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ESSAYS IN OPERATIONS MANAGEMENT

For the degree of Doctor of Philosophy

Is approved by the final examining committee:

Ananth V. Iyer
Chair

Suresh Chand

Gemma Berenguer

Yaroslav Rosokha

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Approved by Major Professor(s): Ananth V. Iyer

Approved by: Mark Bagnoli 7/25/2016

Head of the Departmental Graduate Program Date

ESSAYS IN OPERATIONS MANAGEMENT

A Dissertation

Submitted to the Faculty

of

Purdue University

by

Heejong Lim

In Partial Fulfillment of the

Requirements for the Degree

of

Doctor of Philosophy

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To my family

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ABSTRACT

Lim, Heejong PhD, Purdue University, August 2016. Essays in Operations Management. Major Professor: Anath V. Iyer.

In the first essay, we investigate the impact of reciprocity in the dyadic supply chain. Our study is motivated by the experiences of the semiconductor and LCD industries, we investigate the impact of reciprocity in the dyadic supply chain. A notable characteristic in the above technology industries is the alternating possession of bargaining power caused by cyclical demand. We incorporate a reciprocal game in a dyadic supply channel over two periods. We investigate how a supplier is influenced and protects himself during the oversupply period by anticipating the buyer's reciprocal behavior. Our results show that a supplier's understanding of a buyer's reciprocal behavior can mitigate double marginalization and can even fully coordinate the channel. This implies that even without a costly mechanism to resolve the double marginalization, appropriate consideration of the counterpart will increase channel efficiency.

In the second essay, we consider a firm that manages a portfolio of customers placing orders that need replacement parts. The firm has both long-term and short-term customers. A long-term customer places both routine orders for routine maintenance and urgent orders due to emergency with a low margin for the firm and a short-term customer places urgent orders with a high margin for the firm. Routine orders provide stable loads and generate efficiency. Considering the increase in efficiency by routine orders, there is a trade-off between the efficiency and profitability of the order portfolio. Motivated by data provided by the company, we build an analytical model to support optimal decision making. We identify the impact of an additional urgent

order to the cost embedded in the future operations. Finally, we model the mixed integer program to support the company's capacity plan. We conclude with in sights provided to the firm and managerial insights for optimal customer order portfolios.

In the third essay, we focus on the economic benefit of profound technology projects as milestones are achieved. Ce-Al alloy project by CMI promotes an example. The project we use replaces the current aluminum (Al) alloy with Al-cerium (Ce) alloy in an engine block and an engine head to increase the operational efficiency of the vehicle. We can expect higher fuel efficiency as well as a lower cost of production. The Ce-Al alloy development project by the Critical Material Institute (CMI) announces an achievement level at every milestone. The model keeps track of two goals, efficiency improvement and production cost reduction. Based on the progress about those two R&D tracks, the research question involves when to add capacity for production to maximize profits and how to adjust the R&D strategy to maximize benefit. The problem is modeled in a Bayesian update and a stochastic dynamic program. Insights from the model were used to estimate the economic benefit for CMI and suggestion for improvement.

1. INTRODUCTION

We describe the ability of production by the measure called capacity. In operations management, capacity has been extensively discussed by many researchers. When the cost to change capacity is expensive, capacity is considered to be inflexible. In case that capacity is not flexible, the company faces challenges such as capacity idleness, capacity shortage, and loss of customer satisfaction. Furthermore, investment in capacity is a problematic issue. In the traditional operations literature, many strategies have been suggested such as designing a contract or a mechanism.

Long-term relationship is one of strategies to deal with challenges because building a good relationship can reduce transaction costs. In this dissertation, we will discuss how long-term relationship impacts on the supply chain and the optimal timing strategy to expand the capacity. Chapter 2 and 3 considers the long-term relationship in the supply chain. Chapter 4 investigates the timing of capacity expansion according to research and development (R&D) progress.

In chapter 2, motivated by the experiences of the semiconductor and the Liquid Crystal Display (LCD) industries, we investigate the impact of reciprocity in the dyadic supply chain. Alternating possession of bargaining power causes demand cycle in the technology industry. While demand swings are huge, the capacity of the manufacturing facility is not flexible. In the shortage period, procuring quality products reliably is the issue, and in the oversupply period, maintaining capacity utilization is another problem. Under this circumstance, we have observed that the supplier makes business decisions considering long term relationship.In this chapter, we ask questions as follows:

1. Does considering the opponent's benefit make sense in terms of the player's long term profit?
2. How does the presence of kindness and reciprocity impact on the dyadic supply chain?
3. What is the manager's optimal decision if he expects a long-term relationship with the opponent?

In order to take into account reciprocal behavior, we incorporate a reciprocal game in a dyadic supply channel over two periods. we investigate how a buyer's anticipated reciprocal behavior influences a supplier's order so as to protect the supplier during the oversupply period. Our analysis of the influence of reciprocity can provide managers in participating firms insights about how suppliers and buyers make decisions. On the other hand, we also examine the supply channel coordination and the double marginalization problem that are conventional areas of interest in the supply chain literature. We examine the impact of reciprocity in the sense of channel coordination. Our results show that a supplier's correct understanding of a buyer's reciprocal propensity can mitigate double marginalization and can even fully coordinate the channel. This implies that even without a costly mechanism to resolve the double marginalization, appropriate consideration of the counterpart will increase channel efficiency.

Chapter 3 is driven by a project with the metal fabrication company located in Texas. They supply various metal parts for oil refineries and chemical plants. The company, as a supplier, wants to strengthen relationships to customer firms by means of lower price for urgent orders from long-term customers and maximize their long-term profit. They believe that a positive relationship leads to more routine orders from customers and that increased routine orders that will compensate for any losses stemming from the low pricing strategy for urgent orders.

After exploring data provided by the company, we found interesting observations. The first observation is that the customer relation affects likelihood of placing urgent orders. The second is that the company charges fewer margins for the urgent order from the customer with routine orders (long-term customer) than those without routine orders (short-term customer). However, margins of routine orders are not differentiated. The third is that they work urgent jobs more efficiently when the shop is highly loaded. We found that the firm needs to maintain a certain level of work load from routine orders for efficiency and they need to accept urgent orders from short-term customers for profitability.

Based on data exploration, we developed a deterministic analytic model for the pricing decision. Findings are:

1. Price of a low margin urgent job is relative to that of a high margin urgent job
2. Loss due to a low margin urgent order is compensated by margin of a routine order
3. When capacity is large, the firm needs to fill the capacity with routine orders

In addition, we will study the option to postpone routine orders. The optimal quantity to be postponed will be investigated. The cost impact of an additional urgent order will be identified.

In chapter 4 considers the project of the Critical Materials Institute (CMI), which aims to reduce US dependence on critical materials. One of projects CMI aims at developing advanced alloy by adding critical material. Replacing current aluminum alloy with Ce-Al alloy in an engine block and an engine head increases efficiency of a vehicle. Material property of Ce-Al alloy features lighter weight and better thermodynamic performance. In addition, the production time can be reduced up to 80%. We can expect higher fuel efficiency as well as lower cost of production. The Ce-Al alloy development project announces an achievement level at every milestone. The research question is when to add capacity for production and how to adjust R&D

strategy. As an extension, we will consider two research tracks that report their own progress. Under given additional resource such as post-doc researchers or funds, we will investigate the optimal decision to invest additional resources. The problem is modeled in a Bayesian stochastic dynamic program.

2. ORDERS AND RECIPROCITY IN THE TECHNOLOGY SUPPLY CHAIN

2.1 Introduction

Our objective in this research is to examine how reciprocal decisions affect the nature of decision making in a supply chain. Reciprocity is defined to be behavioral response to kindness signaled by the counterpart. [1] Reciprocity motivates the one to pay back for kind actions by taking actions that are kind to the counterpart. Reciprocity is conditional to the first mover's action. Thus, reciprocity is different from altruism. [2] There are two main motivations to investigate the impact of reciprocity. First, behavioral economics literature has indicated that if somebody is nice to the other, the other would be nice to somebody by fairness. The nature of reciprocity clearly has an implication in economics (Rabin, 1993) In organizational behavior literature, there are many research in fairness, reciprocity, and trust. [3] highlighted that fairness generates trust and reciprocity in fairness and trust leads to the effective team. Reciprocity also proves that the one is trustworthy. They also found that there are two aspects in fairness: fairness in outcome and in process. They observed two aspects in unexpected ways: people accept unfair outcomes when the process is fair or people reject fair outcomes when the process is unfair. This implies that how fairness in the process is perceived more importantly than fairness of outcomes. They also illustrated how fairness is operationalized by the manager. In our problem, we assume that two companies already went through the operationalizing fair process. Therefore, we suppose that two companies consider each other trustworthy. Second, we observed reciprocal decisions in high-tech industry. The notable characteristics of high-tech industry is that the production capacity is not sufficient at early stage and the market is oversupplied as competitors enter the market. At some point, the leading company develops the advanced technology and the market faces shortage. In this environment, we observed that buyers reciprocal decisions are made according to suppliers favorable decisions. We consider the particular case of Liquid Crystal Display (LCD) industry. In early 2000s, the new display technology, LCD started to emerge. Its advantages were light weight, thinness and scalability of size. Once the new technology was introduced, the manufacturing capacity for LCD panels was a critical constraint for both the LCD manufacturer and the Original Equipment Manufacturer (OEM). In the LCD industry, the shortage and oversupply are inevitable due to demand cycles, i.e. periods of under capacity and overcapacity. Consequently, there is an alternating possession of bargaining power. For the LCD manufacturer, the manufacturer cannot easily invest in building capacity for the shortage because in the oversupply period, unutilized capacity hurts financial performance. In addition, low utilization hurts the production yield severely when they want to ramp up the production quantity due to the characteristics of manufacturing process. The OEM also wants to prevent low utilization during the oversupply, expecting the reliable supply of quality LCD panels over time. We found that the LCD manufacturer cares for big OEMs during the shortage with low prices and adequate supply so that OEMs order a certain level of quantity during the oversupply as a return.

There is a similar practice in the apparel industry. Ruentex was a Taiwanese textile company producing various textiles such as yarn, printed flannel and denim. Liz Claiborne, a US based apparel company, was looking for a supplier who could supply quality textiles reliably. Liz Claiborne chose Ruentex for its potential capability even though Ruentex could not provide quality textiles. When Ruentex had problem in quality or production, Liz Claiborne instead of finding an alternative supplier, helped Ruentex to solve those problems and to improve their quality. As their relationship became stronger, Liz Claiborne could procure various high quality textiles at a good price and obtain market competitiveness. [4]

2.1.1 Characteristics of LCD Industry

LCD fabrication process is similar to that of semiconductor manufacturing.

- Process industry and high investment cost: Like chemical industries, iron and steel mills, or the petroleum refineries, LCD manufacturing requires a huge investment for its manufacturing facility. As with the semiconductor industry, the photolithography machine is essential and critical to fabricate circuits on the glass panel and the photolithography machine costs approximately 25 million US dollars. Though the number depends on the target production capacity, an LCD manufacturing plant is usually equipped with about 20 photolithography machines. Including other equipment, it costs about 3.5 billion US dollars to build the 8th generation FAB with a capacity of a hundred thousand panels per month.

- Demand cycle and uncertainty: There are three main markets for LCD. The first is the IT market focusing LCD displays for computers. Corporate buyers are biggest consumers of LCD displays. Usually they lease laptops, desktops and other peripherals, especially monitors, from PC manufacturers such as Dell, HP, Acer, Lenovo, and so on. Expiration of leasing contracts generates a demand of LCD panels periodically. The second market is the television (TV) market. a TV has been called a 10 year appliance. In other words, TV is expected to last about 10 years. Besides, big sports events such as Olympics and World Cup Soccer attract consumers to buy newer and larger TVs. Relatively long lifetime and periodic big events generate another stream of the seasonality. The third market is the mobile device market. Mobile devices require low-power consumption and different dimensions of LCD screens to meet their requirements. Smartphones and tablet PCs are recently introduced to public. Their demand is growing fast. However, speed of demand growth depends on the world economics forecast is uncertain and demand is uncertain.

- Limited number of customers: Once the LCD is fabricated and assembled into the LCD module, it is sold to OEMs or set manufacturers. (OEMs are HP, Dell, Lenovo, Apple, Samsung, LG, and so on) There are several big buyers and many small buyers.

- Mix of Make-to-Order and Make-to-Stock: We can divide the manufacturing process into three phases i.e. panel, cell, and module. In the panel phase, semiconductor circuits are fabricated on a glass panel (TFT glass). In the cell phase, a fabricated TFT glass and a color filter glass are attached together and liquid crystal is injected between them. Then the original assembled glass panel is cut into the specified size. In the module phase, a cell is assembled with the product control board, aluminum chassis, and back light units. Most of buyer's requests are met in the cell phase. Requests are different from different buyers. Therefore, it is produced in make-to-order.

- Outsourcing is not preferred: Each LCD manufacturer has developed his own technology and mass production technology. For example, Samsung and Sharp have developed VA mode LCD. But LG has developed IPS mode LCD. Besides, since the production yield relies on the mass production technology, the mass production technology is the top secret for the manufacturer. Therefore, outsourcing for the shortage period is not an option to be considered. Manufacturers concern leakage of the mass production technology, the production capacity, and weakness of their models very much. Most of all, there is a compatibility problem in adapting parts from other manufacturer.

The characteristics of LCD manufacturing allow us to assume that stocking inventory is not appropriate and the production capacity is fixed.

2.1.2 Research Question

In summary in LCD industry, the LCD manufacturer and the OEM engage in reciprocal behavior. For example, the LCD manufacturer offers a lower wholesale price for a big OEM (a high priority customer) during a capacity shortage period expecting a larger order quantity from the OEM during the oversupply period. We show that the presence of trust embedded kindness and reciprocity in a dyadic supply chain, improves not only channel efficiency but also profits for both players than the double marginalization case focusing on the LCD supply chain practice. In particular, we show that the seller's (LCD manufacturer) lower wholesale price offer than the outside option during the shortage period is perceived as kindness to the buyer (OEM) and, in return, the buyer will order more than his outside option during the excess period by keeping the seller's kindness in her mind. We show that the supply chain efficiency is always better off in the presence of trust as manifested by kindness and reciprocity than without them and we study conditions that they induce the full channel coordination.

2.2 Literature

A comprehensive understanding of supply chains requires as to incorporate the understanding of human behavior to explain real work practices [5]. This needs to incorporate behavioral factors into operations management was emphasized by [6], and has been discussed by [5].

Trust has been discussed in many literature. Destroying trust between a supplier and a buyer results in long-term loss [7]. Trust is defined as the anticipation that the other organization may be relied on to fulfill its commitments, to behave predictably, and to act and negotiate fairly even when the opportunistic behavior is possible [8]. There are several benefits when trust is maintained between organizations. Trust reduces transactional costs related to bargaining and monitoring. Therefore enhanced performance is expected with trust [9]. Transaction costs are lower with self-enforcing agreements that are based on trust [10]. [5] highlighted fairness, trust and reciprocity as notable topics for OM. Fairness was defined as satisfaction of expectations of participants in the system. Fairness enhances trust between two agents. Reciprocity in fairness and trust leads to high performance [3].

There is empirical evidence of the role of trust in the supply chain. [11] showed that the buyer's satisfaction with past transaction, more specifically reciprocity positively affects the supplier and buyer relationship. In addition, he showed that trust and mutual dependency also affect supply chain relationship positively. More recently, [12] examined the impact of relationship-level factors such as asymmetric dependence and trust. Their empirical results emphasized the importance of trust between firms and showed that its impact can be mediated by factors such as communication and commitment. In other words, trust was necessary but not sufficient for the success of the supply chain. [13] investigated if the background of the supply chain participants affects the inclination to trust. Specifically they examined how the national origin of firms, China and US, affects trust, trustworthiness, and strategic information sharing in a dyadic supply chain. Their experiments found that Chinese firms tend to show lower trust and trustworthiness when there is no long-term perspective, and tend to trust US firms. [14] studied that coordinating contracts underperformed compared to prediction in laboratory experiments. Channel coordination was lower than 100% because of incomplete information. There was unexplained contract rejects by players, and players tend to split profit 50-50 rather than 100-0. They developed a model that incorporates fairness and incomplete information. Their model explained rejects by players, fair profit split in the experiments. Past empirical studies support, the idea that supply chain participants' propensities to reciprocity and trust affect their behavior and they do not focus only on their own well-being.

In the economics literature, there is extensive research that deals with fairness and reciprocity. [15] developed a game theoretic framework incorporating game player's perception and emotions towards the opponent. His framework was intended to model three facts. They are; people are willing to sacrifice their welfare to help the opponent who is kind, people are willing to sacrifice their welfare to hurt the opponent which is unkind, and those considerations are more significant when the sacrifice cost is smaller. He defined kindness as a ratio of what the player can get benefit and the maximum benefit. We use a modified revision of his definition of kindness for our model. [16] uses a model a model, in which one player's payoff was linear in the player's profit and the opponent's profit. Information about the weight of the opponent profit was not shared with the opponent. Experiments were performed under various settings and his model explained the experiments. [17] developed a tractable model by revising Levine's model. The model provide ease of analysis and was used in experiments under various circumstances. In previous fairness or reciprocal literature, belief of the opponent's kindness complicates the analysis. They developed a model that does not require as to model this belief. In our study, we revised their model for two period game and investigated player's choices analytically.

In theoretical supply chain relationship literature, the majority of work concerns trust of buyer regarding shared information under asymmetric information. There are two papers related to fairness which is related to reciprocity and trust. [7] proposed a simple relational contract when the supplier ramps up capacity is uncertain while the buyer needs a certain quantity. They concluded that the benefit of the relational contract is substantial, especially when the capacity cost is moderated and bargaining powers are similar. They also found that with a proper informal contract helps the buyer avoid monitoring cost incurred by the seller's investment decision. [18] studied how fairness affects channel coordination. In their study, if the buyer considers fairness, the seller would offer a simple wholesale price that is just above the seller's marginal cost to achieve maximum channel profit and maximum channel utility. They concluded that a constant wholesale price would fully coordinate channel in the presence of concern about fairness. Their models, however, have shown a limited ability to incorporate reciprocity. Simply speaking, reciprocity is a return action to kindness. We need at least a two period setting to model reciprocity. Another limitation is that relational contract requires an outside option. [19] suggested a model for channel coordinating contract in the presence of a fairness preference. Their model explained rejections and low efficiency in the experiments applied by conventional models. [20] extended [18]. They used a non-linear demand function and generalized the results of [18]. Recently, [21] applied the reciprocal game to two player supply chain based on Stackelberg model. They showed that intention is an important factor in decision making and changes equilibrium.

In the operations area, reciprocity has not been studied analytically. Our work contributes to the operation literature in three ways. First, we model the reciprocal game in a dyadic supply chain setting over two periods. In the first period, the seller takes actions signaling kindness to the buyer. Then the buyer takes action reciprocally in the next period. A reciprocal game is modeled for the technology supply chain. More specifically, we incorporate the characteristics of technology industry, which is the alternating possession of bargaining power caused by cyclical demand. Second, we consider the capacity of the seller. Capacity is a critical constraint in the technology industry such as the semiconductor or LCD industries. Lastly, actions related to kindness are determined endogenously. Our model does not require outside options or intention of the counterpart.

2.3 Model

We describe the two player supply chain over two periods and the supplier's kindness and the buyer's reciprocal reaction. Participants make decisions sequentially in the traditional operations literature.

In our model, we first assume that we operate as a Make-to-Order system so that carrying inventory over periods is not allowed. an LCD panel is not a consumer commodity but an intermediate product. As final display products are adjusted, the product specification required by a buyer changes over periods. The second assumption is that demand has a significant cycle. Large corporations or educational organizations usually lease IT assets from computer companies like Dell, HP, Apple, and Lenovo. Period of lease leads demand cycle. On the other hand, in the TV market, demand surges at certain times such as for big sports events like the Olympics and World cup.

We model a two period game and the time line starts with high demand (or capacity shortage). In the shortage period, the demand is so high that the order quantity is always equal to or greater than the allocated capacity. Likewise, in the oversupply period, the demand is so low that the order quantity is always equal to or less than the allocated capacity. Thirdly, we assume that the seller's capacity for the buyer is not flexible in the short term perspective. In other words, the production capacity is fixed, and it requires substantial time and capital to ramp up the capacity. The seller is, however, able to provide quantity more than the allocated capacity for the buyer by reallocating capacity from other buyers. In this case, the seller must pay a penalty cost to other buyers, the cost of changing production specifications, and the cost for loss of reputation. The fourth assumption is that the seller has the bargaining power in the shortage period and the buyer has it in the oversupply period. When the seller has the bargaining power, he decides the wholesale price. If the buyer has the bargain power, she decides the wholesale price and the order quantity. Lastly, we assume that demand is deterministic and the market size is forecasted in advance.

2.3.1 Sequence of Moves

We consider a two period game in the dyadic supply chain as described in Figure 2.1. The market demand has a cycle. In the first period, the demand is high and the

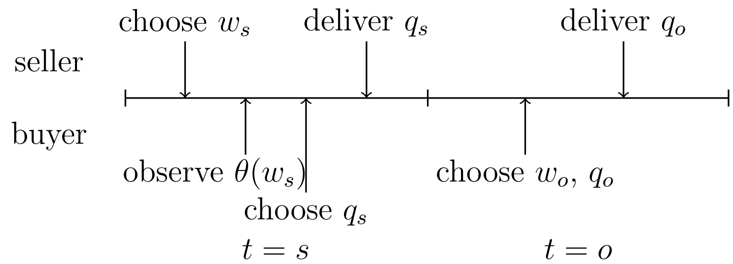

Figure 2.1. Sequence of the game

seller (he) faces a capacity shortage. In the shortage period, the seller announces the wholesale price to the buyer (she). The wholesale price is determined under expectation of a certain order quantity and the capacity overage cost. The buyer observes the seller's kindness from the wholesale price. According to both the perceived kindness and the wholesale price, the buyer decides LCD panel order quantity. This order quantity is intended by the seller when he makes a decision. The seller thus fulfills the buyer's order. The demand in the second period is low enough for the seller to face the capacity oversupply. In the oversupply period, the competition among suppliers is fierce. The buyer possesses the bargaining power during the oversupply period. In the second period, the buyer choses both the wholesale price and the LCD panel order quantity based on both the anticipated kindness by the seller and the wholesale price in the previous period.

2.3.2 Profit function

One of critical constraints in our model is the capacity allocated for the buyer. As assumed earlier, in the shortage period the seller may reallocate capacity assigned to other buyers. c_e is the unit capacity excess cost that includes loss of goodwill by other buyers, resource switching cost, and so on. In the oversupply period, the unit cost c_i is incurred by unutilized capacity. c_i represents financial loss and cost by the low yield.

t: Time period, $t = \in \{s, o\}$, where s and o represents the shortage and the oversupply period, respectively, and the shortage period comes first

w_t: Wholesale price at time t

q_t: Order quantity at time t

c: Unit production cost of the seller

k: Predetermined capacity allocation for the buyer

D_t: Potential market size at time t

We define the seller's profit functions

$$\pi_{seller}^{shortage}(w_s, q_s) = (w_s - c)\ q_s - c_e\ (q_s - k)^+ - c_i\ (k - q_s)^+ \tag{2.1}$$

$$\pi_{seller}^{oversupply}(w_o, q_o) = (w_o - c)\ q_o - c_e\ (q_o - k)^+ - c_i\ (k - q_o)^+ \tag{2.2}$$

We define $x^+ = \max\{0, x\}$. The buyer's profit is not related to the capacity. Thus,

$$\pi_{buyer}^{shortage}(w_s, q_s) = (r_s(q_s) - w_s)\ q_s \tag{2.3}$$

$$\pi_{buyer}^{oversupply}(w_o, q_o) = (r_o(q_o) - w_o)\ q_o \tag{2.4}$$

As we assume that the demand curve is linear, the inverse demand function is $r_t(q_t) = \dfrac{D_t - q_t}{a}$ where $t \in \{s, o\}$ and a is the slope of the curve.

2.3.3 Definition of kindness

We next model the extent of kindness explicitly. [15] defined kindness as a function of how much payoff a player gives to the opponent than the equitable payoff, and [17] normalized Rabin's definition. We use a modified version of this definition of kindness. The sellers's kindness is defined to be the buyer's additional profit over two periods despite of the possibility of the seller's opportunistic behavior.

Definition 2.3.1 (Kindness) *The seller's kindness is the buyer's additional profit in the shortage period normalized by the difference between the maximum and the minimum profit.*

Let $\theta(w_s)$ denote kindness by the seller's choice w_s in the shortage period and β denote the buyer's kindness sensitivity. Then,

$$\theta(w_s) = \beta \, \frac{\left(\left(\frac{(D_s - a\,w_s)^2}{4\,a} + \max \pi_{buyer}^{oversupply}\right) - \left(\frac{(D_s - a\,c - a\,c_e)^2}{16\,a} + \frac{(D_o - a\,c)^2}{4\,a}\right)\right)}{\left(\max \pi_{buyer}^{shortage} + \max \pi_{buyer}^{oversupply}\right) - \left(\min \pi_{buyer}^{shortage} + \min \pi_{buyer}^{oversupply}\right)} \tag{2.5}$$

where,

$$\max \pi_{buyer}^{shortage} = \frac{(D_s - a\,c - a\,c_e)^2}{4\,a} \tag{2.6}$$

$$\max \pi_{buyer}^{oversupply} = \frac{(D_o - a\,c + a\,c_i)^2}{4\,a} \tag{2.7}$$

The buyer's kindness sensitivity, β, describes the extent to which the buyer perceives kindness with the seller's shortage wholesale price, w_s.

2.3.4 Buyer's utility

[18] modeled a buyer's interest in fairness compared to the outside option in a form of the utility function. In our model, the buyer considers her profit as well as the opponent's profit over all periods *in proportion to the kindness that she has perceived in the seller.* We model the buyer's concern in the utility function. We modified [17]'s model for our problem.

Definition 2.3.2 Buyer's utility *Once the buyer perceives the seller's kindness. She considers her utility as incorporating both her own profit and the seller's profit over all periods. But for her opponent, she takes his overall profit into account weighted by the kindness perceived by the buyer. The utility function is defined as below,*

$$\begin{aligned} u(w_s, q_s, w_o, q_o) = {} & \pi_{buyer}^{shortage}(w_s, q_s) + \pi_{buyer}^{oversupply}(w_o, q_o) \\ & + \theta(w_s)\left(\pi_{seller}^{shortage}(w_s, q_s) + \pi_{seller}^{oversupply}(w_o, q_o)\right) \end{aligned}$$

2.3.5 Seller's objective

The seller's objective function is to maximize his profit over two periods. The seller chooses his wholesale price expecting the buyer's choice to maximize his profit. Once the wholesale price is chosen, the buyer chooses the order quantity in the shortage and decides both the wholesale price and the quantity in the oversupply.

$$\max_{w_s}\left(\pi_{seller}^{shortage}(w_s,q_s)+\pi_{seller}^{oversupply}(w_o,q_o)\right)$$

2.4 Analysis

In this section, we first provide results for participants' optimal decisions. We then explore the impact of parameters on the discussion. The analysis proceeds backward starting from the second period. We analyze the buyer's decisions in the oversupply period. They are the wholesale price and the order quantity decision for the oversupply period. Based on the optimal outcome, the buyer makes a decision on order quantity in the shortage period. While the buyer maximizes the utility function defined in the definition 2.3.2, the seller maximizes his overall profit by choosing the optimal wholesale price in the shortage period. First, participants' optimal decisions are investigated. Then we analyze the kindness function defined in the definition 2.3.1. In the next chapter, We compare the supply chain with the presence of reciprocity to that without the presence of reciprocity as benchmark.

2.4.1 Buyer's choices in the oversupply period

The buyer has perceived the seller's kindness expressed by the wholesale price w_s. To convey his kindness, the seller offers a lower wholesale price with the expectation of a certain amount of the order quantity. Given w_s in the first period, and perceived kindness $\theta(w_s)$ in the first period, the buyer chooses q_o to maximize her utility as defined in definition 2.3.2.

$$\pi_{buyer}^{shortage}(w_s,q_s)+\pi_{buyer}^{oversupply}(w_o,q_o)+\theta(w_s)\left(\pi_{seller}^{shortage}(w_s,q_s)+\pi_{seller}^{oversupply}(w_o,q_o)\right) \tag{2.8}$$

The utility function is concave in q_o. Note that we only consider the case of $q_o \leq k$. When $q_o > k$, the seller does not have any problem due to oversupply, and has no motivation to express his kindness, because the capacity is already fully utilized in the second period. By investigating the first order condition of equation (2.8),

$$\frac{\partial u(w_s, q_s, w_o, q_o)}{\partial q_o} = \frac{D_o - 2q_o - aw_o}{a} + \theta(w_s)\,(w_o - c + c_i) \tag{2.9}$$

$$q_o^*(w_s, w_o) = \frac{D_o - a\,w_o + a\theta(w_s)\,(w_o - c + c_i)}{2} \tag{2.10}$$

The seller's marginal profit is assumed to be always positive, i.e., $w_o - c + c_i \geq 0$. In equation (2.10), we show that kindness positively impacts the buyer's order quantity.

Proposition 2.4.1 (Buyer's reciprocal order quantity) *Under the assumption that* $w_o - c + c_i \geq 0$*, the following properties hold,*

1. *if* $\theta(w_s) = 0$*, the buyer becomes selfish. She pursues her own profit by ordering as much as she needs optimally, i.e.,* $q_o^* = q_{o,no\ reciprocity}^*$
2. *if* $\theta(w_s) > 0$*, the buyer becomes kind. She tends to share the profit by ordering more than she needs optimally, i.e.,* $q_o^* > q_{o,no\ reciprocity}^*$
3. *if* $\theta(w_s) < 0$*, the buyer becomes spiteful. She hurts the seller's profit by ordering less than she needs optimally, i.e.,* $q_o^* < q_{o,no\ reciprocity}^*$

Note that $q_{o,no\ reciprocity}^* = \dfrac{D_o - aw_o}{2}$ *is the optimal order quantity in the oversupply period without the presence of reciprocity.*

In the oversupply period, the bargaining power is possessed by the buyer. The buyer chooses the wholesale price, w_o. The utility function, $u(w_s, q_s, w_o, q_o)$, is linear in w_o. We investigate the first order condition.

$$\frac{\partial u(w_s, q_s, w_o, q_o)}{\partial w_o} = q_o(\theta(w_s) - 1) \tag{2.11}$$

The quantity has to be always greater than 0, $q_o > 0$, to run the business. Hence the wholesale price decision relies on the slope of the utility function affected by kindness $\theta(w_s)$. When kindness is more than 1, the buyer's utility function is increasing in the wholesale price, w_o. Therefore, the buyer wants to pay as much as she can. the If kindness is 1, the buyer's utility function is constant or she is indifferent in the wholesale price of the oversupply period. When kindness is less than 1, the buyer's utility function is decreasing in the wholesale price of the oversupply period. Thus, she will pay the minimum possible wholesale price. The wholesale price of the oversupply period is to be bounded by the unit production cost and the market price, $c \leq w_o \leq \dfrac{D_o - q_o}{a}$.

Proposition 2.4.2 (Buyer's reciprocal wholesale price) *With the condition $q_o > 0$,*

1. *if $\theta(w_s) = 1$, the buyer is indifferent with the wholesale price w_o. She chooses $w_o \in \left[c, \dfrac{D_o - q_o}{a}\right]$.*
2. *if $\theta(w_s) > 1$, the buyer takes care of the seller's profit actively. She chooses $w_o = \dfrac{D_o - q_o}{a}$.*
3. *if $0 < \theta(w_s) < 1$, the buyer takes care of the seller's profit passively by ordering more than the order quantity that she can maximize her profit at the wholesale price $w_o = c$.*
4. *if $\theta(w_s) \leq 0$ the buyer takes revenge by ordering less quantity than she needs and chooses $w_o = c$.*

By proposition 2.4.1 and 2.4.2, when kindness $\theta(w_s) = 1$, $q_o^* = \dfrac{D_o - a\,c + a\,c_i}{2}$

$$w_o^* = \begin{cases} \dfrac{D_o - q_o}{a} & \text{if} \quad \theta(w_s) > 1 \\ \left\{x | x \in \left[c, \max\left\{c, \dfrac{D_o + a\,c - a\,c_i}{a}\right\}\right]\right\} & \text{if} \quad \theta(w_s) = 1 \\ c & \text{if} \quad \theta(w_s) < 1 \end{cases} \tag{2.12}$$

In equation (2.12), when $\theta(w_s) > 1$, $w_o^* = \dfrac{D_o - q_o}{a}$. We plug w_o^* in $u(w_s, q_s, w_o, q_o)$ and find the first order condition. We obtain the optimal $q_o^* = \dfrac{D_o - ac + ac_i}{2}$. For $\theta(w_s) < 1$, $w_o^* = c$. Hence, $q^* = \dfrac{D_o - ac + ac_i\theta(w_s)}{2}$. When $\theta(w_s) = 1$, the buyer is indifferent to $w_o \in \left[c, \max\left\{c, \dfrac{D_o + a\,c - a\,c_i}{a}\right\}\right]$ in terms of buyer's utility. If utility is the same in that range, the buyer will pursue her maximum profit. Thus, $w_o^* = c$ when $\theta(w_s) = 1$.

Theorem 2.4.1 (Buyer's optimal order quantity in the oversupply) *Under proposition 2.4.1 and 2.4.2, if kindness $\theta(w_s) < 1$, the buyer's optimal order quantity is proportional to perceived kindness $\theta(w_s)$. If kindness $\theta(w_s) \geq 1$, the buyer's optimal order quantity is fixed. Because the seller cannot expect more order quantity to utilize his facility by doing a kindness more than 1, the seller does not have incentive to doing kindness more than 1, $\theta(w_s) > 1$.*

$$q_o^* = \begin{cases} \dfrac{D_o - ac + ac_i}{2} & \text{if} \quad \theta(w_s) \geq 1 \\ \dfrac{D_o - ac + ac_i\theta(w_s)}{2} & \text{if} \quad \theta(w_s) < 1 \end{cases} \tag{2.13}$$

When there is positive kindness, the buyer tends to order proportionally more to received kindness, and it is more than $\dfrac{D_o - ac}{2}$. She would return the kind behavior received in the shortage period. By theorem 2.4.1, the seller does not need to send a signal of kindness more than 1. Excessive kindness only hurts seller's financial performance in the shortage period but cannot bring extra benefit in the oversupply period. In the next section, we will investigate optimal decision in the first period.

2.4.2 Buyer's order quantity choice in the shortage period

As we study the sequence described in Figure 3.3, we look at buyer's decision, i.e, which the order quantity in the first period. The buyer's concern is her utility, $u(w_s, q_s, w_o, q_o)$, is concave in q_s. To maximize utility, we investigate the first order condition.

$$\frac{\partial u(w_s, q_s, w_o, q_o)}{\partial q_s} = \frac{(D_s - 2q_s - aw_s)}{a} - \theta(w_s)\,(c + c_e - w_s) \tag{2.14}$$

The marginal profit for the seller is $w_s - c - c_e$ and is assumed to be negative because delivering more LCD panels than the allocated capacity requires the seller to sacrifice his profit. Because the buyer orders in accordance with her perception about kindness, the buyer orders less with the positive perception of kindness and the buyer orders more with negative perception of kindness.

Theorem 2.4.2 (Buyer's optimal order quantity in the shortage) *The buyer's order quantity in the shortage period depends on kindness. If the buyer perceives that the seller is kind, she will order less to save the seller's capacity excess cost. If the buyer perceives that the seller is spiteful, i.e. not kind, she will order more to hurt the seller (i.e. force excess capacity cost to be incurred).*

$$q_s^* = \frac{D_s - aw_s + a\theta(w_s)(w_s - c - c_e)}{2} \tag{2.15}$$

2.4.3 Seller's wholesale price choice and kindness

In this section, we analyze perceived kindness. We dissect the kindness function to demonstrate how the wholesale price, w_s, impacts on the kindness perception.

$$\frac{\partial\theta(w_s)}{\partial w_s} = -\frac{\beta\left(\frac{D_s}{2} - \frac{a\,w_s}{2}\right)}{\frac{(D_o - a\,c + a\,c_i)^2}{4\,a} + \frac{(D_s - a\,c - a\,c_e)^2}{4\,a}} \leq 0 \tag{2.16}$$

The kindness sensitivity β describes the buyer's propensity to kindness. When the buyer has several good outside options, β is low or she is not sensitive to kindness. On the other hand, if the buyer has limited outside options or he relies on the seller, β is high or she is sensitive to kindness.

Theorem 2.4.1 implies that the kindness is bounded from above. The upper bound of the perceived kindness is $\theta(w_s) = 1$. The seller is certainly able to show more kindness than 1, but, as we discussed, it hurts the seller's performance. The seller also wants the buyer not to be spiteful, and hence the lower bound of kindness is 0, $\theta(w_s) = 0$. Equation (2.16) proves that the kindness function is monotonously decreasing in w_s. Therefore we define the upper and the lower bound of the wholesale price of the shortage period, w_s. The lower bound w_s^{lb} satisfies $\theta(w_s^{lb}) = 1$. The upper bound w_s^{ub} results in $\theta(w_s^{ub}) = 0$ due to monotonous nonincreasing property in w_s. Solution of $\theta(w_s^{lb}) = 1$ is,

$$w_s^{lb} = \frac{D_s}{a} - \frac{\sqrt{(4+\beta)\ (D_s - a\,c - a\,c_e)^2 + 4\,(D_o - a\,c + a\,c_i)^2}}{2\sqrt{\beta}\,a} \tag{2.17}$$

Likewise, we find the root of $\theta(w_s^{ub}) = 0$. That is,

$$w_s^{ub} = \frac{D_s + a\,c + a\,c_e}{2\,a} \tag{2.18}$$

Theorem 2.4.3 (Wholesale price and kindness) *Offering a lower wholesale price in the shortage period gives the buyer the perception of more kindness. The wholesale price is bounded by equation (2.17) and (2.18)*

$$w_s^{lb} \leq w_s^{*} \leq w_s^{ub} \tag{2.19}$$

Theorem 2.4.3 narrows extent of the seller's wholesale price choice. Under the business setting of the LCD industry, the seller is better off expecting the buyer to act with good will. In other words, the seller does not want the buyer to be upset at the pricing in the shortage period. Theorem 2.4.3 implies that extremely low price or high price are not feasible for the buyer (by the seller during the shortage period). In the following section, the optimal choice of the wholesale price w_s is discussed.

2.4.4 Seller's wholesale price choice in the shortage period

As a first mover, the seller does not make decision with unconditional kindness. Rather than kindness, the seller wants to maximize his profit by taking the buyer's reciprocity into account when he chooses the wholesale price. In other words, the seller uses a calculated kindness perspective. This setting is reasonable because the seller only has an expectation about the buyer's reaction. There is a paper which showed that both the seller and the buyer have concerns about fairness (or kindness) the channel cannot be coordinated ([18]). They showed that when the buyer concerns fairness the channel is always coordinated. We take their idea in our model. The overall profit is not concave in the wholesale price, w_s, in general. However, since the seller's profit function, $\pi_s^{seller}(w_s) + \pi_o^{seller}(w_s)$, is a quartic function in w_s, its second derivative function is a quadratic function in w_s. Therefore, in order to confirm concavity in the bounded range of w_s, both $\frac{\partial^2 \pi_{seller}}{\partial w_s^2}(w_s^{ub})$ and $\frac{\partial^2 \pi_{seller}}{\partial w_s^2}(w_s^{lb})$ should be negative.

$$\begin{aligned}\frac{\partial^2 \pi_{seller}}{\partial w_s^2}\left(w_s^{ub}\right) &= \frac{\partial^2 \pi_{seller}}{\partial w_s^2}\left(\frac{D_s + a\,c + a\,c_e}{2\,a}\right) \\ &= -a\,\frac{(4+3\,\beta)\,(D_s - a\,c - a\,c_e)^2 + 4\,(D_o - a\,c + a\,c_i)^2}{4\,(D_s - a\,c - a\,c_e)^2 + 4\,(D_o - a\,c + a\,c_i)^2} \\ &\leq 0\end{aligned} \tag{2.20}$$

However, $\frac{\partial^2 \pi_{seller}}{\partial w_s^2}(w_s^{lb})$ needs conditions on parameters.

$$\begin{aligned}\frac{\partial^2 \pi_{seller}}{\partial w_s^2}\left(w_s^{lb}\right) &= \frac{(20+9\,\beta)\,(D_s - a\,c - a\,c_e)^2 + 20\,(D_o - a\,c + a\,c_i)^2}{4\,(D_s - a\,c - a\,c_e)^2 + 4\,(D_o - a\,c + a\,c_i)^2} \\ &\quad - \frac{12\sqrt{\beta}\,\sqrt{(4+\beta)\,(D_s - a\,c - a\,c_e)^2 + 4\,(D_o - a\,c + a\,c_i)^2}\,(D_s - a\,c - a\,c_e)}{4\,(D_s - a\,c - a\,c_e)^2 + 4\,(D_o - a\,c + a\,c_i)^2} \\ &= \frac{\left\{(4-3\,\beta)\,(D_s - a\,c - a\,c_e)^2 + 4\,(D_o - a\,c + a\,c_i)^2\right\}\left\{(100+21\,\beta)\,(D_s - a\,c - a\,c_e)^2\right\}}{4\,(D_s - a\,c - a\,c_e)^2 + 4\,(D_o - a\,c + a\,c_i)^2} \\ &\quad + \frac{\left\{(4-3\,\beta)\,(D_s - a\,c - a\,c_e)^2 + 4\,(D_o - a\,c + a\,c_i)^2\right\}\left\{100\,(D_o - a\,c + a\,c_i)^2\right\}}{4\,(D_s - a\,c - a\,c_e)^2 + 4\,(D_o - a\,c + a\,c_i)^2}\end{aligned} \tag{2.21}$$

In order for equation (2.21) to be negative,

$$\frac{4}{3}\left(\frac{(D_o - a\,c + a\,c_i)^2}{(D_s - a\,c - a\,c_e)^2} + 1\right) \leq \beta \tag{2.22}$$

As long as equation (2.22) holds, the seller's profit function is concave in the bounded range of w_s as shown in equation 2.19.

Assuming concavity, by the first order condition and the feasible interval of w_s, the seller's optimal choice of the wholesale price is,

$$\begin{aligned}w_s^{FOC} &= \frac{D_s + a\,c + a\,c_e}{2\,a} \\ &\quad - \frac{\frac{1}{2}^{1/3}}{8}\left(\frac{2\left(4\,(D_o - a\,c + a\,c_i)^2 + (3\,\beta+4)\,(D_s - a\,c - a\,c_e)^2 - 4\,\beta\,a^2\,c_i^2\right)^3}{27\,\beta^3}\right)^{1/6} \\ &\left(2\,\cos\alpha + 2\sqrt{3}\,\sin\alpha\right)\end{aligned} \tag{2.23}$$

where,

$$\alpha = \frac{\arctan\left(- \frac{\sqrt{\frac{2\left(4\,(D_o - a\,c + a\,c_i)^2 + (3\,\beta+4)\,(D_s - a\,c - a\,c_e)^2 - 4\,\beta\,a^2\,c_i{}^2\right)^3}{27\,\beta^3} - \left((D_s - a\,c - a\,c_e)^2 + 4\,a^2\,c_i{}^2\right)^2 (D_s - a\,c - a\,c_e)^2}}{\left((D_s - a\,c - a\,c_e)^2 + 4\,a^2\,c_i{}^2\right)(D_s - a\,c - a\,c_e)} \right)}{3}$$

and $-\frac{\pi}{6} \leq \alpha \leq 0$.

Because the seller's overall profit function is a quartic equation, even though the function is not guaranteed to be concave, we can derive the optimal decision in the interval of the wholesale price, w_s using the shape of the profit function curve. By bounds of w_s, the seller's optimal choice on the wholesale price in the shortage period is,

$$w_s^* = \max\left\{w_s^{lb}, w_s^{FOC}\right\} \tag{2.24}$$

We will discuss the seller's decision in detail in later this section with buyer's kindness sensitivity.

We now investigate the impact of buyer's kindness sensitivity on the seller's decision. First if we take derivative of w_s^{FOC} with respect to β,

$$\begin{aligned}\frac{\partial w_s^{FOC}(\beta)}{\partial \beta} &= \frac{\frac{1}{2}^{1/3}\,\sigma_1}{48\,a\,\sigma_2^{5/6}}\left(2\,\cos\alpha + 2\sqrt{3}\,\sin\alpha + 6\,\frac{1}{\tan\alpha}\left(\sin\alpha - \sqrt{3}\cos\alpha\right)\right)\\ &= \frac{\frac{1}{2}^{1/3}\,\sigma_1}{48\,a\,\sigma_2^{5/6}}\left(8\,\cos\alpha - 6\sqrt{3}\cos^2\alpha + 2\sqrt{3}\sin\alpha\right) < 0\end{aligned} \tag{2.25}$$

where,

$$\begin{aligned}\sigma_1 &= \frac{2\left(4\,(D_o - a\,c + a\,c_i)^2 + (3\,\beta+4)\,(D_s - a\,c - a\,c_e)^2 - 4\,\beta\,a^2\,c_i{}^2\right)^3}{9\,\beta^4}\\ &\quad - \frac{2\,\left(3\,(D_s - a\,c - a\,c_e)^2 - 4\,a^2\,c_i{}^2\right)\,\left(4\,(D_o - a\,c + a\,c_i)^2\right)^2}{9\,\beta^3}\\ &\quad - \frac{2\,\left(3\,(D_s - a\,c - a\,c_e)^2 - 4\,a^2\,c_i{}^2\right)\,\left((3\,\beta+4)\,(D_s - a\,c - a\,c_e)^2 - 4\,\beta\,a^2\,c_i{}^2\right)^2}{9\,\beta^3} \geq 0\end{aligned}$$

$$\sigma_2 = \frac{2\left(4\,(D_o - a\,c + a\,c_i)^2 + (3\,\beta+4)\,(D_s - a\,c - a\,c_e)^2 - 4\,\beta\,a^2\,c_i{}^2\right)^3}{27\,\beta^3} \geq 0$$

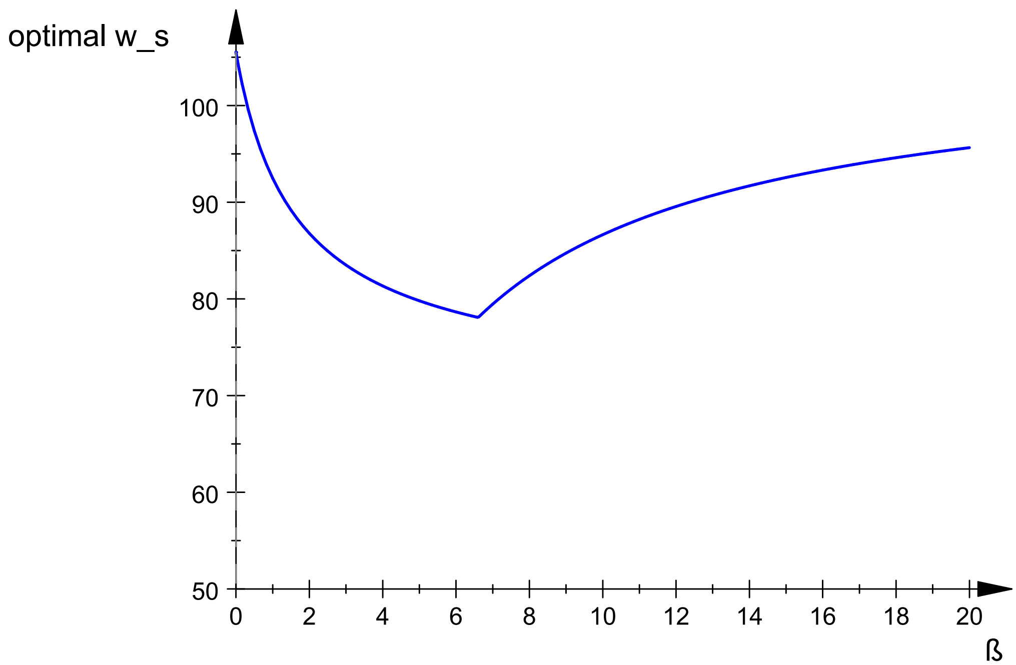

Figure 2.2. Optimal whole price and kindness sensitivity

Therefore, w_s^{FOC} is decreasing in β. So, if the buyer is sensitive to the seller's kindness, the seller is better off by offering a lower wholesale price than usual.

If we differentiate w_s^{lb} with respect to β, its derivative is always positive. Therefore, w_s^{lb} is increasing in β. Thus, the wholesale price choice is as described in Figure 2.2. Regardless of the extent of the buyer's kindness sensitivity, the seller tends to lower the wholesale price when the overall channel profit is larger.

Theorem 2.4.4 (Seller's optimal wholesale price in shortage) *if $\beta \geq \gamma$, the optimal wholesale price, w_s^*, is nonincreasing in β. Otherwise, w_s^* is nondecreasing in β.*

Theorem 2.4.4 implies that the seller tends to sacrifice his profit when the buyer is insensitive to the kindness. When the buyer is easily moved because she is too sensitive to the kindness, the seller would take advantage of the buyer's reciprocity. The wholesale price is the minimum when the seller has the kindness sensitivity at the threshold level γ. Recall that the perceived kindness is 1 when the seller chooses the lower bound of w_s. Therefore, if the buyer's kindness sensitivity is more than the threshold γ, the kindness is always 1. Another important implication of theorem 2.4.4 is that if the buyer is more sensitive to the kindness or more grateful for the seller's good will, this attitude of the buyer induces the seller to offer more kindness.

2.5 Benchmark

We now present a benchmark for the supply chain efficiency without the presence of reciprocity. When the buyer makes reciprocal decisions to kindness, the seller has the incentive to behave kindly. Reciprocity leads the seller to offer lower wholesale price than his selfish decision. We will check the channel efficiency for each period in following sections.

2.5.1 Shortage period

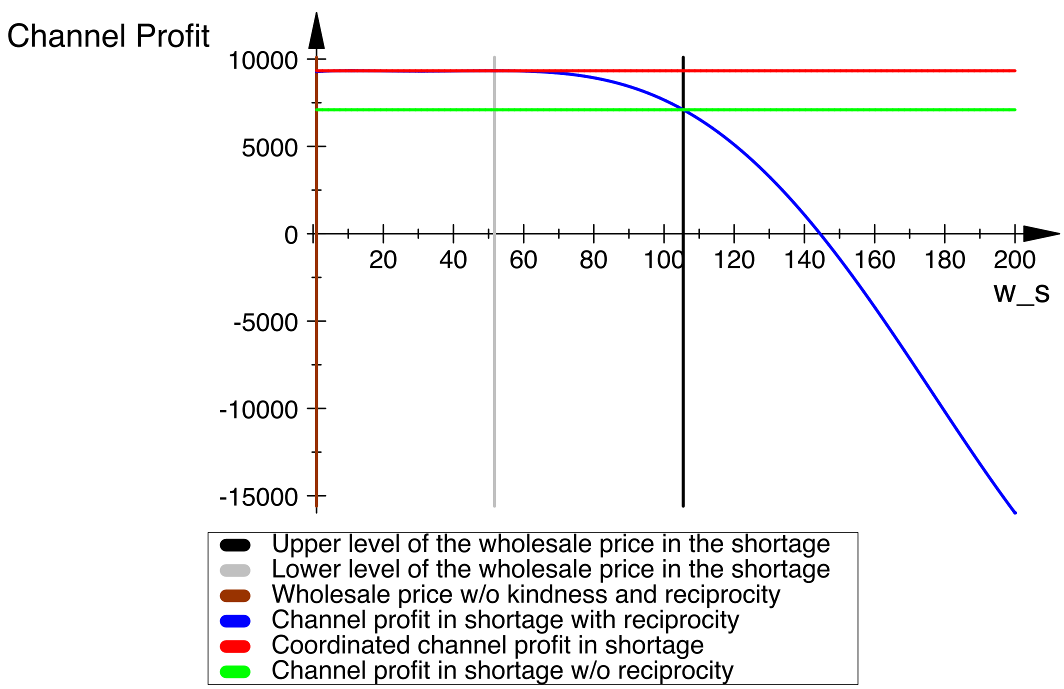

Figure 2.3. Channel profit in shortage

When the seller chooses the wholesale price, he has the feasible range, $w_s^{lb} \leq w_s \leq w_s^{ub}$. The lower bound induces kindness of 1 and the upper bound results in no kindness. Let's confirm how kindness and reciprocity impact the channel coordination. We check the channel profit in the shortage period. Let's define,

$$\pi_s^{channel}(w_s, q_s) = \pi_s^{seller}(w_s, q_s) + \pi_s^{buyer}(w_s, q_s) \tag{2.26}$$

$$\pi_s^{channel}(w_s^{lb}, q_s^*) = \frac{(D_s - a\,c - a\,c_e)^2 + 4\,k\,a\,c_e}{4\,a} \tag{2.27}$$

The channel coordination order quantity is $q_s^{ch} = \dfrac{D_s - a\,c - a\,c_e}{2}$

$$\pi_s^{seller}(w_s, q_s^{ch}) + pi_s^{buyer}(w_s, q_s^{ch}) = \frac{(D_s - a\,c - a\,c_e)^2 + 4\,k\,a\,c_e}{4\,a} \tag{2.28}$$

w_s^{lb} results in the fully coordinated channel profit.

Without the presence of kindness and reciprocity, in other words, when the seller and the buyer behave selfishly, the channel profit is

$$\begin{aligned} \pi_s^{channel}(w_s^{ub}) &= \pi_s^{channel,no\,reciprocity} \\ &= \frac{3\,(D_s - a\,c - a\,c_e)^2 + 16\,k\,a\,c_e}{16\,a} \geq 0 \end{aligned} \tag{2.29}$$

If we compare equation 2.27 and 2.29, $\pi_s^{channel}(w_s^{lb}) \geq \pi_s^{channel}(w_s^{ub})$

Now we show that $\dfrac{\partial \pi^s_{channel}}{\partial w_s}(w_s)$ is monotonously nonincreasing in w_s.

$$\frac{\partial \pi_s^{channel}}{\partial w_s}(w_s^{lb}) = 0 \tag{2.30}$$

$$\begin{aligned} \frac{\partial \pi_s^{channel}}{\partial w_s}(w_s^{ub}) = &-\frac{(D_s - a\,c - a\,c_e)\left(\beta\,(D_s - a\,c - a\,c_e)^2\right)}{8\,(D_s - a\,c - a\,c_e)^2 + 8\,(D_o - a\,c + a\,c_i)^2} \\ &- \frac{(D_s - a\,c - a\,c_e)\left(2\,(D_s - a\,c - a\,c_e)^2 + 2\,(D_o - a\,c + a\,c_i)^2\right)}{8\,(D_s - a\,c - a\,c_e)^2 + 8\,(D_o - a\,c + a\,c_i)^2} \leq 0 \end{aligned} \tag{2.31}$$

$\dfrac{\partial \pi_s^{channel}}{\partial w_s}(w_s)$ is a quintic equation in w_s. By comparing roots of $\dfrac{\partial \pi_s^{channel}}{\partial w_s}(w_s)$, w_s^{lb} is one of maximum points and w_s^{ub} is less than the closest neighboring root on the right hand side. Therefore, $\dfrac{\partial \pi_s^{channel}}{\partial w_s}(w_s)$ is always negative in the interval, $w_s^{lb} \le w_s \le w_s^{ub}$. $\pi_s^{channel}(w_s)$is monotonously nonincreasing in w_s when $w_s^{lb} \le w_s \le w_s^{ub}$. By equation 2.27, 2.29 and monotonously nonincreasing property of $\pi_s^{channel}(w_s)$, we conclude that the supply chain is always better off with presence of kindness and reciprocity.

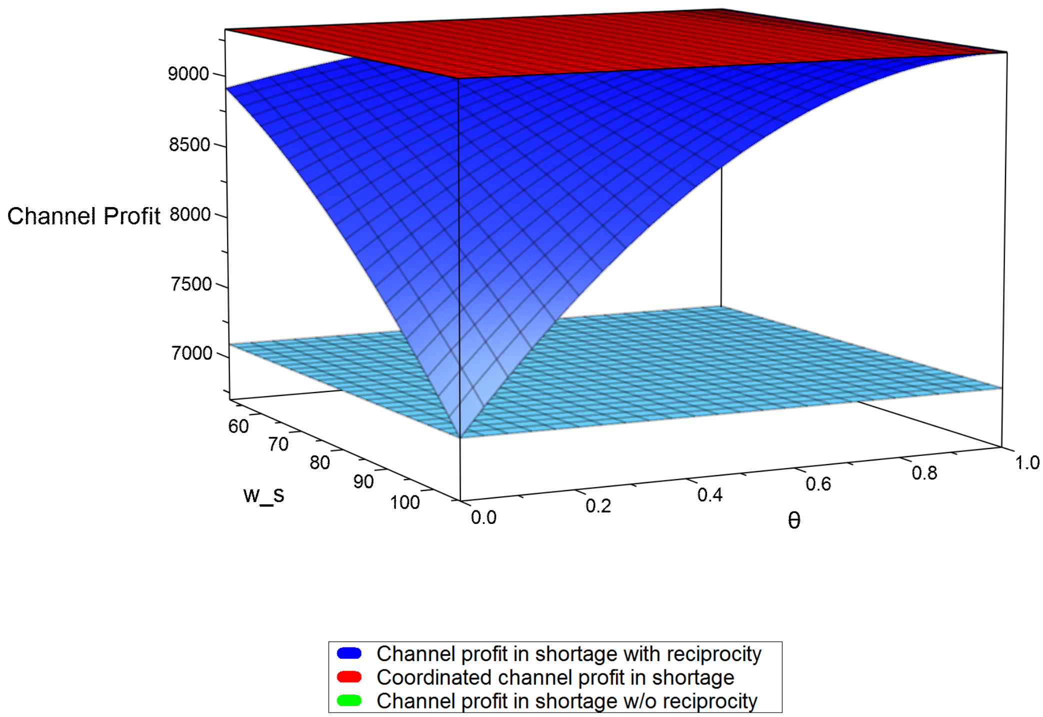

Figure 2.4. Channel profit in shortage

Theorem 2.5.1 (channel efficiency by kindness sensitivity in the shortage period) *In the range of* $0 \le \beta \le \beta^*$, *where* $\theta(\beta^*) = 1$, *the channel profit is monotonously nondecreasing. With* β^*, *channel is fully coordinated.*

Proof

$$\begin{aligned}\frac{\partial^2 \pi_s^{channel}}{\partial \beta^2}(\beta) = &-\frac{(w_s - c - c_e)^2 \left(3\, {D_s}^2 + 2\, D_s\, a\, c + 2\, D_s\, a\, c_e - 8\, D_s\, a\, w_s\right)^2}{512\, a \left(\frac{(D_o - a\, c + a\, c_i)^2}{4\, a} + \frac{(a\, c - D_s + a\, c_e)^2}{4\, a}\right)^2} \\ &- \frac{(w_s - c - c_e)^2 \left(-a^2\, c^2 - 2\, a^2\, c\, c_e - a^2\, {c_e}^2 + 4\, a^2\, {w_s}^2\right)^2}{512\, a \left(\frac{(D_o - a\, c + a\, c_i)^2}{4\, a} + \frac{(a\, c - D_s + a\, c_e)^2}{4\, a}\right)^2} \\ &< 0\end{aligned} \tag{2.32}$$

and the first order condition of $\pi_s^{channel}(\beta)$ is the root of $\theta(\beta) = 1$. ■

Figure 2.4 explains that perceived kindness sensitivity, i.e, a higher β, helps channel coordination. When the seller's wholesale price, w_s, is fixed, a larger kindness sensitivity, i.e., higher β, results in higher kindness. This higher kindness leads the buyer to consider seller's profit to a greater extent, i.e., the higher β increase channel coordination. However, Theorem 2.5.1 points that too much kindness sensitivity makes decreasing channel profit. Thus if $\hat{\beta}$ is very large and $\theta(\hat{\beta})|_{w_s} > 1$, then the channel profit begins to decrease. (Figure 2.3) Thus, more kindness sensitivity up to some point is better off for the channel. But with too much kindness sensitivity the channel is worse off.

2.5.2 Oversupply period

We check the channel efficiency in the oversupply period in the feasible interval of w_s.

$$\pi_o^{channel}(w_o^{lb}) = \frac{(D_o - a\, c + a\, c_i)^2 - 4\, a\, c_i\, k}{4\, a} \tag{2.33}$$

Channel coordination order quantity is $q_o^{ch} = \dfrac{D_o - a\, c + a\, c_i}{2}$

$$\pi_{seller}^o(w_o, q^{ch})_o + \pi_{buyer}^o(w_o, q_o^{ch}) = \frac{(D_o - a\, c + a\, c_i)^2 - 4\, a\, c_i\, k}{4\, a} \tag{2.34}$$

w_s^{lb} results in the fully coordinated channel profit again.

When there is no kindness and reciprocity,

$$\pi_o^{channel}(w_s^{ub}) = \frac{(D_o - a\, c + a\, c_i)^2 - a^2\, c_i^2 - 4\, a\, c_i\, k}{4a} \tag{2.35}$$

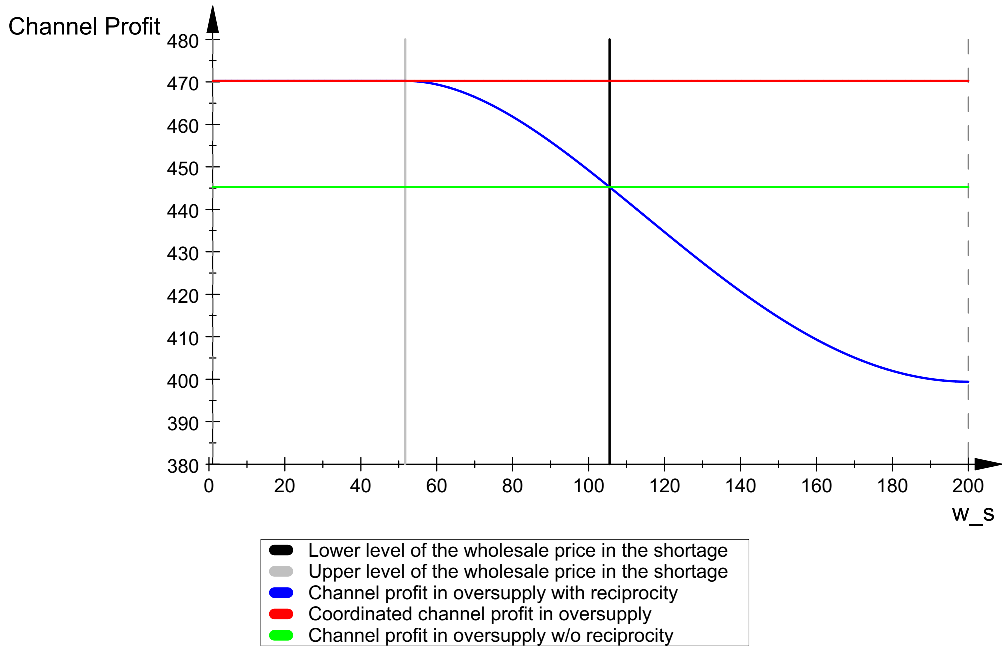

Figure 2.5. Channel profit in oversupply

Since the buyer has the bargaining power in the oversupply period, without the presence of reciprocity, the buyer chooses the order quantity, $q_o^{no\,reciprocity} = \dfrac{D_o - a\,c}{2}$. Considering the capacity idling cost, the supply chain is not coordinated.

$$\pi_o^{seller}(w_o, q_o^{no\,reciprocity}) + \pi_o^{buyer}(w_o, q_o^{no\,reciprocity}) = \frac{(D_o - a\,c + a\,c_i)^2 - a^2\,c_i^2 - 4\,a\,c_i\,k}{4a} \tag{2.36}$$

It turns out to be the equation (2.35) and (2.36) are the same.

By equation (2.33) and (2.35), $\pi_o^{channel}(w_s^{lb}) \geq \pi_o^{channel}(w_s^{ub})$. Now we show that $\dfrac{\partial \pi_o^{channel}}{\partial w_s}(w_s)$ is monotonously decreasing in w_s.

$$\frac{\partial \pi_o^{channel}}{\partial w_s}(w_s^{lb}) = 0 \tag{2.37}$$

$\dfrac{\partial \pi_o^{channel}}{\partial w_s}(w_s)$ is a cubic equation in w_s. By comparing roots of $\dfrac{\partial \pi_o^{channel}}{\partial w_s}(w_s)$, w_s^{lb} is one of maximum points and w_s^{ub} is less than the closest neighboring roots on the right hand side, $\dfrac{D_s}{a}$. Therefore, $\dfrac{\partial \pi_o^{channel}}{\partial w_s}(w_s)$ is always negative in the interval, $w_s^{lb} \leq$

$w_s \leq w_s^{ub}$. $\pi_o^{channel}(w_s)$is monotonously nonincreasing in w_s when $w_s^{lb} \leq w_s \leq w_s^{ub}$. By monotonously nonincreasing property of $\pi^o_{channel}(w_s)$, we conclude that the presence of kindness and reciprocity is better off to no-reciprocity case.

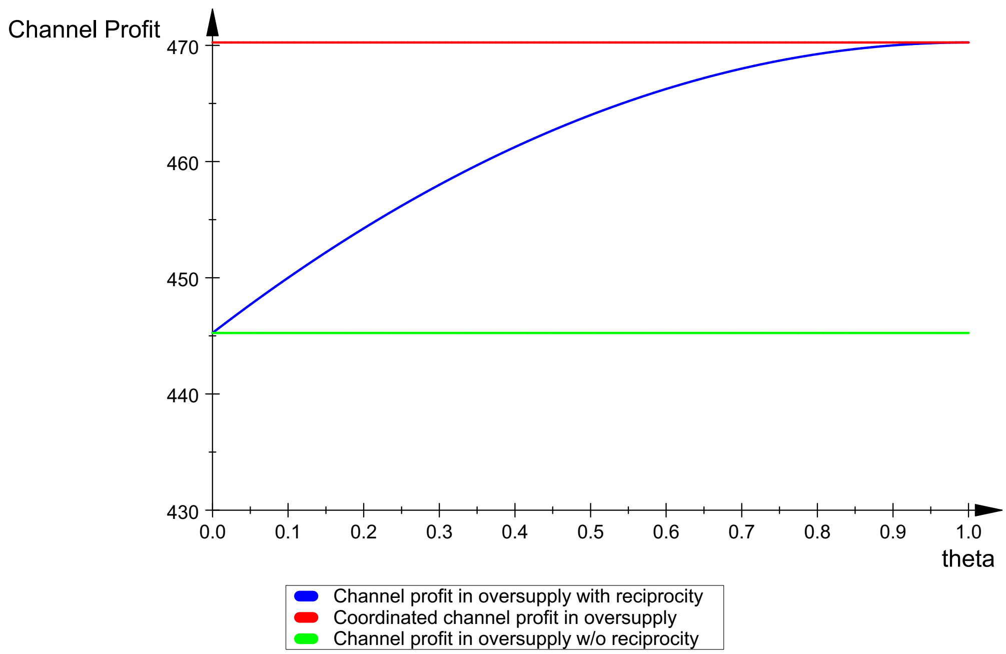

Figure 2.6. Channel profit in oversupply

Theorem 2.5.2 (Channel efficiency by kindness sensitivity in the oversupply period) *In the range of $0 \leq \beta \leq \beta^*$, the channel profit is monotonously nondecreasing where $\theta(\beta^*) = 1$. With a knowledge of β^*, the channel is fully coordinated.*

Proof

$$\frac{\partial^2 \pi_o^{channel}}{\partial \beta^2}(\beta) = -\frac{{c_i}^2 \left(3\,{D_s}^2 + 2\,D_s\,a\,c + 2\,D_s\,a\,c_e - 8\,D_s\,a\,w_s - a^2\,c^2 - 2\,a^2\,c\,c_e - a^2\,{c_e}^2 + 4\,a^2\,{w_s}^2\right)^2}{512\,a\left(\frac{(D_o - a\,c + a\,c_i)^2}{4\,a} + \frac{(a\,c - D_s + a\,c_e)^2}{4\,a}\right)^2} < 0 \tag{2.38}$$

and the first order condition of $\pi_o^{channel}(\beta)$ is the root of $\theta(\beta) = 1$. ■

In the oversupply period, again, more kindness coordinates the channel more efficiently. Figure 2.6 shows kindness perceived in the previous period leads to the more coordinated channel in the second (oversupply) period. There is a unique β that maximizes the channel profit and that achieves the full channel coordination. At the same w_s, higher kindness sensitivity β derives higher kindness. By concavity of the channel profit function, more kindness sensitivity up to some point is better for the channel. But with too much kindness sensitivity the channel is worse off.

2.6 Optimal Capacity Allocation

We have confirmed the impact of kindness and reciprocity on the supply chain. We will now investigate the impact of the capacity allocation when the seller knows the buyer's kindness sensitivity in advance. The seller's interest is his total profit over two periods, $\pi_s^{seller}(k) + \pi_o^{seller}(k)$. By differentiating in the capacity, k,

$$\frac{\partial(\pi_s^{seller}(k) + \pi_o^{seller}(k))}{\partial k} = c_e - c_i \tag{2.39}$$

If $c_e > c_i$, seller's total profit is nondecreasing in k, and choosing the upper bound of k is optimal. ($k^* = q_s^* = \frac{D_s - a\,w_s + a\,\theta(w_s)\,(w_s - c - c_e)}{2}$) When $c_e < c_i$, seller's total profit is nonincreasing in k, and choosing the lower bound of k, is the optimal when $k^* = q_o^* = \frac{D_o - a\,c + a\,c_i\,\theta(w_s)}{2}$. If $c_e = c_i$, the seller is indifferent between capacities in $\left\{\frac{D_o - a\,c + a\,c_i\,\theta(w_s)}{2}, \frac{D_s - a\,w_s + a\,\theta(w_s)\,(w_s - c - c_e)}{2}\right\}$. This result implies that when the cost of the capacity excess is higher than the cost of idle capacity, the seller is better off preparing capacity as much as he will deliver in the shortage period. Since we assume $(w_s - c - c_e) < 0$, capacity decreases in the kindness sensitivity β. This means that when the buyer is more sensitive to kindness (or wholesale price, w_s), the buyer is more willing to bear the capacity excess cost. If being idle is more hurtful than being having excess capacity, the seller is better off allocating the capacity as much as he will deliver in the oversupply period. In this case, k increases in the kindness sensitivity β. It implies that as the buyer is more sensitive to the kindness, the seller is more willing to bear the idle capacity cost. In the case that the capacity excess cost and the capacity idle cost are the same, the seller can choose any capacity, $k^* \in \left\{ \frac{D_o - a\,c + a\,c_i\,\theta(w_s)}{2}, \frac{D_s - a\,w_s + a\,\theta(w_s)\,(w_s - c - c_e)}{2} \right\}$.

While the seller must take care of capacity allocation, the buyer's total profit is indifferent to the capacity allocation. $\dfrac{\partial(\pi_s^{buyer}(k) + \pi_o^{buyer}(k))}{\partial k} = 0$.

2.7 Industry Examples

2.7.1 Other Example

Reciprocal decisions are not restricted to the specific industry such as LCD. Reciprocal decisions are widely made in Business-to-Business (B2B) practices. Figure 2.7 provided by a metal fabrication company that supplies parts for oil refineries and chemical plants. Customers of the company are grouped into two categories, i.e. long term customers and short term customers. For long term customers, there are urgent orders and routine orders while there are only urgent orders for non-preferred customers. The signal of kindness is conveyed to long term buyers by charging lower price for the urgent orders. While the conventional intuition tells us that the urgent order is expensive due to additional cost such as rescheduling and delay costs, a lower price for the urgent order can induce customers' reciprocal behavior through having routine orders. Customers' reciprocal decisions are represented by increased routine orders in both hourly volume and the number. Figure 2.7 shows long term customers' reciprocal decisions in response to lower prices for urgent orders.

There are examples in other industry. The first case is the trade between steel mills and steel wholesalers. In the accordance with the assumption that the seller and the buyer are leading players in the industry and that they have alternating bargaining powers according to the demand cycle, we explore data from only firms whose sales volume class is top in the steel industry. We study data from 2009 to 2014. The number of firms that fall in the top range of sales volume differs each

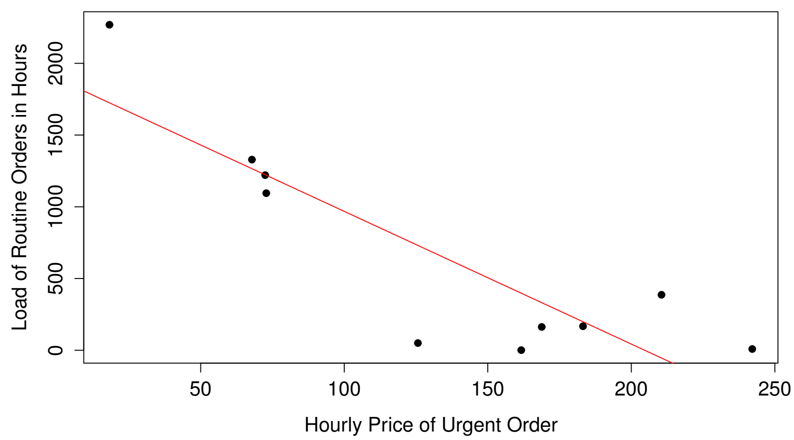

Figure 2.7. Price of urgenet order and hourly volume of routine order

year. Average annual revenues of steel mills in each year are compared to the average annual cost of sales of the steel wholesalers in the Figure 2.8.

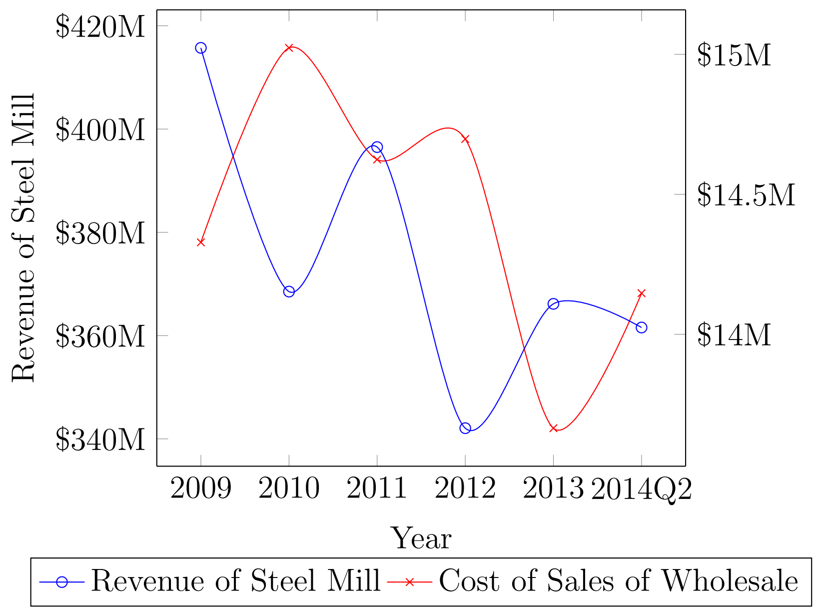

Figure 2.8. Example of reciprocity in the steel mill industry

We can find that when steel mills face low demand, the cost of sales of wholesalers is relatively high. This implies that wholesalers bear a higher cost of sales for the steel mills. On the other hand, when steel mills enjoy a good season, the wholesaler could lower the cost of sales thanks to the steel mills' kindness. There may be other reasons for this observation. However, alternating peaks of revenue and cost of sales gives us indirect evidence of the existence of reciprocity in practice. There is similar behavior in the oil extraction and refinery industry. We study data from 2009 to 2014. Average annual revenues of oil-gas extraction firms are compared to annual cost of sales of refineries in Figure 2.9. Similar alternating peaks of revenue and cost of sales are discovered and the existence of reciprocity in their trade can be observed.

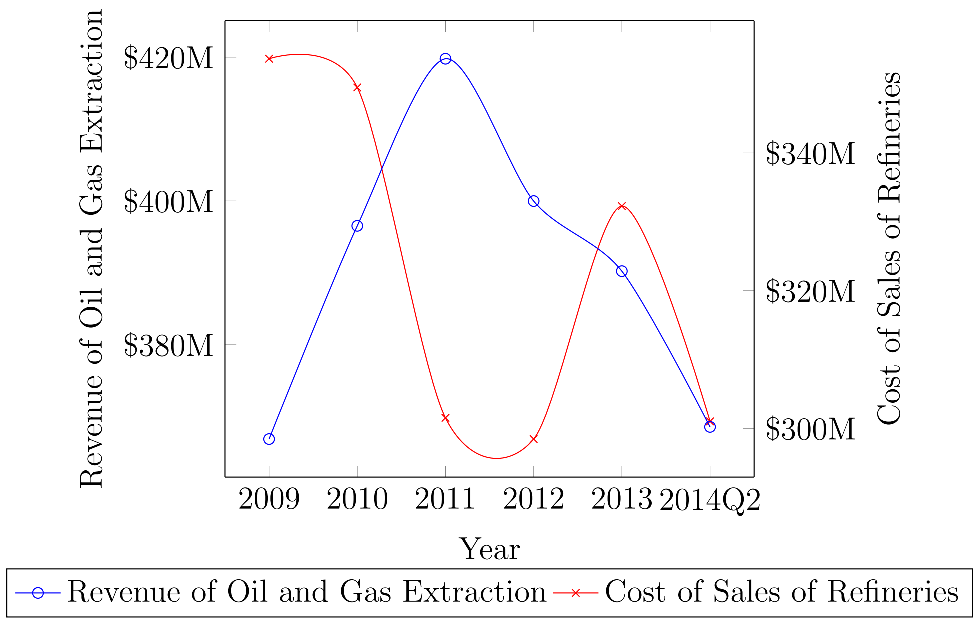

Figure 2.9. Example of reciprocity in the oil extraction industry

2.8 Managerial Insights

The goal of his section is to illustrate managerially implications that are suggested by the model. First, the supply channel is coordinated without the costly contracts. In specific condition, i.e., when kindness is 1, the supply channel is fully coordinated. This implies that the performance of the supply channel can be improved when participants have trust each other and their decisions are reciprocal. The second implications is that the participants financial performance is improved with trust and the presence of reciprocity. Considering the opponent's reciprocal decision, the seller can reduce operation costs such as capacity excess cost and idling cost. Lastly, supply channel participants need to understand kindness sensitivity. The second mover's sensitivity affects seller's decision. When the sensitivity is at a reasonable level, the seller will offer a good price. But either being too sensitive or too insensitive to kindness induces the seller offer a higher price. This implies that the buyer needs to consider fairness in the relationship for her own benefit.

2.9 Conclusion

With the presence of reciprocity, the long term transaction is a different story from the case without the presence of reciprocity. The alternating possession of the bargaining power greatly amplifies the impact of reciprocity. A spiteful decision in the current period induces revenge in the future. On the other hand, a kind decision may lead the opponent to repay kindness.

In our research, we model the kindness function and the reciprocal utility function. In the dyadic supply chain over two periods, the seller makes a decision of wholesale price with the bargaining power in the shortage period. Next period when the oversupply hurts the buyer's utilization, the buyer repays or revenges according to her perception on the seller. Decisions of two periods are connected by kindness of the seller. First, we analyzed participants' optimal decisions. If the seller offers lower wholesale price than expected, the buyer would order less in the shortage to save the seller's capacity excess cost. Furthermore she would order more than she needs for maximizing the profit in the oversupply period. Consequently, the seller may reduce the capacity idling cost. Interestingly, the buyer repays his indebtedness by ordering more quantity instead of paying a higher unit wholesale price. Only if the seller's kindness is more than a certain level (in this analysis, $\theta(w_s) = 1$), the buyer increases the wholesale price slightly. Second, we investigated the impact of the buyer's kindness sensitivity. Being more sensitive to kindness implies that she has sufficient reason to leave the table. She may have good outside options such as a reliable supplier who suggests a better price. The seller's lower wholesale price in the shortage period impresses the buyer. We found that if the buyer is more sensitive to kindness, the seller is better off when he offers a lower wholesale price. Lastly, the impact of the presence of kindness and reciprocity was analyzed. The presence of kindness and reciprocity coordinates the channel in both the shortage period and the oversupply period. Especially when the seller offers kindness of 1, the channel is fully coordinated in both periods. Even without implementing costly contracts, the presence of kindness and reciprocity relaxes or even solves the double marginalization problem.

Our work has contribution to the literature in three ways. First, we modeled and analyzed the supply chain presence of kindness and reciprocity. To our best knowledge, the current literature is about relational contract in a single period and trust regarding information asymmetry, specifically forecasting information. Our work is different because we model the tractable reciprocal game. Second, we consider capacity of the seller. Capacity is an important constraint in the technology industry such as LCD, semiconductor, and smartphones. Third, our model considers two periods. More specifically, we incorporate the notable characteristics of technology industry, which is the alternating possession of bargaining power caused by the cyclical demand. Lastly, kindness is determined endogenously. Our model does not require outside options or intention of the counterpart. Outside option and the intention is also hard to model and estimate.

There are further details that can be included when the randomness of cycle duration is taken into account, we believe the impact of the presence of kindness and reciprocity will be more significant. Our model considers two periods. Due to tractability of the analytical model, the model is simplified into a two period game. A multiple period game analysis would provide for further rich managerial insight. We leave these extensions for future research.

3. OPTIMAL CAPACITY DEPLOYMENT BETWEEN LONG-TERM AND SHORT-TERM CUSTOMERS

3.1 Introduction

In business-to-business markets, capacity utilization is an important concern. [22] When it comes to making operational decisions, the under-utilization of expensive facilities and the cost of lost sales are frequent problems for companies. In other words, a company wants to be assured that the optimal profitable use of its capacity. [22] presented approaches for the company's assurance for profitable capacity usage. Among their approaches, we focus on establishing and maintaining long-term relationships [23].

Long-term relationships have been recognized as a strategic factor in buyer-seller relationships ([24] and [25]). A long-term customer is profitable because usually he occupies the sellers production capacity consistently, and thus reduces market uncertainty. The customer also benefits by securing a source of supply at a negotiated price which is usually lower than a spot market price. There are multiple strategies that firms can choose to strengthen a relationship such as price contracts and trust based delivery guarantees.

While long-term relationships reduce the uncertainty in capacity utilization, the expected profit may not be substantial. Orders from buyers with short-term relationships, or the spot market, generates higher margins [26]. One can find similar problems in the health care area. While routine patients occupy the service capacity, there is serious uncertainty in the random arrival of new patients. As a service provider, a hospital does not want to lose their new patient revenue stream. Thus, trade-off between long-term and short-term customers has been an interesting question in any industries with a serious concern regarding capacity utilization, in both capital-intensive industries such as the steel, semiconductors, chemicals, and oil industry and service industries like the health-care and hospitality industries.

In this paper, we will use data from a metal fabrication company to motivate our model. The company produces metal fabrication parts for oil refineries and chemical plants. They have routine orders for replacement parts from long-term customers and urgent orders from both long-term and short-term customers. The benefit of routine orders is that they use capacity consistently, thereby reducing uncertainty. The other benefit is that the production efficiency is improved by the load from routine orders. The benefit of handling urgent orders from routine customers at lower margins is that such customers then increase routine orders when they perceive the company treats them well. We will discuss these points in detail later. Urgent orders from non-routine customers are the most profitable but they are random and can be considered as short work.

Our goal in this research is to establish the optimal portfolio of orders and associated pricing to maximize the long-term profit. We also want to understand the impact that additional urgent orders from non-routine customers have on cost considering the given shop load. We first provide analysis of acquired data and use the data insights to build a model. Based on our observations from the model, we identify the underlying managerial insight into their business

In the next section, we provide a review of the relevant literature. Section 3 describes our observations from the data. Section 4 presents the analytic model to provide a managerial insight. Section 5 discusses the exact decision model based on the mixed integer program. Finally in section 6, we conclude and provide an extension.

3.2 Literature

Our research fits into the research streams that consider multiple customer classes, long-term relationships, and job shop capacity planning. Extensive studies have been performed on multiple customer classes. [27] characterized the optimal policies when the firm has two demand classes. They considered deterministic demand (or long-term contracts) and stochastic demand (or urgent orders). Based on their analytical results, they developed a heuristic approaches to run the system. [28] developed an optimal differentiation strategy for pricing, lead time, and delivery reliability to maximize the profit of a firm selling express and regular products under a fixed capacity. They emphasized the importance of understanding the demand characteristics regarding price, lead time, and reliability. [29] studied the inventory policy of two demand classes with Poisson arrivals and backorder. They showed that the cost can be explained in a single relevant dimension, and then presented the optimal levels in charts and lookup tables for easy implementation. [30] considered a make-to-stock queue for multi-class customers with different cost structures. They presented an efficient algorithm for calculating optimal decisions. [31] considered inventory models, where, a supplier offers different lead times to its customers. The orders of those customers who are patient can be postponed to the next period, while the orders of who are impatient must be fulfilled during the current period. They characterized the optimal policy and described the benefits and downsides of offering an alternative lead time. [32] looked at the case of a single-period assemble-to-order production of two products to satisfy two different customers. In addition, one customer can confirm her order prior to the others and the manufacturer must fulfill her order. They proposed the optimal policy for the inventory and the production.

In the supply chain literature, long-term contracts have been considered as a strategy to deal with uncertainty. [22] surveyed the theories and practices for business-to-business markets. They pointed out that long-term relationships are one of the more favored strategies. For one thing, a long-term relationship based on trust reduces transaction costs. [33] and [34] considered a single product make-to-order business targeting both a longterm contract and a spot market. They provided the manufacturers optimal decision for the long-term contract price and optimal production level.

[35] focused on congestion and complexity in the job shop. They assumed that quality is affected when expediting jobs. [36] considered the pricing policy given facility congestion. [37] worked on job shop capacity planning using mixed integer programming and considered recourse strategies such as overtime and outsourcing.

To our best knowledge, there is no research has considered a customer class, longterm relationships, and job-shop planning focusing on cost measures such as efficiency with the shop load that varies. We consider two types of customers, i.e., routine and non-routine customers and two types of orders, i.e., urgent and routine orders. In addition, we take the shop load into account to consider the impact on work efficiency. We identify optimal customer order portfolios. In the next chapter, we address the company description and empirical observations.

3.3 Description of the Company

We focus on data from a company that does metal fabrication for oil refineries and chemical plants. There are two streams of orders, routine and urgent orders. Customers doing periodic maintenance to keep their facility operation generate routine orders. Usually, routine orders are sent to the supplier with a past relationship. However, since the market is competitive, the price is low and the margin is slim. Due to unexpected events, such as facility failure, urgent orders are placed by either routine customers or non-routine customers. In most cases, a certain level of the capacity of the supplier is occupied by routine orders. thus it is common for the customer to find a non-routine supplier for emergency cases. Therefore, there are two types of urgent orders, which are an urgent order from the routine customer and an urgent order from the non-routine customer. To maximize its long-term profit, the metal fabrication company wants to compose a portfolio of customer orders. They believe that generous pricing for the urgent order from routine customer will generate a greater volume of routine orders from those customers. Another concern is how to price the urgent order from a non-routine customer. When the urgent order is received, they have to postpone current routine orders to complete the urgent order. For pricing an incoming urgent order, they want to estimate the cost of any additional congestion influenced by the new urgent order.

Table 3.1 describes the statistics of orders. Urgent orders are more profitable than routine orders from the company. Especially, urgent orders from non-routine customers have profit margin of 73.1%. The margin of urgent orders from routine customers is 43.5%. The difference in margins confirms that the company's strategic pricing to treat routine customers well. Similar behavior is observed in routine orders as well. Routine orders from customers who have an urgent order are not profitable, while routine orders from customers who do not have urgent orders have profit margin by 20.4%.

3.3.1 Emprical Observations

Figure 3.1 shows that the company charges a lower margin for a routine customer. For example, customer A places a small quantity of routine orders and the company charges a high margin for urgent orders. Customer B frequently places routine orders. The company confirmed that they treat routine customers well so that the relationship can be maintained on an ongoing basis (Table 3.1).

Table 3.1.
Statistics of Orders for 2014

	Urgent from routine	Urgent from non-routine	Routine with Urgent	Routine w/o Urgent	p-jobs
Planned Hrs	10,942 (14.41%)	612 (0.8%)	32,681 (43%)	31,682 (35.79%)	12,614 (14.25%)
Actual Hrs	11,331 (12.8%)	559 (0.63%)	32,681 (40.7%)	31,242 (35.29%)	10,392 (11.74%)
No. of Jobs	38	16	62	27	439
Total Profit	570,173	93,200	-78,206	974,932	363,232
Total Sales	1,310,344	127,413	3,631,660	4,769,652	1,250,291
Margin	43.5%	73.1%	-2.2%	20.4%	29.1%
Margin	46.1%		10.7%		29.1%

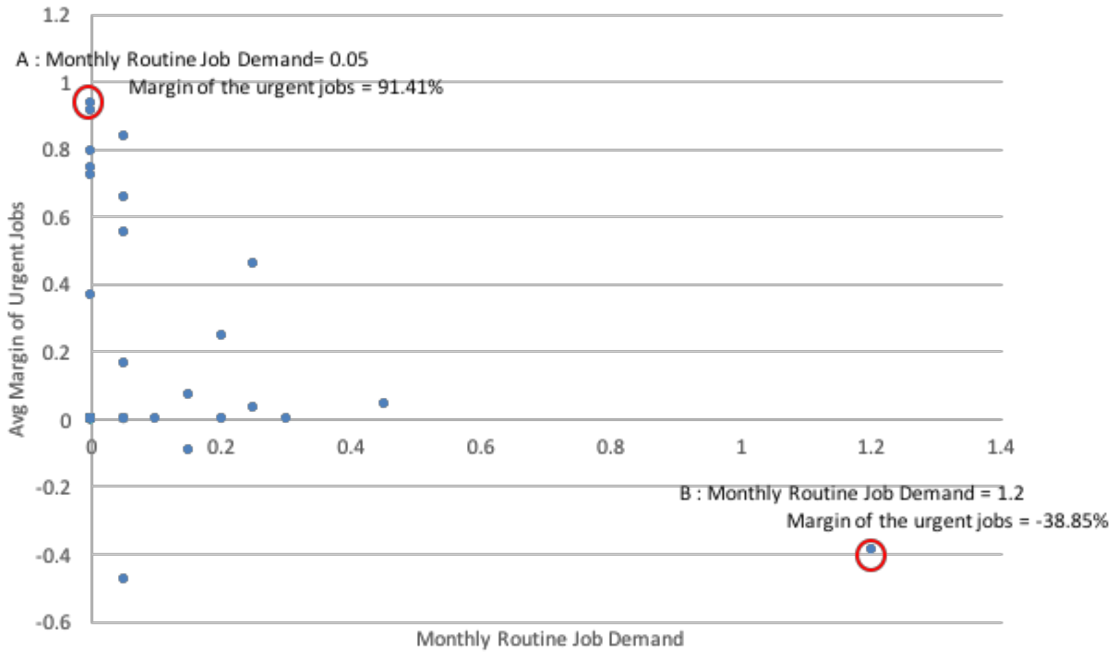

Figure 3.1. Routine order demand and urgent order margin

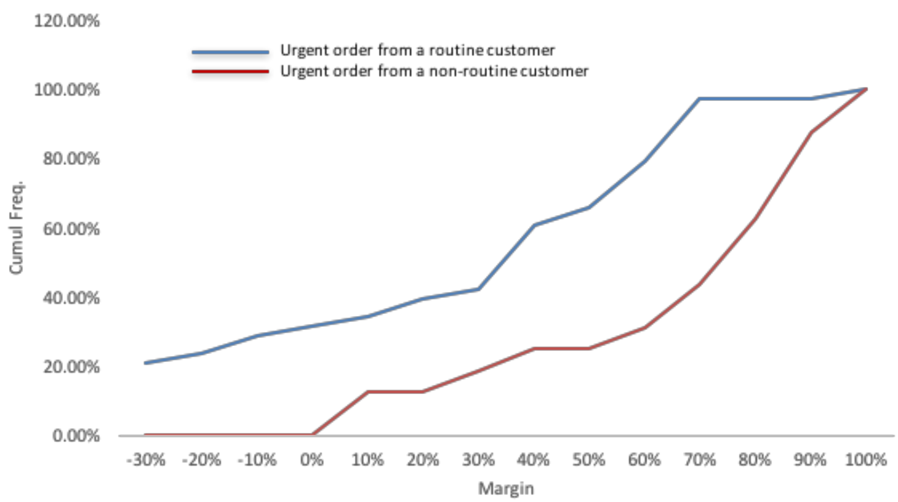

Figure 3.2. Urgent order margin comparison

Figure 3.2 shows that the margin of an urgent order from a routine customer is lower than that of an urgent order from a non-routine customer. Urgent orders from a routine customer are more likely to be less profitable, as shown in figure 3.2 .

$$Pr(Act > Est|Load_{Routine} > 30000) = 56.5\% \tag{3.1}$$

$$Pr(Act > Est|Load_{Routine} \leq 30000) = 77.4\% \tag{3.2}$$

where Act and Est are actual hours spent for the order and estimated hours, respectively.
We observed that the process efficiency of urgent orders increases when the load from routine orders is large. (Equation 3.1 and 3.2) The company representative confirmed that when workers face a high volume of routine orders, their working speed increases. In the operations literature, the learning effect is a traditional topic and extensively studied topic. [38] surveyed various learning models. We will use the exponential model among their summarized models.

The data analysis and the company discussions confirmed that the pricing of urgent orders from routine customers will affect routine orders in the future, and urgent orders from non-routine customer are more profitable. Also, there is significant efficiency improvement when the shop is loaded by routine orders.

In the next section, we will build a model that accounts for the long-term relationship based pricing and the learning effect to identify the optimal order portfolios.

3.4 Model

In this section, we first model the problem as a newsvendor model to choose capacity and price. When capacity is not flexible or there is difficulty to expand over a short term period, a newsvendor model provides rich operational insight. In the model, we consider overage cost, c_e. which is incurred when orders are more than the predetermined capacity, as the cost of outsourcing, overtime of labors, and hiring part time workers are strategies that the company deploy when they have an excess of orders over capacity.

3.4.1 Nomenclature

K : Capacity. Decision variable.

c : Capacity maintenance cost.

c_e : Overtime cost.

p_l : Price of an urgent order from a routine customer. The supplier's decision variable.

p_r : Price of a routine order.

p_h : Price of an urgent order from a non-routine customer.

D_l : Random demand for urgent orders from a routine customer.

D_h : Random demand for urgent orders from a non-routine customer.

The demand for routine orders fro longterm customers is deterministic and calculated as $y_r(p_l) = a_r - b_r\, p_l$, in other words, routine order volume increases as urgent order prices decrease. The market price for the routine orders is fixed because we assume that the market is competitive, thus if the supplier raise the price, customers will leave. The demand for urgent orders from routine customers is random. As described in previous chapters, urgent orders are generated by unexpected accidents.

Once the price is determined by agreement, any demand for urgent orders is purely random and is not influenced by any other factors, i.e., an urgent order from a routine customer, D_l, is random and described as $D_l \sim N(\mu_l, \sigma_l^2)$. On the other hand, an urgent order from a non-routine customer is controlled by the supplier through pricing. The inverse demand function for the urgent order from a non-routine customer is, $D_h(p_l) = a_h - b_h\, p_h + e_h$, where $e_h \sim N(0, \sigma_h^2)$. We define plan accuracy to be $\frac{\text{Actual Hours of a job}}{\text{Planned Hours of a job}}$. By the learning effect, when the supplier processes the routine orders of $y_r(p_l)$, the efficiency is defined to be $s(y_r(p_l)) = a_s\ (a_r - b_r\, p_l)^{b_s}$

3.4.2 The single period case

We consider a single period with two customers, one of whom is a routine customer and the other a non-routine customer. The routine customer places urgent and routine orders, D_l and D_r, respectively. The non-routine customer only places urgent orders, D_h. An urgent order, D_h is random and the price p_h is announced before D_h is observed by the supplier. In other words, the seller is able to control the demand of the urgent order from the non-routine customer by price p_h. However, the routine order demand $D_r(p_l)$ is determined by the routine customer's perception about how he is treated by the seller. This signal is transferred by the price announcement of p_l. When p_l is meaningfully lower, the routine customer places more routine orders as a return. However, the urgent order from the routine customer is not influenced by price p_l because the urgent order is for an emergency event such as a facility failure. The supplier accepts all orders. We model the problem as a single period newsvendor problem with a backorder for the routine customer. When capacity shortage occurs, the supplier will work overtime or hire part time workers to expedite the work. This generates linear cost c_e and we assume $c_e \geq p_h$ The profit function is,

$$\begin{aligned} \pi(p_l, K) = {} & p_r\, y_r(p_l) + p_l\, D_l + p_h\, D_h(p_h) \\ & - c_e\ [(y_r(p_l) + (D_l + D_h(p_h))\, s(y_r(p_l))) - K]^+ - c\, K \end{aligned} \tag{3.3}$$

The first three terms are revenue generated by orders. The fourth term describes the cost when the demand is greater than the given capacity, K.

We transform the expectation of equation (3.3) into the tractable model. We define

$$(y_r(p_l) + (D_l + D_h)\, s(y_r(p_l))) = (y_r(p_l) + (\mu_l + \mu_h)\, s(y_r(p_l))) + v$$

where $v \sim N(0, \sigma_h^2 + \sigma_l^2)$

$$K = (y_r(p_l) + (\mu_l + y_h(p_h))\, s(y_r(p_l))) + k$$

where k is a decision variable. We let $f_v(\cdot)$ represent the probability density function of v and $F_v(\cdot)$ the cumulative distribution function.

$$\begin{aligned}\mathbb{E}\left[\pi(p_l, p_h, k)\right] = p_r\, y_r(p_l) + p_l\, \mu_l + p_h\, y_h(p_h) - c_e\ (y_r(p_l) + (\mu_l + y_h(p_h))\, s(y_r(p_l)))\\ - c_e \int_k^{\infty} (v-k)\, f_v(v)\, dv - c\ (y_r(p_l) + (\mu_l + y_h(p_h))\, s(y_r(p_l)) + k)\end{aligned} \tag{3.4}$$

In equation (3.3), the first three terms represent revenue. The fourth term represents the expected cost of orders beyond capacity. The fifth term is the expected cost incurred by randomness. The last term stands for the production cost.

The optimal capacity choice by the newsvendor is,

$$k^* = F^{-1}\left(\frac{c - c_e}{c_e}\right) \tag{3.5}$$

Optimal capacity means that it is a trade-off between the capacity excess cost and opportunity cost incurred by the capacity investment cost. When the supplier's facility requires expensive investment, the supplier is better off to prepare less capacity because any idleness of the facility hurts the financial statement.

$$\begin{aligned}\frac{\partial^2 \mathbb{E}\left[\pi(p_l, p_h, k)\right]}{\partial p_l^2} &= a_s b_r^2(-b_s - 1) b_s c(a_h + \mu_l - b_h p_h)(a_r - b_r p_u)^{-2-b_s}\\ &< 0\end{aligned} \tag{3.6}$$

Therefore, expected profit function (3.4) is concave in p_l.

$$\frac{\partial \mathbb{E}\left[\pi(p_l, p_h, k)\right]}{\partial p_l} = \mu_l - b_r p_r - c(-b_r + a_s b_r b_s (a_h + \mu_l - b_h p_h)(a_r - b_r p_u)^{-1-b_s}) \tag{3.7}$$

Thus, the maximum profit can be obtained by the price of the urgent order from the routine customer, p_l^*.

Proposition 3.4.1 *The optimal price for the urgent order for the routine customer is,*

$$p_l^* = \frac{a_r}{b_r} - \frac{1}{b_r}\left(\frac{b_r c + \mu_l - b_r p_r}{a_s b_r b_s c(a_h + \mu_l - b_h p_h)}\right)^{\frac{1}{-b_s - 1}} \qquad (3.8)$$

Properties of p_l^* are;

1. *p_l^* is non decreasing in μ_l.*

2. *p_l^* is non decreasing in p_h.*

The optimal price for the urgent order from the routine customer increases when the supplier expects more urgent orders from the routine customer. By charging a higher price for the urgent order from the routine customer, the supplier saves a room for the urgent order and hopes to compensate the profit by losing the routine orders. The optimal price is similar for p_h. When the margin for the urgent order from the non-routine customer is high, even though the demand is random, the supplier hopes for potential profitability by preparing more room for urgent orders.

$$\frac{\partial^2 \mathbb{E}\left[\pi(p_l, p_h, k)\right]}{\partial p_h^2} = -2b_h < 0 \qquad (3.9)$$

Therefore, the expected profit function (3.4) is concave in p_h.

$$\frac{\partial \mathbb{E}\left[\pi(p_l, p_h, k)\right]}{\partial p_h} = a_h - 2b_h p_h + a_s b_h c(a_r - b_r p_u)^{-b_s} \qquad (3.10)$$

Thus, the maximum profit can be obtained by the price of the urgent order from the non-routine customer, p_h^*.

Proposition 3.4.2 *The optimal price for the urgent order from the non-routine customer is,*

$$p_h^* = \frac{a_r}{b_r} - \frac{1}{b_r}\left(\frac{(a_r - b_r p_u)^{-b_s}(a_s b_h c + a_h(a_r - b_r p_u)^{b_s})}{2\, b_h}\right) \qquad (3.11)$$

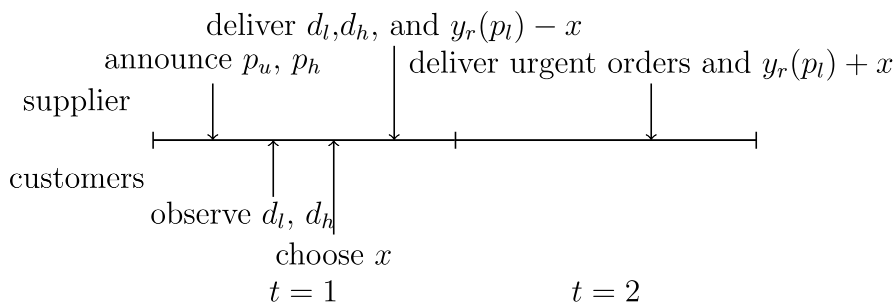

Figure 3.3. Sequence of the event

3.4.3 The two period case with a postponement option

Now we consider the two period case. The prices of all three types of order are announced initially and fixed. In the first period, after urgent order demand is realized (regardless of a customer type), the supplier has the option to postpone some of tbe routine orders. Where the supplier may want the benefit of efficiency with a high volume of routine orders in the first period. Benefit from the supplier may want to prioritize the revenue of urgent orders to routine orders and expect efficiency in the second period. In the second period, the supplier must finish all of the postponed routine orders, and the routine orders and urgent orders in the second period. The amount of postponed routine orders is denoted in the first period by x. When the supplier makes the decision for the amount of postponement, the supplier knows the volumes of both urgent orders, d_l and d_h. The postponement incurs a linear cost of delay, c_d. The profit function over two periods is,

$$\begin{aligned} V(d_l, d_h, x) = {} & p_r(y_r(p_l) - x) + p_l\, d_l + p_h\, d_h - cK \\ & - c_e((d_h + d_l)s(y_r(p_l) - x) + y_r(p_l) - x - K)^+ - c_d\, x + V_2(x) \end{aligned} \tag{3.12}$$

where the profit function of the second period is,

$$\begin{aligned} V_2(x) = {} & p_r(y_r(p_l) + x) + p_l\, \mu_l + p_h\, y_h(p_h)h - cK \\ & - c_e((\mu_l + y_h(p_h))s(y_r(p_l) + x) + y_r(p_l)) - c_e \int_{K-v}^{\infty} (v + x - K)\, f_v(v)\, dv \end{aligned} \tag{3.13}$$

$$\begin{aligned} \frac{\partial^2 V(d_l, d_h, x)}{\partial x^2} & = a_s(-1 - b_s)b_s c_e(d_l + d_h)(a_r - b_r p_l - x)^{-2-b_s} - c_e f(K - x) \\ & < 0 \end{aligned} \tag{3.14}$$

Therefore, $V(d_l, d_h, x)$ is concave in x and there exists the unique optimal solution x^*.

$$\frac{\partial V_1(d_l, d_h, x)}{\partial x} = \begin{cases} -c_d - c_e(-1 + a_s b_s (d_l + d_h)(a_r - b_r p_l - x)^{-1-b_s}) - c_e(1 - F(K - x)) \\ \qquad (d_h + d_l)s(y_r(p_l) - x) + y_r(p_l) - x - K > 0 \\ -c_d - c_e(1 - F(k - x)) \\ \qquad (d_h + d_l)s(y_r(p_l) - x) + y_r(p_l) - x - K \leq 0 \end{cases} \tag{3.15}$$

The optimal postponement quantity, x^*, cannot be simply calculated because of the power function in the learning function and distribution function of the urgent orders. However we can find the properties by comparative statistics.

Proposition 3.4.3 *The optimal amount of routine order postponement x^* is,*

$$x^* = \begin{cases} \textit{no explicit solution} & (d_h + d_l)s(y_r(p_l) - x) + y_r(p_l) + F^{-1}(\frac{c_d + c_e}{c_e}) - 2K > 0 \\ K - F^{-1}(\frac{c_d + c_e}{c_e}) & (d_h + d_l)s(y_r(p_l) - x) + y_r(p_l) + F^{-1}(\frac{c_d + c_e}{c_e}) - 2K \leq 0 \end{cases} \tag{3.16}$$

When $(d_h + d_l)s(y_r(p_l) - x) + y_r(p_l) + F^{-1}(\frac{c_d + c_e}{c_e}) - 2K > 0$,

1. *x decreases in $d_u + d_h$.*

2. *x decreases in variances of either or both urgent orders.*

When $(d_h + d_l)s(y_r(p_l) - x) + y_r(p_l) + F^{-1}(\frac{c_d + c_e}{c_e}) - 2K \leq 0$,

1. *x decreases in c_d.*

2. *x increases in c_e.*

The threshold $(d_h + d_l)s(y_r(p_l) - x) + y_r(p_l) + F^{-1}(\frac{c_d + c_e}{c_e})$ means the sum of the observed shop load in the first period and the optimal capacity. If it is greater than $2K$, when their observed volume of urgent orders is large, the supplier wants to take the advantage of efficiency by keeping more routine orders (or reducing the postponement amount). When there is more uncertainty regarding urgent orders, the supplier wants to save room for urgent orders in the second period by reducing x. When the threshold is less than $2K$, x is decided by cost. Please note that the x is a newsvendor solution considering the postponement cost and capacity excess cost. When postponement cost is high, the supplier is better off to postpone less. On the other hand, if capacity excess cost is low, the supplier is better off to complete more routine order in the first period. We have found the supplier's optimal decision and its properties. In the next chapter, based on managerial insights, we will build a model for the optimal planning.

3.5 Extension

One important question is how the new arrival of urgent order impacts operational costs. It is obvious that operational cost would vary by the facility work load because it is a combination of production, capacity excess, and overtime (or outsourcing) cost. First, we will take into account the learning effect by routine orders. We found that the impact of increased load from routine orders is to get workers to work faster from the data set. As the learning curve is not linear, we approximate the curve in a piecewise linear function. Second, we will consider the pricing decision for the urgent order from non-routine customers. Once the pricing decision at period t is made and announced, the impact will be observed at the same period t. We consider that the expected urgent demand from the non-routine customer will change with the pricing. [39] suggested how the scenario approach can be applied in the case of capacity planning. Their idea is to optimize the expected objected function by incorporating probabilities of scenarios. Model is essentially developed in the mixed integer program. We use the ideas from [39] and developed production planning model using

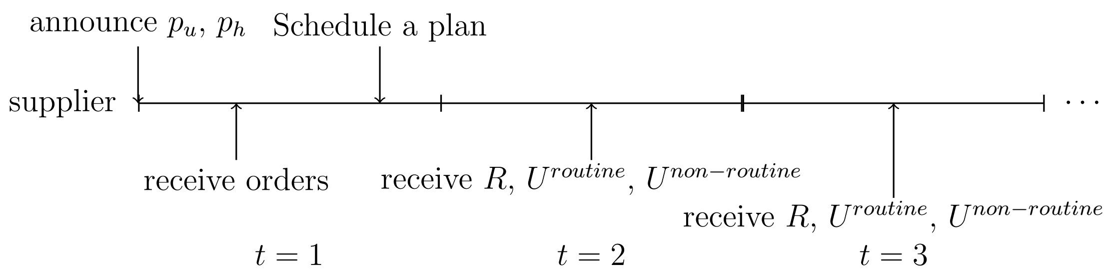

Figure 3.4. Sequence of the event

the mixed integer program considering possible scenarios.

3.5.1 Model

We start the planning at period 1. (Figure 3.4) The plan covers the time window from period 1 through period t. At period 1, the supplier announces the price for the urgent order from the routine customer and the urgent order from the non-routine customer. Then, the supplier receives the newly arrived orders including routine and urgent orders. The firm has historical records about demand. Based on the historical record, the supplier knows the potential demand size for all types of orders and their associated probabilities. In order to avoid quadratic forms, we have several relaxations. First, we used a piecewise-linear curve for the learning curve. Second, the expected profit was originally measured by the product of the price and the inverse demand function, which is eventually a quadratic function. So we prepared a combination of the price and its corresponding demand as a scenario and designed to have the model select the optimal combination. The parameters and decision variables are defined as follows:

Set Definition

H The set of resources (machine). $\{h \in H\}$

S The set of sources (The studied company and outsource). $s \in \{W, O\}$

I The set of existing orders. $\{i \in I\}$

J_i The set of operations for order i. $\{j \in J_i\}$

M The set of scenarios. $\{m \in M\}$

L The set of ranges of shop load by routine orders. $\{l \in L\}$

$Q_{non-routine}$ The set of price and demand combination for non-routine urgent orders. $\{q_n \in Q_{non-routine}\}$

$Q_{routine}$ The set of price and demand combination for routine urgent orders. $\{q_r \in Q_{routine}\}$

Monetary Parameters

r^r Market price of routine orders.

$r_{q_n}^{non-routine\ urgent}$ Price of urgent orders for non-routine customers.

$r_{q_r}^{routine\ urgent}$ Price of urgent orders for routine customers.

Demand Parameters

$U_{q_n mt}^{non-routine\ urgent}$ Urgent order demand from non-routine customers when the price is announced as $r_{q_n}^{non-routine\ urgent}$ under scenario m at period t.

$U_{mt}^{routine\ urgent}$ Urgent order demand from routine customers under scenario m at period t.

$R_{q_r mt}$ Routine order demand from routine customers when the price of urgent order for routine customers is announced as $r_{q_r}^{routine\ urgent}$ under scenario m at period t.

$R'_{q_r mt}$ Product of routine order demand from routine customers when the price of an urgent order for routine customers is announced as $r_{q_r}^{routine\ urgent}$ under scenario m at period t and acceleration by the learning effect. $R'_{q_r mt} = s\, R_{q_r mt}$

u_i Indicator variable of urgency for order i.

$$u_i = \begin{cases} 1 & \text{urgent order} \\ 0 & \text{routine order} \end{cases}$$

v_i Indicator variable of urgent order from routine customer for order i.

$$v_i = \begin{cases} 1 & \text{urgent order from the routine customer} \\ 0 & \text{urgent order from the non-routine customer} \end{cases}$$

Capacity Parameters

k_{ht} Production capacity of resource h.

τ_{ijh} Amount of capacity required for operation j to process order i at resource h.

$S_l(\cdot)$ The piecewise linear function of working speed under the load of routine orders. This function is originally an increasing concave function. We will approximate the function in a piecewise linear function.

Cost Parameters

c^p_{ijh} Production cost for operation j of order i at resource h.

c^o_{jh} Outsourcing cost for operation j at resource h when capacity is not sufficient.

c^d_i Delay cost of order i. c^p Average production cost.

Probability Parameters

p_{mt} The probability that scenario m happens at period t.

Decision Variables

x_{ijhsmt} Number of hours for operation j where the order i is processed at resource h under scenario m at period t under scenario m.

y_{ijhsmt} Binary variable. 1 if operation j of order i is assigned at resource h under scenario m at period t under scenario m, 0 otherwise.

o_{ijm} Binary variable. 1 if operation j of order i is outsourced under scenario m, 0 otherwise.

$w_{q_n m}$ Binary variable. 1 if price schedule q for urgent order from non-routine customers is selected. 0 otherwise under scenario m.

$z_{q_r m}$ Binary variable. 1 if price schedule q for urgent order from routine customers is selected. 0 otherwise under scenario m.

Temporary Variables

C_{im} Completion period of order i under scenario m.

δ_{im} Tardiness of order i under scenario m.

$\epsilon_l m$ Binary variable. 1 if the shop load is in the range l under scenario m.

Based on the definition, we develop the optimal planning model.

Objective

$$
\begin{aligned}
\max & \sum_{i \in I} (1-u_i)\,(r^r - c^p) + \sum_{i \in I} \sum_{q_r \in Q_{routine}} z_{q_r m}(r_{q_r}^{routine\ urgent} - c^p) u_i\, v_i \\
&+ \sum_{i \in I} \sum_{q_n \in Q_{non-routine}} w_{q_n m}(r_{q_n}^{non-routine\ urgent} - c^p) u_i\,(1 - v_i) \\
&+ \sum_{m \in M} \sum_{t \in T \setminus \{1\}} \sum_{q_r \in Q_{routine}} z_{q_r m}(r^r - c^p) R_{q_r m t} p_m \\
&+ \sum_{m \in M} \sum_{t \in T \setminus \{1\}} \sum_{q_r \in Q_{routine}} z_{q_r m}(r_{q_r}^{routine\ urgent} - c^p) U_{mt}^{routine\ urgent} p_m \\
&+ \sum_{m \in M} \sum_{t \in T \setminus \{1\}} \sum_{q_n \in Q_{non-routine}} w_{q_n m}(r_{q_n}^{non-routine\ urgent} - c^p) U_{q_n m t}^{non-routine\ urgent} p_m \\
&- \sum_{m \in M} \sum_{i \in I} c_i^d\, \delta_{im}^{+}\,(1-u_i)\, p_m - \sum_{m \in M} \sum_{h \in H} \sum_{i \in I} \sum_{j \in J_i} c_{jh}^o\, o_{ijm}\, \tau_{ijh}\, p_m
\end{aligned}
\tag{3.17}
$$

Subject to

$$
\sum_{t \in T} x_{ijh\{w\}mt} + \sum_{t \in T} x_{ijh\{o\}mt} = \tau_{ijh} \qquad \forall i, j, h, m \tag{3.18}
$$

$$
\sum_{t \in T} x_{ijh\{o\}mt} = \tau_{ijh} o_{ij} \qquad \forall i, j, h, m \tag{3.19}
$$

$$
\begin{aligned}
\sum_{i \in I} \sum_{j \in J_i} u_i\, x_{ijh\{w\}mt} \le k_h s - \sum_{q_r \in Q_{routine}} z_{q_r m} R'_{q_r m t} - \sum_{q_r \in Q_{routine}} z_{q_r m} U_{mt}^{routine\ urgent} \\
- \sum_{q_n \in Q_{non-routine}} w_{q_n m} U_{q_n m t}^{non-routine\ urgent} \quad \forall h, m, t \setminus \{1\}
\end{aligned}
\tag{3.20}
$$

$$
\begin{aligned}
\sum_{i \in I} \sum_{j \in J_i} (1-u_i) x_{ijh\{w\}mt} \le k_h - \sum_{q_r \in Q_{routine}} z_{q_r m} R_{q_r m t} - \sum_{q_r \in Q_{routine}} z_{q_r m} U_{mt}^{routine\ urgent} \\
- \sum_{q_n \in Q_{non-routine}} w_{q_n m} U_{q_n m t}^{non-routine\ urgent} \quad \forall h, m, t \setminus \{1\}
\end{aligned}
\tag{3.21}
$$

$$
\sum_{i \in I} \sum_{j \in J_i} x_{ijh\{w\}m\{1\}} \le k_h \quad \forall h, m \tag{3.22}
$$

$$\sum_{q_r \in Q_{routine}} z_{q_r m} = 1 \quad \forall m \tag{3.23}$$

$$\sum_{q_n \in Q_{non-routine}} w_{q_n m} = 1 \quad \forall m \tag{3.24}$$

$$\sum_{s \in S} \sum_{j \in J_i} \sum_{h \in H} u_i \, x_{ijhsmt} \leq 24\, s \qquad \forall i, m, t \tag{3.25}$$

$$\sum_{s \in S} \sum_{j \in J_i} \sum_{h \in H} (1 - u_i)\, x_{ijhsmt} \leq 24 \qquad \forall i, m, t \tag{3.26}$$

$$\sum_{l=1}^{n} \epsilon_{lm} = 1 \qquad \forall m \tag{3.27}$$

$$\sum_{q_r \in Q_{routine}} z_{q_r m} R_{q_r mt} \leq E_l + O(1 - \epsilon_{lm}) \qquad \forall l, m \tag{3.28}$$

$$\sum_{q_r \in Q_{routine}} z_{q_r m} R_{q_r mt} \geq E_{l-1} - O(1 - \epsilon_l) \qquad \forall l, m \tag{3.29}$$

$$s \leq S_l(\sum_{q_r \in Q_{routine}} z_{q_r m} R_{q_r mt}) + O(1 - \epsilon_l) \qquad \forall l, m \tag{3.30}$$

$$s \geq S_l(\sum_{q_r \in Q_{routine}} z_{q_r m} R_{q_r mt}) - O(1 - \epsilon_l) \qquad \forall l, m \tag{3.31}$$

$$C_{im} = \sum_{t \in T} \sum_{h \in H} \sum_{s \in S} t \, y_{i|J_i|hsmt} \qquad \forall i, m \tag{3.32}$$

$$\delta^+_{im} - \delta^-_{im} = C_{im} - d_i \qquad \forall i, m \tag{3.33}$$

$$\delta^+_{im} \geq 0 \qquad \forall i, m \tag{3.34}$$

$$\delta^-_{im} \geq 0 \qquad \forall i, m \tag{3.35}$$

$$x_{ijhsmt} \geq y_{ijhsmt} \qquad \forall i, j, h, s, m, t \tag{3.36}$$

$$x_{ijhsmt} \leq \tau_{ijh} y_{ijhsmt} \qquad \forall i, j, h, s, m, t \tag{3.37}$$

$$\sum_{h \in H} \sum_{s \in S} \sum_{t'=1}^{t} y_{i'(j-1)hsmt'} \geq \sum_{h \in H} \sum_{s \in S} y_{ijhsmt} \qquad \forall i, j \in J_i \setminus \{1\}, t, m \tag{3.38}$$

$$\sum_{s \in S} \sum_{h \in H} \sum_{t'=1}^{t} x_{i(j-1)hsmt'} \geq \sum_{s \in S} \sum_{h \in H} \tau_{i(j-1)h} y_{ijhsmt} \qquad \forall i, j \in J_i \setminus \{1\}, t, m \tag{3.39}$$

The objective function (3.17) is a maximization of the expected profit from period 1 through period t. The first term is revenue subtracted by production cost generated by existing routine orders. The second term is revenue subtracted by production cost generated by existing urgent orders from the routine customer. The third term is revenue subtracted by production cost generated by existing urgent orders from the non-routine customer. The fourth term is expected revenue subtracted by production cost by routine orders from period 2 to period t. Similarly, the fifth and sixth terms are for urgent orders from the routine customer and the non-routine customer, respectively. The seventh and the eighth terms mean delay cost and outsourcing cost for order i, respectively.

Equation (3.18) means that operation j of order i is processed as required at resource h and equation (3.19) implies that when the operations j is outsourced, it should be totally outsourced. Equation (3.20) restricts current urgent orders so that these cannot occupy resources to a degree that exceeds the remaining capacity. Since there is an efficiency improvement for urgent orders when the load by routine orders is high, the remaining capacity after routine orders is considered, $k_h - \sum_{q_r \in Q_{routine}} z_{q_r m} R_{q_r mt}$, is multiplied by acceleration variable s, i.e. $s(k_h - \sum_{q_r \in Q_{routine}} z_{q_r m} R_{q_r mt}) = k_h s - \sum_{q_r \in Q_{routine}} z_{q_r m} R'_{q_r mt}$. The left-hand side is the required capacity amount for urgent orders. The right-hand side represents the expected remaining capacity considering the routine and urgent orders that will be ordered in the future. The routine orders' capacity occupation is restricted by equation (3.21) and an efficiency gain is not considered. Equation (3.22) is the capacity constraint for the first period. We do not consider the efficiency by the learning effect, because currently the supplier has orders placed in period 1 only, which means that shop load really doesn't matter in terms of the efficiency. As we discussed, we want to avoid a quadratic form to maintain linearity. Therefore, there are potential combinations of price and demand. Equations (3.23) and (3.24) imposes z_{q_rm} and w_{q_nm} can choose only one value of 1, i.e. z_{q_rm} and w_{q_nm} are selection variable among the combinations. While equations (3.20) and (3.21) are of resource (or machine) perspective, equations (3.25) and (3.26) are restrictive in terms of orders' processing time. Orders cannot be processed more than 24 hours. In case of urgent orders, there is acceleration, s, by learning effect. Therefore, urgent orders can be processed at most $24\,s$ hours.

In equations (3.27) through (3.31), the efficiency factor is selected. Equation (3.27) has the model choose an appropriate piece among piecewise linear learning curves. Equations (3.28) and (3.29) check if the load of routine orders is in the range of a piece one by one. Once the piece is selected, ϵ_{lm} is set to 1. Using ϵ_{lm}, equations (3.30) and (3.31) returns the corresponding efficiency factor s. The period of an order is completed and is obtained in equation (3.32). Equations (3.33) through (3.35) returns the value about how long the jobs are delayed. We do not consider the case in which the order is completed early.

Equation (3.36) and (3.37) impose an constraint to placing a link between decision variables x_{ijhsmt} and y_{ijhsmt}. When $y_{ijhsmt} = 0$, the decision variable concerning time spent on resource h, x_{ijhsmt}, cannot be non-zero. If $y_{ijhsmt} = 1$ or the order is assigned to resource h at time t, the model can decide the time to occupy resource h and imposes a constraint not to spend more than the required time at resource h. A sequence of required operations for the order is imposed by equations (3.38) and (3.39). In equation (3.38) when the previous operation, $j-1$, is not assigned, or $y_{i(j-1)hsmt} = 0$ then the current operation j cannot be assigned to any resource. We also need the operations to be completed for the next operation. Equation (3.39) requires that the previous operation must be fully completed before the current operations are assigned.

3.5.2 Numerical Study

In this section, we numerically identify the impact of shop load on performance measures such as expected delay cost, expected outsourcing cost, cost impact of the additional order, and expected profit by varying the initial shop load. We assume that the supplier is making optimal decisions. Thus the impact of shop load determined by optimal decisions is studied. The mixed integer program (MIP) in the previous chapter is implemented in ILOG Cplex 12.5 in the Java language. The planning time horizon is 20. The number of machines (or resources) and the number of operations are both 4. However, the sequence of operations and the required machine are random. We assume there are three possible demand scenario over periods with corresponding probabilities. In our setting, we assume the equally distributed demand scenarios, i.e. their probabilities are 0.33, 0.34, and 0.33.

Since our main concern is shop load, we generate 60 data sets varying the shop load. Each data set is created by random number generation. In each data set, numbers of routine orders, urgent orders from the routine customer, and urgent orders from the non-routine customer are randomly generated. However the expected ratios are 88%, 8%, and 4% for routine orders, urgent orders from the routine customer, and urgent orders from the non-routine customer, respectively. The required processing time for each operation of each order is randomly generated by uniform distribution of $U(1,3)$. The outsource cost per hour for each operation of each order follows $U(1,2)$. Deadlines for orders are randomly determined by $U(2,16)$ Delay cost per order is generated by $U(5,20)$.

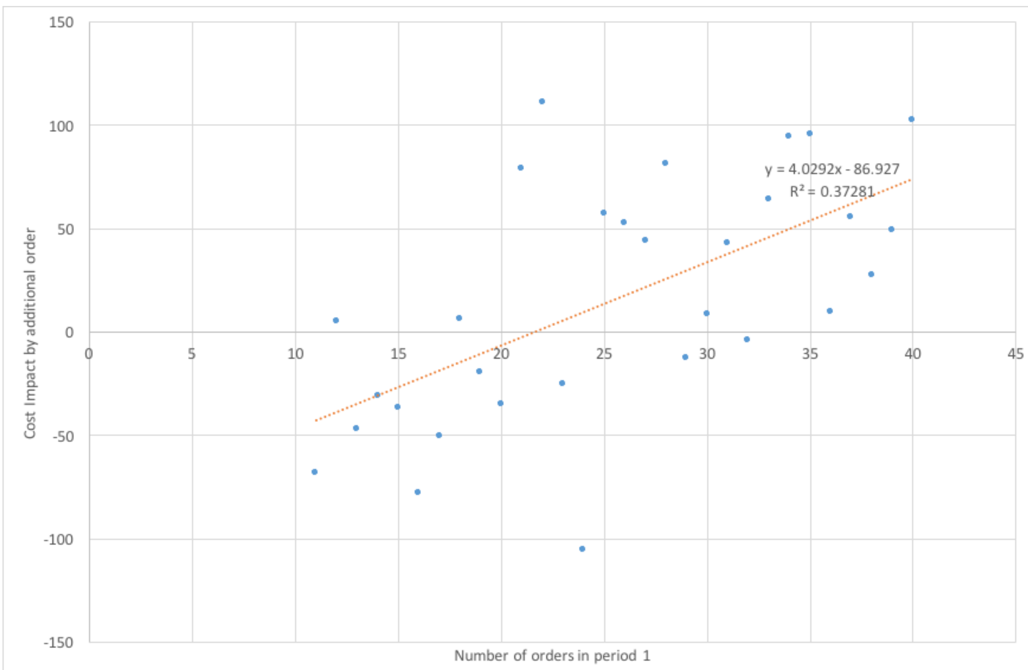

Figure 3.5. Cost impact of shop load

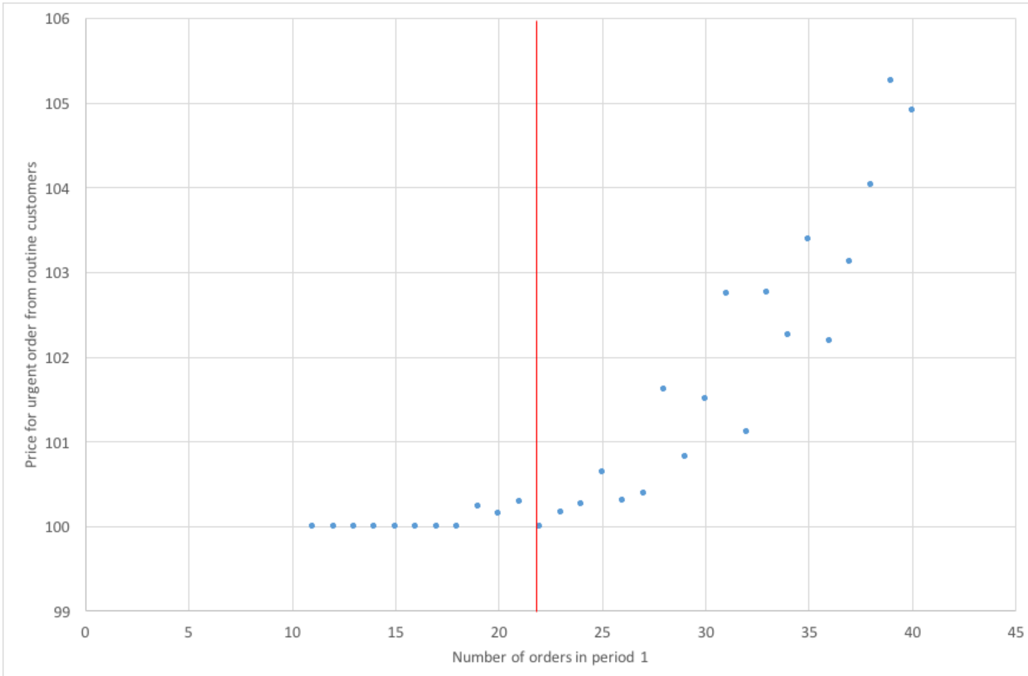

Figure 3.6. Pricing Urgent Order from Routine Customers

Cost impact is determined by comparing the total profit of a data set and that of the data set with an additional urgent order, i.e., $\pi(\text{Load}) - \pi(\text{Load}+1)$, which implies profit loss by accepting one unit of order. The impact of an additional urgent order on cost is larger when the shop is loaded more. The slope determined by regression is 4.0292 and $R^2 = 0.03018$ (Figure 3.5). We observed that there is a strong negative impact. This implies that the negative impact of additional urgent orders is getting stronger as the firm receives more shop load. Figure 3.6 illustrates how the optimal price for urgent orders from routine customers changes by initial shop load. When the shop is not loaded the optimal price is around 100. But, when shop load is more than the threshold, the optimal price increases dramatically. This implies that when the shop is fully loaded, the firm wants to reduce the volume of routine orders, while the shop capacity is not fully utilized, the firm wants both to attract more routine order and to keep the minimum margin on routine orders.

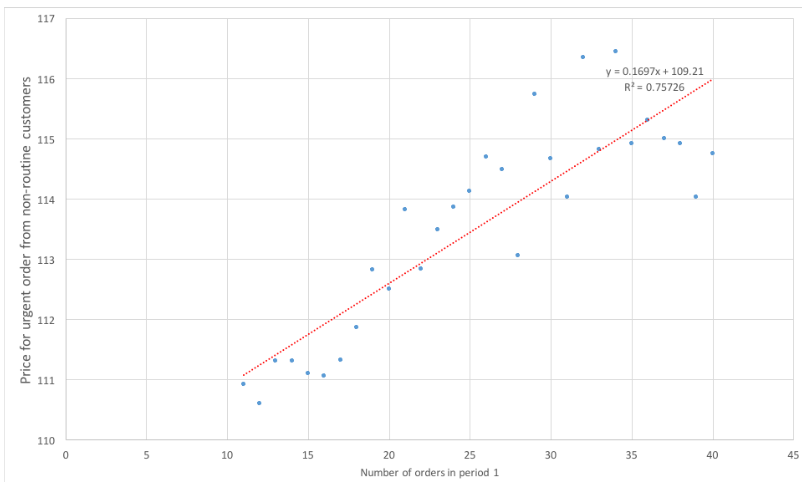

Figure 3.7. Pricing Urgent Order from Non-Routine Customers

The firm controls the volume of urgent orders from non-routine customers by pricing. When the shop is loaded, the firm wants to reduce the volume of urgent orders from non-routine customers by charging high margins. However, when the shop capacity is not fully utilized, the firm wants to attract more urgent orders to fill the slack capacity and enjoy high margin of urgent orders from non-routine customers (Figure 3.7).

3.6 Conclusion

In this research, we consider the supplier that has both routine orders and urgent orders from routine customers and non-routine customers. Since long-term relationships can reduce transaction costs, there is room in price discounts for routine customers. [10]. Thus routine customers may expect lower costs. While urgent orders from routine customers are discounted, ones from non-routine customer are profitable. Through data analysis, we confirmed there is efficiency improvement by routine orders. Workers accelerate the pace of their labor when they face more work. Thus our research question is: What is the optimal order portfolio under the situation of two classes of orders and two classes of customers.

Our contribution to the operations management literature is that we derive an optimal decision strategy considering the trade off between profitability and efficiency based on the actual data provided by the company. First, we analyze the data and identify several characteristics of the company's business. They are efficiency by routine orders and profitability by urgent orders. Also, we observed the company has two types of orders and two types of customers. Second, we model a stochastic dynamic program to extract managerial insights. The company confirmed they control the volume of orders by pricing. Thus, we apply a linear inverse demand function. When they expect a larger demand of urgent orders from either routine or non-routine customers, they are better off to increase the price for urgent orders. As an extension, we also look at the case of demand postponement. We consider two periods and the firm can decided the amount of routine orders to postpone. Then in the next period, the firm will deliver all orders. In this case, when they decide the level of urgent orders is enough, the supplier wants to take the advantage of efficiency by maintaining a pattern of more routine orders. (or reducing the postponement amount) When there is more uncertainty regarding urgent orders, the supplier wants to save room for urgent orders in the second period. Third, we identify the impact of additional urgent orders. Specifically, when the shop is loaded more, the impact is more negative. Lastly, we model the mixed integer program (MIP) for order scheduling. With a brief forecast of demand, the MIP provides the optimal scheduling considering outsourcing and delivery delay costs. The firm may use this model to estimate both the direct and indirect costs incurred by newly arrived urgent orders. Such a cost estimation may be helpful to the company in pricing for urgent orders.

In the future, we will identify the cost impact by additional urgent order in detail. Our current analysis is intuitive but simple. In order to find out more factors that affects cost, we will polish the model. In addition, we will run more numerical experiments and feed real data to the MIP. Ultimately, we will suggest a firm a practical decision support system for pricing to the firm.

4. COORDINATED CAPACITY INVESTMENT IN CLEAN ENGINE TECHNOLOGY UNDER CRITICAL MATERIAL R&D

4.1 Introduction

Although the crude oil price has been dropped due to sufficient supply, the concern about the environment, such as global warming, still warrant significant attention. The most severe cause of global warming is carbon emission.

> Emissions resulting from human activities are substantially increasing the atmospheric concentrations of the greenhouse gases: carbon dioxide, methane, chlorofluorocarbons (CFCs) and nitrous oxide. These emissions will enhance the greenhouse effect, resulting on average in an additional warming of the Earth's surface.
> -*Working Group I of the United Nations Intergovernmental Panel on Climate Change (IPCC), 1990*

In the automotive industry, properties such as better fuel efficiency and lower emissions have gained attention. Since the mid 1990s, aluminum (Al) alloy engines have been widely used due to their many advantages; they are lighter than traditional cast iron engines, which means they offer better fuel efficiency. Another benefit is their thermal conductivity. [40] As of 2012, [41] reported that 80% of engine blocks and 99% of cylinder head were already being made of Al alloy. They also forecasted that Al alloy would more penetrate the market in the future. However, Al has poor mechanical properties so is required to be 1.5 to 2 times thicker than steel.

The Critical Materials Institute (CMI) is doing research on new material for a new high performance Al casting alloy that uses cerium (Ce). Ce is the most abundant, but least used among the rare earth elements (REEs). The aim of the research is to develop castable aluminum cerium (Al-Ce) alloys. Ce-Al alloys exhibits high temperature mechanical properties that are superior to existing commercial Al casting alloys in the current market (CMI white paper). The net effect of this new alloy is to permit thickness smaller to steel and higher temperature operation

The project follows a planned technology roadmap. The milestones and associated TRLs highlight progress from lab to market. The roadmaps are used to develop a model that incorporates project progress on manufacturers' decisions regarding investment for capacity expansion. Once the model is properly developed, we estimate the parameters and evaluate the real option value of projects according to project results.

In our model, the project's success is linked to technology roadmapping. The technology roadmap coordinates and presents planned tasks and schedule about research objectives that must be achieved in order to develop technology that satisfy requirements for the product. It documents clarified product and process goal, and milestones to meet those goals. The technology roadmap aggregates all this information and evaluates according to a technology readiness level (TRL). Figure 4.1 is a TRL example. The figure illustrates an expected technology according to its level of completion and commercialization.

The model describes a manufacturer that determines the time and volume of the manufacturing capacity extension for a new engine manufactured with a new aluminum and cerium (Al-Ce) alloys. Assume the manufacturer currently produces the aluminum alloy-based engines and plans to produce the Al-Ce alloy engines as CMI R&D project milestones progresses. Our research questions are as follows: How

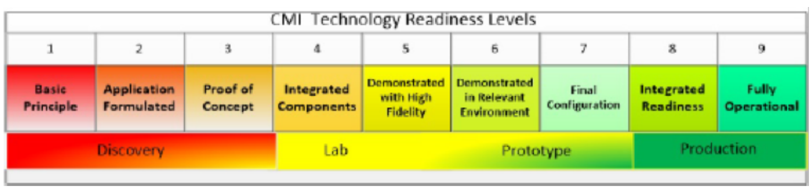

Figure 4.1. Technology Readiness Level

to expand the capacity as a function of milestones achievement? When to expand the capacity for new material engines with technology for R&D?

4.2 Literature Review

Extensive research has contributed to literature related to investments in manufacturing capacity under uncertainty. [42] worked on a survey regarding capacity expansion . In their pioneering book, [43] claimed that many projects, e.g., building ships or aircrafts, take a significantly long time to complete, and there are likely to be stopped momentarily or permanently abandoned.

[44] and [45] worked on theoretical decision models for firms' technology adoption behavior and found that firms might postpone technology adoption to collect information on an innovation and progress when profitability is uncertain initially. [46] conducted similar work to ours. He assessed the reconciled decision that considers both R&D and technology adoption. He modeled a firm over infinite time periods. The firm can conduct R&D and deploy the technology at the status of the current period. R&D is modeled in independent draws with a fixed cost in his model. In our model, R&D is exogenous and R&D achievement is fed to the model in a form of predefined scores at each period. In particular, [47] and [48] considered diffusion with given supply constraints. Especially, [48] concluded that a supplier with a supply constraint would postpone the introduction of the new product after the supplier completes the production of a sufficient quantity.

There are many papers focused on sequential capacity investment following the development progress of new technology. [49] considered the case in which the supplier determines the capacity addition for the a new pharmaceutical drug's production by coordinating investment with test trials. In the automotive industry, there are extensive research streams concerning capacity and technology. [50] examined the competition of firms and the choice of technology and capacity. They concluded that contrary to conventional ideas, flexibility is not always the best choice for competition.

There is another stream regarding product diffusion. [51] considered the capacity decision during a product's transition. They gave an example of Intel. During the generation transition of chips, the firm may consider either new capacity investment or the conversion of existing capacity. In terms of product transition, we also consider a similar transition from the an existing Al alloy engine to the an Al-Ce alloy engine. While the situation is similar, the setting is different. We consider sequential capacity additions and the demand varies depending the properties of the Ce-Al alloy engines. In [52]'s seminal paper, they described how a successive technology product substitutes the previous generation's product. They developed a model considering both diffusion and substitution. [53] worked on a DOE project related to the magnet material, providing initial insight into the Bayesian learning process regarding the project achievement.

4.3 Model

Our model incorporates two R&D progress along two dimension, i.e., production cost and fuel efficiency improvement by accounting for paths of the prospective technologies. The main dimension is a model for adding capacity that includes supply and demand mechanism for the newly developed product in a monopoly setting but with existing products as alternatives. If we consider the automotive industry as one entity, a monopolistic market promotes insights in a Bayesian environment. The models thus describe capacity addition decisions in accordance with R&D progress. We will consider a duopoly case with competition in the future as an extension.

4.3.1 Technology Readiness Level (TRL)

The R&D of technologies is performed following a plan or technology roadmap that plans milestones during a project's assessment. As we approach the time period near the commercialization, it is more likely to influence capacity decisions by the industry. Evaluation of the R&D project success is weighted by a Technology Readiness Level (TRL) score for each task. A higher TRL task means the task is close to commercialization. When the industry finds a higher TRL, it would consider capacity addition. For instance, when the TRL is determined as 5 for a specific lab-scale experiment with a simulated environment. If the task includes a literature survey and hypothesis formulation, TRL would be determined as 1.

The model for R&D describes the TRL according to the percentage of discovered progress. We applied the percent-done curves described in [54]. Poisson variables N^{cost} and N^{eff} are used for the cumulative progress of the production cost task and fuel efficiency task, respectively, over the time horizon of the R&D project. In each period, t, g_t^{cost} and g_t^{eff} denote the proportion of the progress of the production cost task and fuel efficiency task, respectively, observed in the period, whereas G_t^{cost} and G_t^{eff} represents the proportion of the cumulative progress of the two tasks. We place wights by the TRL on arrivals to capture the fact that milestones closer to commercialization influence industry decisions more than milestones in the early stages. In other words, we measure the maturity of the R&D by the product of weight and TRL scores. In each project, TRL the table provides TRL scores. (Table 4.2)

There is significant uncertainty in conducting R&D projects. In an ideal situation, one can achieve the initially targeted performance. However, in reality, performance variability caused by trade-offs among multiple technical criteria brings about uncertainty [55]. The Al-Ce alloy project considers two tasks of targets, production cost reduction and fuel efficiency improvement. Depending on the realized performance

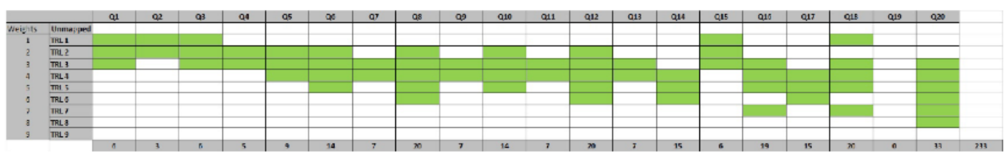

Figure 4.2. Scoring TRL tasks

of the project, high or low realization can be obtained in each task. Table 4.1 gives an example of the pure distribution. When the research project of fuel efficiency is successful, or the research project is in the high (H), the chance of 43.72mpg is 99% and the probability of 34.35mpg is 1% in this example. The cumulative arrival, N, represents the overall success throughout the R&D. In addition to our previous description, superior performance corresponds to higher arrival rates. In other words, a higher TRL score is achieved in each experiment. Therefore, the Poisson process with arrival rates of λ_1^{eff} and λ_2^{eff} corresponds to the random arrival N in cases of 32.35mpg and 43.72mpg, respectively when we consider fuel efficiency. Similarly, the Poisson process with arrival rates of λ_1^{cost} and λ_2^{cost} corresponds to the random arrival N in cases of $23,975.63 and $29,508.96, respectively, for the cost task.

Proposition 4.3.1 *Given observed progress N_1, N_2, ..., N_t in each period, the posterior density P_t in period t depends on the sum $N = N_1 + N_2 + ... + N_t$.*

In Proposition 4.3.1 ([53]), the cumulative arrival, N, is a sufficient statistic to describe the future arrival distribution of success. The Poisson process is appropriate to model the R&D project's progress with various advantages. We can use the cumulative progress for the state variable to update the automotive industry's belief. Although there is an unexpected event and due to the task being missed, the industry can maintain the updating process while the project follows the schedule and the research institute attempts to return to the schedule. The other advantage of the process is its memoryless property, meaning that the manufacturer in the industry does not have to consider individual tasks' achievement in their capacity planning decision.

Proposition 4.3.2 *Priors are updated in each period by the cumulative progress, N.*

$$\begin{aligned} \mathbf{P_t(N)} &= (P_{1t}, P_{2t})(N) \\ &= \left(\frac{e^{\lambda_1 G(t)} \lambda_1^N}{\sum_i e^{\lambda_i G(t)} \lambda_i^N}, \frac{e^{\lambda_2 G(t)} \lambda_2^N}{\sum_i e^{\lambda_i G(t)} \lambda_i^N} \right) \end{aligned}$$

The proposition 4.3.2 ([53]), illustrates the priors updated at every period according to the cumulative progress, N, by period t. Cumulative progress is determined by the

Table 4.1.
Pure distribution

	MPG(Base MPG=31.1mpg)	
Pure Dist.	34.35mpg (10% improvement)	43.72mpg (40% improvement)
Low	99%	1%
High	1%	99%

	Cost (base cost = \$28811.26)	
Pure Dist.	\$28975.63 (Ce-Al \$10/kg)	\$29508.96 (Ce-Al \$30/kg)
Low	1%	99%
High	99%	1%

score determined by product of TRL and weight. The score represents information about the cumulative maturity of development. The manufacturer is required to choose the capacity investment in advance of technology commercialization, as there is always a lead time in investment. For instance, even without the new facility construction, the manufacturer needs to place an order for the new equipment and renovation of the facility, which takes significant time. The arrival rates are different in every milestone. It is determined by $G(t)$ and $G(t)$ stand for the percentage completed until time t. In the next section, we will illustrate the optimal capacity investment decision corresponding to the R&D progress.

4.3.2 Market Behavior

While the manufacturer produces existing Al alloy engines, the new technology permits for Al-Ce alloy engines. But since the development is uncertain, it is difficult to forecast the demand of the new engines. Thus, the manufacturer monitors R&D status and determines the capacity expansion or not to invest and to postpone the decision in every period. The Al-Ce alloy engines are produced under the constraint of the available capacity, x. We consider a linear inverse demand function, $P(q) = a - b\,q$, where p is the price of the product, a represents the maximum willingness to pay (WTP), and b denotes the price elasticity. c denotes the production cost for the engine with the prospective technology. e represents the fuel efficiency corresponding to the current technology. In other words, the distributions of c and e are determined by technology maturity. We now consider the manufacturer's decision in a single period.

4.3.3 Single Period Case

The profit of the manufacturer when the capacity is x is illustrated as follows:

$$\begin{aligned}&\pi\left(x,c,e\right)\\&=\max_{q_r,q_n}\left\{\left(a_r-b_q^r\,q_r+b_e^r\,e_r-c_r-b_x^r\,q_n\right)\,q_r+\left(a_n-b_q^n\,q_n+b_e^n\,e_n-c_n-b_x^n\,q_r\right)\,q_n\right\}\\&\text{subject to } 0\le q_n\le x\end{aligned}\tag{4.1}$$

Let j denotes the engine type, $j \in \{r, n\}$. r stands for Al alloy engine cars and n stands for Al-Ce alloy engine cars. a_j is WTP. b_q^j denotes the quantity elasticity. b_e^j denotes the fuel efficiency elasticity. b_x^j represents the cross elasticity. Fuel efficiency and the cost of production impacts on the market price, and note that the production quantity q is limited by the available capacity. The optimal production quantity is

$$q_n^* = \min\left\{\frac{2a_r b_q^r - a_r b_x^n - a_r b_x^r + 2b_q^r b_e^n e_n - 2b_q^r c_n - b_e^r b_x^n e_r - b_e^r b_e^n e_r + b_x^n c_r + b_x^r c_r}{4b_q^n b_q^r - {b_x^n}^2 - 2b_x^n b_x^r - {b_x^r}^2}, x\right\}.$$

Proposition 4.3.3 *The expected profit of the manufacturer in a period is given by,*

$$\Pi\left(x, f_c(c), f_e(e)\right) = \int_{c_l}^{c_h}\int_{e_l}^{e_h} \pi\left(x,c,e\right)\, f_c(c)\, f_e(e)\, dc\, de \tag{4.2}$$

where $f_c(c)$ is distribution function of cost c with support $[c_l, c_h]$ and $f_e(e)$ is distribution function of cost e with support $[e_l, e_h]$. $\Pi\left(x, f_c(c), f_e(e)\right)$ is concave in x

As the outcome of the development is uncertain c and e are random variables with distributions f_c and f_e, respectively. ([53])

4.3.4 Multi-Period Case

Now, we consider the multi-period case. We model the problem in a T period model. The engine manufacturer obtains the information regarding R&D achievement in each period. The manufacturer then determines whether to add capacity in a particular period; there is an option to postpone the capacity expansion in the period. We suppose that the manufacturer sequentially invests in the capacity expansion. In other words, the manufacturer has an option to add the capacity of k in each period. It is not possible for the manufacturer to add capacity in another quantity. Thus, the capacity expands as follows: 0, k, $2k$, $\cdots$.

In our model, we have three state variables: the currently available capacity, x, the cumulative progress in the production cost task, N^{cost}, and the cumulative progress in the fuel efficiency task, N^{eff}. Previously, we noted that the we consider two tasks of research, production cost reduction and fuel efficiency improvement, previously. The expected profit in period t is,

$$\begin{aligned} &\Pi_t\left(x, N^{cost}, N^{eff}\right) \\ &\quad = \max \Bigg\{ -c_c\, k \\ &\qquad + \sum_{n_c=0}^{\infty} \sum_{n_e=0}^{\infty} \Pi_{t+1}\left(x+k, N^{cost}+n_c, N^{eff}+n_e\right) p_t^e\left(n_e | N^{eff}\right) p_t^c\left(n_c | N^{cost}\right), \\ &\quad \sum_{n_c=0}^{\infty} \sum_{n_e=0}^{\infty} \Pi_{t+1}\left(x, N^{cost}+n_c, N^{eff}+n_e\right) p_t^e\left(n_e | N^{eff}\right) p_t^c\left(n_c | N^{cost}\right) \Bigg\} \end{aligned} \tag{4.3}$$

where, $p_t^e\left(n_e | N^{eff}\right) = \sum_{i=1}^{2} P_{it}^e\, p\left(\lambda_i^e\, g^e(t+1), n_e\right)$ and $p_t^c\left(n_c | N^{cost}\right) = \sum_{i=1}^{2} P_{it}^c\, p\left(\lambda_i^c\, g^c(t+1), n_c\right)$. $p(\lambda, n)$ is Poisson density function of mean λ and n arrivals. The terminal value $\Pi_T\left(x, N^{cost}, N^{eff}\right) = \pi\left(x, f_T^c\left(c | N^{cost}\right), f_T^e\left(e | N^{eff}\right)\right)$ where, $f_T^e\left(e | N^{eff}\right) = \sum_{i=1}^{2} P_{iT}^e(N^{eff}) f_i^e(e)$ and $f_T^c\left(c | N^{cost}\right) = \sum_{i=1}^{2} P_{iT}^c(N^{cost}) f_i^c(c)$

Proposition 4.3.4 *There is a threshold $x_t^*(N^{cost}, N^{eff})$ in period t for all $t \in T$. If $x \leq x_t^*(N^{cost}, N^{eff})$, the manufacturer invests for the capacity, otherwise, the manufacture holds the investment and wait at period t.*

Proposition 4.3.4 ([53]) he concavity in proposition 4.3.3. The manufacturer updates information regarding the maturity of technology. Based on this information, the firm will determine threshold policy.

4.3.5 Parameters

As noted previously, our problem is a practical one related to R&D projects' performance. When we have parameters and the sample path, we can derive capacity addition decision. In this section, we demonstrate decision making using our model. Since the model is implemented in Mathematica, the research institute or the manufacturer can explore different sample paths or different parameters.

An automobile engine is the most important component due to its role, which generates power out of fossil fuel. Any function of automobiles related to physical movement or electronic operation is supplied energy by the engine either directly or indirectly. Conventionally, engines were made of cast-iron due to its durability and thermo dynamics properties. In the mid 1990s, Al alloy began to replace the existing cast-iron engines to reduce their weight and ensure a higher operation temperature. Al alloy engines provided higher fuel efficiency than the cast-iron engines. However, due to their material properties, Al alloy requires 50% more thickness to maintain the equivalent mechanical strength to cast iron [40]. Although Al alloy reduces the engine weight by 50% despite of its thickness, there is room to reduce the weight as long as we improve the mechanical properties of the material. Al-Ce alloy is better than Al alloy in terms of the thermal dynamic properties. Al-Ce is durable even at higher temperatures than an Al alloy engine's operational temperature. Therefore, we can expect higher fuel efficiency with Al-Ce alloy engines.

According to CMI's whitepaper (2014) , the price of Al-Ce alloy is expected to be $10/kg in the best case and $30/kg in the worst case. Thus, we estimates the material cost of engine blocks and cylinder heads and take thickness reduction into account. Assuming the aluminum alloy is replaced with Al-Ce alloy, the cost of the engine would be $28,975.63 ($c_l$) and $29,508.96 ($c_h$) in the best case and worst cases of production cost reduction research task. [56] Possible fuel efficiencies are estimated to be 34.35mpg (e_l) and 43.72mpg (e_h). Based on the data in the U.S. Department of Transportation (US DOT), we assumed that there would be 10%improvement for the worst outcome and 40% improvement for the best outcome regarding fuel efficiency improvement research task.

In the technology roadmap, the number of milestones is 8. Having two research tasks makes it problematic to consider combinations of two state variables because of curse of dimension. Thus, we had to reduce the time horizon to 4 instead of 8. Considering two possible outcomes for one research task, we model the success as a random variable according to the Poisson arrival of success with arrival rates $\lambda \in \left\{\lambda_1^j, \lambda_2^j\right\}$ where $j \in \{cost, eff\}$. We choose $\lambda_1^j = 5$ and $\lambda_2^j = 10$. The percent done curve was calculated by the TRL scores and some weights. We had 4 miles stones and each had associated tasks. Each task was assigned a TRL by the importance of the task. To emphasize the higher TRL to magnify the closeness to the commercialization, we multiplied weights to TRLs. Weights were multiplied as follows: TRL 1, 2, and 3 are weighted by 1. TRL 4 is weighted by 2. TRL 5 is weighted by 3. TRL 6 is weighted by 4. TRL 7 is weighted by 5. Weights are increasing in TRLs. We calculate the percent-done curve by dividing the weighted sum of TRL with the cumulative percent-done curve over 7 periods. The cumulative percent-done curve is $G(1) = 0.04$, $G(2) = 0.16$, $G(3) = 0.28$, $G(4) = 0.4$, $G(5) = 0.56$, $G(6) = 0.68$, and $G(7) = 1$. The initial prior is chosen as $\mathbf{P^j} = 0.5, 0.5$. Thus we do not know how the research will unfold. The manufacturer repeat updating his prior to $\mathbf{P_t}(N)$ in period t by proposition 4.3.2.

Supply and Demand

In the case of hybrid cars, a previous study found no significant dereference in the willingness-to-pay (WTP) between regular internal combustion cars and hybrid cars [57]. Although [57] compared hybrid cars to regular cars, we assume that the WTP for Al-Ce alloy engine cars would be very similar to regular cars, as Al-Ce alloy engine cars are expected to cost more than regular cars, similar to hybrid cars.

Demand elasticity, b_q, fuel efficiency elasticity, b_e, and cross elasticity, b_x were estimated by a regression with historical data. The annual sales quantity of regular cars and hybrid cars, and the annual average fuel efficiency (mile per gallon) were collected from public data such as *www.statistica.com*, *www.autoalliance.org*, *www.afdc.energy.gov/data/10301*, and *www.fueleconomy.gov*. The regression gave us $b_q^r = 493.7$, $b_e^r = 3392.11$, and $b_x^r = 10269.1$ for Al alloy engine cars. For Ce-Al alloy engine cars, we obtained $b_q^n = 13742.1$, $b_e^n = 2139.42$, and $b_x^n = 656.5$. The WTP for Al alloy engine cars was estimated as $a_r = -62080.3$ for Al alloy engine cars and $a_n = -27559.3$ for Ce-Al alloy engine cars.

We solved the stochastic dynamic program and obtain the option values for different observations based on our parameter estimations. Using the estimations, we evaluated the option values for the project for outcomes. For example, the capacity addition decision is illustrated in Figure 4.3. Period 1 is the early stage and the arrival of success is low. However, the manufacturer expected the Ce-Al engines to have some potential, so the firm invested the capacity of 130,000 cars/year. From period 2 to period 5, the firm sought to foresee potential and did want to lose the market. The firm still expect successful R&D. Thus, the firm invest on the capacity extension one unit by one unit of capacity. In period 6, the firm observed the cumulative success arrival of (3, 7) Now the firm observed that the R&D would not improve. Therefore, the firm decided to stop capacity investment.

Table 4.1 provides the expected option value and cumulative capacity that is invested at every period for a given sample path. The option value of capacity addition grows when the success arrival increases. But, if the progress is staggered i.e. the

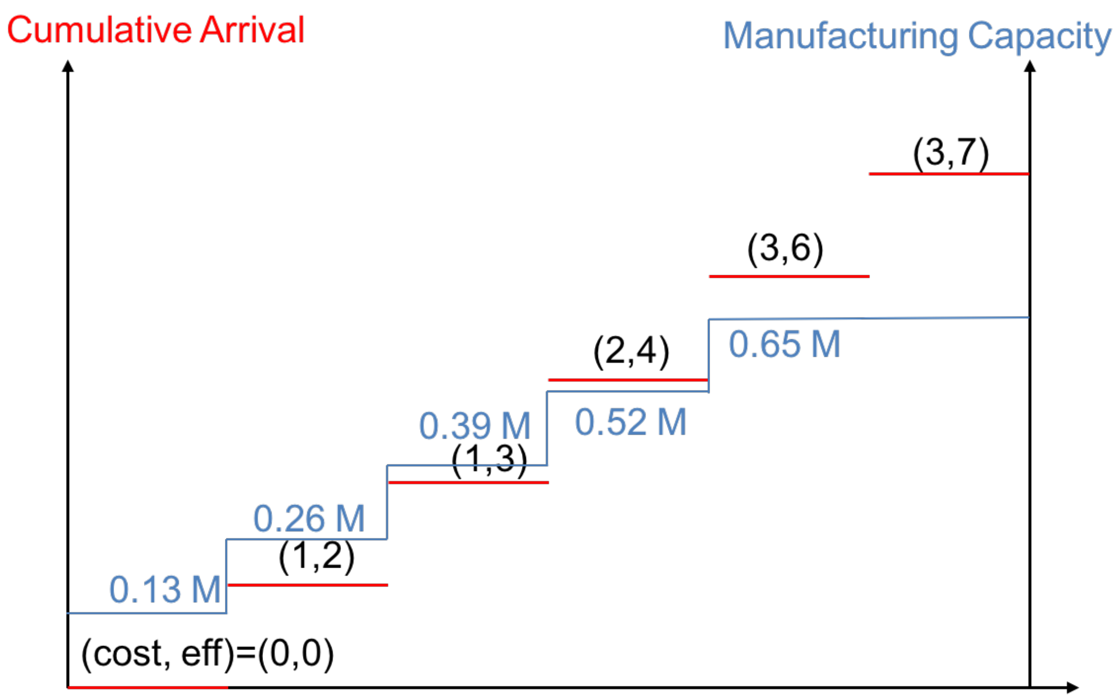

Figure 4.3. Capacity additions for the sample path, $k = 130,000$ engines/year

number of arrivals remains the same, the option value decreases over time. Therefore, the option value increases with the arrival of success in the same period. The option value decreases in the time with the same success arrivals in time (Table 4.2).

Capacity expansion is illustrated in Table 4.3. In this sample, when the research is successful in fuel efficiency improvement, the firm can benefit from investing in more capacity.

4.4 Extension

We modeled the R&D project with two tasks, production cost reduction and fuel efficiency improvement. Parameterizing and running the model led us to propose a new question. What if we can adjust resources based on project outcome? Let us suppose that the project manager is given an option to invest resources to expedite the project. For instance, the project manager receives additional funds, he may want to hire a post-doc researcher to speed up the study of fuel efficiency improvement. When the project is expedited, the uncertainty of the outcome is somewhat resolved. Although in the sample path the fuel efficiency task is successful, the manager may want to a firm and tangible outcome. When he has an additional researcher for the fuel efficiency task, the manager has to spend the funds but the expected option value should be greater. A second option for the manager is to hire a researcher for the production cost reduction task. If the manager believes that the fuel efficiency improvement research is mature. he may want to accelerate the task behind the schedule. In this section, we illustrate expedition options and their values.

Figure 4.4 illustrates an example of how expedition works. The blue and dashed and dotted line represents the original percent-done curve. The red line indicates when the project manager decides to invest additional resources in period 4. Thus,

Table 4.2.
Option value of the sample path

(Cost, Eff)	P1	P2	P3	P4	P5	P6
(0, 0)	\$116.665 M	\$116.024 M	\$115.456 M	\$115.102 M	\$114.859 M	\$114.770 M
(1, 2)	\$119.054 M	\$118.183 M	\$117.311 M	\$116.423 M	\$115.612 M	\$115.241 M
(1, 3)	\$120.014 M	\$119.352 M	\$118.512 M	\$117.638 M	\$116.493 M	\$115.865 M
(2, 4)	\$120.701 M	\$120.310 M	\$119.687 M	\$118.868 M	\$117.697 M	\$116.800 M
(3, 6)	\$121.301 M	\$121.284 M	\$121.146 M	\$120.838 M	\$120.055 M	\$119.090 M
(3, 7)	\$121.396 M	\$121.453 M	\$121.443 M	\$121.334 M	\$120.900 M	\$120.187 M

Table 4.3.
Capacity addition of the sample path

(Cost, Eff)	P1	P2	P3	P4	P5	P6
(0, 0)	0.13M	0.26M	0.26M	0.26M	0.26M	0.26M
(1, 2)	0.13M	0.26M	0.39M	0.39M	0.39M	0.39M
(1, 3)	0.13M	0.26M	0.39M	0.52M	0.52M	0.52M
(2, 4)	0.13M	0.26M	0.39M	0.52M	0.65M	0.65M
(3, 6)	0.13M	0.26M	0.39M	0.52M	0.65M	0.65M
(3, 7)	0.13M	0.26M	0.39M	0.52M	0.65M	0.65M

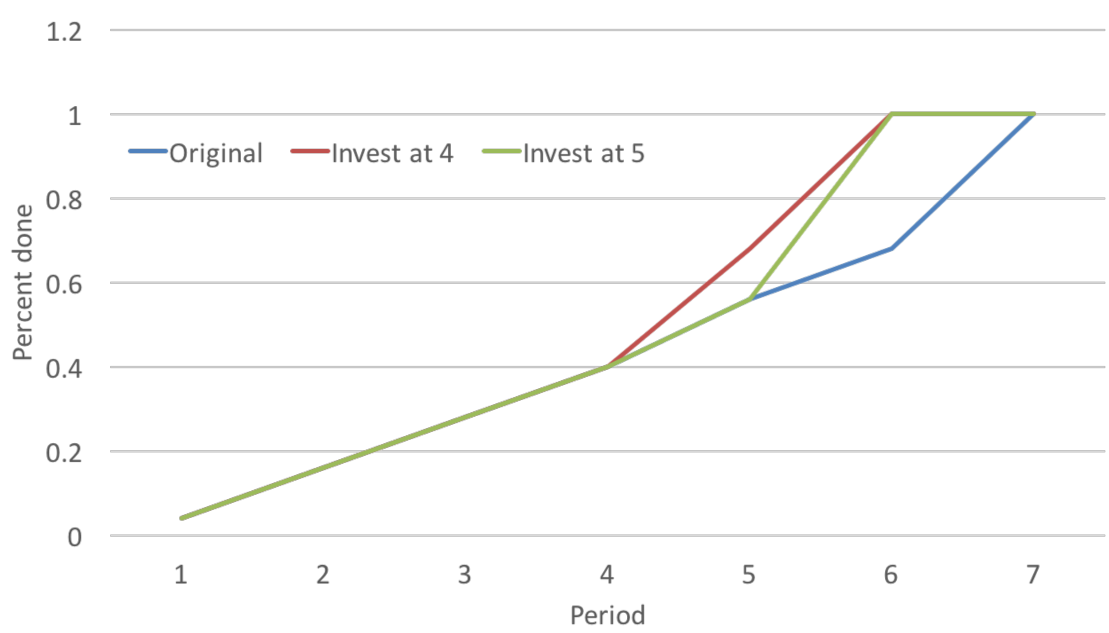

Figure 4.4. Percent-done curves for expedition options

the impact will be observed in period 5, and he expects completions of 68% in period 5 and 100% in period 6. When the project manager invests additional resources in period 5, the impact will be observed in period 6. That follows the green line. The manager expects 100% completion in period 6. The project manager may expedite one research task by hiring one researcher. As such, the progress acceleration is effective in only one task.

Examples in Table 4.4 and Table 4.5 use the same sample path in which research regarding cost reduction is not well progressed but research regarding efficiency improvement is successful. Table 4.4 illustrates the expected outcome of the option to hire a researcher for the cost reduction task. We assume there is lead time of one month for the additional researcher's output. The first table is the case in which the researcher is hired in period 4 and the second is when the researcher is hired in period 5. Comparing Table 4.2, while expected profits until period 5 are larger than those of the original sample path, the research ends up with less expected profit in the last period. This implies that hiring an additional researcher reduces uncertainty. Thus, the cost reduction research task would end up with the low pure distribution in Table 4.1 in this example. Thus, the expected profit in the last period decreases.

What if the manager assigns an additional researcher to the efficiency improvement task to speed up experiments? Table 4.5 describes the outcome when the manager concentrates on the successfully progressing research task. In this case, the manager is better off to invest early. It is optimal for him to hire the researcher in period 4. This means that reducing uncertainty for the successful research task is beneficial. Therefore, the manager's optimal choice is to invest additional resources on the successful research task in period 4.

Table 4.4.
Hire a researcher for the cost-reduction task

Hire a research at period 4						
(Cost, Eff)	P1	P2	P3	P4	P5	P6
(0, 0)	$116.665 M	$116.024 M	$115.456 M	$115.102 M	$114.859 M	$114.770 M
(1, 2)	$119.054 M	$118.183 M	$117.311 M	$116.423 M	$115.612 M	$115.241 M
(1, 3)	$120.014 M	$119.352 M	$118.512 M	$117.638 M	$116.493 M	$115.865 M
(2, 4)	$120.701 M	$120.310 M	$119.687 M	$118.868 M	$117.697 M	$116.800 M
(4, 6)	$121.331 M	$121.324 M	$121.193 M	$120.881 M	$120.061 M	$119.073 M
(5, 7)	$121.443 M	$121.526 M	$121.538 M	$121.435 M	$120.950 M	$120.186 M
Hire a researcher at period 5						
(Cost, Eff)	P1	P2	P3	P4	P5	P6
(0, 0)	$116.665 M	$116.024 M	$115.456 M	$115.102 M	$114.859 M	$114.770 M
(1, 2)	$119.054 M	$118.183 M	$117.311 M	$116.423 M	$115.612 M	$115.241 M
(1, 3)	$120.014 M	$119.352 M	$118.512 M	$117.638 M	$116.493 M	$115.865 M
(2, 4)	$120.701 M	$120.310 M	$119.687 M	$118.868 M	$117.697 M	$116.800 M
(3, 6)	$121.301 M	$121.284 M	$121.146 M	$120.838 M	$120.055 M	$119.090 M
(5, 7)	$121.442 M	$121.523 M	$121.534 M	$121.431 M	$120.978 M	$120.186 M

Table 4.5.
Hire a researcher for the fuel efficiency improvement task

Hire a researcher at period 4						
(Cost, Eff)	P1	P2	P3	P4	P5	P6
(0, 0)	$116.665 M	$116.024 M	$115.456 M	$115.102 M	$114.859 M	$114.770 M
(1, 2)	$119.054 M	$118.183 M	$117.311 M	$116.423 M	$115.612 M	$115.241 M
(1, 3)	$120.014 M	$119.352 M	$118.512 M	$117.638 M	$116.493 M	$115.865 M
(2, 4)	$120.701 M	$120.310 M	$119.687 M	$118.868 M	$117.697 M	$116.800 M
(3, 7)	$121.393 M	$121.446 M	$121.427 M	$120.296 M	$120.210 M	$119.035 M
(3, 10)	$121.488 M	$121.611 M	$121.710 M	$121.794 M	$121.726 M	$121.008 M
Hire a researcher at period 5						
(Cost, Eff)	P1	P2	P3	P4	P5	P6
(0, 0)	$116.665 M	$116.024 M	$115.456 M	$115.102 M	$114.859 M	$114.770 M
(1, 2)	$119.054 M	$118.183 M	$117.311 M	$116.423 M	$115.612 M	$115.241 M
(1, 3)	$120.014 M	$119.352 M	$118.512 M	$117.638 M	$116.493 M	$115.865 M
(2, 4)	$120.701 M	$120.310 M	$119.687 M	$118.868 M	$117.697 M	$116.800 M
(3, 6)	$121.301 M	$121.284 M	$121.146 M	$120.838 M	$120.055 M	$119.090 M
(3, 10)	$121.484 M	$121.610 M	$121.709 M	$121.790 M	$121.819 M	$121.008 M

4.5 Conclusion

We have developed a model for the problem of capacity investment in accordance with the R&D progress. We evaluated the value of R&D project progress by tasking the Technology Readiness Level (TRL) and obtained the capacity addition decision for Ce-Al alloy engine cars. The major contributions are as follows:, First, we modeled development uncertainty as a mixture of pure distributions and TRL, and second, we examined the value of additional resources for the R&D project. Since we consider two tasks of the research, an additional resource deployment strategy has been suggested by our model. In addition, we estimated the parameters of our model so that the model improves not only practical decision support in terms of sequential capacity additions and recourse strategies but also the option value of the project.

Our research had several limitations. We had to reduce the number of possible outcomes in order to avoid the curse of dimension. Simplified results are unavoidable. We will develop a technique to bypass dimension reduction. In addition, a more sophisticated model will be devised for a research progress adjustment strategy.

5. SUMMARY

We have studied topics regarding capacity. The first two chapters studied the long-term relationship in the supply chain and operations. The last chapter studied how to expand capacity in accordance with research and development progress.

In the second chapter, we identified the impact of reciprocity in the supply chain. The supply channel is coordinated without the costly contracts. This implies that the performance of the supply channel can be improved when participants have trust each other and their decisions are reciprocal. The second implication is that the participants' financial performance is improved with trust and the presence of reciprocity. Lastly, when the sensitivity is at a reasonable level, the seller will offer a good price. But either being too sensitive or too insensitive to kindness induces the seller to offer a higher price. This implies that the buyer needs to consider fairness in the relationship for her own benefit.

In the third chapter, we explored data provided by the real company. We observed that how long term relationships impacts on the operation and studied suppliers optimal portfolios among routine and urgent orders. We studied that the impact of additional orders to operation costs varies by the shop load and there is a threshold where operation costs increase much.

In the fourth chapter, the optimal capacity expansion strategy was studied, The project of the Critical Materials Institute (CMI) aims to reduce US dependence on critical materials. One of the projects CMI aims at developing advanced alloy by adding critical material. The Ce-Al alloy development project announces an achievement level at every milestone. We modeled the stochastic dynamic program with

Bayesian update. We run the model with parameters and economic benefits were estimated. Based on the progress of those two R&D tasks, additional resource investment strategy was studied.

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Research Interests:

My research interest is relational issue in supply chain. The impact of the long-term relationship in the supply chain and capacity decision are investigated in my research. Contributions of my dissertation are exploring three topics in the supply chain motivated by real practice and data supporting our finding: the impact of reciprocity in the supply chain, where the manufacturer can be benefited to offer favorable price and quantity expecting buyer's favorable actions in the next period; exploring order portfolio between long-term and short-term customers; and the capacity expansion according to the achievement under multiple tracks of R&D. I will explore my research to supply chain problems related to the long-term relationship and capacity investment.