k_{tj}^H-k_2} \leq r_{tj}$ does not exist. Therefore, $k_{tj}^L, k_{tj}^H \in S_{[k_{tjo},k_{tje}]}$. According to Proposition 2, $S_{[k_{tjo},k_{tje}]} \subseteq S^r_{[k_{tjo},k_{tje}]} = [k_{tj}^L, k_{tj}^H]$. Hence, k_{tj}^L and k_{tj}^H are the lowerbound and the upperbound of $S_{[k_{tjo},k_{tje}]}$. □

Proposition 3.4. *The rolling up and rolling down procedures eliminate all non-stayput capacity values from the interval $[I_o^n, I_e^n]$.*

Proof. At each iteration of the rolling up procedure, k is eliminated if $k \notin S^r_{[I_o^n,k]}$. According to Proposition 2, $k \notin S_{[I_o^n,k]}$ if $k \notin S^r_{[I_o^n,k]}$. If k is a non-stayput point in $\mathscr{K}$, k is also a non-stayput point in any space that contains $\mathscr{K}$. Hence, $k \notin S_{[a,b]}$, for any $[a,b] \supseteq [I_o^n, k]$, thus $k \notin S_{[I_o^n,I_e^n]}$. In other words, capacity values that are eliminated by the rolling up procedure are the non-stayput points in the interval $[I_o^n, I_e^n]$. By the same token, capacity values that are eliminated by the rolling down procedure are also the non-stayput points.

Next, we prove that all of the remaining values are the stayput points in the interval $[I_o^n, I_e^n]$. At each iteration of the rolling up procedure, k is kept if $k \in S^r_{[I_o^n,k]}$. According to Proposition 3, $k \in S_{[I_o^n,k]}$ if $S^r_{[I_o^n,k]} = [\cdot, k]$. The rolling down procedure follows the same argument as the rolling up procedure: $k \in S_{[k,I_e^n]}$ if $S^r_{[k,I_e^n]} = [k, \cdot]$. After the rolling up and rolling down procedures, any remaining capacity value k is a stayput point in the interval $[I_o^n, I_e^n]$ as k should neither be adjusted to any point in $[I_o^n, k]$ nor to any point in $[k, I_e^n]$. □

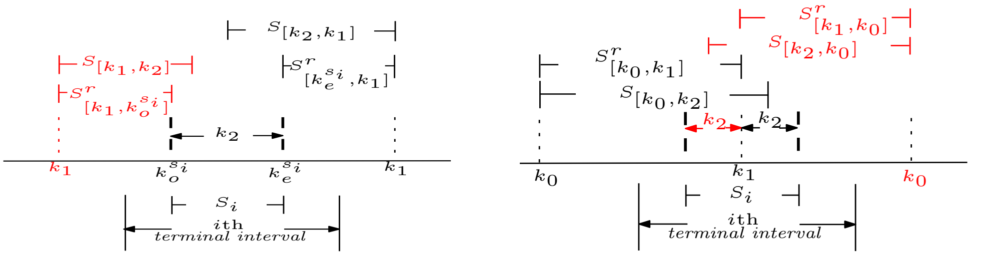
Proposition 3.5. *Given the stayput region in the ith terminal interval,* $S_i = [k_o^{s_i}, k_e^{s_i}]$*, if there exists a capacity value* $k_1 > k_e^{s_i}$ *satisfying* $k_1 \in S^r_{[k_e^{s_i},k_1]}$ *(or* $k_1 < k_o^{s_i}$ *satisfying* $k_1 \in S^r_{[k_1,k_o^{s_i}]}$*), then* $k_1 \in S_{[k_2,k_1]}$ *(or* $k_1 \in S_{[k_1,k_2]}$*),* $\forall k_2 \in S_i$.

Proof. Given $S_i = [k_o^{s_i}, k_e^{s_i}]$, $\frac{G(k_e^{s_i})-G(k)}{k_e^{s_i}-k} > r$, $\forall k \in [k_o^{s_i}, k_e^{s_i})$. If there exists a capacity value $k_1 > k_e^{s_i}$ satisfying $k_1 \in S^r_{[k_e^{s_i},k_1]}$, then $k_1 \in S_{[k_e^{s_i},k_1]}$ according to Proposition 3. Thus, $\frac{G(k_1)-G(k_e^{s_i})}{k_1-k_e^{s_i}} > r$. Adding the inequality $G(k_1)-G(k_e^{s_i}) > r(k_1-k_e^{s_i})$ to the inequality $G(k_e^{s_i})-G(k) > r(k_e^{s_i}-k)$, we get: $\frac{G(k_1)-G(k)}{k_1-k} > r$, $\forall k \in [k_o^{s_i}, k_e^{s_i})$. In conclusion, $k_1 \in S_{[k_2,k_1]}$, $\forall k_2 \in S_i$. The proof for the case where $k_1 < k_o^{s_i}$ follows the same argument. See Figure A.1a for an illustration. The red symbols indicate the case in the brackets. □

Proposition 3.6. *Given the stayput region in the ith terminal interval,* S_i*, if there exists* $k_1 \in S_i$ *and* $k_0 < k_1$ *such that* $k_1 \in S^r_{[k_0,k_1]}$ *(or exists* $k_0 > k_1$ *such that* $k_1 \in S^r_{[k_1,k_0]}$*), then* $k_2 \in S_{[k_0,k_2]}$*,* $\forall k_2 : k_1 < k_2 \in S_i$ *(or* $k_2 \in S_{[k_2,k_0]}$*,* $\forall k_2 : k_1 > k_2 \in S_i$*).*

Proof. If there exists $k_1 \in S_i$ and $k_0 < k_1$ such that $k_1 \in S^r_{[k_0,k_1]}$, then $k_1 \in S_{[k_0,k_1]}$ according to Proposition 3. Thus, $\frac{G(k_1)-G(k_0)}{k_1-k_0} > r$. $\forall k_2 : k_1 < k_2 \in S_i$, $\frac{G(k_2)-G(k_1)}{k_2-k_1} > r$. Adding the inequality $G(k_1) - G(k_0) > r(k_1 - k_0)$ to the inequality $G(k_2) - G(k_1) > r(k_2 - k_1)$, we get: $\forall k_2 : k_1 < k_2 \in S_i$, $\frac{G(k_2)-G(k_0)}{k_2-k_0} > r$, i.e., $k_2 \in S_{[k_0,k_2]}$. The proof for the case where $k_0 > k_1$

follows the same argument. See Figure A.1b for an illustration. The red symbols indicate the case in brackets. □



(a) Proposition 5 (b) Proposition 6

Figure A.1: Figures illustrating Propositions 5 and 6

Theorem 3.2. *Given S_{ti}, $k_{t-1i} \in \mathscr{K}_{t-1i}$ $(i \neq j)$, and $\omega_t \in \Theta$, the solution to firm j's optimization problem in period t (see equation* (3.11) *or* (3.12)*) can be represented in the form of an ISD policy. The stayput region $S_{tj}(S_{ti}, k_{t-i}, \omega_t)$, can be derived by the Decomposition Algorithm.*

Proof. The first part of theorem follows directly as the optimal solution to firm j's investment problem in period t can be expressed by a set of capacity values, of which the associated value of equation (3.11) or (3.12) cannot be improved. According to Propositions 3.2-3.6, the set of capacity values computed by the *Decomposition Algorithm* is firm j's stayput region in period t. □

Proposition 3.7. *Given $k_{t-1j} = k$ and $k \notin S_{tj}(S_{ti}, k_{t-1i}, \omega_t)$ $(i \neq j)$, if the optimal investment policy indicated by $S_{tj}(S_{ti}, \omega_t)$ assigns $k_{tj} = b$, then no stayput values exist in the interval $[k, b)$, $\forall k < b$, or in the interval $(b, k]$, $\forall k > b$. In other words, the interval $[k, b)$ or $(b, k] \nsubseteq S_{tj}(S_{ti}, k_{t-1i}, \omega_t)$.*

Proof. The optimal investment policy assigns $k_{tj} = b$ when $k_{t-1j} = k$, thus $G_{tj}(b) - c_{tj} \times (b - k) \geq G_{tj}(k') - c_{tj} \times (k' - k)$, $\forall k' \geq k$ in the case where $b > k$,. Therefore, $\frac{G_{tj}(b) - G_{tj}(k')}{b - k'} \geq c_{tj}$, $\forall k' \in [k, b)$. In other words, capacity values in the interval $[k, b)$ need to be adjusted to b in order to maximize the value of the objective function in equation (11) or (12), i.e., $[k, b] \nsubseteq S_{tj}(S_{ti}, k_{t-1i}, \omega_t)$. The proof for the case where $b < k$ follows the same argument. □

Corollary 3.2. *Given two consecutive stayput intervals, $[k^{L1}, k^{H1}]$ and $[k^{L2}, k^{H2}]$, there exists an investment threshold k, $k^{H1} \leq k \leq k^{L2}$, such that the optimal investment policy assigns all capacity in (k^{H1}, k) to be adjusted downwards to the upperbound of the lower stayput interval (i.e., k^{H1}) and assigns all capacity in (k, k^{L2}) to be adjusted upwards to the lowerbound of the higher stayput interval (i.e., k^{L2}). If $k^{H1} < k < k^{L2}$, there is no difference between adjusting k to the closet boundary of either close-by interval.*

Proof. For any non-stayput capacity value k, $k^{H1} < k < k^{L2}$, that is between the two consecutive stayput intervals, $[k^{L1}, k^{H1}]$ and $[k^{L2}, k^{H2}]$, an adjustment should be made to either k^{L2} or k^{H1} according to Proposition 3.7. By comparing the expected NPV of adjusting k to k^{H1} with the one of adjusting k to k^{L2}, a decision whether to invest or disinvest can be made. Under Assumption 3.2, which specifies $r_{tj} < c_{tj}$, the function $Threshold(k, k^{H1}, k^{L2}) = G_{tj}(k^{L2}) - c_{tj} \times (k^{L2} - k) - G_{tj}(k^{H1}) - r_{tj} \times (k - k^{H1})$ is monotonously increasing in k. The rest of corollary then follows. □

Lemma 4.1. *If a monopolist with a total capacity k_m and unit investment cost c_m^A for the NGP decides to invest at the early stage, its optimal NGP capacity is $k_{m|e}^{*A} = \frac{N}{2} - \frac{c_m^A}{2\bar{\theta}\triangle S} N$ and its optimal profit is $\mathbb{E}_e[\Pi_m^*(k_m^A, \theta)] = \frac{\bar{\theta}}{N} S^B k_m(N - k_m) + \frac{\bar{\theta}\triangle S - c_m^A}{2} \times (\frac{N}{2} - \frac{c_m^A}{2\bar{\theta}\triangle S} N)$. If it decides to invest at the late stage, its optimal NGP capacity is $k_{m|l}^{*A} = \frac{N}{2} - \frac{c_m^A}{2\theta\triangle S} N$, and its optimal ex-ante profit is $\mathbb{E}_l[\Pi_m^*(k_m^A, \theta)] = \frac{\bar{\theta}}{N} S^B k_m(N - k_m) + \frac{\bar{\theta}\triangle S - c_m^A}{2} \times (\frac{N}{2} - \frac{c_m^A}{2\triangle S} N\mathbb{E}(\frac{1}{\theta}))$.*

Proof. Substituting $k_{-i} = \widehat{k_{-i}^A} = 0$ into equations (4.5) and (4.6) and solving for k_i^{*A}, respectively. The Lemma then follows. □

Proposition 4.1. *A monopolist will always invest late.*

Proof. Since the arithmetic mean $\overline{\theta}$ is always larger than the harmonic mean $\frac{1}{\mathbb{E}(\frac{1}{\theta})}$, $\mathbb{E}_e[\Pi_m^*(k_m^A, \theta)] > \mathbb{E}_l[\Pi_m^*(k_m^A, \theta)]$ (see Lemma 4.1). Thus, a monopolist will always postpone its investment until demand uncertainty is resolved. □

Lemma 4.2. *If both firms invest early, i.e., (E, E), then the equilibrium capacity is $k_i^{*A} = \frac{N}{3} + \frac{c_{-i}^A - 2c_i^A}{3\overline{\theta}\triangle S}N$, and the equilibrium expected profit is $\mathbb{E}_e[\pi_i^*(k_i^A, k_{-i}^{*A}, \theta)] = \frac{\overline{\theta}}{N}S^B k_i(N - k_i - k_{-i}) + (\frac{N}{3} + \frac{c_{-i}^A - 2c_i^A}{3\overline{\theta}\triangle S}N)(\frac{\overline{\theta}\triangle S}{3} + \frac{c_{-i}^A - 2c_i^A}{3})$, $\forall i = x, y$.*

Proof. In the equilibrium strategy where both firms invest simultaneously, $k_i^{*A} = R_i(k_{-i}^{*A})$ and $k_{-i}^{*A} = R_{-i}(k_i^{*A})$. Substituting the best response function of the other firm, i.e., $R_{-i}(k_i^{*A}) = \frac{N}{2} - \frac{k_i^{*A}}{2} - \frac{c_{-i}^A}{2\theta\triangle S}N$, into k_i^{*A} and taking the expected value of θ, firm i's optimal NGP capacity at the early investment stage is: $k_i^{*A} = \frac{N}{3} + \frac{c_{-i}^A - 2c_i^A}{3\overline{\theta}\triangle S}N$. Firm i's optimal expected profit is then $\mathbb{E}_e[\pi_i^*(k_i^A, k_{-i}^{*A}, \theta)] = \frac{\overline{\theta}}{N}S^B k_i(N - k_i - k_{-i}) + (\frac{N}{3} + \frac{c_{-i}^A - 2c_i^A}{3\overline{\theta}\triangle S}N)(\frac{\overline{\theta}\triangle S}{3} + \frac{c_{-i}^A - 2c_i^A}{3})$. □

Lemma 4.3. *If firm i invests early and firm $-i$ invests late, i.e., (E, L) or (L, E), then the equilibrium capacity is $k_i^{*A} = \frac{N}{2} + \frac{c_{-i}^A - 2c_i^A}{2\overline{\theta}\triangle S}N$ and $k_{-i}^{*A} = \frac{N}{4} + \frac{2c_i^A - c_{-i}^A}{4\overline{\theta}\triangle S}N - \frac{c_{-i}^A}{2\theta\triangle S}N$. The equilibrium expected profits are $\mathbb{E}_e[\pi_i^*(k_i^A, k_{-i}^{*A}, \theta)] = \frac{\overline{\theta}}{N}S^B k_i(N - k_i - k_{-i}) + (\frac{N}{2} + \frac{c_{-i}^A - 2c_i^A}{2\overline{\theta}\triangle S}N)(\frac{\overline{\theta}\triangle S}{4} + \frac{c_{-i}^A - 2c_i^A}{4})$ and $\mathbb{E}_l[\pi_{-i}^*(k_{-i}^A, k_i^{*A}, \theta)] = \frac{\overline{\theta}}{N}S^B k_{-i}(N - k_i - k_{-i}) + \frac{\overline{\theta}\triangle S}{16}N - \frac{c_{-i}^A}{4}N + (2c_i^A - c_{-i}^A)(\frac{N}{8} + \frac{2c_i^A - 5c_{-i}^A}{16\overline{\theta}\triangle S}N) + \frac{(c_{-i}^A)^2}{4\triangle S}N\mathbb{E}(\frac{1}{\theta})$.*

Proof. If firm i moves first, we substitute the best response function of the other firm, i.e., $R_{-i}(k_i^A) = \frac{N}{2} - \frac{k_i^A}{2} - \frac{c_{-i}^A}{2\theta\triangle S}N$, into firm i's profit function: $\pi_i(k_i^A, k_{-i}^{*A}, \theta) = \frac{\theta}{N}S^B k_i(N - k_i - k_{-i}) + \frac{\theta}{N}\triangle S k_i^A(\frac{N}{2} - \frac{k_i^A}{2}) + \frac{c_{-i}^A - 2c_i^A}{2}k_i^A$, which is concave in k_i^A. Taking the expected value of θ, firm i's optimal NGP capacity at the early investment stage is $k_i^{*A} = \frac{N}{2} + \frac{c_{-i}^A - 2c_i^A}{2\overline{\theta}\triangle S}N$ and the optimal expected profit is $\mathbb{E}_e[\pi_i^*(k_i^A, k_{-i}^{*A}, \theta)] = \frac{\overline{\theta}}{N}S^B k_i(N - k_i - k_{-i}) + (\frac{N}{2} + \frac{c_{-i}^A - 2c_i^A}{2\overline{\theta}\triangle S}N)(\frac{\overline{\theta}\triangle S}{4} + \frac{c_{-i}^A - 2c_i^A}{4})$. If firm i moves second in the competition, its optimal NGP capacity is derived by substituting the optimal NGP capacity of the first mover into the best response function of firm i: $k_i^{*A} = \frac{N}{4} + \frac{2c_{-i}^A - c_i^A}{4\overline{\theta}\triangle S}N - \frac{c_i^A}{2\overline{\theta}\triangle S}N$. Firm i's optimal ex-ante expected profit is then $\mathbb{E}_l[\pi_i^*(k_{-i}^A, k_i^{*A}, \theta)] = \frac{\overline{\theta}}{N}S^B k_i(N - k_i - k_{-i}) + \frac{\overline{\theta}\triangle S}{16}N - \frac{c_i^A}{4}N + (2c_{-i}^A - c_i^A)(\frac{N}{8} + \frac{2c_{-i}^A - 5c_i^A}{16\overline{\theta}\triangle S}N) + \frac{(c_i^A)^2}{4\triangle S}N\mathbb{E}(\frac{1}{\theta})$. □

Lemma 4.4. *If both firms invest late, i.e., (L, L), then the equilibrium capacity is $k_i^{*A} = \frac{N}{3} + \frac{c_{-i}^A - 2c_i^A}{3\theta\triangle S}N$, and the equilibrium expected profit is $\mathbb{E}_l[\pi_i^*(k_i^A, k_{-i}^{*A}, \theta)] = \frac{\overline{\theta}}{N}S^B k_i(N - k_i - k_{-i}) + \frac{\overline{\theta}\triangle S}{9}N + \frac{2}{9}N(c_{-i}^A - 2c_i^A) + \frac{(c_{-i}^A - 2c_i^A)^2}{9\triangle S}N\mathbb{E}(\frac{1}{\theta})$, $\forall i = x, y$.*

Proof. In the equilibrium strategy where both firms invest simultaneously, $k_i^{*A} = R_i(k_{-i}^{*A})$ and $k_{-i}^{*A} = R_{-i}(k_i^{*A})$. Substituting the best response function of the other firm, i.e., $R_{-i}(k_i^{*A}) = \frac{N}{2} - \frac{k_i^{*A}}{2} - \frac{c_{-i}^A}{2\theta\triangle S}N$, into k_i^{*A}, firm i's optimal NGP capacity at the late investment stage is $k_i^{*A} = \frac{N}{3} + \frac{c_{-i}^A - 2c_i^A}{3\theta\triangle S}N$. Firm i's optimal ex-ante expected profit is then $\mathbb{E}_l[\pi_i^*(k_i^A, k_{-i}^{*A}, \theta)] = \frac{\overline{\theta}}{N}S^B k_i(N - k_i - k_{-i}) + \frac{\overline{\theta}\triangle S}{9}N + \frac{2}{9}N(c_{-i}^A - 2c_i^A) + \frac{(c_{-i}^A - 2c_i^A)^2}{9\triangle S}N\mathbb{E}(\frac{1}{\theta})$. □

Theorem 4.1. *In the competition with no demand uncertainty, the following pure strategy equilibria to the investment timing game exist:*

1. *If $M_i > \frac{1}{7}(c_i^A - c_{-i}^A)$, $\forall i = x, y$, then both firms invest early, i.e., (E, E).*

2. *If $M_{-i} \leq \frac{1}{7}(c_{-i}^A - c_i^A)$, then firm i invests early and firm $-i$ invests late.*

Proof. Substituting $\mathbb{E}(\frac{1}{\theta}) = \frac{1}{overline\theta}$ into a firm's equilibrium (ex-ante) expected profit described in Lemmas 4.2-4.4 and comparing the profit of firm x or firm y in different equilibrium strategies, we find: (i) if $\Big((\overline{\theta} \triangle S - c_y^A) - (c_y^A - c_x^A)\Big) \times \Big((\overline{\theta} \triangle S - c_y^A) - \frac{17}{7}(c_x^A - c_y^A)\Big) > 0$ and $\Big((\overline{\theta} \triangle S - c_x^A) - (_x^A - c_y^A)\Big) \times \Big((\overline{\theta} \triangle S - c_x^A) - \frac{17}{7}(c_y^A - c_x^A)\Big) > 0$, then both firms invest early, i.e., (E, E); (ii) $\Big((\overline{\theta} \triangle S - c_y^A) - 2(c_x^A - c_y^A)\Big)^2 \geq 0$, which will always hold, and $\Big((\overline{\theta} \triangle S - c_x^A) - (c_x^A - c_y^A)\Big) \times \Big((\overline{\theta} \triangle S - c_x^A) - \frac{17}{7}(c_y^A - c_x^A)\Big) \leq 0$, then firm x invests early and firm y invests late, i.e., (E, L); (iii) if $\Big((\overline{\theta} \triangle S - c_y^A) - (c_y^A - c_x^A)\Big) \times \Big((\overline{\theta} \triangle S - c_y^A) - \frac{17}{7}(c_x^A - c_y^A)\Big) \leq 0$ and $\Big((\overline{\theta} \triangle S - c_x^A) - 2(c_y^A - c_x^A)\Big)^2 \geq 0$, which will always hold, then firm x waits and firm y invests early, i.e., (L, E); (iv) since $\Big((\overline{\theta} \triangle S - c_y^A) - 2(c_x^A - c_y^A)\Big)^2 < 0$ and $\Big((\overline{\theta} \triangle S - c_x^A) - 2(c_y^A - c_x^A)\Big)^2 < 0$, will never hold, the equilibrium strategy where both firms invest late, i.e., (L, L), will not exist.

The function $g = \Big((\overline{\theta} \triangle S - c_y^A) - \times(c_y^A - c_x^A)\Big) \times \Big((\overline{\theta} \triangle S - c_y^A) - \frac{17}{7} \times (c_x^A - c_y^A)\Big)$ is concave in $(c_y^A - c_x^A)$. Let the function g equals 0, we get: $c_x^A - c_y^A = \frac{7}{17} \times (\overline{\theta} \triangle S - c_y^A)$ or $c_y^A - c_x^A = \frac{1}{2} \times (\overline{\theta} \triangle S - c_x^A)$. The function $f = \Big((\overline{\theta} \triangle S - c_x^A) - \times(c_x^A - c_y^A)\Big) \times \Big((\overline{\theta} \triangle S - c_x^A) - \frac{17}{7} \times (c_y^A - c_x^A)\Big)$ is concave in $(c_y^A - c_x^A)$. Let the function f equals 0, we get: $c_x^A - c_y^A = \frac{1}{2} \times (\overline{\theta} \triangle S - c_y^A)$ or $c_y^A - c_x^A = \frac{7}{17} \times (\overline{\theta} \triangle S - c_x^A)$. The *non-negativity* assumption in equation (4.4) specifies $\overline{\theta} \triangle S \geq \max\{2c_{-i}^A - c_i^A, \forall i = x, y\}$ (see equation (4.9)), the theorem then follows. □

Theorem 4.2. *The following pure strategy equilibria to the investment timing game exist:*

1. *If* $M_{-i} \times \Big(M_i - \frac{1}{7}(c_i^A - c_{-i}^A)\Big) > \frac{4}{7}r \times \Big(c_i^A\Big)^2$, $\forall i = x, y$, *then both firms invest early, i.e.,* (E, E).
2. *If* $\Big(M_i\Big)^2 > \frac{8}{9}r \times \Big(c_{-i}^A - 2c_i^A\Big)^2$ *and* $M_i \times \Big(M_{-i} - \frac{1}{7}(c_{-i}^A - c_i^A)\Big) \leq \frac{4}{7}r \times \Big(c_{-i}^A\Big)^2$, *then firm* i *invests early and firm* $-i$ *invests late, i.e.,* (E, L) *or* (L, E).
3. *If* $\Big(M_{-i}\Big)^2 \leq \frac{8}{9}r \times \Big(c_i^A - 2c_{-i}^A\Big)^2$, $\forall i = x, y$, *then both firms invest late, i.e.,* (L, L).

Proof. Comparing the profit of firm x or firm y in each equilibrium strategy (see Lemmas 4.2-4.4), we find: (i) if $\big(c_x^A\big)^2 \times (-Cov) < \frac{7}{36} \times \Big((\overline{\theta} \triangle S - c_x^A) - 2(c_y^A - c_x^A)\Big) \times \Big((\overline{\theta} \triangle S - c_y^A) - \frac{17}{7}(c_x^A - c_y^A)\Big)$ and $\big(c_y^A\big)^2 \times (-Cov) < \frac{7}{36} \times \Big((\overline{\theta} \triangle S - c_y^A) - 2(_x^A - c_y^A)\Big) \times \Big((\overline{\theta} \triangle S - c_x^A) - \frac{17}{7}(c_y^A - c_x^A)\Big)$, then both firms invest early, i.e., (E, E); (ii) $\big(c_y^A - 2c_x^A\big)^2 \times (-Cov) < \frac{1}{8}\Big((\overline{\theta} \triangle S - c_y^A) - 2(c_x^A - c_y^A)\Big)^2$ and $\big(c_y^A\big)^2 \times (-Cov) \geq \frac{7}{36} \times \Big((\overline{\theta} \triangle S - c_y^A) - 2(c_x^A - c_y^A)\Big) \times \Big((\overline{\theta} \triangle S - c_x^A) - \frac{17}{7}(c_y^A - c_x^A)\Big)$, then firm x invests early and firm y invests late, i.e., (E, L); (iii) if $\big(c_x^A\big)^2 \times$

$(-Cov) \geq \frac{7}{36} \times \Big((\overline{\theta} \triangle S - c_x^A) - 2(c_y^A - c_x^A) \Big) \times \Big((\overline{\theta} \triangle S - c_y^A) - \frac{17}{7}(c_x^A - c_y^A) \Big)$ and $\big(c_x^A - 2c_y^A\big)^2 \times (-Cov) < \frac{1}{8}\Big((\overline{\theta} \triangle S - c_x^A) - 2(c_y^A - c_x^A) \Big)^2$, then firm x waits and firm y invests early, i.e., (L, E); (iv) if $\big(c_y^A - 2c_x^A\big)^2 \times (-Cov) \geq \frac{1}{8}\Big((\overline{\theta} \triangle S - c_y^A) - 2(c_x^A - c_y^A) \Big)^2$ and $\big(c_x^A - 2c_y^A\big)^2 \times (-Cov) \geq \frac{1}{8}\Big((\overline{\theta} \triangle S - c_x^A) - 2(c_y^A - c_x^A) \Big)^2$, then both firms invest late, i.e., (L, L). □

Proposition 4.2. *For a monopolist with unit investment costs c_m^A and $c_m^{A^+}$ for A and A^+: if $r \times \Big((1 - pr)(c_m^A)^2 + \frac{\triangle S}{S} pr (c_m^{A^+})^2 \Big) < pr \times \Big(\frac{\triangle S}{S} c_m^{A^+} (\overline{\theta} S - c_m^{A^+}) - c_m^A(\overline{\theta} \triangle S - c_m^A) - \overline{\theta} \triangle S \big(\overline{\theta} \triangle S^+ - (c_m^{A^+} - c_m^A) \big) \Big)$, it will invest early; otherwise, it will invest late.*

Proof. If a monopolist decides to invest early, its optimal NGP capacity is $k_m^{*A} = \frac{\overline{\theta}\triangle S - c_m^A}{2\overline{\theta}\triangle S} N$ and the optimal profit is $\mathbb{E}_e[\Pi_m^*(k_m^A, \theta)] = \frac{\overline{\theta}}{N} S^B k_m (N - k_m) + \frac{\overline{\theta}\triangle S - c_m^A}{2} \times (\frac{N}{2} - \frac{c_m^A}{2\overline{\theta}\triangle S} N)$. If it decides to invest late, its optimal NGP capacity is $k_m^{*A} = \frac{\overline{\theta}\triangle S - c_m^A}{2\theta\triangle S} N$ or $k_m^{*A^+} = \frac{\overline{\theta} S - c_m^{A^+}}{2\theta S} N$ and its optimal ex-ante profit is $\mathbb{E}_l[\Pi_m^*(k_m^A, \theta)] = (1 - pr) \times \Big(\frac{\overline{\theta}}{N} S^B k_m (N - k_m) + \frac{\overline{\theta}\triangle S - c_m^A}{2} \times (\frac{N}{2} - \frac{c_m^A}{2\triangle S} N \mathbb{E}(\frac{1}{\theta})) \Big) + pr \times \Big(\frac{\overline{\theta}}{N} S^B k_m (N - k_m) + \frac{\overline{\theta} S - c_m^{A^+}}{2} \times (\frac{N}{2} - \frac{c_m^{A^+}}{2S} N \mathbb{E}(\frac{1}{\theta})) \Big)$. If $r \times \Big((1 - pr)(c_m^A)^2 + \frac{\triangle S}{S} pr (c_m^{A^+})^2 \Big) < pr \times \Big(\frac{\triangle S}{S} c_m^{A^+} (\overline{\theta} S - c_m^{A^+}) - c_m^A(\overline{\theta} \triangle S - c_m^A) - \overline{\theta} \triangle S \big(\overline{\theta} \triangle S^+ - (c_m^{A^+} - c_m^A) \big) \Big)$, $\mathbb{E}_e[\Pi_m^*(k_m^A, \theta)] > \mathbb{E}_l[\Pi_m^*(k_m^A, \theta)]$, i.e., it should invest early. Otherwise, $\mathbb{E}_e[\Pi_m^*(k_m^A, \theta)] \leq \mathbb{E}_l[\Pi_m^*(k_m^A, \theta)]$, i.e., it should wait. □

Lemma 4.5. *If firm i invests early and firm $-i$ invests late, i.e., (E, L) or (L, E), then the equilibrium capacity is $k_i^{*A} = \frac{N}{2\overline{\theta}(\triangle S + \frac{\triangle S \triangle S^+}{S} pr)} \times M_i^{A or A^+}$ and $k_{-i}^{*A} = \frac{N}{2} - \frac{c_{-i}^A N}{2\theta\triangle S} - \frac{k_i^{*A}}{2}$ or $k_{-i}^{*A^+} = \frac{N}{2} - \frac{c_{-i}^{A^+} N}{2\theta S} - \frac{\triangle S k_i^{*A}}{2S}$. The equilibrium expected profits are $\mathbb{E}_e[\pi_i^*(k_i^A, k_{-i}^{*A or *A^+}, \theta)] = \frac{\overline{\theta}}{N} S^B k_i (N - k_i - k_{-i}) + \frac{(M_i^{A or A^+})^2 N s}{8\overline{\theta}\triangle S(s + \triangle S^+ pr)}$ and $\mathbb{E}_l[\pi_{-i}^*(k_{-i}^{A or A^+}, k_i^{*A}, \theta)] = \frac{\overline{\theta}}{N} S^B k_{-i}(N - k_i - k_{-i}) + \frac{N}{4}\mathbb{E}(\frac{1}{\theta})[\frac{1}{\triangle S}(1 - pr)(c_{-i}^A)^2 + \frac{1}{S} pr (c_{-i}^{A^+})^2] + (1 - pr)\frac{N}{\overline{\theta}\triangle S}(\frac{\overline{\theta}\triangle S}{2} - \frac{M_i^{A or A^+}}{4(1 + \frac{\triangle S^+}{S} pr)})(\frac{\overline{\theta}\triangle S}{2} - \frac{M_i^{A or A^+}}{4(1 + \frac{\triangle S^+}{S} pr)} - c_{-i}^A) +$*

$pr\frac{N}{\bar{\theta}S}(\frac{\bar{\theta}S}{2} - \frac{M_i^{AorA^+}}{4(1+\frac{\triangle S^+}{S}pr)})(\frac{\bar{\theta}S}{2} - \frac{M_i^{AorA^+}}{4(1+\frac{\triangle S^+}{S}pr)} - c_{-i}^{A^+})$.

Proof. If firm i moves first, with probability $1-pr$, its optimal NGP capacity is $k_i^A = \frac{N}{2} + \frac{c_{-i}^A - 2c_i^A}{2\bar{\theta}\triangle S}N$ based on Lemma 4.3. With probability pr, the other firm will launch A^+ and all three products (B, A and A^+) exist in the market. Same as in Figure 4.1, we can derive the demand of each product based on the quality S^j and price p^j. Based on the joint capacity clearing prices, we set $d^B = k_i^B + k_{-i}^B$, $d^A = k_i^A$, $d^{A^+} = k_{-i}^{A^+}$, and solve for p^j: $p^B = \frac{\theta}{N}S^B(N - k_i - k_{-i})$, $p^A = \frac{\theta}{N}\Big(NS^A - \triangle S(k_i^A + k_{-i}^{A^+}) - S^B(k_i + k_{-i})\Big)$, $p^{A^+} = \frac{\theta}{N}\Big(NS^{A^+} - \triangle S^+ k_{-i}^{A^+} - \triangle S(k_i^A + k_{-i}^{A^+}) - S^B(k_i + k_{-i})\Big)$. Given k_i^A, firm $-i$'s profit function $\Pi_{-i}(k_{-i}^{A^+}, k_i^A, \theta) = p^B k_{-i}^B + p^{A^+}k_{-i}^{A^+} - c_{-i}^{A^+}k_{-i}^{A^+}$ is concave in $k_{-i}^{A^+}$ and thus the best response function is $R_{-i}^{A^+}(k_i^A) = \frac{N}{2} - \frac{\triangle S}{2S}k_i^A - \frac{N}{2\theta S}c_{-i}^{A^+}$. Substituting $R_{-i}^{A^+}(k_i^A)$ into the profit function of firm i, i.e., $\Pi_i(k_i^A, k_{-i}^{A^+}, \theta)$, which is concave in k_i^A. Taking the expected value of θ, firm i's optimal NGP capacity is $k_i^{*A} = \frac{S}{2S-\triangle S}(\frac{N}{2} + \frac{N}{2\bar{\theta}S}c_{-i}^{A^+} - \frac{N}{\bar{\theta}\triangle S}c_i^A)$. Considering both scenarios, firm i's optimal NGP capacity at the early investment stage is $k_i^{*A} = (1-pr) \times \Big(\frac{N}{2} + \frac{c_{-i}^A - 2c_i^A}{2\bar{\theta}\triangle S}N\Big) + pr \times \Big(\frac{S}{2S-\triangle S}(\frac{N}{2} + \frac{N}{2\bar{\theta}S}c_{-i}^{A^+} - \frac{N}{\bar{\theta}\triangle S}c_i^A)\Big) = \frac{N}{2\bar{\theta}(\triangle S + \frac{\triangle S \triangle S^+}{S}pr)} \times M_i^{AorA^+}$. The Lemma then follows. □

Lemma 4.6. *If both firms invest late, i.e., (L, L), then the equilibrium capacity is $k_i^{*A} = \frac{N}{3} + \frac{c_{-i}^A - 2c_i^A}{3\theta\triangle S}N$ or $k_i^{*A^+} = \frac{N}{3} + \frac{c_{-i}^{A^+} - 2c_i^{A^+}}{3\theta S}N$, and the equilibrium expected profit is $\mathbb{E}_l[\pi_i^*(k_i^{AorA^+}, k_{-i}^{*Aor*A^+}, \theta)] = \frac{\bar{\theta}}{N}S^B k_i(N - k_i - k_{-i}) + \frac{N\bar{\theta}}{9}(\triangle S + pr\triangle S^+) + \frac{2}{9}N\Big((1-pr)(c_{-i}^A - 2c_i^A) + pr(c_{-i}^{A^+} - 2c_i^{A^+})\Big) + \frac{N}{9}\Big(\frac{1}{\triangle S}(1-pr)(c_{-i}^A - 2c_i^A)^2 + \frac{1}{S}pr(c_{-i}^{A^+} - 2c_i^{A^+})^2\Big)\mathbb{E}(\frac{1}{\theta})$, $\forall i = x, y$.*

Proof. If both firms invest late: with probability $1-pr$, the equilibrium capacity is $k_i^{*A} = \frac{N}{3} + \frac{c_{-i}^A - 2c_i^A}{3\theta\triangle S}N$ based on Lemma 4.4; with probability pr, they launch A^+ instead of A, and the equilibrium capacity is $k_i^{*A^+} = \frac{N}{3} + \frac{c_{-i}^{A^+} - 2c_i^{A^+}}{3\theta S}N$. According to Lemma 4.4, the equilibrium expected profit when only B and A exist is: $\frac{\bar{\theta}}{N}S^B k_i(N - k_i - k_{-i}) + \frac{\bar{\theta}\triangle S}{9}N + \frac{2}{9}N(c_{-i}^A - 2c_i^A) + \frac{(c_{-i}^A - 2c_i^A)^2}{9\triangle S}N\mathbb{E}(\frac{1}{\theta})$. When either B and A, or B and A^+ exist, the equilibrium ex-ante expected profit is $\mathbb{E}_l[\pi_i^*(k_i^{AorA^+}, k_{-i}^{*Aor*A^+}, \theta)] = (1-pr) \times \Big(\frac{\overline{\theta}}{N} S^B k_i(N-k_i-k_{-i}) + \frac{\overline{\theta}\triangle S}{9} N + \frac{2}{9} N(c_{-i}^A - 2c_i^A) + \frac{(c_{-i}^A - 2c_i^A)^2}{9\triangle S} N\mathbb{E}(\frac{1}{\theta})\Big) + pr \times \Big(\frac{\overline{\theta}}{N} S^B k_i(N-k_i-k_{-i}) + \frac{\overline{\theta}S}{9} N + \frac{2}{9} N(c_{-i}^{A^+} - 2c_i^{A^+}) + \frac{(c_{-i}^{A^+} - 2c_i^{A^+})^2}{9S} N\mathbb{E}(\frac{1}{\theta})\Big) = \frac{\overline{\theta}}{N} S^B k_i(N-k_i-k_{-i}) + \frac{N\overline{\theta}}{9}(\triangle S + pr\triangle S^+) + \frac{2}{9}N\Big((1-pr)(c_{-i}^A - 2c_i^A) + pr(c_{-i}^{A^+} - 2c_i^{A^+})\Big) + \frac{N}{9}\Big(\frac{1}{\triangle S}(1-pr)(c_{-i}^A - 2c_i^A)^2 + \frac{1}{S}pr(c_{-i}^{A^+} - 2c_i^{A^+})^2\Big)\mathbb{E}(\frac{1}{\theta})$. □

Theorem 4.3. *The following pure strategy equilibria to the investment timing game with potential quality improvement exist:*

1. *If* $(1-Cov) \times c_i^{AorA^+} \leq \frac{4}{9} M_{-i}^2 - (1-pr)(\overline{\theta}\triangle S - 2\alpha_{-i,i})(\overline{\theta}\triangle S - 2\alpha_{-i,i} - 2c_i^A) - \frac{\triangle S}{S} pr(\overline{\theta}S - 2\alpha_{-i,i})(\overline{\theta}S - 2\alpha_{-i,i} - 2c_i^{A^+})$*,* $\forall i = x, y$*, then both firms invest early, i.e.,* (E, E)*.*

2. *If* $(1-Cov) \times c_{-i}^{AorA^+} \geq \frac{4}{9} M_i^2 - (1-pr)(\overline{\theta}\triangle S - 2\alpha_{i,-i})(\overline{\theta}\triangle S - 2\alpha_{i,-i} - 2c_{-i}^A) - \frac{\triangle S}{S} pr(\overline{\theta}S - 2\alpha_{i,-i})(\overline{\theta}S - 2\alpha_{i,-i} - 2c_{-i}^{A^+})$ *and* $(1-Cov) \times c_{-i,i}^{AorA^+} \leq 18(1 + \frac{\triangle S^+}{S} pr)(\alpha_{i,-i})^2 + \overline{\theta}\triangle S\Big((1-pr)(\overline{\theta}\triangle S - 2M_{-i}) + pr(\overline{\theta}S - 2M_{-i}^+)\Big)$*, then firm* i *invests early and firm* $-i$ *invests late, i.e.,* (E, L) *or* (L, E)*.*

3. *If* $(1-Cov) \times c_{-i,i}^{AorA^+} \geq 18(1 + \frac{\triangle S^+}{S} pr)(\alpha_{i,-i})^2 + \overline{\theta}\triangle S\Big((1-pr)(\overline{\theta}\triangle S - 2M_{-i}) + pr(\overline{\theta}S - 2M_{-i}^+)\Big)$*,* $\forall i = x, y$*, then both firms invest late, i.e.,* (L, L)*.*

Proof. We examine the viability of each subgame. An equilibrium strategy exists if no firm has incentive to unilaterally deviate. (i) The equilibrium strategy where both firms invest early, i.e., (E, E), exists if firm x enjoys greater expected profit than in (L, E) and firm y enjoys greater expected profit than in (E, L). (ii) The equilibrium strategy where firm x invests early and firm y invests late, i.e., (E, L), exists if firm x enjoys greater expected profit than in (L, L) and firm y enjoys greater expected profit than in (E, E). (iii) The equilibrium strategy where firm x invests late and firm y invests early, i.e., (L, E), exists if firm x enjoys greater expected profit than in (E, E) and firm y enjoys greater expected profit than in (L, L). (iv) The equilibrium strategy where both firms invest late, i.e., (L, L), exists if firm x enjoys greater expected profit than in (E, L) and firm y enjoys greater expected profit than in (L, E). Comparing the profit of firm x or firm y in each equilibrium (see Lemma 4.2, 4.5 and 4.6), the theorem then follows. □

Lemma 5.1. *At the third stage, there exist unique optimal prices of authentic products and non-deceptive counterfeits, i.e., p_o^* and p_n^*, which are derived by substituting the OEM's optimal response function $\mathbb{R}_o(p_n)$ into the counterfeiter's optimal response function $\mathbb{R}_n(p_o)$; $\mathbb{R}_o(p_n)$ and $\mathbb{R}_n(p_o)$ satisfy the first-order derivative conditions: $(\frac{\partial \Pi_o}{\partial p_o}) \mid_{p_o=\mathbb{R}_o(p_n)}= 0$ and $(\frac{\partial \Pi_n}{\partial p_n}) \mid_{p_n=\mathbb{R}_n(p_o)}= 0$.*

Proof. In each subgame (κ, e_n), the OEM's profit Π_o is concave in p_o, given the counterfeiter's price p_n. The counterfeiter's profit Π_n is concave in p_n, given p_o. Therefore, there exists optimal response prices of authentic products and counterfeits. The unique optimal prices can then be derived by substituting the OEM's optimal response function into the counterfeiter's optimal response function.

In the subgame $(\overline{\kappa}, \overline{e_n}) = (0, 0)$, the optimal price of authentic products is $p^*_{o|(0,0)} = \frac{2-2q_n}{4-q_n}$, while the optimal price of counterfeits is $p^*_{n|(0,0)} = \frac{q_n-q_n^2}{4-q_n}$. The optimal market shares of authentic products and counterfeits are $m^*_{o|(0,0)} = \frac{2}{4-q_n}$ and $m^*_{n|(0,0)} = \frac{1}{4-q_n}$.

In the subgame $(\overline{\kappa}, \overline{e_n}) = (1, 0)$, the optimal price of authentic products is $p^*_{o|(1,0)} = \frac{2(1-q_n)}{4-q_n} + \frac{2(1-\overline{\alpha})C_o}{4-q_n} + \frac{\beta_1}{1-\beta_1}\frac{L_f}{4-q_n}$, while the optimal price of counterfeits is $p^*_{n|(1,0)} = \frac{q_n(1-q_n)}{4-q_n} + \frac{q_n(1-\overline{\alpha})C_o}{4-q_n} + \frac{\beta_1}{1-\beta_1}\frac{2L_f-q_nL_o}{4-q_n}$. The optimal market shares of authentic products and counterfeits are $m^*_{o|(1,0)} = \frac{2}{4-q_n} - \frac{(2-q_n)(1-\overline{\alpha})C_o}{(4-q_n)(1-q_n)} + \frac{\beta_1}{1-\beta_1}\frac{L_f}{(4-q_n)(1-q_n)}$ and $m^*_{n|(1,0)} = \frac{1}{4-q_n} + \frac{(1-\overline{\alpha})C_o}{(4-q_n)(1-q_n)} - \frac{\beta_1}{1-\beta_1}\frac{(2-q_n)L_f}{(4-q_n)(1-q_n)q_n}$.

In the subgame $(\overline{\kappa}, \overline{e_n}) = (1, 1)$, the optimal price of authentic products is $p^*_{o|(1,1)} = \frac{2(1-q_n)}{4-q_n} + \frac{2(1-\overline{\alpha})C_o}{4-q_n} + \frac{\beta_1-\beta_2}{1-\beta_1+\beta_2}\frac{L_f}{4-q_n} + \frac{1}{1-\beta_1+\beta_2}\frac{C_n}{4-q_n}$, while the optimal price of counterfeits is $p^*_{n|(1,1)} = \frac{q_n(1-q_n)}{4-q_n} + \frac{q_n(1-\overline{\alpha})C_o}{4-q_n} + \frac{\beta_1-\beta_2}{1-\beta_1+\beta_2}\frac{2L_f}{4-q_n} + \frac{1}{1-\beta_1+\beta_2}\frac{2C_n}{4-q_n}$. The optimal market shares of authentic products and counterfeits are $m^*_{o|(1,1)} = \frac{2}{4-q_n} - \frac{(2-q_n)(1-\overline{\alpha})C_o}{(4-q_n)(1-q_n)} + \frac{\beta_1-\beta_2}{1-\beta_1+\beta_2}\frac{L_f}{(4-q_n)(1-q_n)} + \frac{1}{1-\beta_1+\beta_2}\frac{C_n}{(4-q_n)(1-q_n)}$ and $m^*_{n|(1,1)} = \frac{1}{4-q_n} + \frac{(1-\overline{\alpha})C_o}{(4-q_n)(1-q_n)} - \frac{\beta_1-\beta_2}{1-\beta_1+\beta_2}\frac{(2-q_n)L_f}{(4-q_n)(1-q_n)q_n} - \frac{1}{1-\beta_1+\beta_2}\frac{(2-q_n)C_n}{(4-q_n)(1-q_n)q_n}$.

□

Proposition 5.1. *Based on the optimal decision of Customs α^*, the OEM's optimal (response) decision, κ^*, and the non-deceptive counterfeiter's optimal (response) decision e_n^*, the following five Nash equilibrium strategies exist at the first stage:*

$$(\alpha^*, \kappa^*, e_n^*) = \begin{cases} (0,0,0) & \textit{OEM resorts to pricing only} \\ (0,1,0) & \textit{OEM initiates the PPP \& counterfeiter does not disguise} \\ (1,1,0) & \textit{Customs initiates the PPP \& counterfeiter does not disguise} \\ (0,1,1) & \textit{OEM initiates the PPP \& counterfeiter disguises} \\ (1,1,1) & \textit{Customs initiates the PPP \& counterfeiter disguises} \end{cases} \tag{5}$$

Proof. The conditions under which an equilibrium strategy exists can be derived by comparing the profits of Customs in different strategies, the OEM's profits in different strategies, and the counterfeiter's profits in different strategies. □

Proposition 5.2. *In the non-deceptive case, Customs will not initiate the PPP, i.e., neither the equilibrium strategy* $(1,1,0)$ *nor* $(1,1,1)$ *exists at the first stage, if either of the following conditions hold:*

- $q_n \leq 1 - \frac{1}{2}\max\{L_e - \frac{2\beta_1}{1-\beta_1}L_f, L_e - \frac{2(\beta_1-\beta_2)}{1-\beta_1+\beta_2}L_f - \frac{C_n}{1-\beta_1+\beta_2}\}$,
- $L_e \leq \frac{\beta_1-\beta_2}{1-\beta_1+\beta_2}L_f$.

Proof. If $2q_n \leq \frac{2\beta_1}{1-\beta_1}L_f+2-L_e$, then $\Pi_{b|(0,1,0)} \geq \Pi_{b|(1,1,0)}$. If $2q_n \leq \frac{2(\beta_1-\beta_2)}{1-\beta_1+\beta_2}L_f + 2 - L_e + \frac{C_n}{1-\beta_1+\beta_2}$, then $\Pi_{b|(0,1,1)} \geq \Pi_{b|(1,1,1)}$. Therefore, when $\max\{L_e - \frac{2\beta_1}{1-\beta_1}L_f, L_e - \frac{2(\beta_1-\beta_2)}{1-\beta_1+\beta_2}L_f - \frac{C_n}{1-\beta_1+\beta_2}\} \leq 2(1-q_n)$, neither $(1,1,0)$ nor $(1,1,1)$ exists at the first stage.

In addition, if $L_e \leq \frac{\beta_1-\beta_2}{1-\beta_1+\beta_2}L_f$, then the condition $\max\{L_e - \frac{2\beta_1}{1-\beta_1}L_f, L_e - \frac{2(\beta_1-\beta_2)}{1-\beta_1+\beta_2}L_f - \frac{C_n}{1-\beta_1+\beta_2}\} \leq 2(1-q_n)$ holds, thus neither the equilibrium strategy $(1,1,0)$ nor $(1,1,1)$ exists. □

Proposition 5.3. *Set* $\mathbb{G}(L_f) = \Pi^*_{o|(0,0,0)} - \Pi_{o|(0,1,0)}$. *In the presence of a non-deceptive counterfeiter, there exist two thresholds for* L_f*, i.e., the lowerbound* $L_f^{lo} = \max\{0, \arg\min_{L_f}\{\mathbb{G}(L_f) = 0\}\}$*, and the upperbound* $L_f^{uo} =$

$\max\{0, \arg\max_{L_f}\{\mathbb{G}(L_f) = 0\}\}$ *such that when* $L_f^{lo} < L_f < L_f^{uo}$*, the outcome where the PPP is not formed will never happen, i.e., the equilibrium strategy* $(0, 0, 0)$ *will not exist at the first stage.*

Proof. $\frac{\partial^2 \mathbb{G}(L_f)}{\partial L_f^2} = (\frac{\beta_1}{1-\beta_1})^2 \frac{2}{(4-q_n)(1-q_n)} > 0$. Thus, $\mathbb{G}(L_f)$ is convex for L_f. There exists a lower- and a upperbound in L_f: $L_f^{lo} = \max\{0, \arg\min_{L_f}\{\mathbb{G}(L_f) = 0\}\}$, $L_f^{uo} = \max\{0, \arg\max_{L_f}\{\mathbb{G}(L_f) = 0\}\}$ and $L_f^{lo} \leq L_f^{uo}$. A necessary condition for the OEM to choose not to invest is when $L_f < L_f^{lo}$ or $L_f > L_f^{uo}$. The proposition then follows. □

Proposition 5.4. *Set* $\mathbb{H}(L_f) = \Pi^*_{n|(\overline{\alpha},1,0)} - \Pi^*_{n|(\overline{\alpha},1,1)}$*, where* $\overline{\alpha}$ *is the given decision of Customs. In the presence of a non-deceptive counterfeiter, suppose the PPP is formed, there exist a threshold for* L_f*, i.e.,* $L_f^{uc} = \arg\max_{L_f}\{\mathbb{H}(L_f) = 0\}$*, such that if* $L_f > L_f^{uc}$*, the counterfeiter will disguise, i.e.,* $e_n^* = 1$.

Proof. $\mathbb{H}(L_f)$ is concave in L_f and $\mathbb{H}(0) > 0$. Then there exists a threshold for L_f, i.e., L_f^{uc}, satisfying: $\mathbb{H}(L_f^{uc}) = 0$. Therefore, $\forall L_f > L_f^{uc}$, $\mathbb{H}(L_f) \leq 0$. When $\mathbb{H}(L_f) \leq 0$, the counterfeiter will disguise, i.e., the equilibrium strategy $(\overline{\alpha}, \kappa^*, e_n^*) = (\overline{\alpha}, 1, 1)$. □

Proposition 5.5. *To combat the non-deceptive counterfeiter:*

1. *the OEM should choose a lower price than that without any counterfeit, if the PPP is not formed;*

2. *the OEM should choose a higher price than that without any counterfeit, if the PPP is formed and* $\frac{3}{2}q_n - 2(1-\overline{\alpha})C_o \leq \min\{\frac{\beta_1}{1-\beta_1}L_f, \frac{\beta_1-\beta_2}{1-\beta_1+\beta_2}L_f + \frac{C_n}{1-\beta_1+\beta_2}\}$ *, where* $\overline{\alpha}$ *is the given decision of Customs;*

3. *compared to the situation without any counterfeit, the OEM could earn more profit if the PPP is formed; without the PPP, the OEM will earn less profit than that without any counterfeit.*

Proof. When no counterfeits exist, the OEM's profit is $\Pi_o = p_o m_o$, and the optimal price of authentic products is $\frac{1}{2}$. According to Lemma 5.1, the optimal price of authentic products in the strategy $(0,0,0)$ is $p^*_{o|(0,0,0)} = \frac{2-2q_n}{4-q_n}$, which is smaller than $\frac{1}{2}$. The optimal market share of authentic products in $(0,0,0)$ is $\frac{2}{4-q_n}$, and the market share of authentic products in a market without any counterfeit is $\frac{1}{2}$. The OEM's profit in $(0,0,0)$ is $\frac{4-4q_n}{(4-q_n)^2}$, which is smaller than $\frac{1}{4}$, thus, the OEM will earn less profit in $(0,0,0)$ than that without any counterfeit. The optimal prices of authentic products in the strategies $(\overline{\alpha},1,0)$ and $(\overline{\alpha},1,1)$ are $p^*_{o|(\overline{\alpha},1,0)} = \frac{2(1-q_n)}{4-q_n} + \frac{2(1-\overline{\alpha})C_o}{4-q_n} + \frac{\beta_1}{1-\beta_1}\frac{L_f}{4-q_n}$ and $p^*_{o|(\overline{\alpha},1,1)} = \frac{2(1-q_n)}{4-q_n} + \frac{2(1-\overline{\alpha})C_o}{4-q_n} + \frac{\beta_1-\beta_2}{1-\beta_1+\beta_2}\frac{L_f}{4-q_n} + \frac{1}{1-\beta_1+\beta_2}\frac{C_n}{4-q_n}$, respectively. When $\frac{3}{2}q_n - 2(1-\overline{\alpha})C_o < \min\{\frac{\beta_1}{1-\beta_1}L_f, \frac{\beta_1-\beta_2}{1-\beta_1+\beta_2}L_f + \frac{C_n}{1-\beta_1+\beta_2}\}$, $\min\{p^*_{o|(\overline{\alpha},1,0)}, p^*_{o|(\overline{\alpha},1,1)}\} > \frac{1}{2}$. The optimal market shares of authentic products in the strategies $(\overline{\alpha},1,0)$ and $(\overline{\alpha},1,1)$ are $m^*_{o|(\overline{\alpha},1,0)} = \frac{2}{4-q_n} - \frac{(2-q_n)(1-\overline{\alpha})C_o}{(4-q_n)(1-q_n)} + \frac{\beta_1}{1-\beta_1}\frac{L_f}{(4-q_n)(1-q_n)}$ and $m^*_{o|(\overline{\alpha},1,1)} = \frac{2}{4-q_n} - \frac{(2-q_n)(1-\overline{\alpha})C_o}{(4-q_n)(1-q_n)} + \frac{\beta_1-\beta_2}{1-\beta_1+\beta_2}\frac{L_f}{(4-q_n)(1-q_n)} + \frac{1}{1-\beta_1+\beta_2}\frac{C_n}{(4-q_n)(1-q_n)}$, which can be larger than the marker share of authentic products in a market without any counterfeit, i.e., $\frac{1}{2}$. Therefore, it is possible for the OEM to earn more profit in $(\overline{\alpha},1,0)$ and $(\overline{\alpha},1,1)$ than that without any counterfeit. □

Proposition 5.6. *To combat the non-deceptive counterfeiter:*

1. *when only using pricing, the OEM captures a higher market share than the counterfeiter;*

2. *with the PPP, the OEM captures a higher market share than the counterfeiter if it is Customs who initiates the PPP; if the OEM initiates the PPP, under certain conditions related to the quality of counterfeits, the market share of counterfeits may exceed the market share of authentic products;*

   - *if* $-\frac{1}{4-q_n} + \frac{(3-q_n)C_o}{(4-q_n)(1-q_n)} - \frac{\beta_1}{1-\beta_1}\frac{2L_f}{(4-q_n)(1-q_n)q_n} > 0$, *then* $m^*_{n|(0,1,0)} > m^*_{o|(0,1,0)}$;
   - *if* $-\frac{1}{4-q_n} + \frac{(3-q_n)C_o}{(4-q_n)(1-q_n)} - \frac{\beta_1-\beta_2}{1-\beta_1+\beta_2}\frac{2L_f}{(4-q_n)(1-q_n)q_n} - \frac{1}{1-\beta_1+\beta_2}\frac{2C_n}{(4-q_n)(1-q_n)q_n} > 0$, *then* $m^*_{n|(0,1,1)} > m^*_{o|(0,1,1)}$;

3. *when Customs decides not to initiate the PPP, the OEM's investment in the PPP will result in an increase in both the prices of authentic*

products and counterfeits, i.e., $\min\{p^*_{o|(0,1,0)}, p^*_{o|(0,1,1)}\} > p^*_{o|(0,0,0)}$ *and* $\min\{p^*_{n|(0,1,0)}, p^*_{n|(0,1,1)}\} > p^*_{n|(0,0,0)}$*;*

4. *when* $(\frac{\beta_1}{1-\beta_1} - \frac{\beta_1-\beta_2}{1-\beta_1+\beta_2})L_f < \frac{C_n}{1-\beta_1+\beta_2}$*, the non-deceptive counterfeiter's disguise effort will result in an increase in the price of authentic products, i.e.,* $p^*_{o|(\overline{\alpha},1,1)} > p^*_{o|(\overline{\alpha},1,0)}$*, where* $\overline{\alpha}$ *is the given decision of Customs.*

Proof. According to Lemma 5.1, $m^*_{o|(0,0,0)} > m^*_{n|(0,0,0)}$. Set $\mathbb{D}_{(\overline{\alpha},1,0)} = m^*_{n|(\overline{\alpha},1,0)} - m^*_{o|(\overline{\alpha},1,0)} = -\frac{1}{4-q_n} + \frac{(3-q_n)(1-\overline{\alpha})C_o}{(4-q_n)(1-q_n)} - \frac{\beta_1}{1-\beta_1}\frac{2L_f}{(4-q_n)(1-q_n)q_n}$ and $\mathbb{D}_{(\overline{\alpha},1,1)} = m^*_{n|(\overline{\alpha},1,1)} - m^*_{o|(\overline{\alpha},1,1)} = -\frac{1}{4-q_n} + \frac{(3-q_n)(1-\overline{\alpha})C_o}{(4-q_n)(1-q_n)} - \frac{\beta_1-\beta_2}{1-\beta_1+\beta_2}\frac{2L_f}{(4-q_n)(1-q_n)q_n} - \frac{1}{1-\beta_1+\beta_2}\frac{2C_n}{(4-q_n)(1-q_n)q_n}$. If $\overline{\alpha} = 1$, $\mathbb{D}_{(\overline{\alpha},1,0)} < 0$ and $\mathbb{D}_{(\overline{\alpha},1,1)} < 0$. If $\overline{\alpha} = 0$, $\mathbb{D}_{(\overline{\alpha},1,0)}$ and $\mathbb{D}_{(\overline{\alpha},1,1)}$ could be positive values depending on the values of q_n and other parameters. According to Lemma 5.1, $\min\{p^*_{o|(0,1,0)}, p^*_{o|(0,1,1)}\} > p^*_{o|(0,0,0)}$, $\min\{p^*_{n|(0,1,0)}, p^*_{n|(0,1,1)}\} > p^*_{n|(0,0,0)}$, and $p^*_{o|(\overline{\alpha},1,1)} > p^*_{o|(\overline{\alpha},1,0)}$. □

Proposition 5.7. *The following results on the expected consumer welfare* ECS_n *hold:*

1. *In each strategy* (α, κ, e_n)*, there exists a unique* $q^*_{n|(\alpha,\kappa,e_n)}$ *such that the expected consumer welfare* $ECS_{n|(\alpha,\kappa,e_n)}$ *is decreasing as* q_n *is exceeding* $q^*_{n|(\alpha,\kappa,e_n)}$*.*

2. *A necessary condition for* ECS_n *to be higher in the situation where the PPP is formed than that without the PPP is when the PPP is initiated by the OEM and* $q_n > \frac{1}{2}$*.*

3. *A sufficient condition for* ECS_n *to be higher in the situation where the PPP is not formed than that with the PPP is when* $q_n < \frac{1}{3}$*.*

Proof. $ECS_{n|(0,0,0)} = \frac{1}{2} + \frac{2q_n-1}{4-q_n}$, which is concave in q_n. $ECS_{n|(\alpha,1,0)} = \frac{1}{2} - \frac{\beta_1}{4} + (1-\beta_1) \times \frac{2q_n-1}{4-q_n} + (1-\beta_1) \times \frac{(2q_n-1)(1-\alpha)C_o}{(1-q_n)(4-q_n)} + \beta_1 \times \frac{(3q_n-5)L_f}{2(1-q_n)(4-q_n)}$, and $ECS_{n|(\alpha,1,1)} = \frac{1}{2} - \frac{\beta_1-\beta_2}{4} + (1-\beta_1+\beta_2) \times \frac{2q_n-1}{4-q_n} + (1-\beta_1+\beta_2) \times \frac{(2q_n-1)(1-\alpha)C_o}{(1-q_n)(4-q_n)} + (\beta_1-\beta_2) \times \frac{(3q_n-5)L_f}{2(1-q_n)(4-q_n)} + \frac{(3q_n-5)C_n}{2(1-q_n)(4-q_n)}$. Both $ECS_{n|(\alpha,1,0)}$ and $ECS_{n|(\alpha,1,1)}$ is concave in q_n. Therefore, there exists a unique q^*_n in each strategy (α, κ, e_n)

such that the expected consumer welfare is maximized; when q_n exceeds the threshold q_n^*, the expected consumer welfare is decreasing in q_n.

$CS_o = \frac{1}{4}$, $CS_{n|(0,0,0)} = \frac{1}{2} + \frac{2q_n-1}{4-q_n}$, $CS_{n|(\alpha,1,0)} = \frac{1}{2} + \frac{2q_n-1}{4-q_n} + \frac{(2q_n-1)(1-\alpha)C_o}{(1-q_n)(4-q_n)} + \frac{\beta_1}{1-\beta_1}\frac{(3q_n-5)L_f}{2(1-q_n)(4-q_n)}$ and $CS_{n|(\alpha,1,1)} = \frac{1}{2} + \frac{2q_n-1}{4-q_n} + \frac{(2q_n-1)(1-\alpha)C_o}{(1-q_n)(4-q_n)} + \frac{(\beta_1-\beta_2)}{1-\beta_1+\beta_2}\frac{(3q_n-5)L_f}{2(1-q_n)(4-q_n)} + \frac{1}{1-\beta_1+\beta_2}\frac{(3q_n-5)C_n}{2(1-q_n)(4-q_n)}$. When $(1-\beta_1)(2q_n-1)C_o + \beta_1\frac{(3q_n-5)L_f}{2} > \beta_1\frac{7q_n(1-q_n)}{4} > 0$, $ECS_{n|(0,1,0)} > ECS_{n|(0,0,0)}$. When $(1-\beta_1+\beta_2)(2q_n-1)C_o + (\beta_1-\beta_2)\frac{(3q_n-5)L_f}{2} > (\beta_1-\beta_2)\frac{7q_n(1-q_n)}{4} + \frac{(5-3q_n)C_n}{2} > 0$, $ECS_{n|(0,1,1)} > ECS_{n|(0,0,0)}$. Thus, a necessary condition for $\min\left\{ECS_{n|(0,1,0)}, ECS_{n|(0,1,1)}\right\} > ECS_{n|(0,0,0)}$ is that $q_n > \frac{1}{2}$.

In each strategy, $CS_n = \frac{1}{2} + \frac{(3q_n-1)p_o-2p_n}{2(1-q_n)}$ and it is decreasing in p_n. If $q_n < \frac{1}{3}$, CS_n is also decreasing in p_o. If $q_n < \frac{1}{3}$, CS_n is also decreasing in p_o and $p^*_{o|(0,0,0)} < \min\left\{p^*_{o|(0,1,0)}, p^*_{o|(0,1,1)}, p^*_{o|(1,1,0)}, p^*_{o|(1,1,1)}\right\}$, $p^*_{n|(0,0,0)} < \min\left\{p^*_{n|(0,1,0)}, p^*_{n|(0,1,1)}, p^*_{n|(1,1,0)}, p^*_{n|(1,1,1)}\right\}$. Thus, CS_n is the highest in the strategy $(0,0,0)$. Because $CS_{n|(0,0,0)} > CS_o = \frac{1}{4}$, the expected consumer welfare ECS_n is the highest in the equilibrium $(\kappa, e_n) = (0,0,0)$ when $q_n < \frac{1}{3}$. □

Lemma 5.2. *In the presence of a deceptive counterfeiter:*

1. *when no consumer is proactive (i.e., $\lambda = 0$), the deceptive counterfeiter's optimal market seize is: if $p^*_{o|\lambda=0} < C$, $s^*_{\lambda=0} = 0$; otherwise, $s^* = \frac{1}{2} - \frac{S}{2(p^*_o-C)(1-p^*_o)}$,. The optimal price(s) for authentic products is $p^*_o = \arg\max_{p_o} \Pi_o = (p_o - C_o(1-\alpha)\kappa)(\frac{1-p_o}{2} + \frac{S}{2(p_o-C)})$.*

2. *for $\lambda \in [0,1]$, if $p^*_o < (1-s^*+s^*q_d)^2$, there exists a unique market seize s^* of the deceptive counterfeiter, which solves $\frac{\partial \Pi_d}{\partial s} = 0$. The optimal price(s) of authentic product is $p^*_o = \arg\max_{p_o} \Pi_o$.*

Proof. When $\lambda = 0$, given the price of authentic products $\overline{p_o}$, if $\overline{p_o} < C$, the optimal market seize of the counterfeiter is $s^* = 0$. If $\overline{p_o} \geq C$, the counterfeiter's profit function Π_d is concave in s. Thus, the optimal market seize is $s^* = \frac{1}{2} - \frac{S}{2(p^*_o-C)(1-p^*_o)}$. Substituting s^* into the OEM's profit function, the optimal price(s) of authentic products is the one(s) which maximizes the profit function.

When $\lambda \in [0,1]$, the counterfeiter's profit is $\Pi_d = (\overline{p_o} - C)\Big((1-s)s\lambda(1-\frac{\overline{p_o}}{1-s+sq_d}) + (1-s)s(1-\lambda)(1-\overline{p_o})\Big) - sS$. The second derivative is $\frac{\partial^2 \Pi_d}{\partial s^2} = (\overline{p_o} - C)\Big(-\lambda(1-s)\frac{2\overline{p_o}(1-q_d)}{(1-s+sq_d)^3} - 2\lambda(1-\frac{\overline{p_o}}{(1-s+sq_d)^2}) - 2(1-\lambda)(1-\overline{p_o})\Big) = \frac{2\lambda\overline{p_o}q_d}{(1-s+sq_d)^3} - 2(1-(1-\lambda)\overline{p_o})$. A sufficient condition for $\frac{\partial^2 \Pi_d}{\partial s^2} < 0$ is that $\overline{p_o} < (1-s+sq_d)^2$. That is to say, if $\overline{p_o} < (1-s^*+s^*q_d)^2$, Π_d is concave in s, i.e., there exists an unique optimal market seize s^*, which solves $\frac{\partial \Pi_d}{\partial s} = (\overline{p_o} - C)\Big((1-2s^*)\big(1-\frac{\overline{p_o}\lambda}{1-s^*+s^*q_d} - \overline{p_o}(1-\lambda)\big) - \frac{\overline{p_o}(1-q_d)s^*(1-s^*)\lambda}{(1-s^*+s^*q_d)^2}\Big) - S = 0$. Substituting s^* into the OEM's profit function, the optimal price(s) of authentic products is the one(s) which maximizes the profit function. □

Proposition 5.8. *In a market where no consumer is proactive, i.e., $\lambda = 0$, to combat the deceptive counterfeiter:*

1. *the OEM should choose a lower price than that without any counterfeit, if the PPP is initiated by Customs or if the PPP is not formed;*

2. *the OEM should choose a higher price than that without any counterfeit, if the PPP is initiated by the OEM and $C < C_o$.*

Proof. The optimal price of authentic products in a market without any counterfeit is $\frac{1}{2}$. When $\alpha = 1$ and $\kappa = 1$, or when $\kappa = 0$, the OEM's profit function is $\Pi_o = p_o\frac{1-p_o}{2} + \frac{p_o}{p_o - C}\frac{S}{2}$. The first term is concave, and the second term is decreasing in p_o. The optimal solution to the concave function $p_o\frac{1-p_o}{2}$ is $\frac{1}{2}$, which is the optimal price of authentic products in a market without any counterfeit. Adding the decreasing function $\frac{p_o}{p_o-C}\frac{S}{2}$ makes the optimal solution $p^*_{o|(\alpha,\kappa,e_d)} \leq \frac{1}{2}$.

When $\alpha = 0$, $\kappa = 1$ and $C < C_o$, $\Pi_o = (p_o - C_o)\frac{1-p_o}{2} + \frac{p_o - C_o}{p_o - C}\frac{S}{2}$. The first term is concave in p_o. If $C < C_o$, the second term is increasing in p_o. The optimal solution to the concave function $(p_o - C_o)\frac{1-p_o}{2}$ is larger than $\frac{1}{2}$ since $C_o > 0$. Adding the increasing function $\frac{p_o - C_o}{p_o - C}\frac{S}{2}$ makes the new optimal solution $p^*_{o|(0,1,-)} \geq \frac{1}{2}$. □

Lemma 5.3. *In a market where no consumer is proactive, i.e., $\lambda = 0$:*

- *if the PPP is initiated by Customs or if the PPP is not formed, the optimal market seize of the deceptive counterfeiter s^* is increasing in the price of authentic products p_o;*

- *if the PPP is initiated by the OEM and $C < C_o$, the optimal market seize of the deceptive counterfeiter s^* is decreasing in the price of authentic products p_o.*

Proof. According to Lemma 5.2, the optimal market seize of the deceptive counterfeiter in a market with no proactive consumers is $s^* = \frac{1}{2} - \frac{S}{2(p_o^*-C)(1-p_o^*)}$, if $p_o^* > C$. The first derivative is $\frac{S(C-2p_o^*+1)}{(1-p_o^*)^2(p_o^*-C)^2}$. Thus, s^* is increasing in p_o^* if $p_o^* < \frac{C+1}{2}$, and decreasing otherwise. According to Proposition 5.8, if the PPP is initiated by Customs or if the PPP is not formed, $p_o^* < \frac{1}{2} \leq \frac{C+1}{2}$. If the PPP is initiated by the OEM and $C < C_o$, then $p_o^* > \frac{1+C_o}{2} > \frac{1+C}{2}$. The Lemma then follows. □

Proposition 5.9. *In a market where no consumer is proactive, i.e., $\lambda = 0$:*

- *given the same disguise effort of the deceptive counterfeiter, the expected consumer welfare ECS_d is higher if the PPP is initiated by Customs, than that if the PPP is initiated by the OEM and $C < C_o$;*

- *if the quality of deceptive counterfeits is sufficiently low, the expected consumer welfare ECS_d is higher if the PPP is formed, than that if the PPP is not formed.*

Proof. When $\lambda = 0$, $CS_d = (1 - p_o)(1 - s(1 - q_d))$ and $ECS_d = (1 - \mathbb{P}_d^r(\kappa, e_d))(1 - p_o)(1 - s(1 - q_d)) + \frac{1}{4}\mathbb{P}_d^r(\kappa, e_d)$, both of which is decreasing in p_o. According to Proposition 5.8, p_o is lower if the PPP is initiated by Customs than that if the PPP is initiated by the OEM and $C < C_o$. Thus, ECS_d is higher if the PPP is initiated by Customs than that if the PPP is initiated by the OEM and $C < C_o$, given the same disguise effort of the deceptive counterfeiter e_d. If the PPP is not formed, $ECS_{d|(0,0,0)} = CS_{n|(0,0,0)} = (1 - \mathbb{P}_d^r(\kappa, e_d))CS_{d|(0,0,0)} + \mathbb{P}_d^r(\kappa, e_d)CS_{d|(0,0,0)}$. There exists a sufficiently low q_d such that $CS_{d|(0,0,0)} < CS_o = \frac{1}{4}$ and $ECS_{d|(0,0,0)} < ECS_{d|(\alpha,1,e_d)}$. □

Appendix B

Relaxing the *non-negativity* (NN) assumption (Chapter 4)

To avoid trivial results, we assume that the two firms' mutual best responses at the early investment stage are positive: $\overline{\theta} \triangle S > \max\{2c^A_{-i} - c^A_i, \forall i = x, y\}$. We exclude the situation where both firms choose the decision not to invest to avoid losses at the early stage. The two firms' optimal NGP capacity and expected profits in the equilibrium strategy (E, E) are the same as in Lemma 4.2. Without the *non-negativity* assumption in equation (4.4), firm i that invests late will choose not to launch the NGP if given the realized θ, its best response to the other firm's capacity $\widehat{k^A_{-i}}$ is negative, i.e., $\frac{N}{2} - \frac{\widehat{k^A_{-i}}}{2} - \frac{c^A_i}{2\theta \triangle S} N < 0$. Therefore, if any firm decides to invest late, both firms need to consider the probability that the late firm's capacity would be 0 and this decision not to invest should be considered differently from the optimal capacity using the best response function. At the phase of the *timing game*, we use the notation L' to denote a firm's decision to invest at the late stage.

Lemmas B.1 and B.2 illustrate the capacity and expected profits of both firms in the equilibrium strategy where a firm invests early and the other firm waits, and in the equilibrium strategy where both firms wait. Theorem B.1 describes all the possible equilibria of two competing firms to the *timing game* without the *non-negativity* assumption.

Lemma B.1. *If firm i, $i = x, y$, invests early and the other firm invests late, i.e., (L', E) or (E, L'), the equilibrium capacity is $k_i^{*A} = \arg\max_k \mathbb{E}_e[\pi_i^*(k, k_{-i}^{*A}, \theta)]$ and $k_{-i}^{*A} = \max\{\frac{N}{2} - \frac{k_i^{*A}}{2} - \frac{c_{-i}^A}{2\theta\triangle S}N, 0\}$. The equilibrium expected profits are: $\mathbb{E}_e[\pi_i^*(k_i^A, R_{-i}(k_i^A), \theta)] = \max_k \Big\{ \frac{\overline{\theta}}{N} S^B k_i(N - k_i - k_{-i}) - c_i^A k + \int_{\theta_l}^{a_i} \Big(\frac{\theta}{N}\triangle Sk(N - k)\Big) f(\theta)d\theta + \int_{a_i}^{\theta_u} \Big(\frac{\theta}{N} \triangle Sk(\frac{N}{2} - \frac{k}{2}) + \frac{c_{-i}^A}{2}k\Big) f(\theta)d\theta \Big\}$, where $a_i = \frac{c_{-i}^A}{\triangle S(1-\frac{k}{N})}$; and $\mathbb{E}_l[\pi_{-i}^*(k_i^{*A}, k_{-i}^A, \theta)] = \frac{\overline{\theta}}{N} S^B k_{-i}(N - k_i - k_{-i}) + \int_{a_i^*}^{\theta_u} \Big(\frac{\theta\triangle S}{N}(\frac{N}{2} - \frac{k_i^{*A}}{2} - \frac{c_{-i}^A}{2\theta\triangle S}N)^2\Big) f(\theta)d\theta$, where $a_i^* = \frac{c_-^A i}{\triangle S(1-\frac{k_i^{*A}}{N})}$.*

Proof. If firm i invests early and the other firm waits until it observes the realized θ: if $\theta \geq \frac{c_{-i}^A}{\triangle S(1-\frac{k_i^A}{N})}$, the other firm's best response is $R_{-i}^*(k_i^A) = \frac{N}{2} - \frac{k_i^A}{2} - \frac{c_{-i}^A}{2\theta\triangle S}N$ and firm i's profit function is then $\pi_i(k_i^A, R_{-i}(k_i^A), \theta) = \frac{\theta}{N} S^B k_i(N - k_i - k_{-i}) + \frac{\theta}{N} \triangle Sk_i^A(\frac{N}{2} - \frac{k_i^A}{2}) + \frac{c_{-i}^A - 2c_i^A}{2} k_i^A$; if $\theta \leq \frac{c_{-i}^A}{\triangle S(1-\frac{k_i^A}{N})}$, $R_{-i}(k_i^A) = 0$ and firm i's profit function is then $\pi(k_i^A, R_{-i}(k_i^A), \theta) = \frac{\theta}{N} S^B k_i(N - k_i - k_{-i}) + \frac{\theta}{N} \triangle Sk_i^A(N - k_i^A) - c_i^A k_i^A$. Taking the expected value of θ, firm i's optimal expected profit function at the early stage is $\mathbb{E}_e[\pi_i^*(k_i^A, R_{-i}(k_i^A), \theta)] = \max_k \Big\{ \int_{\theta_l}^{a_i} \Big(\frac{\theta}{N} S^B k_i(N - k_i - k_{-i}) + \frac{\theta}{N}\triangle Sk(N-k) - c_i^A k\Big) f(\theta)d\theta + \int_{a_i}^{\theta_u} \Big(\frac{\theta}{N} S^B k_i(N - k_i - k_{-i}) + \frac{\theta}{N} \triangle Sk(\frac{N}{2} - \frac{k}{2}) + \frac{c_{-i}^A - 2c_i^A}{2} k\Big) f(\theta)d\theta \Big\}$, where $a_i = \frac{c_{-i}^A}{\triangle S(1-\frac{k}{N})}$. Firm i's optimal NGP capacity is $k_i^{*A} = \arg\max_k \mathbb{E}_e[\pi_i^*(k, k_{-i}^{*A}, \theta)]$. The other firm's optimal NGP capacity is $k_{-i}^{*A} = \max\{\frac{N}{2} - \frac{k_i^{*A}}{2} - \frac{c_{-i}^A}{2\theta\triangle S}N, 0\}$ and the optimal ex-ante expected profit is $\mathbb{E}_l[\pi_{-i}^*(k_i^{*A}, k_{-i}^A, \theta)] = \int_{\theta_l}^{a_i^*} \Big(\frac{\theta}{N} S^B k_{-i}(N - k_i - k_{-i})\Big) f(\theta)d\theta + \int_{a_i^*}^{\theta_u} \Big(\frac{\theta}{N} S^B k_{-i}(N - k_i - k_{-i}) + \frac{\theta\triangle S}{N}(\frac{N}{2} - \frac{k_i^{*A}}{2} - \frac{c_{-i}^A}{2\theta\triangle S}N)^2\Big) f(\theta)d\theta$, where $a_i^* = \frac{c_-^A i}{\triangle S(1-\frac{k_i^{*A}}{N})}$. □

Lemma B.2. *If both firms invest late, i.e., (L', L'), and $c_i^A \leq c_{-i}^A$, $i = x, y$, the equilibrium capacity is as follows: if $\theta \triangle S \leq c_i^A$, then $k_i^{*A} = k_{-i}^{*A} = 0$, i.e., (LN, LN); if $c_i^A \leq \theta \triangle S \leq 2c_{-i}^A - c_i^A$, then $k_i^{*A} = \frac{N}{2} - \frac{c_i^A}{2\theta\triangle S}N$ and $k_{-i}^{*A} = 0$, i.e., (L, LN); if $\theta \triangle S \geq 2c_{-i}^A - c_i^A$, then $k_i^{*A} = k_{-i}^{*A} = \frac{N}{3} + \frac{c_{-i}^A - 2c_i^A}{3\theta\triangle S}N$, i.e.,*

(L,L); The equilibrium expected profits are $\mathbb{E}_l[\pi_i^*(k_i^A, k_{-i}^{*A}, \theta)] = \frac{\bar{\theta}}{N} S^B k_i(N - k_i - k_{-i}) + \int_{c_i^A}^{2c_{-i}^A - c_i^A} \left(\frac{N}{4\theta \triangle S}(\theta \triangle S - c_i^A)^2\right) f(\theta) d\theta + \int_{2c_{-i}^A - c_i^A}^{\theta_u} \left(\frac{\theta \triangle S}{9} N + \frac{2}{9} N(c_{-i}^A - 2c_i^A) + \frac{(c_{-i}^A - 2c_i^A)^2}{9\theta \triangle S} N\right) f(\theta) d\theta$ *and* $\mathbb{E}_l[\pi_{-i}^*(k_i^{*A}, k_{-i}^A, \theta)] = \frac{\theta}{N} S^B k_{-i}(N - k_i - k_{-i}) + \int_{2c_{-i}^A - c_i^A}^{\theta_u} \left(\frac{\theta \triangle S}{9} N + \frac{2}{9} N(c_i^A - 2c_{-i}^A) + \frac{(c_i^A - 2c_{-i}^A)^2}{9\theta \triangle S} N\right) f(\theta) d\theta$.

Proof. If both firms decide to wait, there are three potential outcomes after θ is realized: neither firm invests, i.e., (LN, LN); the low-cost firm invests and the opponent does not, i.e., (L, LN) or (LN, L); both firms invest (L, L). The details are listed in Table B.1, where $R_i(k)$ is firm i's best response function to the other firm's capacity decision k.

When $c_x^A \le c_y^A$	
If $R_x(0) < 0$,	then (LN, LN)
If $R_x(0) \ge 0$ and $R_y(R_x(0)) < 0$,	then (L, LN)
If $R_y(R_x(k_y^{*A})) \ge 0$,	then (L, L)

When $c_x^A \ge c_y^A$	
If $R_y(0) < 0$,	then (LN, LN)
If $R_y(0) \ge 0$ and $R_x(R_y(0)) < 0$,	then (LN, L)
If $R_x(R_y(k_x^{*A})) \ge 0$,	then (L, L)

Table B.1: *Capacity subgame* outcomes in the equilibrium strategy (L', L')

When $c_i^A \le c_{-i}^A$, $i = x, y$: **(1)** if $\theta \triangle S \le c_i^A$, then $k_i^{*A} = k_{-i}^{*A} = 0$, i.e., (LN, LN); **(2)** if $c_i^A \le \theta \triangle S \le 2c_{-i}^A - c_i^A$, then $k_i^{*A} = \frac{N}{2} - \frac{c_i^A}{2\theta \triangle S} N$ and $k_{-i}^{*A} = 0$, i.e., (L, LN); **(3)** if $\theta \triangle S \ge 2c_{-i}^A - c_i^A$, then $k_i^{*A} = \frac{N}{3} + \frac{c_{-i}^A - 2c_i^A}{3\theta \triangle S} N$, i.e., (L, L). Firm i's and firm $-i$'s optimal ex-ante expected profits from simultaneous late investments are $\mathbb{E}_l[\pi_i^*(k_i^A, k_{-i}^{*A}, \theta)] = \frac{\bar{\theta}}{N} S^B k_i(N - k_i - k_{-i}) + \int_{c_i^A}^{2c_{-i}^A - c_i^A} \left(\frac{N}{4\theta \triangle S}(\theta \triangle S - c_i^A)^2\right) f(\theta) d\theta + \int_{2c_{-i}^A - c_i^A}^{\theta_u} \left(\frac{\theta \triangle S}{9} N + \frac{2}{9} N(c_{-i}^A - 2c_i^A) + \frac{(c_{-i}^A - 2c_i^A)^2}{9\theta \triangle S} N\right) f(\theta) d\theta$ and $\mathbb{E}_l[\pi_{-i}^*(k_i^{*A}, k_{-i}^A, \theta)] = \frac{\theta}{N} S^B k_{-i}(N - k_i - k_{-i}) + \int_{2c_{-i}^A - c_i^A}^{\theta_u} \left(\frac{\theta \triangle S}{9} N + \frac{2}{9} N(c_i^A - 2c_{-i}^A) + \frac{(c_i^A - 2c_{-i}^A)^2}{9\theta \triangle S} N\right) f(\theta) d\theta$. □

Theorem B.1. *Set* $f_i^1 = \frac{\bar{\theta}}{N} S^B k_i(N - k_i - k_{-i}) + (\frac{N}{3} + \frac{c_{-i}^A - 2c_i^A}{3\bar{\theta}\triangle S} N)(\frac{\bar{\theta}\triangle S}{3} + \frac{c_{-i}^A - 2c_i^A}{3})$*; set* $f_i^2 = \frac{\bar{\theta}}{N} S^B k_i(N - k_i - k_{-i}) + \int_{a_{-i}^*}^{\theta_u} \left(\frac{\theta \triangle S}{N}(\frac{N}{2} - \frac{k_{-i}^{*A}}{2} - \frac{c_i^A}{2\theta\triangle S} N)^2\right) f(\theta) d\theta$*, where* $a_{-i}^* = \frac{c_i^A}{\triangle S(1 - \frac{k_{-i}^{*A}}{N})}$ *and* $k_{-i}^{*A} = \arg\max_{k_{-i}^A} f_{-i}^3$*; set* $f_i^3 = \max_k \Big\{ \frac{\bar{\theta}}{N} S^B k_i(N - k_i - k_{-i}) + \frac{\triangle S k(N-k)}{N} \int_{\theta_l}^{a_i} \theta f(\theta) d\theta + \frac{\triangle S k(N-k)}{2N} \int_{a_i}^{\theta_u} \theta f(\theta) d\theta + \frac{c_{-i}^A}{2} k \int_{a_i}^{\theta_u} f(\theta) d\theta - c_i^A k \Big\}$*, where* $a_i = \frac{c_{-i}^A}{\triangle S(1 - \frac{k}{N})}$*; set* $f_i^4 = \frac{\bar{\theta}}{N} S^B k_i(N - k_i - k_{-i}) + \int_{c_i^A}^{2c_{-i}^A - c_i^A} \left(\frac{N}{\theta\triangle S}(\frac{\theta\triangle S}{2} - \frac{c_i^A}{2})^2\right) f(\theta) d\theta + \frac{N\triangle S}{9} \int_{2c_{-i}^A - c_i^A}^{\theta_u} \theta f(\theta) d\theta + \frac{2N(c_{-i}^A - 2c_i^A)}{9} \int_{2c_{-i}^A - c_i^A}^{\theta_u} f(\theta) d\theta + \frac{(c_{-i}^A - 2c_i^A)^2 N}{9\triangle S} \int_{2c_{-i}^A - c_i^A}^{\theta_u} \frac{1}{\theta}$ *and set* $f_i^5 = \frac{\bar{\theta}}{N} S^B k_i(N - k_i - k_{-i}) + \frac{N\triangle S}{9} \int_{2c_i^A - c_{-i}^A}^{\theta_u} \theta f(\theta) d\theta + \frac{2N(c_{-i}^A - 2c_i^A)}{9} \int_{2c_i^A - c_{-i}^A}^{\theta_u} f(\theta) d\theta + \frac{(c_{-i}^A - 2c_i^A)^2 N}{9\triangle S} \int_{2c_i^A - c_{-i}^A}^{\theta_u} \frac{1}{\theta} f(\theta) d\theta$*. Without the profitability assumption, we find the following four equilibrium strategies to the investment timing game when* $c_i^A \le c_{-i}^A$*,* $i = x, y$*:*

1. *if* $f_i^1 \ge f_i^2$ *and* $f_{-i}^1 \ge f_{-i}^2$*, then both firms invest early, i.e.,* (E, E)*.*

2. *if* $f_i^3 \ge f_i^4$ *and* $f_{-i}^1 \le f_{-i}^2$*, then firm* i *invests early and firm* $-i$ *invests late;*

3. *if* $f_i^1 \le f_i^2$ *and* $f_{-i}^3 \ge f_{-i}^5$*, then firm* i *invests late and firm* $-i$ *invests early;*

4. *if* $f_i^3 \le f_i^4$ *and* $f_{-i}^3 \le f_{-i}^5$*, then both firms invest late, i.e.,* (L, L)*;*

Proof. set $f_i^1 = \frac{\bar{\theta}}{N} S^B k_i(N - k_i - k_{-i}) + (\frac{N}{3} + \frac{c_{-i}^A - 2c_i^A}{3\bar{\theta}\triangle S} N)(\frac{\bar{\theta}\triangle S}{3} + \frac{c_{-i}^A - 2c_i^A}{3})$, $i = x, y$. In the equilibrium strategy (E, E), $\mathbb{E}_e[\pi_i^*(k_i^A, k_{-i}^{*A}, \theta)] = f_i^1$, $i = x, y$. Set $f_i^3 = \max_k \Big\{ \frac{\bar{\theta}}{N} S^B k_i(N - k_i - k_{-i}) + \frac{\triangle S k(N-k)}{N} \int_{\theta_l}^{a_i} \theta f(\theta) d\theta + \frac{\triangle S k(N-k)}{2N} \int_{a_i}^{\theta_u} \theta f(\theta) d\theta + \frac{c_{-i}^A}{2} k \int_{a_i}^{\theta_u} f(\theta) d\theta - c_i^A k \Big\}$, where $a_i = \frac{c_{-i}^A}{\triangle S(1 - \frac{k}{N})}$; and set $f_{-i}^2 = \frac{\bar{\theta}}{N} S^B k_{-i}(N - k_{-i} - k_i) + \int_{a_i^*}^{\theta_u} \left(\frac{\theta\triangle S}{N}(\frac{N}{2} - \frac{k_i^{*A}}{2} - \frac{c_{-i}^A}{2\theta\triangle S} N)^2\right) f(\theta) d\theta$, where $a_i^* = \frac{c_{-i}^A}{\triangle S(1 - \frac{k_i^{*A}}{N})}$ and $k_i^{*A} = \arg\max_k f_i^3$. Based on Lemma B.1, in the equilibrium strategy where firm i invests early and firm $-i$ invests late, i.e., (E, L) or (L, E), we set: $\mathbb{E}_e[\pi_i^*(k_i^A, k_{-i}^{*A}, \theta)] = f_i^3$ and $\mathbb{E}_l[\pi_{-i}^*(k_{-i}^A, k_i^{*A}, \theta)] = f_{-i}^2$. set $f_i^4 = \frac{\bar{\theta}}{N} S^B k_i(N - k_i - k_{-i}) + \int_{c_i^A}^{2c_{-i}^A - c_i^A} \left(\frac{N}{\theta\triangle S}(\frac{\theta\triangle S}{2} - \frac{c_i^A}{2})^2\right) f(\theta) d\theta + \frac{N\triangle S}{9} \int_{2c_{-i}^A - c_i^A}^{\theta_u} \theta f(\theta) d\theta + \frac{2N(c_{-i}^A - 2c_i^A)}{9} \int_{2c_{-i}^A - c_i^A}^{\theta_u}$

$\frac{(c^A_{-i}-2c^A_i)^2N}{9\triangle S}\int_{2c^A_{-i}-c^A_i}^{\theta_u}\frac{1}{\theta}f(\theta)d\theta$; and set $f^5_i = \frac{\overline{\theta}}{N}S^Bk_i(N-k_i-k_{-i})+\frac{N\triangle S}{9}\int_{2c^A_i-c^A_{-i}}^{\theta_u}\theta f(\theta)d\theta+\frac{2N(c^A_{-i}-2c^A_i)}{9}\int_{2c^A_i-c^A_{-i}}^{\theta_u}f(\theta)d\theta+\frac{(c^A_{-i}-2c^A_i)^2N}{9\triangle S}\int_{2c^A_i-c^A_{-i}}^{\theta_u}\frac{1}{\theta}f(\theta)d\theta$. In the equilibrium strategy $(L^{'},L^{'})$: if $c^A_x \leq c^A_y$, we set $\mathbb{E}_l[\pi^*_x(k^A_x,k^{*A}_y,\theta)] = f^4_x$, and $\mathbb{E}_l[\pi^*_y(k^{*A}_x,k^A_y,\theta)] = f^5_y$; if $c^A_x \geq c^A_y$, $\mathbb{E}_l[\pi^*_x(k^A_x,k^{*A}_y,\theta)] = f^5_x$, and $\mathbb{E}_l[\pi^*_y(k^{*A}_x,k^A_y,\theta)] = f^4_y$.

Comparing the profit of firm i, $i = x, y$, in each equilibrium strategy, we find the following four equilibria to the *investment timing game* when $c^A_i \leq c^A_{-i}$, $i = x, y$:

1. if $f^1_i \geq f^2_i$ and $f^1_{-i} \geq f^2_{-i}$, then both firms invest early, i.e., (E, E).
2. if $f^3_i \geq f^4_i$ and $f^1_{-i} \leq f^2_{-i}$, then firm i invests early and firm $-i$ invests late;
3. if $f^1_i \leq f^2_i$ and $f^3_{-i} \geq f^5_{-i}$, then firm i invests late and firm $-i$ invests early;
4. if $f^3_i \leq f^4_i$ and $f^3_{-i} \leq f^5_{-i}$, then both firms invest late, i.e., (L, L);

□

Appendix C

Survey (Chapter 6)

The survey is based on Ellis et al. (2010). Some of the survey questions (IC3, II3, MT1, PSD1, OSR1) are reversely coded so that high scores indicate high risk.

Survey Instruction for the procurement department of the MRO

- Answers are on a seven-point scale, from 1 (strongly disagree) to 7 (strongly agree).
- The spare part evaluated in the survey is referred to as 'Item X'.
- The major supplier (manufacturer) of this spare part is referred to as 'Supplier Y'.

Item Customization (IC)

- IC1: Item X is custom built for us.
- IC2: We basically buy the same component that Supplier Y sells to other customers.
- IC3: Item X is pretty much an "off-the-shelf" item.

Technological Uncertainty (TU)

- TU1: Rapid changes in Item X's industry necessitate frequent product modifications.
- TU2: Technology developments in Item X's industry are frequent.
- TU3: Technology changes in Item X's industry provide major opportunities.

Item Importance (II)

- II1: If our company ranked all purchased items in order of importance, Item X would be near the top of the list.
- II2: Compared to other items our company purchases, Item X is a high priority with our company's purchasing managers.
- II3: Most other items that our company purchases are more important than Item X.

Market Thinness (MT)

- MT1: We could purchase Item X from several other vendors (i.e. other OEMs).
- MT2: Supplier Y is really the only supplier we could use for Item X.
- MT3: Supplier Y almost has a monopoly for Item X.

Probability of Supply Disruption (PSD)

- PSD1: It is highly unlikely that we will experience an interruption in the supply of Item X from Supplier Y.
- PSD2: There is a high probability that Supplier Y will fail to supply Item X to us.
- PSD3: We worry that Supplier Y may not supply Item X as specified within our purchase agreement.

Magnitude of Supply Disruption (MSD)

- MSD1: An interruption in the supply of Item X from Supplier Y would have severe negative financial consequences for our business.
- MSD2: Supplier Y's inability to supply Item X would jeopardize our business performance.
- MSD3: We would incur significant costs and/or losses in revenue if Supplier Y failed to supply Item X.

Overall Supply Disruption Risk (ODR)

- ODR1: Overall, supply of Item X from Supplier Y is characterized by low levels of risk.

Search for Alternate Source of Supply (SAS)

- SAS1: We are actively seeking alternate sources of Item X.

Appendix D

Personal Contribution Statement

- **Chapter 3. Dynamic Capacity Investment under Competition**

This chapter originates from a paper that shares the same title. It is coauthored with R. Zuidwijk, M.B.M. de Koster, and R. Dekker. As the first author, I am responsible for building the model, developing the algorithm, collecting the data, and writing the manuscript. This paper is currently under review at a journal and is available at SSRN; see Li et al. (2016b).

- **Chapter 4. Launching Next-Generation Products (NGP) in a Competitive Market**

This chapter originates from a paper that shares the same title. It is coauthored with R. Zuidwijk, M.B.M. de Koster, and S. P. Sethi. As the first author, I am responsible for building the model, performing the analysis, presenting the results, and writing the manuscript. This paper is currently under review at a journal.

- **Chapter 5. Combating Strategic Cross-Border Counterfeiters: *Public and/or Private Responsibility?***

This chapter originates from a paper that shares the same title. It is coauthored with M. Pourakbar. As the first author, I am responsible for building the model, performing the analysis, presenting the results, and writing the manuscript. This paper is currently under review at a journal.

- **Chapter 6. Assessing End-of-Supply Risk of Spare Parts Using the Proportional Hazard Model (PHM)**

This chapter originates from a paper that shares the same title. It is coauthored with R. Dekker, C. Heij, and M. Hekimoğlu. As the first author, I am responsible for developing the methodology, collecting the data, applying the methodology, validating the results, and writing the manuscript. This paper was accepted by *Decision Sciences* in 2016 (Volume 47, Issue 2); see Li et al. (2016a).

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Summary

This dissertation studies the impact of uncertainty and competition on a firm's decision making in the field of operations management (OM). Chapter 2 provides an overview on dynamic and competitive strategies in OM. The remainder of the dissertation focuses on three specific decisions areas of OM: (1) capacity planning at the strategic and tactic levels (Chapters 3 and 4), (2) anti-counterfeiting strategies at the tactic level (Chapter 5), and (3) risk management for long field-life systems at the operational level (Chapter 6).

In Chapter 3, we study the optimal dynamic capacity strategies under competition. We develop an algorithm to derive full optimal policies in terms of investment timing and size for both the leader and follower firms. We validate our model using detailed data from the container shipping market (2000-2015). Although the investments of shipping lines are often questioned to be irrational, our results show that they are close to the optimal capacity choices determined by proactive competitive strategies. By reviewing the underlying structures of various strategies, we demonstrate that in nearly all cases competing firms can gain more profit and market share by adopting a proactive strategy rather than a reactive one.

In Chapter 4, we study the optimal launch timing for next-generation products (NGPs) in a competitive market. A firm's optimal timing considers the trade-off between demand risk and competition. To measure the impact of demand risk in a market, a firm should measure the correlation between the average consumer taste and the heterogeneity in consumer taste: a strong

correlation indicates a large exposure to demand risk. We measure a firm's competitive advantage and disadvantage on a two-dimensional scale, which includes the firm's capacity investment cost advantage over its competitor and the competitor's gain from offering the product quality upgrade. Based on the competitive advantage and disadvantage of both firms and the demand risk, we distinguish different competitive situations of a firm, and derive the optimal investment strategy of a firm in each situation.

In Chapter 5, we study the optimal anti-counterfeiting strategy in a global supply chain. To combat counterfeiting, the OEM can either resort to pricing or building a public-private partnership (PPP) with Customs, in which the OEM helps Customs hinder the entry of counterfeits. Customs can also be the one who initiates the PPP and thus the OEM can join it with no cost. Using a game theoretic framework, we derive the optimal equilibrium strategies of Customs and the OEM, based on their decisions towards the PPP. We consider two types of counterfeits, non-deceptive and deceptive counterfeits. Our results show that government should play a bigger role in combating non-deceptive counterfeits, while the OEM should play a bigger role in combating deceptive counterfeits.

In Chapter 6, we study how to assess end-of-supply risk of parts of long field-life systems. Using the proportional hazard model and quantified supply chain condition data, we develop a methodology for firms purchasing spare parts to manage end-of-supply risk. Our methodology is demonstrated using data on about 2,000 spare parts collected from a maintenance repair organization in the aviation industry. Cross-validation results and out-of-sample risk assessments show good performance of the method to identify spare parts with high end-of-supply risk. Further validation is provided by survey results obtained from the maintenance repair organization, which show strong agreement between the firms' and our model's identification of high-risk spare parts.

Chapter 7 concludes the dissertation.

Nederlandse Samenvatting (Summary in Dutch)

Dit proefschrift bestudeert de impact van onzekerheid en concurrentie op de besluitvorming van een bedrijf op het gebied van operations management (OM). Hoofdstuk 2 biedt een overzicht van dynamische en concurrerende strategieën in OM. De rest van het proefschrift richt zich op drie specifieke beslissingsgebieden van OM: (1) capaciteitsplanning op strategisch en tactisch niveau (hoofdstuk 3 en 4), (2) strategieën ter bestrijding van namaak op tactisch niveau (hoofdstuk 5), en (3) risicobeheer voor systemen met een lange product life cycle op operationeel niveau (hoofdstuk 6).

In hoofdstuk 3 bestuderen we de optimale dynamische capaciteitsstrategieën onder concurrentie. We ontwikkelen een algoritme om een volledig optimaal beleid af te leiden in termen van timing en investeringsomvang voor zowel de marktleider als diens volger. We valideren ons model aan de hand van gedetailleerde gegevens van de containerscheepvaartmarkt (2000-2015). Hoewel de gemaakte investeringen van scheepvaartmaatschappijen vaak als irrationeel worden beschouwd, laten onze resultaten zien dat ze dicht bij de optimale capaciteitsbeleid liggen volgens proactieve concurrentiestrategieën. Door de onderliggende structuren van verschillende strategieën te herzien, laten we zien dat concurrerende bedrijven in vrijwel alle gevallen meer winst en marktaandeel kunnen behalen door een proactieve strategie te volgen in plaats van een reactieve strategie.

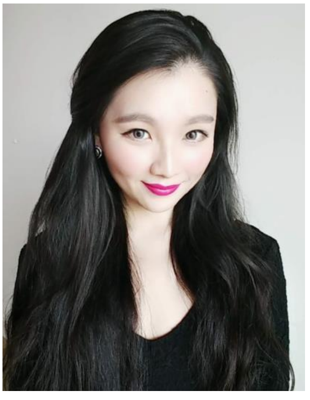
In hoofdstuk 4 bestuderen we de optimale starttiming voor producten van de volgende generatie (NGP's) in een concurrerende markt. De optimale timing van een bedrijf beschouwt de afweging tussen vraagrisico en concurrentie. Om de impact van vraagrisico's in een markt te meten, moet een bedrijf de correlatie meten tussen de gemiddelde consumentensmaak en de heterogeniteit in consumentensmaak: een sterke correlatie duidt op een grote blootstelling aan vraagrisico. We meten het concurrentievoordeel en nadeel van een bedrijf op een tweedimensionale schaal. Dit houdt ook rekening met het investeringskostenvoordeel van de onderneming ten opzichte van zijn concurrent, en de winst van de concurrent door een betere productkwaliteit aan te bieden. Op basis van het concurrentievoordeel en nadeel van beide bedrijven en het vraagrisico, onderscheiden we verschillende concurrentiesituaties van een bedrijf en bepalen we de optimale investeringsstrategie van een bedrijf voor ieder van deze situaties.

In hoofdstuk 5 bestuderen we de optimale anti-namaakstrategie in een globale supply chain. Om namaak tegen te gaan, kan de OEM ofwel zijn prijzen veranderen of een publiek-private samenwerking (PPS) met de Douane opzetten, waarbij de OEM de Douane helpt de invoer van namaken te belemmeren. De Douane kan ook degene zijn die de PPS initieert waarbij de OEM kan deelnemen zonder kosten. Met behulp van een speltheoriekader leiden we de optimale balans voor de Douane en de OEM af op basis van hun beslissingen aan de hand van de PPS. We beschouwen zowel niet-misleidende als misleidende namaken. Onze resultaten tonen aan dat de overheid een grotere rol zou moeten spelen in de strijd tegen niet-misleidende namaken, terwijl de OEM een grotere rol zou moeten spelen in de strijd tegen misleidende namaken.

In hoofdstuk 6 bestuderen we hoe het end-of-supply risico kan worden beoordeeld van onderdelen van systemen met een lange levensduur. Door middel van een proportioneel hazard-model en gekwantificeerde supply chain-conditiegegevens, ontwikkelen we een methodologie voor bedrijven die reserveonderdelen kopen om het end-of-supply risico in te tomen. Onze methodologie wordt gedemonstreerd met behulp van gegevens van circa 2.000 reserveonderdelen van een onderhoudsreparatieorganisatie in de luchtvaartindustrie. Cross-validatieresultaten en out-of-sample risicobeoordelingen tonen aan dat de methode reserveonderdelen met een hoog end-of-supply risico uitstekend kan identificeren. Verdere validatie heeft plaatsgevonden door middel van een survey bij de onderhoudsreparatieorganisatie, waarbij een sterke overeenkomst is gevonden tussen het door het bedrijf gemaakte identificaties van risicovolle reserveonderdelen en dat van ons model.

Hoofdstuk 7 besluit het proefschrift.

About the Author



Xishu Li (1990) received her bachelor's degree with a major in Logistics Management from Southwestern University of Finance and Economics, Chengdu, China, in 2011, and graduated from the ERIM MPhil Research Master program at Rotterdam School of Management (RSM), Erasmus University in 2013. Her master thesis focused on risk management of spare parts of long field-life systems. After her graduation, she worked at RSM to pursue a PhD degree. Her research is in the fields of operations management, economic modelling, data analytics, software development, and quantitative logistics. She focuses on topics including capacity investment, dynamic pricing, consumer-based revenue management, new product launch, supply disruption risk management, and sustainability. She works closely with private and public organizations in her research, focusing on project-specific problems and using industry data. In 2016, she was a visiting scholar in Naveen Jindal School of Management, University of Texas at Dallas, USA. Her research findings have been presented at various international conferences, including POMS and INFORMS, and the chapters of her dissertations have been published or currently under review at prestigious journals, including *Manufacturing & Service Operations Management* and *Decision Sciences*. In the fall of 2017, she started her tenure track at Science Based Business, Institute of Advanced Computer Science, Leiden University.

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Education

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2011 - 2013	**M.Phil.** (Domain of Logistics) Erasmus Research Institute of Management, the Netherlands Thesis: *Obsolescence Forecasting using the Proportional Hazards Model* Supervisors: Prof. Rommert Dekker, Dr. Christiaan Heij, Dr. Erwin van der Laan

Research

1. **Assessing End-of-Supply Risk of Spare Parts Using the Proportional Hazard Model**
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2. **Competitive Capacity Investment under Uncertainty**
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Presentations

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2009	ELAVIO, *Fortaleza*
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2013 - 2016 Seven Master theses on Supply Chain Management
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2014 - 2015 One Master thesis on International Management

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