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Essays on supply chain analytics: Investment and capacity planning under uncertainty

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ESSAYS ON SUPPLY CHAIN ANALYTICS: INVESTMENT AND CAPACITY PLANNING UNDER UNCERTAINTY

ABSTRACT

In this dissertation, we study a firm's investment and capacity planning strategies in the presence of different types of supply uncertainties and risks. Both essays in this dissertation benefit from empirical analysis as the analytical models build on the findings and observations from the corresponding empirical investigation. Each essay shows the benefits from utilizing flexible options that are deemed to be less preferable before conducting the analysis. Wine futures investment represents the flexible option (due to its liquidity) in the first essay, however, it exhibits greater uncertainty in price than the traditional bottled wine. We find in our empirical analysis that both weather and market fluctuations influence the evolution of the price in wine futures, and thus, despite being the flexible option, it also represents the riskier investment. On the other hand, capacity expansion at a geographically remote facility represents the flexible option (due to its greater backup capabilities) in the second essay, however, it is a more costly backup alternative than a nearby facility. As a result, both essays examine the trade-offs between these flexible, yet risker and/or costlier, alternatives, and shed light on the risk-reward structure of these various operational levers.

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by

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CHAPTER 1: INTRODUCTION

In this dissertation, we study a firm's investment and capacity planning strategies in the presence of different types of supply uncertainties and risks. Both essays in this dissertation benefit from empirical analysis as the analytical models build on the findings and observations from the corresponding empirical investigation. Each essay shows the benefits from utilizing flexible options that are deemed to be less preferable before conducting the analysis. Wine futures investment represents the flexible option (due to its liquidity) in the first essay, however, it exhibits greater uncertainty in price than the traditional bottled wine. We find in our empirical analysis that both weather and market fluctuations influence the evolution of the price in wine futures, and thus, despite being the flexible option, it also represents the riskier investment. On the other hand, capacity expansion at a geographically remote facility represents the flexible option (due to its greater backup capabilities) in the second essay, however, it is a more costly backup alternative than a nearby facility. As a result, both essays examine the trade-offs between these flexible, yet risker and/or costlier, alternatives, and shed light on the risk-reward structure of these various operational levers.

1.1. Overview of Essay 1

We examine a risk-averse distributor's decision in selecting between bottled wine and wine futures under weather and market uncertainty. At the beginning of every summer, a fine wine distributor has to choose between purchasing bottled wine made from the harvest collected two years ago and wine futures of wine still aging in the barrel from the harvest of the previous year. At the end of the summer, after realizing weather and market fluctuations, the distributor can adjust her allocation by trading futures and bottles.

Using comprehensive data obtained from Liv-ex that is an online trading platform for registered wine merchants, we empirically show how young wine prices can be explained through weather and market fluctuations. We then build an optimization model based on our empirical findings to examine the distributor's investment decisions in wine futures and bottled wine. Our analytical model employs a two-stage stochastic program with recourse under budget and value-at-risk constraints.

The paper makes three contributions. First, we develop an analytical model in order to determine the optimal selection of bottled wine and wine futures under weather and market uncertainty. Our model is built on an empirical foundation in which the functional forms describing the evolution of futures and bottle prices are derived from comprehensive data associated with the most influential Bordeaux winemakers. Second, we develop structural properties of optimal decisions. We show that a wine distributor should always invest in wine futures because it increases the expected profit in spite of being a riskier asset than bottled wine. We characterize the influence of variation in various uncertainties in the problem. Third, our study empirically demonstrates the financial benefits from using our model for a large distributor. The average profit improvement is significant at over 22%, and its value is higher under risk aversion. The analysis is beneficial for fine wine distributors as it provides insights into how to improve their selection in order to make financially healthier allocations.

1.2. Overview of Essay 2

The second essay helps a firm determine its capacity expansion decisions as a mitigation strategy against disruptions in a delivery supply chain. The delivery supply chain involves fulfillment centers that are responsible for delivering orders within the next day. The operations at a fulfillment center (e.g., sorting, bundling, and wrapping) require agility and flexibility since each customer order consists of a unique combination of multiple products. If any of these operations halt due to a disruption, that facility cannot serve its customers while the disruption lasts. As a result, the firm might not be able to comply with its next-day delivery promise.

We formulate the firm's capacity planning problem using a two-stage model. The firm determines the capacity expansion amount in each fulfillment center in stage 1. If a disruption occurs in stage 2, then the firm determines the optimal allocation of the backup capacity in order to satisfy the orders arriving at the disrupted fulfillment center. We consider the length of disruption as random, and the firm operates under a value-at-risk measure for satisfying its customer orders arriving at the disrupted fulfillment center.

This essay makes five main contributions. First, we use capacity planning, rather than inventory planning, as a proactive measure against supply chain disruptions. Unlike inventory planning, capacity planning adds agility and flexibility to a delivery supply chain. Second, our work incorporates two types of disruptions that are (1) low-impact and high-likelihood disruptions, and (2) high-impact and low-likelihood disruptions. This provides a better representation of the set of disruptions a firm would face in its daily operations. Third, we show that geographic proximity does not necessarily serve as an anchor when determining the location of capacity expansion, i.e., the firm may be economically better off by adding capacity at a remotely located facility, even though providing backup from that facility would cost more than providing from a closer facility in case of a disruption. Fourth, we find that the capacity expansion decisions at the remote facility and the nearby facility may be substitutes. Fifth, as a further consequence of the substitution effect, we find that, as risk aversion increases, the total capacity expansion may first decrease, then stabilize, and then increase. This type of non-monotone behavior is a result of the flexibility of the remote facility.

CHAPTER 2: WINE ANALYTICS: FINE WINE PRICING AND SELECTION UNDER WEATHER AND MARKET UNCERTAINTY

2.1. Introduction

This paper examines a wine distributor's annual decision regarding the selection of bottled wine and wine futures under weather and market uncertainty. At the end of each summer, a winemaker harvests grapes, crushes them in order to produce wine. A fine wine goes through a long aging process ranging between 18 to 24 months. The wine can be sold in advance in the form of wine futures, often referred to as "en primeur" due to the popular futures campaign for Bordeaux wines. Wine futures begin to trade before the first summer following the harvest (approximately eight months after harvest). The wine gets bottled in the second summer and is sold for retail and distribution; those who purchased this wine in the form of futures also receive their wine shipment.

To understand the difference between bottled wine and wine futures, let us consider the 2013 vintage of a fine wine as an example provided in Figure 2.1. The 2013 vintage of this wine is made from the grapes harvested in September 2013; its futures are sold in May 2014, and the wine is bottled and sold in May 2015. Similarly, the 2014 vintage is produced from the grapes harvested in September 2014, and its futures come out in May 2015. As a result, the distributor has two products in May 2015 from the same fine wine producer: (1) The 2013 vintage in the form of bottled wine, and (2) the 2014 vintage in the form of wine futures (a contract to take the possession of the 2014 vintage wine in May 2016). Thus, in May 2015, a fine wine distributor has to select the amounts of bottled wine from the 2013 vintage and wine futures of the 2014 vintage. A distributor's business involves buying the wine from the winemaker and immediately pushing it downstream to the wholesalers and retail stores. Thus, its profits are based on quick movement of wine, rather than opportunistic sale based on wine prices. Our paper assists wine distributors by developing an analytical model to determine the allocation decisions between bottled wine and wine futures under weather and market uncertainty. The model relies on an empirical foundation that describes the price evolution of futures and bottles. The empirical analysis provides the justification for the functional forms describing the impact of weather and market conditions on prices.

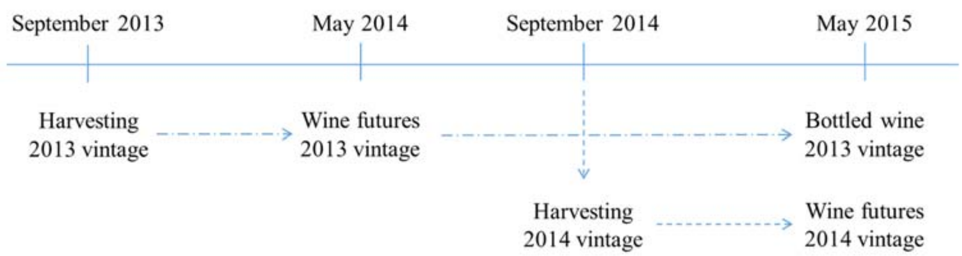


Figure 2.1. The timeline of futures and bottle trade in wine production.

Quality of a fine wine is greatly influenced by weather conditions during the grape growing season; often higher temperatures lead to better quality of grapes and wine. Due to differences in weather conditions from one year to the other, two consecutive vintages of the same wine may have very different quality, and hence, price. A striking example regarding the impact of weather on wine futures prices can be seen from the Bordeaux region where the summer of 2005 was very hot and dry, resulting in one of the finest vintages in recent years. Prior to the growing season in 2005, the wine futures for the 2004 vintage of Troplong Mondot was released to the market at the price of \$62/bottle. The impact of superior weather in the summer of 2005 was so big that the wine futures price for the 2005 Troplong Mondot jumped to \$233/bottle, corresponding to a 276% increase when compared with the futures price of the previous vintage. This is an example of the improved weather conditions from 2004 to 2005, and its impact on wine futures prices. Moreover, the positive weather during the summer of 2005 negatively impacted the 2004 vintage wine, and caused the bottle price of the 2004 vintage to go down to \$54 per bottle, resulting in a 13% reduction from its futures price from the prior year. This is an example where the growing weather condition not only influences the wine futures price of its vintage but also the evolution of a futures price to the bottle price in the previous vintage.

In addition to weather fluctuations, changes in the market conditions also drive fine wine prices. All fine wine futures and bottles are traded in London International Vintner's Exchange (Liv-ex) with standardized contracts. We use Liv-ex 100 index, composed of 100 most sought-after wines, in order to describe the fine wine market conditions. This index is declared as the "fine wine industry's leading benchmark" by Reuters. When Liv-ex 100 index decreased by 17.17% in 2008 (in comparison to 2007), the top Bordeaux winemakers priced their 2008 vintage wines 16.66% less than their 2007 vintage wines on average despite the highly similar weather conditions between the two growing seasons. Our analysis combines the impact of weather and market fluctuations in explaining the price evolution of wine futures and bottled wine. These price evolution functions are utilized in developing an analytical model to help the distributor's selection between wine futures and bottled wine.

Wine distribution is an important business around the world. In the US alone, the wine industry generates \$37.6 billion each year with a projected 8.2% growth in the upcoming years. Under the presence of drastic changes in vintage prices depending on weather and market conditions, a wine distributor is often puzzled with whether to invest in wine futures of the previous year's vintage or buy recently bottled wine from two vintages ago. While wine futures exhibit a greater uncertainty as future weather conditions can negatively influence the bottle price as in the example of the 2004 Troplong Mondot, it also allows the distributor to lock up limited supply at lower prices. Moreover, futures can be easily traded in Liv-ex, the exchange platform for fine wine without having to make physical shipments and comply with legal restrictions. Thus, wine futures are highly liquid in comparison to bottled wine. Purchasing bottles can be perceived as a safer bet upfront as the bottle prices are revealed. However, market conditions continue to influence these prices. The distributor can observe the summer weather conditions getting comparative indications as to how the futures price is going to evolve to the bottle price. Moreover, the distributor can later change its allocation through buying additional or selling existing futures with limited ability to move its bottled wine inventory.

When should a wine distributor engage in futures? Our work finds motivation from conversations with the executives at the largest wine distributor in the US and in the world that does not invest in wine futures due to the lack of knowledge about futures prices and their evolution to bottle prices. Earlier research (Ashenfelter et al. 1995 and Ashenfelter 2008) has shown that mature Bordeaux wine prices can be predicted accurately using growing season weather conditions, but these studies conclude that young wine prices (i.e., futures prices and prices for the recently released bottled wines) cannot be predicted using weather conditions. Our empirical analysis provides an explanation for the impact of weather and market changes in young wine prices. It serves as a foundation for our analytical model, and enables us to estimate the distributor's economic benefit from investing in a combination of wine futures and bottled wine (when compared with a distributor that invests only in bottled wine).

Wine futures are often perceived to be a riskier alternative than bottled wine. Our empirical analysis confirms this perception as it shows that wine futures prices are influenced by both weather and market fluctuations, whereas bottled wine prices are influenced only by the changes in market conditions. Thus, a distributor would not be encouraged to make investments in futures. Rather, the distributor would spend its money in physical bottles where the price is already evolved and has smaller uncertainty. Indeed, this has been the practice at some of the distributors as they invest solely in bottled wine, bypassing the futures alternative. Our analytical model shows, however, that a distributor should always make some investment in futures. This finding is confirmed through a numerical analysis using comprehensive data.

Our paper makes three main contributions. First, we develop an analytical model in order to determine the optimal selection of bottled wine and wine futures under weather and market uncertainty. The model is built on an empirical foundation that guides the functional forms describing the evolution of futures and bottle prices. Our empirical analysis shows how futures and bottle prices evolve through changes in weather and market conditions: (1) futures price of a vintage is negatively influenced by a warmer growing season for the upcoming vintage, leading to a lower bottle price; (2) bottle prices are not influenced by weather conditions; and, (3) improving market conditions lead to increases in futures and bottle prices. Second, we describe the optimal selection of bottled wine and wine futures with a limited budget and using a time-consistent value-at-risk measure under weather and market uncertainty. We develop the structural properties of the optimal decisions and we show that a distributor should always invest in wine futures because it increases expected profit despite being a riskier asset than bottled wine. Third, our study demonstrates the financial benefits from using our analytical model based on the empirical findings. The average profit improvement is 22.78%, and the benefit is higher under risk aversion. Our analysis provides insights into how to improve the distributor's selection and make financially healthier allocations between futures and bottled wine.

The remainder of the paper is organized as follows. Section 2.2 reviews the relevant literature from economics, operations and supply chain management, and demonstrates how our work differs from earlier publications. Section 2.3 develops an analytical model to help a distributor determine the allocation decisions between wine futures and bottled wine. Section 2.4 presents the economic benefit from our proposed model using comprehensive data from the most influential Bordeaux winemakers. Section 2.5 presents our conclusions and managerial insights. All proofs and derivations, and the details of our empirical analysis are presented in the appendix (Section 2.6).

2.2. Literature Review

The economics literature has shown significant interest in understanding, explaining, and predicting wine prices. Ashenfelter et al. (1995) and Ashenfelter (2008) are the two seminal papers showing that mature Bordeaux wine prices can be predicted using weather and age with accuracy, however, they both conclude that their models fail to explain young wine prices. For a wine distributor, however, most trade takes place when the wine is young, and therefore, it is important to understanding the evolution of young wine prices. Our work examines how young wine prices are impacted by the fluctuations in weather and market conditions. While we complete this analysis in order to build an analytical model that determines the optimal selection of wine futures and bottled wine, our empirical findings complement earlier publications by providing an explanation for the evolution of young wine prices.

Jones and Storchmann (2001), Lecocq and Visser (2006), Ali and Nauges (2007), Ali et al. (2008), and Ashenfelter and Jones (2013) also address the price prediction of Bordeaux wines based on weather conditions and/or tasting scores. Byron and Ashenfelter (1995) and Wood and Anderson (2006) extend this stream to Australian wines while Haeger and Storchmann (2006) and Ashenfelter and Storchmann (2010) examine American wines and German wines, respectively. However, none of these papers focus on young wine pricing nor have a selection analysis that can benefit distributors.

Noparumpa et al. (2015) investigate the impact of tasting scores on young wine prices, and then provide a model for winemakers to determine the optimal amount of wine to be sold in the form of futures and the optimal amount that should be sold after the wine is bottled. Their work concludes that wine futures help a winemaker collect her revenues in advance while passing the risk of having a poor quality vintage to the distributor. They estimate that selling wine in advance in the form of futures increases Bordeaux winemakers' profits by 10% on average. If winemakers are the clear winners of futures trade, then one asks what is in it for the wine distributors. Our paper sheds light on this question by providing an analytical model which incorporates the advantages (i.e., being easily tradable through the Liv-ex platform) and the disadvantages (i.e., bearing a greater price uncertainty) of wine futures for distributors. We utilize weather and market fluctuations instead of tasting scores (correlated with weather) to explain futures prices; this leads to considerably higher explaining power with greater adjusted R^2 values in a larger sample featuring the leading Bordeaux winemakers. Moreover, our explanation of the evolution of a futures price into bottle price is a unique aspect of our study.

Wine futures is a form of advance selling and purchasing, and recent publications advocate the use of advance selling in various settings. Xie and Shugan (2001) exemplify the benefits in electronic tickets and online platforms. Cho and Tang (2013) examine the influence of supply and demand uncertainty, and Tang and Lim (2013) investigate the influence of speculators in advance selling. Boyacı and Özer (2010) demonstrate the advantages of advance selling in capacity planning. Our work departs from these studies in three features: (1) The wine distributor has to choose between advance purchase of an upcoming product in replacement of the present product; (2) as the price evolves through revelations of uncertainty, the distributor has the ability to adjust its selection between the two product offerings; (3) the sources of uncertainty in our problem are weather and market fluctuations differentiating our problem setting.

Wine futures depart from the commodity futures described in Fama and French (1987) and Geman (2005). In commodity markets (e.g., corn, soybean, cocoa), a settlement in a futures contract means that the agricultural product delivered to the buyer can be produced by any farmer. In fine wine, however, if a buyer is asking for a bottle of 2008 Lafite Rothschild, the seller cannot substitute it with a bottle of 2007 Lafite Rothschild, or a bottle of 2008 Troplong Mondot. Thus, fine wine cannot be substituted across producers or vintages, and therefore, is not a commodity. Moreover, in traditional commodities, futures contracts and spot purchases occur simultaneously for the commodity product. However, spot purchases of bottled fine wine do not begin until the completion of the futures trade of the same wine.

Fine wines are also treated as a long-term investment. Storchmann (2012) provides a comprehensive review about wine economics, and covers the use of wine as an investment option. Dimson et al. (2014) find that young Bordeaux wines yield greater returns than the mature ones. This finding further amplifies the importance of explaining the evolution of young wine prices. Jaeger (1981), Burton and Jacobsen (2001), and Masset and Weisskopf (2010) also examine the return on wines as a long-term investment. Jaeger (1981), Burton and Jacobsen (2001), and Dimson et al. (2014) conclude that wines can yield greater returns than treasury bills, but less than equities. Masset and Weisskopf (2010), on the other hand, demonstrate that fine wines can outperform equities during a financial crisis when financial assets are highly correlated. While these studies consider wine as a long-term investment, our paper focuses on the benefits as a short-term investment from a distributor's perspective who buys the recently released young wines from winemakers and sells to the wholesalers and retailers shortly after.

Supply uncertainty is another related stream as quality and price may vary dramatically across different vintages of the same wine depending on weather and market conditions. Yano and Lee (1995) provide a comprehensive review of the literature that focuses on supply uncertainty as a consequence of yield fluctuations. Jones et al. (2001) examine the impact of yield uncertainty in the corn seed industry for a firm that utilizes farmland in two opposing hemispheres, and develop a two-stage production scheme to better match supply and demand. Kazaz (2004) introduces the impact of yield fluctuations into what he defines as the yield-dependent cost and price structures in the olive oil industry. Kazaz and Webster (2011) add a price-setting capability, and show how yield fluctuations influence a firm's pricing decisions. Their study also demonstrates the benefits of using fruit futures (if existed) in mitigating supply uncertainty. Boyabatli et al. (2011) and Boyabatli (2015) examine the purchasing contracts for fixed-proportion technology products in the presence of random spot prices. Kazaz and Webster (2015) develop optimal price and quantity decisions under supply and demand uncertainty and under risk aversion. Tomlin and Wang (2008) develop price and quantity decisions in a co-production setting that results from random yield in the split of two distinct products. Li and Huh (2011) also develop price and quantity decisions for multiple products using a multinomial logit model. Departing from these papers, we define supply uncertainty in the form of variation in quality due to growing season weather; hence, wine futures have a quality-dependent price structure. Moreover, the secondary (emergency) investment option utilized in some of these papers becomes available in the second stage whereas, in our model, both wine futures and bottled wines are simultaneously available at the beginning.

Weather and market realizations provide signals to the wine industry, and the impact of similar signals, in particular for estimating demand, is examined widely in the operations management literature. Gümüş (2014), for example, investigates the impact of forecast as a signal for demand. Our work departs from this body of literature as we study signals that influence the evolution of price over time.

2.3. The Model and its Analysis

This section develops and analyzes a model that helps the wine distributor determine the investment allocation between wine futures and bottled wine. The prices of wines futures and bottled wine are influenced by the randomness in weather and market conditions after these decisions take place. In this model, the functional forms describing the evolution of futures and bottle prices rely on an empirical foundation.

In each May, a risk-averse wine distributor has to select between wine futures (of new vintage) and bottled wine (of previous vintage) of a winemaker. Specifically, in May of calendar year t, the distributor has to determine the amount of money to be invested in wine futures from vintage $t - 1$ and bottled wine from vintage $t - 2$.

2.3.1. Empirical Foundation for the Model

In this section, we present an empirical analysis that serves as a foundation for our mathematical model that will be presented in Section 2.3.2. We begin our discussion with the specification of functional forms that will be used in the description of the price evolution of young wines as functions of weather and market random variables.

Figure 2.2 illustrates the notation we employ in order to describe futures and bottled wine prices as functions of weather and market random variables. In May of calendar year t, futures for vintage $t - 1$ are released at the price of f_1. We express the futures price of the same vintage in September of calendar year t as f_2, and in May of calendar year $t + 1$ as f_3. In May of calendar year t, bottled wine from vintage $t - 2$ is also released, and we express this bottle price as b_1. We denote the bottle price of vintage $t-2$ in September of calendar year t with b_2, and in May of calendar year $t+1$ with b_3.

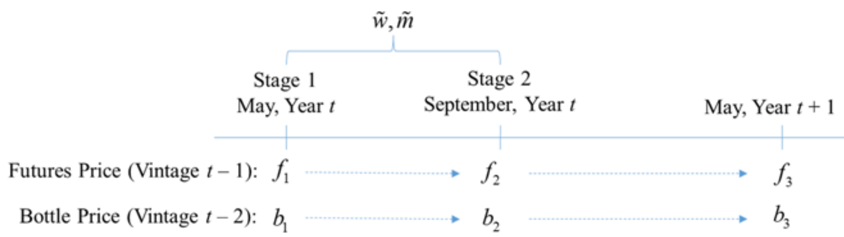


Figure 2.2. The evolution of futures and bottled wine prices under weather and market uncertainty.

After the wine distributor makes investments in futures of vintage $t-1$ and bottled wine of vintage $t-2$ in May of calendar year t, a new summer weather information becomes available in calendar year t. This new summer weather information, which is fully observed by September of calendar year t, provides a relative comparison to the wines that are from vintages $t-1$ and $t-2$. For the case of wine futures of vintage $t-1$, the new weather information from May–September period of year t compared to the growing season of grapes (i.e., May–September period of year t – 1) can play a role. Thus both f_2 and f_3 can be influenced by the new weather information. For the case of bottled wine of vintage $t-2$, the new weather information from May–September period of year t compared to the growing season of grapes (i.e., May–September period of year t – 2) can also influence the values of b_2 and b_3. Similarly, market conditions change from May to September of year t. As a consequence, the weather and market information observed at the end of summer in calendar year t can have an impact of the values of f_2, f_3, b_2, and b_3.

We next examine the impact of weather and market on the evolution of wine futures and bottled wine prices. Let us denote weather fluctuations with random variable $\tilde{w}$ and its realization with w, and we denote market fluctuations with random variable $\tilde{m}$ and its realization with m. Specifically, we provide justification for the description of f_2, f_3, b_2, and b_3 as functions of w and m. The detailed explanation of our data and the empirical models are provided in Appendix B (Section 2.6.2).

We begin our discussion with wine futures. Table 2.1 provides the regression analysis of the impact of new summer weather and market information on the price evolution of futures with f_2 (in Model 1A) and f_3 (in Model 1B). The analysis in Table 2.1 provides three results. First, better weather of the upcoming vintage (i.e., higher value of w) has a negative impact on the evolution of futures price from f_1 to f_2. This weather effect is statistically significant at 1% level. This can be easily understood as the upcoming vintage had better weather conditions than the vintage of futures, and therefore, the price of wine futures would decrease. Second, better weather of the upcoming vintage (i.e., higher value of w) has a continued negative impact (statistically significant at 1%) on the evolution of futures price from f_2 to f_3. Thus, this implies that the new weather information is not completely priced in the futures as of September of calendar year t. A similar observation is made in Ashenfelter (2008). Moreover, the negative coefficient representing the impact of weather in the evolution of futures price from f_2 to f_3 is greater in absolute value than that of f_1 to f_2. Therefore, we define the functional form of the futures price evolution as $\partial f_3(\cdot)/\partial w < \partial f_2(\cdot)/\partial w < 0$. Third, improving market conditions during the summer of calendar year t (with a higher value of m) has a positive impact on the evolution of futures price both from f_1 to f_2 and from f_2 to f_3. This market effect is statistically significant at 1% level. Moreover, the positive coefficient representing the impact of market conditions in the evolution of futures price from f_2 to f_3 is greater than that of f_1 to f_2. Therefore, we define the functional form of the futures price evolution as $\partial f_3(\cdot)/\partial m > \partial f_2(\cdot)/\partial m > 0$. As a consequence of these findings, we describe the futures prices as $f_2(w, m)$ and $f_3(w, m)$.

	Model 1A: $f_2 - f_1$		**Model 1B:** $f_3 - f_2$	
Parameter	Coefficient	*t-stat*	Coefficient	*t-stat*
Intercept	0.0296	*2.85****	0.0788	*4.45****
w	-0.0501	*-4.58****	-0.1281	*-6.88****
m	0.0079	*5.47****	0.0223	*9.01****
Adjusted R^2	0.19		0.37	
Observations	220		220	

Table 2.1. Linear regression results demonstrating the impact of weather and market conditions on the evolution of futures prices. *** denotes statistical significance at 1%.

Table 2.2 provides the regression analysis of the impact of new summer weather and market information on the evolution of bottle prices described as b_2 (in Model 2A) and b_3 (in Model 2B). The analysis in Table 2.2 provides three results. First, weather conditions of the upcoming vintage (i.e., the value of w) does not have a statistically significant effect on the evolution of bottle prices, neither from b_1 to b_2, nor from b_2 to b_3. Second, improving market conditions during the summer of calendar year t (with a higher value of m) has a positive impact on the evolution of bottle prices both from b_1 to b_2 and from b_2 to b_3. This market effect is statistically significant at 5% level in Model 2A and 1% level in Model 2B. Moreover, the positive coefficient representing the impact of market conditions in the evolution of futures price from b_2 to b_3 is greater than that of b_1 to b_2. Therefore, we define the functional form of the bottle price evolution as $\partial b_3(\cdot)/\partial m > \partial b_2(\cdot)/\partial m > 0$. As a consequence of these findings, we describe the futures prices as $b_2(m)$ and $b_3(m)$.

	Model 2A: $b_2 - b_1$		**Model 2B:** $b_3 - b_2$	
Parameter	Coefficient	*t-stat*	Coefficient	*t-stat*
Intercept	0.0248	*1.52*	0.0187	*0.53*
w	-0.0082	*-0.59*	0.0245	*0.82*
m	0.0059	2.19^{**}	0.0255	4.43^{***}
Adjusted R^2	0.01		0.12	
Observations	220		220	

Table 2.2. Linear regression results demonstrating the impact of weather and market conditions on the evolution of bottle prices. ** and *** denote statistical significance at 5% and 1%, respectively.

2.3.2. The Model

We formulate the distributor's problem using a two-stage stochastic program with recourse. In stage 1 (May of year t), the distributor determines the investment in futures of vintage $t - 1$ (denoted x_1) and bottles of vintage $t - 2$ (denoted y_1) of a single winemaker, respectively, with a limited budget (denoted B) and a value-at-risk (VaR) constraint. Distributors have a well-specified budget for each fine winemaker, and executives describe their risk tolerance in the form of a VaR constraint. Recall that f_1 and b_1 are the unit price of futures and bottles in stage 1. For notational simplicity in this section, we normalize $f_1 = b_1 = 1$ without loss of generality. At the end of stage 1 (September of year t), the distributor observes the realization (w, m) of weather and market random variables. We normalize the means to zero, i.e., $E[\tilde{w}] = E[\tilde{m}] = 0$. The probability density functions (pdf) of $\tilde{w}$ and $\tilde{m}$ are denoted $\phi_w(w)$ and $\phi_m(m)$ on respective support $[w_L, w_H]$ and $[m_L, m_H]$. We let $\Omega = [w_L, w_H] \times [m_L, m_H]$.

At the beginning of stage 2 (September of year t), the distributor determines the amount of futures to buy or sell (denoted x_2) at price $f_2(w, m)$, and the amount of bottles to purchase (denoted y_2) at price $b_2(m)$. The distributor can easily buy or sell futures by transferring the ownership rights through Liv-ex; the transaction does not require any physical flow of good and is not subject to any legal requirements. However, while the distributor can purchase bottles from the winemaker, the selling of bottles faces logistical and legal constraints. First, Bordeaux winemakers prefer shipping the bottled wine in the winter months to prevent any deterioration during transportation. Consequently, the bottles purchased in May of year t (stage 1) are not in distributor's possession as of September of year t (stage 2). Hence, she cannot sell those bottles immediately at the beginning of stage 2. Second, selling a bottle to a different owner has legal constraints in the US where the sale of the bottle from one distributor located in another state can be considered as illegal movement of spirits. The combination of these two facts restrict the distributor from selling the bottled wine in September of year t (stage 2); these bottles are directly sold to the customers of the distributor (wholesalers, liquor stores, and consumers) at the end of stage 2. However, the distributor can buy additional bottles from the winemaker using either the cash leftover from stage 1 or from the sale of futures.

At the end of stage 2, the distributor collects revenues from futures (that are bottled by then) and bottles. Futures and bottle prices at the end of stage 2 are also uncertain. The uncertainty in futures price between September of year t and May of year $t + 1$ is captured by random variable $\tilde{z}_f$. The realized futures price is $f_3(w, m) + z_f$. The uncertainty in bottle price between September of year t and May of year $t + 1$ is captured by random variable $\tilde{z}_b$. The realized bottle price is $b_3(m) + z_b$. We assume that $(\tilde{z}_f, \tilde{z}_b)$ is independent of $(\tilde{w}, \tilde{m})$, and have a mean of zero, i.e., $E[\tilde{z}_f] = E[\tilde{z}_b] = 0$. Thus, $E[f_3(w, m) + \tilde{z}_f] = f_3(w, m)$ and $E[b_3(m) + \tilde{z}_b] = b_3(m)$. By examining our price data, we observe that if futures (bottle) price moves in one direction when it evolves from f_1 to $f_2(w, m)$ (from b_1 to $b_2(m)$), then a wide majority of realized futures (bottle) prices at the end of stage 2 also move in the same direction when they evolve from $f_2(w, m)$ to $f_3(w, m) + z_f$ (from $b_2(m)$ to $b_3(m) + z_b$). We insert the following assumptions that comply with this observation:

If $f_2(w, m) \lozenge f_1$, then $E[f_3(w, m) + \tilde{z}_f] \lozenge f_2(w, m)$ for all $\lozenge \in \{>, =, <\}$ and for all (w, m). (2.1)

If $b_2(m) \lozenge b_1$, then $E[b_3(m) + \tilde{z}_b] \lozenge b_2(m)$ for all $\lozenge \in \{>, =, <\}$ and for all m. (2.2)

All price functions, $f_2(w, m)$, $f_3(w, m)$, $b_2(m)$ and $b_3(m)$, are linear in their arguments. Prices f_2, f_3, b_2, and b_3 are net of transaction, shipping, and other costs, i.e., the prices reflect the net revenues in these two stages. Thus, the realized profit at the end of stage 2 can be expressed as follows:

$$\begin{aligned}&\Pi(x_1, y_1, w, m, x_2, y_2, z_f, z_b) \\ &\quad = -x_1 - y_1 - f_2(w, m)x_2 - b_2(m)y_2 + [f_3(w, m) + z_f](x_1 + x_2) + [b_3(m) + z_b](y_1 + y_2). \qquad (2.3)\end{aligned}$$

At the beginning of stage 2, the distributor selects x_2 and y_2 to maximize expected recourse profit subject to budget and VaR constraints given the initial investments in futures and bottles (x_1, y_1) and the realized values of weather and market random variables (w, m):

$$\max_{x_2, y_2} E\left[\Pi\left(x_1, y_1, w, m, x_2, y_2, \tilde{z}_f, \tilde{z}_b\right)\right] \qquad (2.4)$$

subject to

$$f_2(w, m)x_2 + b_2(m)y_2 \le B - x_1 - y_1 \qquad (2.5)$$

$$P\left[\Pi\left(x_1, y_1, w, m, x_2, y_2, \tilde{z}_f, \tilde{z}_b\right) < -\beta\right] \le \alpha \qquad (2.6)$$

$$x_2 \ge -x_1 \qquad (2.7)$$

$$y_2 \ge 0. \qquad (2.8)$$

Inequality (2.5) is the second-stage budget constraint; the distributor can use the remaining budget from stage 1 in addition to the money generated through the sale of futures in stage 2 (when $x_2 < 0$). Inequality (2.6) is the second-stage VaR constraint; the distributor requires that the probability of loss more than β ($< B$) is no more than α. Alternatively said, the probability of realized profit less than $-\beta$ should not exceed α. Inequality (2.7) indicates that the distributor cannot sell more futures in stage 2 than the amount purchased in stage 1. For given x_1, y_1, w, m, we let (x_2^*, y_2^*) denote the optimal solution, i.e.,

$$\left(x_2^*\left(x_1, y_1, w, m,\right), y_2^*\left(x_1, y_1, w, m,\right)\right) = \underset{x_2, y_2}{\arg\max}\, E\left[\Pi\left(x_1, y_1, w, m, x_2, y_2, \tilde{z}_f, \tilde{z}_b\right)\right] \text{ s.t. (2.5) – (2.8).}$$

Let $z_{f\alpha}$ and $z_{b\alpha}$ denote the realizations of $\tilde{z}_f$ and $\tilde{z}_b$ at fractile α, i.e., $P[\tilde{z}_f \le z_{f\alpha}] = P[\tilde{z}_b \le z_{b\alpha}] = \alpha$. We assume that $z_{f\alpha} < 0$ and $z_{b\alpha} < 0$, i.e., the fractile parameter is such that the risk-averse decision maker in September of year t is concerned about profit realizations in May of year $t + 1$ that are below expectation. We also assume that the VaR constraint is satisfied in the event the distributor invests the entire budget in bottles, i.e.,

$$(1 - b_3(m_L) - z_{b\alpha})B < \beta. \tag{2.9}$$

This assumption is consistent with the practice of distributors who invest solely in bottled wine.

At the beginning of stage 1, the distributor selects x_1 and y_1 to maximize expected profit at the end of stage 2 subject to budget and VaR constraints:

$$\max_{x_1, y_1 \ge 0} E\left[\Pi\left(x_1, y_1, \tilde{w}, \tilde{m}, x_2^*\left(x_1, y_1, \tilde{w}, \tilde{m}\right), y_2^*\left(x_1, y_1, \tilde{w}, \tilde{m}\right), \tilde{z}_f, \tilde{z}_b\right)\right] \tag{2.10}$$

subject to

$$x_1 + y_1 \le B \tag{2.11}$$

$$P\left[\Pi\left(x_1, y_1, w, m, x_2^*\left(x_1, y_1, w, m\right), y_2^*\left(x_1, y_1, w, m\right), \tilde{z}_f, \tilde{z}_b\right) < -\beta\right] \le \alpha \text{ for all } (w, m) \in \Omega \tag{2.12}$$

Inequality (2.11) states that the distributor's initial investment in futures and bottles cannot exceed the allotted budget B. Inequality (2.12) is the VaR constraint under a time-consistent risk measure (e.g., see Boda and Filar 2006 or Devalkar et al. 2015). Some first-stage decisions (x_1, y_1) can satisfy the VaR constraint in stage 1 but may not comply with the VaR constraint in stage

2; such decisions lead to time-inconsistency and are not feasible in our model. To assure that risk aversion is time consistent over the planning horizon, the distributor must account for the VaR constraint in stage 2, and in particular, the choice of (x_1, y_1) must be such that there exists a solution to the stage-2 problem that satisfies the stage-2 VaR constraint for any realization (w, m) of $(\tilde{w}, \tilde{m})$.

We focus on understanding how investment in futures and bottles affect performance ceteris paribus, and therefore, we assume equal and positive expected returns at the end of stage 2, i.e.,

$$E[f_3(\tilde{w}, \tilde{m}) + \tilde{z}_f] = E[b_3(\tilde{m}) + \tilde{z}_b] > 1. \tag{2.13}$$

We relax this assumption in Section 2.4.

2.3.3. Analysis

We begin our analysis by partitioning the support Ω into three sets that identify realizations of $(\tilde{w}, \tilde{m})$ where the distributor would improve expected profit at the end of stage 2 by (1) selling futures, (2) buying futures, and (3) selling futures and buying bottles.

$$\Omega 0 = \{(w, m) \in \Omega : f_3(w, m)/f_2(w, m) = b_3(m)/b_2(m) = 1\}$$

$$\Omega 1 = \{(w, m) \in \Omega : f_3(w, m)/f_2(w, m) < 1 \text{ and } b_3(m)/b_2(m) < 1\}$$

$$\Omega 2 = \{(w, m) \in \Omega : f_3(w, m)/f_2(w, m) \geq \max\{b_3(m)/b_2(m), 1\} \setminus \Omega 0\}$$

$$\Omega 3 = \{(w, m) \in \Omega : b_3(m)/b_2(m) \geq \max\{f_3(w, m)]/f_2(w, m), 1\} \cup \Omega 0\}.$$

We define m_τ as $b_3(m_\tau)/b_2(m_\tau) = 1$ and $f_3(0, m_\tau)/f_2(0, m_\tau) = 1$, and $w_\tau(m)$ as $f_3(w_\tau(m), m)/f_2(w_\tau(m), m) = 1$ for $m \leq m_\tau$. Let $w_\tau^- = w_\tau(m_L)$. Note that

$$m_\tau < 0,\ w_\tau(m) < 0 \text{ for all } m < m_\tau, \text{ and } w_\tau(m_\tau) = 0 \tag{2.14}$$

(follows from (2.1), (2.2), (2.13)). In our analysis, we assume that

$$m_\tau > m_L \text{ and } w_\tau(m_L) > w_L. \tag{2.15}$$

Note that the set Ω1 defines realizations where the expected return on futures and bottles over stage 2 is negative. A reversal of $m_\tau > m_L$ in (2.15) eliminates Ω1, which is advantageous to any decision-maker regardless of whether she is risk-averse or risk-neutral. A reversal of $w_\tau(m_L) > w_L$ in (2.15) (while keeping $E[\tilde{w}] = 0$) implies a reduced weather uncertainty on behalf of wine futures, reducing the riskiness of this asset. As a consequence, (2.15) represents a riskier condition, and thus, our results remain intact when (2.15) does not hold. Figure 2.3 illustrates the above notation.

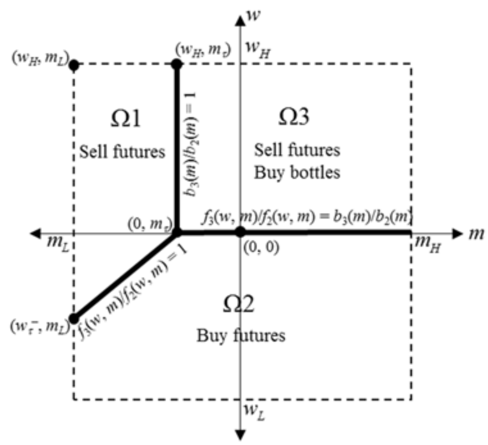


Figure 2.3. Illustration of sets Ω1 – Ω3. Function $w_\tau(m)$ is the line connecting points (w_τ^-, w_m) and (0, m_τ).

We make use of expressions that rely on the solution to the stage-2 problem with the VaR constraint (2.6) relaxed, which we denote as (x_2^0, y_2^0), i.e.,

$$(x_2^0(x_1, y_1, w, m), y_2^0(x_1, y_1, w, m)) = \underset{x_2, y_2}{\arg\max}\, E\left[\Pi\left(x_1, y_1, w, m, x_2, y_2, \tilde{z}_f, \tilde{z}_b\right)\right] \text{ s.t (2.5),(2.7),(2.8).}$$

From the structure illustrated in Figure 2.3, it is clear that (x_2^0, y_2^0) is given as follows:

$$\left(x_2^0, y_2^0\right) = \begin{cases} \left(-x_1, 0\right) & \text{if } \left(w, m\right) \in \Omega 1 \\ \left(\left(B - x_1 - y_1\right)/f_2\left(w, m\right), 0\right) & \text{if } \left(w, m\right) \in \Omega 2 \\ \left(-x_1, \left(B - x_1 - y_1 + f_2\left(w, m\right)x_1\right)/b_2\left(m\right)\right) & \text{if } \left(w, m\right) \in \Omega 3 \end{cases}, \tag{2.16}$$

(see Lemma 2.A1 in the appendix for its derivation). Throughout our analysis we assume that, compared to no investment at the beginning of stage 1 (i.e., $x_1 = y_1 = 0$), an investment in some bottles increases expected profit:

$$\partial E\left[\Pi\left(x_1, y_1, \tilde{w}, \tilde{m}, x_2^0, y_2^0, \tilde{z}_f, \tilde{z}_b\right)\right] \Big/ \partial y_1 \Big|_{(x_1, y_1)=(0,0)} > 0. \tag{2.17}$$

In practice, (2.17) is likely to hold; otherwise, a distributor would not operate in this business. Inequality (2.17) implies that bottles command a higher expected return than holding cash in stage 1 as evidenced by purchases of bottles that occur each spring at the distributor motivating our study.

Proposition 2.1. *For any* (x_1, y_1),

$$\frac{\partial E\left[\Pi\left(x_1, y_1, \tilde{w}, \tilde{m}, x_2^0, y_2^0, \tilde{z}_f, \tilde{z}_b\right)\right]}{\partial x_1} \geq \frac{\partial E\left[\Pi\left(x_1, y_1, \tilde{w}, \tilde{m}, x_2^0, y_2^0, \tilde{z}_f, \tilde{z}_b\right)\right]}{\partial y_1} > 0. \tag{2.18}$$

Proposition 2.1 states that, at the beginning of stage 1 and for any current investment level, additional investment in futures is more profitable than additional investment in bottles for a risk-neutral distributor, and that both investment alternatives are more profitable than holding cash. The result hints that futures offer an inherent advantage over bottles. This advantage stems from the additional flexibilities of liquidity (i.e., being able to sell futures after observing weather and market random variables) and swapping (i.e., the ability to sell futures and buy bottles). As shown below the value from these flexibilities can be quantified.

The distributor has the flexibility to sell futures after observing the upcoming vintage's weather conditions. We denote the value created from the futures liquidation option with V_l. The liquidation flexibility is not present in the bottles asset. In order to derive V_l, we first partition Ω3 into the following two sets:

$$\Omega 3_A = \{(w, m): b_3(m)/b_2(m) \geq 1 > f_3(w, m)/f_2(w, m)\},$$

$\Omega 3_B = \{(w, m): b_3(m)/b_2(m) \geq f_3(w, m)/f_2(w, m) \geq 1\}$.

Futures do not provide a profitable return in $\Omega 3_A$, and continue to be profitable but dominated by the returns from bottles in $\Omega 3_B$. The distributor would sell futures in weather and market realizations in sets $\Omega 1$ and $\Omega 3_A$ in order to avoid any further losses. The value created from the liquidity of futures can then be expressed as follows:

$$V_l = \iint_{\Omega 1 \cup \Omega 3_A} \left(f_2(w,m) - f_3(w,m)\right)\phi_w(w)\phi_m(m)\,dwdm \geq 0. \tag{2.19}$$

The distributor also benefits from the ability to swap futures, even if they are still profitable, with bottles after observing the weather conditions of the upcoming vintage. This occurs in $\Omega 3_B$ when the weather turns out to be better than the previous summer in combination with improved market conditions. In $\Omega 3_B$, futures continue to be profitable, but bottles are preferable to futures. In set $\Omega 3_A$ futures are not profitable, and the distributor sells them and swaps them with bottles. We denote the value created from the swapping flexibility with V_s, can express it as follows:

$$V_s = \iint_{\Omega 3}\left(f_2(w,m)\frac{b_3(m)}{b_2(m)} - f_3(w,m)\right)\phi_w(w)\phi_m(m)\,dwdm \geq 0. \tag{2.20}$$

The liquidation and swapping flexibilities make futures a more desirable asset than bottles. We describe the value gained in stage 2 from liquidation and swapping with $V_{l\cup s}$. Note that the distributor benefits from both liquidating and swapping in set $\Omega 3_A$; thus, the value expression needs to discount the double counting:

$$V_{l\cup s} = V_l + V_s - \iint_{\Omega 3_A}\left(f_2(w,m) - f_3(w,m)\right)\phi_w(w)\phi_m(m)\,dwdm \geq 0. \tag{2.21}$$

The distributor can benefit from holding cash in stage 1. This money can be used to purchase futures in $\Omega 2$ and bottles in $\Omega 3$. The value from holding cash in stage 1, denoted V_c, can be described as:

$$V_c = \iint_{\Omega 2} \left(\frac{f_3(w,m)}{f_2(w,m)} - 1 \right) \phi_w(w)\phi_m(m) dwdm + \iint_{\Omega 3} \left(\frac{b_3(m)}{b_2(m)} - 1 \right) \phi_w(w)\phi_m(m) dwdm \geq 0. \qquad (2.22)$$

Using this notation, we can open up the expressions that appear in Proposition 2.1 (see the proof of Proposition 2.1 for supporting detail):

$$\frac{\partial E\left[\Pi\left(x_1, y_1, \tilde{w}, \tilde{m}, x_2^0, y_2^0, \tilde{z}_f, \tilde{z}_b\right)\right]}{\partial y_1} = E\left[b_3(\tilde{m}) + \tilde{z}_b\right] - 1 - V_c$$

$$\frac{\partial E\left[\Pi\left(x_1, y_1, \tilde{w}, \tilde{m}, x_2^0, y_2^0, \tilde{z}_f, \tilde{z}_b\right)\right]}{\partial x_1} = E\left[f_3(\tilde{w}, \tilde{m}) + \tilde{z}_f\right] - 1 - V_c + V_{l \cup s}$$

$$= \frac{\partial E\left[\Pi\left(x_1, y_1, \tilde{w}, \tilde{m}, x_2^0, y_2^0, \tilde{z}_f, \tilde{z}_b\right)\right]}{\partial y_1} + V_{l \cup s}.$$

We next examine the impact of increasing variation in uncertainty both in weather and market random variables (denoted σ_w^2 and σ_m^2, respectively) on an investment strategy in stage 1. Due to the linearity of the futures and bottle price functions, the expected prices $E\left[f_2(\tilde{w}, \tilde{m})\right]$, $E\left[f_3(\tilde{w}, \tilde{m}) + \tilde{z}_f\right]$, $E\left[b_2(\tilde{m})\right]$, and $E\left[b_3(\tilde{m}) + \tilde{z}_b\right]$ do not change with different values of σ_w^2 and σ_m^2. Moreover, in the absence of a recourse flexibility that enables a wine distributor to change her futures and bottle positions, the expected profit would not change with increasing values of σ_w^2 and σ_m^2. However, the values from liquidity, swapping, and combination flexibilities, and cash, denoted V_l, V_s, $V_{l \cup s}$, and V_c in (2.19) – (2.22) change with higher values of σ_w^2 and σ_m^2. Under symmetric pdfs for weather and market random variables, i.e., $\phi_w(w) = \phi_w(-w)$ with $w_H = -w_L$ and $\phi_m(m) = \phi_m(-m)$ with $m_H = -m_L$, the following proposition establishes their behavior with respect to σ_w^2 and σ_m^2.

Proposition 2.2. *When $\phi_w(w)$ and $\phi_m(m)$ follow symmetric pdf*, (*a*) *the value from liquidity V_l in* (2.19) *increases in σ_w^2 and σ_m^2*; (*b*) *the value from cash V_c in* (2.22) *increases in σ_w^2 and σ_m^2*; (*c*) *the value from swapping V_s in* (2.20) *increases in σ_m^2*; (*d*) *the value from the combination of liquidity and swapping $V_{l\cup s}$ in* (2.21) *increases in σ_m^2*.

The above proposition shows that the values from liquidity and cash flexibilities increase with higher degrees of variation in both weather and market random variables. An increasing value from cash as a consequence of higher degrees of variance in weather and market leads to a higher threshold for justifying investment in bottles in stage 1. As a result, higher variation in these two random variables make bottle investment less attractive. The values from swapping and the combination of liquidity and swapping also increase with higher degrees of market uncertainty. Increasing values from liquidity and the combination of liquidity and swapping as a consequence of a higher degree of market variation makes futures more attractive than bottles in stage 1. However, these two flexibilities can show both an increasing and a decreasing behavior with higher degrees of weather uncertainty. When a higher degree of weather variation causes a reduction in the values of liquidity and the combination from liquidity and swapping, it makes the purchase of futures less attractive in stage 1. Roughly speaking, if the increase in the variation of weather uncertainty causes a greater expansion of region $\Omega 3_A$ than region $\Omega 3_B$, then V_s and $V_{l\cup s}$ exhibit a decreasing behavior in σ_w^2.

Proposition 2.3. *When $\phi_w(w)$ and $\phi_m(m)$ follow symmetric pdf*,

(*a*) $E\left[\Pi\left(x_1, y_1, \tilde{w}, \tilde{m}, x_2^0, y_2^0, \tilde{z}_f, \tilde{z}_b\right)\right]$ *increases in σ_m^2*; (*b*) $E\left[\Pi\left(x_1, y_1, \tilde{w}, \tilde{m}, x_2^0, y_2^0, \tilde{z}_f, \tilde{z}_b\right)\right]$ *increases in σ_w^2 if $\partial V_{l\cup s}/\partial \sigma_w^2 > 0$*.

Proposition 2.3 shows that, for symmetric distributions, the expected profit increases in σ_m^2, however, it may increase or decrease in σ_w^2. Profit improvement from higher variation in market and weather uncertainty is enabled because of the recourse flexibility that allows the distributor to change its futures and bottles position based on the realization of the two random variables.

When the value from the combination of liquidity and swapping increases in the variation in weather, then the expected profit also increases with higher degrees of weather uncertainty.

The preceding analysis has focused on the stage-1 profit function for a risk-neutral distributor. We build on this analysis in our derivation of the optimal solution to the risk-averse distributor problem defined in (2.4) – (2.12) in Proposition 2.4 below. The proposition makes use of the following notation and inequalities:

$x_1^+ = \beta/[1 - f_2(w_H, m_L)]$

$x_1^V = [\beta + z_{b\alpha} B]/([1 - f_2(w_H, m_\tau)][1 + z_{b\alpha}])$

$y_1^V = [\beta - [1 - f_2(w_H, m_L)]x_1^V]/[1 - b_3(m_L) - z_{b\alpha}]$

$x_1^s = (\beta - B[1 - b_3(m_L) - z_{b\alpha}])/[b_3(m_L) + z_{b\alpha} - f_2(w_H, m_L)]$

$y_1^s = (B[1 - f_2(w_H, m_L)] - \beta)/[b_3(m_L) + z_{b\alpha} - f_2(w_H, m_L)]$

$$-z_{f\alpha} < \beta/B \tag{2.23}$$

$$\frac{\partial E\left[\Pi\left(x_1, y_1, \tilde{w}, \tilde{m}, x_2^0, y_2^0, \tilde{z}_f, \tilde{z}_b\right)\right] / \partial y_1\Big|_{(x_1,y_1)=(0,0)}}{\partial E\left[\Pi\left(x_1, y_1, \tilde{w}, \tilde{m}, x_2^0, y_2^0, \tilde{z}_f, \tilde{z}_b\right)\right] / \partial x_1\Big|_{(x_1,y_1)=(0,0)}} < \frac{1 - b_3\left(m_L\right) - z_{b\alpha}}{1 - f_2\left(w_H, m_L\right)}. \tag{2.24}$$

The value of x_1^+ is the number of futures that cause constraint (2.12) to be binding (i.e., satisfied exactly) at point (w_H, m_L) given that $y_1 = 0$. The value of x_1^V is the number of futures that cause constraint (2.12) to be binding (i.e., satisfied exactly) at point (w_H, m_τ), which is independent of the value of y_1. The value of y_1^V is the number of bottles that cause constraint (2.12) to be binding (i.e., satisfied exactly) at point (w_H, m_L) given that $x_1 = x_1^V$. The values of x_1^s and y_1^s are the number of futures and bottles, respectively, that cause constraint (2.12) at point (w_H, m_L) to be intersecting with the budget constraint (2.11). The value of x_1^s is strictly smaller than x_1^+ when $x_1^+ < B$.

Inequality (2.23) restricts the variation in the randomness in futures at the end of stage 2. It implies that having the entire budget invested in futures in stage 2 at point $(w_{\bar{\tau}}, m_L)$ does not violate the VaR constraint (2.6). Note that at point $(w_{\bar{\tau}}, m_L)$, the risk-neutral distributor would keep all futures, and purchase additional futures if the budget allows. Inequality (2.23) is a rather mild condition. Recall (2.9), which says the VaR constraint is not violated if the distributor uses the entire budget to purchase bottles at the beginning of stage 1 (a condition supported by observed practice), i.e., $-z_{b\alpha} < \beta/B - [1 - b_3(m_L)] < \beta/B$. A comparison of (2.23) with (2.9) shows that our model allows for greater uncertainty in the randomness in futures prices than that in bottle prices. Unlike (2.9), inequality (2.23) does not mean that investing the entire budget in futures in stage 1 would not violate the VaR constraint (2.12). Rather, investing the entire budget in futures in stage 1 under (2.23) may violate the VaR constraint (2.12) at (w_H, m_τ) and (w_H, m_L).

Inequality (2.24) is used as a condition in characterizing the optimal solution. It compares the ratio of marginal returns from bottles to futures with the ratio of worst loss from bottles at α-fractile (i.e., $1 - b_3(m_L) - z_{b\alpha}$) to futures $(1 - f_2(w_H, m_L))$ because the distributor can liquidate futures at the worst weather and market realization (w_H, m_L). When (2.24) holds, the firm prefers futures more than bottles even at the worst realizations of weather and market random variables; when the opposite of (2.24) holds, the firm prefers bottles over futures.

The following proposition characterizes the optimal solution in both stages.

Proposition 2.4. *When* (2.23) *holds and* $\left(\tilde{z}_f, \tilde{z}_b\right)$ *follow a bivariate normal distribution*,

(*a*) *If* $\{x_1^+, x_1^V\} \geq B$, *then* $(x_1^*, y_1^*) = (B, 0)$ *and* $(x_2^*, y_2^*) = (x_2^0, y_2^0)$;

(*b*) *If* $x_1^V < B \leq x_1^+$, *then* $(x_1^*, y_1^*) = (x_1^V, B - x_1^V)$ *and* $(x_2^*, y_2^*) = (x_2^0, y_2^0)$;

(*c*) *If* $x_1^+ < \{x_1^V, B\}$, *then*

(*i*) *if* (2.24) *holds, then* $(x_1^*, y_1^*) = (x_1^+, 0)$ *and* $(x_2^*, y_2^*) = (x_2^0, y_2^0)$;

(ii) *if* (2.24) *does not hold*, *then* $(x_1^*, y_1^*) = (x_1^s, y_1^s)$ *and* $(x_2^*, y_2^*) = (x_2^0, y_2^0)$;

(d) *If* $x_1^s < x_1^V \leq x_1^+ < B$, *then*

(i) *if* (2.24) *holds, then* $(x_1^*, y_1^*) = (x_1^V, y_1^V)$ *and* $(x_2^*, y_2^*) = (x_2^0, y_2^0)$;

(ii) *if* (2.24) *does not hold*, *then* $(x_1^*, y_1^*) = (x_1^s, y_1^s)$ *and* $(x_2^*, y_2^*) = (x_2^0, y_2^0)$;

(e) *If* $x_1^V \leq x_1^s < x_1^+ < B$, *then* $(x_1^*, y_1^*) = (x_1^V, B - x_1^V)$ *and* $(x_2^*, y_2^*) = (x_2^0, y_2^0)$.

Proposition 2.4 leads to our main conclusion: It is always optimal to invest in at least some futures because $x_1^* > 0$ in all conditions (see the proof). While it is optimal to invest in futures, it is not necessarily to do so in bottles as in the conditions designated in Proposition 2.4(a) and 2.4(c)(i). This result holds true in spite of the additional uncertainty from weather that is present in futures which is not present in bottles. It should also be noted here that Propositions 2.4(a) and 2.4(c)(i) do not require that $\left(\tilde{z}_f, \tilde{z}_b\right)$ follow a bivariate Normal distribution.

The preceding analysis has built the second-stage results using the fact that the firm can invest its entire budget in futures in stage 2, i.e., when (2.23) holds. However, when (2.23) does not hold, the optimal second-stage decisions can be restricted by the VaR constraint (2.6); thus, x_2^* can be less than x_2^0. The next proposition shows that the firm should invest a positive amount of money in futures even if the second-stage decisions are limited by the VaR constraint (2.6).

Proposition 2.5. *When* $\phi_w(w)$ *follows a symmetric pdf and* $\left(\tilde{z}_f, \tilde{z}_b\right)$ *follow a bivariate normal distribution*,

$$\frac{\partial E\left[\Pi\left(x_1, y_1, \tilde{w}, \tilde{m}, x_2^*, y_2^*, \tilde{z}_f, \tilde{z}_b\right)\right]}{\partial x_1} \geq \frac{\partial E\left[\Pi\left(x_1, y_1, \tilde{w}, \tilde{m}, x_2^*, y_2^*, \tilde{z}_f, \tilde{z}_b\right)\right]}{\partial y_1} > 0. \qquad (2.25)$$

In conclusion, combining the results of propositions 2.4 and 2.5, our analysis shows that the firm should always make a positive investment in wine futures despite the fact that they are tagged as the riskier asset when compared to bottled wine. This is a robust result because it holds under various general conditions, regardless of whether (2.23) holds or not.

2.4. Financial Benefits from Our Proposed Model

Our work is motivated by the world's largest wine distributor that does not invest in wine futures due to lack of knowledge about futures prices and their evolution to bottle prices. How significant is the economic benefit from investing in wine futures? This section demonstrates the financial benefits from using our model and trading futures compared with a benchmark of a distributor that trades only bottled wine.

We use actual futures and bottle prices (f_1 and b_1, respectively) from our data, and compute the evolution of prices $\{f_2(w, m), f_3(w, m), b_2(m)$, and $b_3(m)\}$ and the distribution of $(\tilde{z}_f, \tilde{z}_b)$ for each winemaker by using the coefficient estimates of weather and market variables from our empirical analysis. Our estimation of coefficients is based on the futures and bottle prices that are released in May of calendar year $t \in \{2008, 2009, 2010\}$. We use our analytical model to solve the distributor's problem of allocating budget between the futures of vintage $t - 1$ and the bottles of vintage $t - 2$ for a single winemaker j in May of Year t where $t \in \{2011, 2012\}$. Let $E[\Pi_1^{j,t}(x_1^*, y_1^*)]$ denote the optimal profit coming from winemaker j in year t, and let $E[\Pi_1^{j,t}(0, y_1^{**})]$ describe the expected profit from the distributor's current practice of investing only in bottled wine with no investment in futures, i.e., $(x_1, x_2) = (0, 0)$. We define the financial benefit from using our model as follows:

$$\Delta^{j,t} = (E[\Pi_1^{j,t}(x_1^*, y_1^*)] - E[\Pi_1^{j,t}(0, y_1^{**})])/E[\Pi_1^{j,t}(0, y_1^{**})] \tag{2.26}$$

We simulate 25 equally likely scenarios where weather and market variables take values from the historical observations.

Table 2.3 summarizes the benefits from using our model of investing in futures, bottles and leaving cash under a budget and a VaR constraint described in (2.4) – (2.12). It presents the average benefit from the two vintages examined in this study as $\overline{\Delta}^{j} = (1/2)\sum_t(\Delta^{j,t})$ for each of the Bordeaux winemakers at different levels of risk aversion using tighter requirements regarding the probability of loss (α).

These results show that even the largest distributors, which can be assumed to be risk neutral, would significantly benefit from investing in wine futures. The average expected profit improvement from these 44 Bordeaux wineries is 22.78% where the largest average improvement is observed at 66.99% at Mission Haut Brion. The improvement might disappear in very rare occasions, as seen at Gruaud Larose and Lagrange St Julien; this is the case when $E[f_3(\tilde{w},\tilde{m}) + \tilde{z}_f]/f_1$ is significantly smaller than $E[b_3(\tilde{m}) + \tilde{z}_b]/b_1$ (recall that (2.13) is relaxed in this section).

Table 2.3 also demonstrates that our model leads to greater benefits in the presence of risk aversion. Keeping the distributor's tolerated loss at $\beta = 2000$, by reducing the distributor's tolerated VaR probability to $\alpha = 0.20$ and then to $\alpha = 0.10$ (with stronger risk aversion), we observe that the average profit improvement goes up to 28.69% and 34.46%, respectively. In effect, the introduction of risk aversion on the benchmark case may force the distributor to hold excess cash, i.e., $y_1^{**} < B/b_1$. However, the flexibility of futures leads to a greater total investment in stage 1 (i.e., $f_1x_1^* + b_1y_1^* > b_1y_1^{**}$) that translates into greater average improvement than that for a risk-neutral distributor where $f_1x_1^* + b_1y_1^* = b_1y_1^{**} = B$. This also indicates that relaxing (2.9) makes the benefits of our model even more profound. Therefore, we can conclude that our model advocating the trading of wine futures is generally more beneficial for risk-averse distributors.

Winemaker (j)	Risk Neutral $\overline{\Delta}^j$	Low Risk Aversion $\overline{\Delta}^j$	High Risk Aversion $\overline{\Delta}^j$	Winemaker (j)	Risk Neutral $\overline{\Delta}^j$	Low Risk Aversion $\overline{\Delta}^j$	High Risk Aversion $\overline{\Delta}^j$
Angelus	11.47%	17.23%	22.45%	Lagrange St Julien	0.00%	4.28%	4.60%
Ausone	39.12%	43.76%	50.68%	Latour	39.56%	45.18%	53.38%
Beychevelle	0.98%	4.20%	9.84%	Leoville Barton	18.65%	22.84%	28.58%
Calon Segur	6.01%	12.72%	17.52%	Leoville Las Cases	33.55%	45.42%	52.21%
Carruades de Lafite	33.40%	38.29%	45.72%	Leoville Poyferre	24.86%	37.68%	44.08%
Cheval Blanc	24.05%	28.83%	33.63%	Lynch Bages	19.35%	22.48%	29.23%
Clos Fourtet	13.92%	18.51%	24.32%	Margaux	26.35%	33.61%	40.75%
Conseillante	42.58%	51.27%	57.85%	Mission Haut Brion	66.99%	69.88%	76.93%
Cos d'Estournel	24.85%	37.18%	43.62%	Montrose	27.11%	35.93%	42.38%
Ducru Beaucaillou	43.78%	52.74%	59.19%	Mouton Rothschild	27.77%	32.79%	40.31%
Duhart Milon	13.56%	18.46%	25.12%	Palmer	6.50%	11.56%	16.12%
Eglise Clinet	56.39%	63.74%	71.74%	Pavie	21.82%	24.42%	28.88%
Evangile	24.35%	37.30%	43.65%	Pavillon Rouge	14.93%	14.93%	20.67%
Figeac	33.88%	43.68%	50.43%	Petit Mouton	2.41%	6.23%	8.85%
Fleur Petrus	9.34%	10.44%	15.42%	Petrus	14.29%	22.07%	27.13%
Forts Latour	11.73%	13.66%	19.55%	Pichon Baron	31.83%	32.33%	36.78%
Grand Puy Lacoste	17.44%	19.12%	23.99%	Pichon Lalande	25.41%	34.06%	39.71%
Gruaud Larose	0.00%	5.00%	6.90%	Pin	19.44%	29.00%	35.40%
Haut Bailly	22.34%	26.71%	33.47%	Pontet Canet	15.50%	19.61%	25.22%
Haut Brion	26.86%	35.54%	41.44%	Talbot	7.93%	11.41%	15.19%
Lafite Rothschild	27.05%	35.06%	42.18%	Troplong Mondot	16.10%	21.83%	27.14%
Lafleur	29.97%	36.17%	43.03%	Vieux Chateau Certan	28.74%	35.24%	41.15%

	Risk Neutral $\overline{\Delta}$	**Low Risk Aversion** $\overline{\Delta}$	**High Risk Aversion** $\overline{\Delta}$
Average	**22.78%**	**28.69%**	**34.46%**

Table 2.3. The average financial benefit $\overline{\Delta} = \sum_j \overline{\Delta}^j \big/ 44$ where $\overline{\Delta}^j$ is the average profit improvement for winemaker j, B = 10000 and β = 2000; and, α = {1, 0.20, 0.10} for risk neutral, low risk aversion, and high risk aversion, respectively.

The financial benefits reported in Table 2.3 have significant implications for the wine industry as it complements the discussion regarding the need to establish a wine futures market in the US. Noparumpa et al. (2015) has shown that Bordeaux winemakers improve their profits by approximately 10% due to the wine futures market, and small and artisanal winemakers in the US can increase their profits by approximately 15%. Their study shows the positive effect through the use of tasting expert opinions. Table 2.3 shows that winemakers are not the only constituent benefiting from the wine futures market, and more importantly, wine distributors can benefit significantly when price evolutions can be predicted and a wine futures market is established in the US. In our finding, we utilize a different information, weather and market fluctuations, in demonstrating the financial benefits for distributors.

2.5. Conclusions

We have examined a wine distributor's problem that arises in May of every year, involving the selection between wine futures of the previous year's vintage and bottled wine made from grapes harvested two years ago.

Our paper makes three significant contributions. First, we develop an analytical model in order to determine the optimal selection of bottled wine and wine futures under weather and market uncertainty. The model is built on an empirical foundation where we explain the price evolution of futures and bottles based on the weather of the upcoming vintage and changes in market conditions. The analytical model employs the following information from the empirical analysis that uses a comprehensive data set regarding the trade of 44 most influential Bordeaux winemakers: (1) Futures price of a vintage is negatively influenced by a warmer growing season for the upcoming vintage, leading to a lower bottle price; (2) bottle prices are not influenced by weather conditions; and, (3) improving market conditions lead to increases in futures and bottle prices. We describe the market fluctuations through the changes in the Liv-ex 100 index. In this end, the identification of the Liv-ex 100 index as an explaining variable of the fluctuations in young wine prices also constitutes another contribution to the literature.

Second, we describe the optimal selection of bottled wine and wine futures with a limited budget and using a value-at-risk measure under weather and market uncertainty. We develop the structural properties of the optimal decisions. We conclude that a distributor should always invest in wine futures because it increases expected profit despite being a riskier asset than bottled wine.

Third, we demonstrate the financial benefits from using our analytical model through the numerical illustration using the same data for a large wine distributor. The average profit improvement is a significant 22.78%. Moreover, the average profit improvement is higher under risk aversion. Considering the wine distributor with a revenue of $11.4 Billion that motivated our study, our analysis constitutes a significant economic benefit from our proposed model.

In addition to these three main findings, we also demonstrate the impact of variation in weather and market uncertainty on the distributor's profitability. We show that higher variation in market uncertainty increases the expected profit, however, higher variation in weather can cause both an increase and a decrease in expected profit.

Our findings have significant implications for the wine industry as it is likely to encourage wine distributors to invest in wine futures with better information and expectation. Moreover, it is likely to increase the trading volume in the financial platform Liv-ex, resulting in even better information than what our sample provides.

While the motivation for our empirical and analytical work stems from the wine industry, our modeling perspective applies to a wide range of products and services. In the wine industry, the weather information for the upcoming vintage can be perceived as an information signal that causes a re-evaluation of the quality perception in the eyes of the consumers. There are various industries that have similar structures. In the technology industry, for example, the information regarding the release of new products often negatively influences the price of the current products. This is similar to the consequences of observing an improved weather condition during the growing season of the upcoming vintage. What is unique in our study, however, is that the upcoming vintage's weather information, when it is a relatively colder summer, can lead to an increase in the price of the current vintage. This kind of price increase cannot be observed in the technology industry through new information regarding the upcoming products. The increase in prices are only observed after a significant amount of time as in valuable antiques. However, the price increase in our study occurs without having to wait for a long period of time. Thus, the problem investigated here has unique features as it combines similar characteristics of information signaling from various industries for a single product and in a short span of time.

Our study has some limitations. Longer time series data can be used to test and enrich the price evolution of wine futures and bottled wine. Our study employs data only from the most popular Bordeaux winemakers and ignores fine wine producers from other regions. Our work also sheds light into future research directions. A longer time series data can help develop models that predict the price of wine futures and bottled wine. Such prediction models can help other parties, e.g. restaurateurs and investors who engage in the trade of wine. Our model can be expanded to consider other financing options such as debts and loans in order to increase the distributor's budget allocation. Our study, along with Noparumpa et al. (2015), lead to an elevated desire to establish a futures market in the US. Future research needs to address regulatory policies and legal requirements in order to arrive at an economically healthy futures market.

2.6. Appendix

Appendix A presents the proofs and derivations, and Appendix B explains the details of the empirical foundation.

2.6.1. Appendix A – Proofs and Derivations

Lemma 2.A1. $\left(x_2^0\left(x_1, y_1, w, m\right), y_2^0\left(x_1, y_1, w, m\right)\right) = \underset{x_2, y_2}{\arg\max}\, E\left[\Pi\left(x_1, y_1, w, m, x_2, y_2, \tilde{z}_f, \tilde{z}_b\right)\right]$

s.t. (2.5), (2.7), (2.8); where

$$\left(x_2^0\left(x_1, y_1, w, m\right), y_2^0\left(x_1, y_1, w, m\right)\right) = \begin{cases} \left(-x_1, 0\right) & \text{if } \left(w, m\right) \in \Omega 1 \\ \left(\left(B - x_1 - y_1\right) / f_2\left(w, m\right), 0\right) & \text{if } \left(w, m\right) \in \Omega 2 \\ \left(-x_1, \left(B - x_1 - y_1 + f_2\left(w, m\right) x_1\right) / b_2\left(m\right)\right) & \text{if } \left(w, m\right) \in \Omega 3 \end{cases}.$$

Proof of Lemma 2.A1.

The first derivatives of the stage-2 objective function (2.4) are

$$\partial E[\Pi\left(x_1, y_1, w, m, x_2, y_2, \tilde{z}_f, \tilde{z}_b\right)]/\partial x_2 = f_3(w, m) - f_2(w, m) \tag{2.27}$$

$$\partial E[\Pi\left(x_1, y_1, w, m, x_2, y_2, \tilde{z}_f, \tilde{z}_b\right)]/\partial y_2 = b_3(m) - b_2(m). \tag{2.28}$$

We see that the decision that maximizes expected profit simply depends on the relative profitability of futures and bottles for a given (w, m). In Ω1, both (2.27) and (2.28) are negative (neither futures nor bottles are profitable on expectation) which leads to $x_2^0 = -x_1$ and $y_2^0 = 0$ due to (2.7) and (2.8). In Ω2, (2.27) is nonnegative and greater than (2.28) (futures are more profitable on expectation) which leads to $x_2^0 = [B - x_1 - y_1]/f_2(w, m)$ and $y_2^0 = 0$ due to (2.5) and (2.8). In Ω3, (2.28) is nonnegative and no smaller than (2.27) (bottles are more profitable on expectation) which leads to $x_2^0 = -x_1$ and $y_2^0 = [B + (f_2(w, m) - 1)x_1 - y_1]/b_2(m)$ due to (2.5) and (2.7). ❑

Proof of Proposition 2.1.

Using (x_2^0, y_2^0) (see Lemma 2.A1), we have

$$\partial E[\Pi(x_1, y_1, \tilde{w}, \tilde{m}, x_2^0, y_2^0, \tilde{z}_f, \tilde{z}_b)]/\partial y_1$$

$$= E[b_3(\tilde{m}) + \tilde{z}_b] - \iint_{\Omega 1} \phi_w(w)\phi_m(m)dwdm$$

$$-\iint_{\Omega 2} \left(f_3(w,m)/f_2(w,m)\right)\phi_w(w)\phi_m(m)dwdm - \iint_{\Omega 3} \left(b_3(m)/b_2(m)\right)\phi_w(w)\phi_m(m)dwdm$$

$$= E[b_3(\tilde{m}) + \tilde{z}_b] - 1 - V_c \qquad (2.29)$$

where

$$V_c = \iint_{\Omega 2} \left(\frac{f_3(w,m)}{f_2(w,m)} - 1\right)\phi_w(w)\phi_m(m)dwdm + \iint_{\Omega 3} \left(\frac{b_3(m)}{b_2(m)} - 1\right)\phi_w(w)\phi_m(m)dwdm$$

which is nonnegative because both integrands are nonnegative by definitions of Ω2 and Ω3.

Also, we have

$$\partial E[\Pi(x_1, y_1, \tilde{w}, \tilde{m}, x_2^0, y_2^0, \tilde{z}_f, \tilde{z}_b)]/\partial x_1$$

$$= E[f_3(\tilde{w}, \tilde{m}) + \tilde{z}_f] - \iint_{\Omega 1} \phi_w(w)\phi_m(m)dwdm$$

$$-\iint_{\Omega 2} \left(f_3(w,m)/f_2(w,m)\right)\phi_w(w)\phi_m(m)dwdm - \iint_{\Omega 3} \left(b_3(m)/b_2(m)\right)\phi_w(w)\phi_m(m)dwdm$$

$$+\iint_{\Omega 1} \left(f_2(w,m) - f_3(w,m)\right)\phi_w(w)\phi_m(m)dwdm$$

$$+\iint_{\Omega 3} \left(f_2(w,m)\frac{b_3(m)}{b_2(m)} - f_3(w,m)\right)\phi_w(w)\phi_m(m)dwdm$$

$$= E[f_3(\tilde{w}, \tilde{m}) + \tilde{z}_f] - 1 - V_c + V_{l \cup s} \qquad (2.30)$$

where

$$V_{l\cup s} = \iint_{\Omega 1} \left(f_2(w,m) - f_3(w,m) \right) \phi_w(w) \phi_m(m) \, dw dm$$
$$+ \iint_{\Omega 3} \left(f_2(w,m) \frac{b_3(m)}{b_2(m)} - f_3(w,m) \right) \phi_w(w) \phi_m(m) \, dw dm$$

which is nonnegative because both integrands are nonnegative by definitions of Ω1 and Ω3.

Note that $E[\Pi(x_1, y_1, \tilde{w}, \tilde{m}, x_2^0, y_2^0, \tilde{z}_f, \tilde{z}_b)]$ is linear in x_1 and y_1. As a consequence, (2.29) is positive for any (x_1, y_1) following from (2.17). Moreover, following from (2.13),

$$\partial E[\Pi(x_1, y_1, \tilde{w}, \tilde{m}, x_2^0, y_2^0, \tilde{z}_f, \tilde{z}_b)]/\partial x_1 - \partial E[\Pi(x_1, y_1, \tilde{w}, \tilde{m}, x_2^0, y_2^0, \tilde{z}_f, \tilde{z}_b)]/\partial y_1 = V_{l\cup s}$$

which is nonnegative for any (x_1, y_1). ❑

Proof of Proposition 2.2.

Recall that $E[f_3(w, m) + \tilde{z}_f] = f_3(w, m)$ and $E[b_3(m) + \tilde{z}_b] = b_3(m)$. The price evolution of futures is already described as $\partial f_3(w, m)/\partial w < \partial f_2(w, m)/\partial w < 0$ and $\partial f_3(w, m)/\partial m > \partial f_2(w, m)/\partial m > 0$, and bottles as $\partial b_3(m)/\partial m > \partial b_2(m)/\partial m > 0$.

(a) With higher values of σ_w^2 for a symmetric pdf for $\phi_w(w)$, regions Ω1 and $\Omega 3_A$ expand. Because $\partial f_3(w, m)/\partial w < \partial f_2(w, m)/\partial w < 0$, V_l in (2.19) would be adding increasing values of $f_2(w, m) - f_3(w, m)$ at each increment of w_H. Thus, V_l *in* (2.19) increases in σ_w^2. Similarly, with higher values of σ_m^2 for a symmetric pdf for $\phi_m(m)$, region Ω1 expands. Because $\partial f_3(w, m)/\partial m > \partial f_2(w, m)/\partial m > 0$, V_l in (2.19) would be adding increasing values of $f_2(w, m) - f_3(w, m)$ at each reduction in m_L. Thus, V_l *in* (2.19) increases in σ_m^2.

(b) Increasing σ_w^2 for a symmetric pdf for $\phi_w(w)$ implies expanding region Ω2 by reducing w_L where $f_3(w, m)/f_2(w, m) > 1$ by definition of the set. Because $\partial f_3(w, m)/\partial w < \partial f_2(w, m)/\partial w < 0$, we would be adding increasing values of $[(f_3(w, m)/f_2(w, m)) - 1]$. Similarly, increasing σ_w^2 for a symmetric pdf for $\phi_w(w)$ implies expanding region Ω3 by increasing w_H where $b_3(m)/b_2(m) > 1$

by definition of the set. Because $\partial b_3(m)/\partial w = \partial b_2(m)/\partial w = 0$ and we would not be changing the second term of V_c in (2.22). The changes region Ω2 is positive, and therefore, V_c in (2.22) increases in σ_w^2. A similar proof follows for the impact of σ_m^2. Increasing σ_m^2 for a symmetric pdf for $\phi_m(m)$ implies expanding region Ω2 by reducing m_L and increasing m_H where $f_3(w, m)/f_2(w, m) > 1$ by definition of the set. Because $\partial f_3(w, m)/\partial m > \partial f_2(w, m)/\partial m > 0$, we would be adding increasing values of $[(f_3(w, m)/f_2(w, m)) - 1]$. Similarly, increasing σ_m^2 for a symmetric pdf for $\phi_m(m)$ implies expanding region Ω3 by increasing m_H where $b_3(m)/b_2(m) > 1$ by definition of the set. Because $\partial b_3(m)/\partial m > \partial b_2(m)/\partial m > 0$, we would be adding increasing values of $[(b_3(m)/b_2(m)) - 1]$ to the second term of V_c in (2.22). The changes in region Ω2 and Ω3 are positive, and therefore, V_c in (2.22) increases in σ_m^2.

(c) The value from swapping V_s in (2.20) is defined in Ω3. Increasing σ_m^2 for a symmetric pdf for $\phi_m(m)$ implies expanding Ω1 (by reducing m_L) and Ω3 (by increasing m_H). In Ω3, $b_3(m)/b_2(m) > 1$, and its value is increasing due to $\partial b_3(m)/\partial m > \partial b_2(m)/\partial m > 0$. At the new market realization greater than m_H, we know that $f_2(w, m)[b_3(m)/b_2(m)] - f_3(w, m) > 0$ because of the definition of Ω3 (so that the firm swaps futures with a more profitable bottle investment). Thus, expanding the support beyond m_H adds value and expanding the lower support below m_L does not cause any loss; therefore, V_s in (2.20) is increasing in σ_m^2.

(d) The proof follows from the proofs of parts (a) and (c). ❑

Proof of Proposition 2.3.

(a) Increasing σ_m^2 for a symmetric pdf for $\phi_m(m)$ implies reducing m_L and increasing m_H. Reducing m_L to $m_L - \varepsilon$ (where $\varepsilon > 0$) and increasing m_H to $m_H + \varepsilon$ leads to three cases for investigation.

Case 1: $(w, m_L - \varepsilon) \in \Omega1$ and $(w, m_H + \varepsilon) \in \Omega3$: Because $\partial f_3(w, m)/\partial m > \partial f_2(w, m)/\partial m > 0$ and because bottles are even more profitable than futures in Ω3, the losses from the futures investment at $(w, m_L - \varepsilon) \in \Omega1$ are smaller in absolute value than the gains $(w, m_H + \varepsilon) \in \Omega3$, and thus, the expected profit increases.

Case 2: $(w, m_L - \varepsilon) \in \Omega1$ and $(w, m_H + \varepsilon) \in \Omega2$: If $(w, m_L - \varepsilon) \in \Omega1$, then because $\partial f_3(w, m)/\partial m > \partial f_2(w, m)/\partial m > 0$, the losses from the futures investment at $(w, m_L - \varepsilon) \in \Omega1$ are smaller in absolute value than the gains $(w, m_H + \varepsilon) \in \Omega2$, and thus, the expected profit increases.

Case 3: $(w, m_L - \varepsilon) \in \Omega2$ and $(w, m_H + \varepsilon) \in \Omega2$: If $(w, m_L - \varepsilon) \in \Omega2$, the losses from the futures investment at $(w, m_L - \varepsilon) \in \Omega2$ are recovered by the gains at $(w, m_H + \varepsilon) \in \Omega2$ due to symmetry, and thus, the expected profit does not change. Combining the results from these three cases, the expected profit increases with higher levels of σ_m^2.

(b) Using the proof of Proposition 2.1, the expected profit for any (x_1, y_1) pair can be written as follows:

$$E[\Pi(x_1, y_1, \tilde{w}, \tilde{m}, x_2^0, y_2^0, \tilde{z}_f, \tilde{z}_b)]$$

$$= [E[f_3(\tilde{w}, \tilde{m}) + \tilde{z}_f] - 1 - V_c + V_{l\cup s}]x_1 + [E[b_3(\tilde{m}) + \tilde{z}_b] - 1 - V_c]y_1 + B\, V_c$$

$$= [E[f_3(\tilde{w}, \tilde{m}) + \tilde{z}_f] - 1 + V_{l\cup s}]x_1 + [E[b_3(\tilde{m}) + \tilde{z}_b] - 1]y_1 + (B - x_1 - y_1)V_c.$$

Increasing σ_w^2 does not change $E[f_3(\tilde{w}, \tilde{m}) + \tilde{z}_f]$ and $E[b_3(\tilde{m}) + \tilde{z}_b]$. Proposition 2.2(a) has shown that V_c is increasing in σ_w^2. Thus, it is sufficient to observe that

$$\partial E[\Pi(x_1, y_1, \tilde{w}, \tilde{m}, x_2^0, y_2^0, \tilde{z}_f, \tilde{z}_b)]/\partial\sigma_w^2 > 0 \text{ if } \partial V_{l\cup s}/\partial\sigma_w^2 > 0. \ \square$$

Lemma 2.A2. $[\partial E[\Pi(x_1, y_1, \tilde{w}, \tilde{m}, x_2^0, y_2^0, \tilde{z}_f, \tilde{z}_b)]/\partial y_1 |_{(x1, y1) = (0,0)}]/[\partial E[\Pi(x_1, y_1, \tilde{w}, \tilde{m}, x_2^0, y_2^0, \tilde{z}_f, \tilde{z}_b)]/\partial x_1 |_{(x1, y1) = (0,0)}]$ *equals to* $[\partial E[\Pi(x_1, y_1, \tilde{w}, \tilde{m}, x_2^0, y_2^0, \tilde{z}_f, \tilde{z}_b)]/\partial y_1]/[\partial E[\Pi(x_1, y_1, \tilde{w}, \tilde{m}, x_2^0, y_2^0, \tilde{z}_f, \tilde{z}_b)]/\partial x_1]$ *for any* (x_1, y_1).

Proof of Lemma 2.A2.

Follows from the linearity of $E[\Pi(x_1, y_1, \tilde{w}, \tilde{m}, x_2^0, y_2^0, \tilde{z}_f, \tilde{z}_b)]$ in x_1 and y_1, as shown in the proof of proposition 2.1. ❑

Development of the proof of Proposition 2.4

We first define the following boundary sets

$\Omega 2^E = \{(w, m) \in \Omega 2: m < m_\tau, w = w_\tau(m)\}$ and $\Omega 3^E = \{(w, m) \in \Omega 3: m = m_\tau\}$.

In the following analysis we examine the value of profit function $\Pi(x_1, y_1, w, m, x_2^0, y_2^0, z_{f\alpha}, z_{b\alpha})$ at three points, and use this analysis in the proof of Proposition 2.4. The three points identified in Figure 2.4 correspond the realizations of $(\tilde{w}, \tilde{m})$ that yields low values of $\Pi(x_1, y_1, w, m, x_2^0, y_2^0, z_{f\alpha}, z_{b\alpha})$.

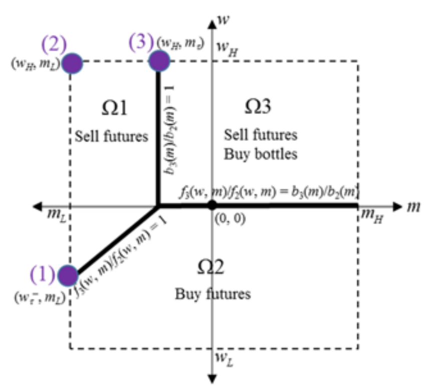


Figure 2.4. Points (1) – (3) are candidates for the minimum value of $\Pi(x_1, y_1, w, m, x_2^0, y_2^0, z_{f\alpha}, z_{b\alpha})$.

Lemma 2.A3. *If* (2.23), *then* $\Pi(x_1, y_1, w_\tau^-, m_L, x_2^0, y_2^0, z_{f\alpha}, z_{b\alpha}) \geq -\beta$ *for any* (x_1, y_1).

Proof of Lemma 2.A3.

Note that $(w_{\bar{\tau}}, m_L) \in \Omega2^E$. This implies $f_3(w_{\bar{\tau}}, m_L)/f_2(w_{\bar{\tau}}, m_L) = 1$ by definition of set. Thus, the realized profit at $(z_{f\alpha}, z_{b\alpha})$ is

$$\Pi(x_1, y_1, w_{\bar{\tau}}, m_L, x_2^0, y_2^0, z_{f\alpha}, z_{b\alpha}) = [b_3(m_L) + z_{b\alpha} - 1]y_1 + z_{f\alpha}[B - y_1]. \tag{2.31}$$

Note first that (2.31) independent of x_1; because $f_3(w_{\bar{\tau}}, m_L)/f_2(w_{\bar{\tau}}, m_L) = 1$ and (2.1) imply that $f_3(w_{\bar{\tau}}, m_L) = f_2(w_{\bar{\tau}}, m_L) = 1$. Because $m_L < m_{\tau}$, it follows that $b_3(m_L)/b_2(m_L) < 1$, and thus from (2.2) it follows that $b_3(m_L) < b_2(m_L) < 1$. Combined with $z_{b\alpha} < 0$ (by assumption), they imply $b_3(m_L) + z_{b\alpha} - 1 < 0$. Following from (2.9), we have $[b_3(m_L) + z_{b\alpha} - 1]y_1 > -\beta$ for any $0 \le y_1 \le B$. Furthermore, following from (2.23), we have $z_{f\alpha}[B - y_1] > -\beta$ for any $0 \le y_1 \le B$. ❑

Lemma 2.A4. *If* (2.23), *then* $\Pi(x_1, y_1, w, m, x_2^0, y_2^0, z_{f\alpha}, z_{b\alpha}) \ge -\beta$ *for all* $(w, m) \in \Omega2$ *for any* (x_1, y_1).

Proof of Lemma 2.A4.

We first focus on $(w, m) \in \Omega2^E$, for which $f_3(w, m)/f_2(w, m) = 1$, which in turn implies $f_3(w, m) = f_2(w, m) = 1$ for all $(w, m) \in \Omega2^E$ (see (2.1)). Thus, for any $(w, m) \in \Omega2^E$,

$$\begin{aligned}\Pi(x_1, y_1, w, m, x_2^0, y_2^0, z_{f\alpha}, z_{b\alpha} \mid (w, m) \in \Omega2^E) &= [b_3(m) + z_{b\alpha} - 1]y_1 + z_{f\alpha}[B - y_1] \\ &\ge [b_3(m_L) + z_{b\alpha} - 1]y_1 + z_{f\alpha}[B - y_1] \\ &= \Pi(x_1, y_1, w_{\bar{\tau}}, m_L, x_2^0, y_2^0, z_{f\alpha}, z_{b\alpha}) \ge -\beta\end{aligned}$$

where the first inequality follows from $b_3(m)$ increasing in m, and the last inequality follows from Lemma 2.A3.

Note that the expression above is independent of x_1 because $f_3(w, m) = f_2(w, m) = 1$ for all $(w, m) \in \Omega2^E$. For any $(w, m) \in \Omega2\backslash\Omega2^E$, we have $f_3(w, m)/f_2(w, m) > 1$ (by the definition of $\Omega2$). This implies that $f_3(w, m) > f_2(w, m) > 1$ (see (2.1)). Hence, the realized profit $\Pi(x_1, y_1, w, m, x_2^0,$

$y_2^0, z_{f\alpha}, z_{b\alpha})$ is increasing in x_1 for any $(w, m) \in \Omega2 \backslash \Omega2^E$, and thus $\Pi(x_1, y_1, w, m, x_2^0, y_2^0, z_{f\alpha}, z_{b\alpha}) \geq -\beta$ for all $(w, m) \in \Omega2$. ❑

Note that the profit at point $(w_H, m_L) \in \Omega1$ is

$$\Pi(x_1, y_1, w_H, m_L, x_2^0, y_2^0, z_{f\alpha}, z_{b\alpha}) = [f_2(w_H, m_L) - 1]x_1 + [b_3(m_L) + z_{b\alpha} - 1]y_1. \tag{2.32}$$

We define $x_1^H(y_1)$ which satisfies $\Pi_1(x_1^H(y_1), y_1, w_H, m_L, x_2^0, y_2^0, z_{f\alpha}, z_{b\alpha}) = -\beta$ for a given y_1, i.e.,

$$x_1^H(y_1) = [\beta - [1 - b_3(m_L) - z_{b\alpha}]y_1]/[1 - f_2(w_H, m_L)]. \tag{2.33}$$

Lemma 2.A5. $\Pi(x_1, y_1, w_H, m_L, x_2^0, y_2^0, z_{f\alpha}, z_{b\alpha}) \geq -\beta$ *for any* $y_1 \leq B$ *and* $x_1 \leq x_1^H(y_1)$.

Proof of Lemma 2.A5.

We know that $f_2(w_H, m_L) < 1$ and $b_3(m_L) < 1$ (follows from $(w_H, m_L) \in \Omega1$, (2.1), and (2.2)). Also, $z_{b\alpha} < 0$ by assumption. Therefore, $\Pi(x_1, y_1, w_H, m_L, x_2^0, y_2^0, z_{f\alpha}, z_{b\alpha})$ in (2.32) is decreasing in x_1 and y_1. This also implies that $x_1^H(y_1)$ in (2.33) is decreasing in y_1. For any $y_1 \leq B$ (due to (2.9)) and $x_1 \leq x_1^H(y_1)$, $\Pi(x_1, y_1, w_H, m_L, x_2^0, y_2^0, z_{f\alpha}, z_{b\alpha}) \geq \Pi(x_1^H(y_1), y_1, w_H, m_L, x_2^0, y_2^0, z_{f\alpha}, z_{b\alpha}) = -\beta$. ❑

Lemma 2.A6. $\Pi(x_1, y_1, w, m, x_2^0, y_2^0, z_{f\alpha}, z_{b\alpha}) \geq -\beta$ *for all* $(w, m) \in \Omega1$ *for any* $y_1 \leq B$ *and* $x_1 \leq x_1^H(y_1)$.

Proof of Lemma 2.A6.

Since $f_2(w, m)$ and $b_3(m)$ are increasing in m, and $f_2(w, m)$ is decreasing in w,

$$\begin{aligned}\Pi(x_1, y_1, w, m, x_2^0, y_2^0, z_{f\alpha}, z_{b\alpha} \mid (w, m) \in \Omega1) &= [f_2(w, m) - 1]x_1 + [b_3(m) + z_{b\alpha} - 1]y_1 \\ &\geq [f_2(w_H, m_L) - 1]x_1 + [b_3(m_L) + z_{b\alpha} - 1]y_1 \\ &= \Pi(x_1, y_1, w_H, m_L, x_2^0, y_2^0, z_{f\alpha}, z_{b\alpha}) \geq -\beta\end{aligned}$$

where the last inequality follows from Lemma 2.A5. ❑

Lemma 2.A7. $\Pi(x_1, y_1, w_H, m_\tau, x_2^0, y_2^0, z_{f\alpha}, z_{b\alpha}) \geq -\beta$ *for any* $x_1 \leq x_1^V$.

Proof of Lemma 2.A7.

Note that $(w_H, m_\tau) \in \Omega 3^E$ implies $b_3(m_\tau)/b_2(m_\tau) = 1$. This further implies $b_3(m_\tau) = b_2(m_\tau) = 1$ (due to (2.2)). Thus,

$$\Pi(x_1, y_1, w_H, m_\tau, x_2^0, y_2^0, z_{f\alpha}, z_{b\alpha}) = [f_2(w_H, m_\tau) - 1][1 + z_{b\alpha}]x_1 + z_{b\alpha}B. \tag{2.34}$$

Note that the expression above is independent of y_1. It is decreasing in x_1 for two reasons: First, $(w_H, m_\tau) \notin \Omega 2$ implies that $f_3(w_H, m_\tau)/f_2(w_H, m_\tau) < 1$ which further implies $f_3(w_H, m_\tau) < f_2(w_H, m_\tau) < 1$ (due to (2.1)), and second, $1 + z_{b\alpha} > 0$ (due to (2.9) and $\beta < B$).

We define x_1^V which satisfies $\Pi(x_1^V, y_1, w_H, m_\tau, x_2^0, y_2^0, z_{f\alpha}, z_{b\alpha}) = -\beta$ for any y_1, i.e.,

$$x_1^V = [\beta + z_{b\alpha} B]/([1 - f_2(w_H, m_\tau)][1 + z_{b\alpha}]). \tag{2.35}$$

Therefore, $\Pi(x_1, y_1, w_H, m_\tau, x_2^0, y_2^0, z_{f\alpha}, z_{b\alpha}) \geq \Pi(x_1^V, y_1, w_H, m_\tau, x_2^0, y_2^0, z_{f\alpha}, z_{b\alpha}) = -\beta$ for any $x_1 \leq x_1^V$. ❑

Lemma 2.A8. $\Pi(x_1, y_1, w, m, x_2^0, y_2^0, z_{f\alpha}, z_{b\alpha}) \geq -\beta$ *for all* $(w, m) \in \Omega 3$ *for any* $x_1 \leq x_1^V$.

Proof of Lemma 2.A8.

We first focus on $(w, m_\tau) \in \Omega 3^E$, for which $b_3(m_\tau) = b_2(m_\tau) = 1$ (follows from the definition of $\Omega 3^E$ and (2.2)). The realized profit can be expressed as

$$\begin{aligned}\Pi(x_1, y_1, w, m, x_2^0, y_2^0, z_{f\alpha}, z_{b\alpha} \mid (w, m) \in \Omega 3^E) &= [f_2(w, m_\tau) - 1][1 + z_{b\alpha}]x_1 + z_{b\alpha}B \\ &\geq [f_2(w_H, m_\tau) - 1][1 + z_{b\alpha}]x_1 + z_{b\alpha}B \\ &= \Pi(x_1, y_1, w_H, m_\tau, x_2^0, y_2^0, z_{f\alpha}, z_{b\alpha}) \geq -\beta\end{aligned}$$

where the first inequality follows from $f_2(w, m_\tau)$ decreasing in w, and the last inequality follows from Lemma 2.A7.

Note that the expression above is independent of y_1 because $b_3(m_\tau) = b_2(m_\tau) = 1$ for all $(w, m_\tau) \in \Omega 3^E$. For any $(w, m) \in \Omega 3 \backslash \Omega 3^E$, $b_3(m)/b_2(m) > 1$ by the definition of $\Omega 3$. This further implies that $b_3(m) > b_2(m) > 1$ (due to (2.2)). Hence, the realized profit at $(z_{f\alpha}, z_{b\alpha})$ increases in y_1 for any $(w, m) \in \Omega3 \backslash \Omega3^E$. Therefore, $\Pi(x_1, y_1, w, m, x_2^0, y_2^0, z_{f\alpha}, z_{b\alpha} \mid (w, m) \in \Omega3 \backslash \Omega3^E) \geq -\beta$. ❑

Lemma 2.A9. *Suppose that* (2.23) *holds. Then* $\Pi(x_1, y_1, w, m, x_2^0, y_2^0, z_{f\alpha}, z_{b\alpha}) \geq -\beta$ *for all* $(w, m) \in \Omega$ *for any* $y_1 \leq B$ *and* $x_1 \leq \min\{x_1^H(y_1), x_1^V\}$.

Proof of Lemma 2.A9.

Follows from lemmas 2.A4, 2.A6, and 2.A8. ❑

Lemma 2.A10. *Suppose that* (2.23) *holds. Then* $P[\Pi(x_1, 0, w, m, x_2^0, y_2^0, \tilde{z}_f, \tilde{z}_b) < -\beta] \leq \alpha$ *for all* $(w, m) \in \Omega$ *for any* $x_1 \leq \min\{x_1^H(0), x_1^V\}$. *This means that* (x_2^0, y_2^0) *and* $(x_1, 0)$ *decisions such that* $x_1 \leq \min\{x_1^H(0), x_1^V\}$ *satisfy both* (2.6) *and* (2.12).

Proof of Lemma 2.A10.

$\Pi(x_1, 0, w, m, x_2^0, y_2^0, \tilde{z}_f, \tilde{z}_b \mid (w, m) \in \Omega1)$ has neither $\tilde{z}_f$ nor $\tilde{z}_b$ term. $\Pi(x_1, 0, w, m, x_2^0, y_2^0, \tilde{z}_f, \tilde{z}_b \mid (w, m) \in \Omega2)$ has only $\tilde{z}_f$, and $\Pi(x_1, 0, w, m, x_2^0, y_2^0, \tilde{z}_f, \tilde{z}_b \mid (w, m) \in \Omega3)$ has only $\tilde{z}_b$. We also know from Lemma 2.A9 that $\Pi(x_1, 0, w, m, x_2^0, y_2^0, z_{f\alpha}, z_{b\alpha}) \geq -\beta$ for all $(w, m) \in \Omega$ for any $x_1 \leq \min\{x_1^H(0), x_1^V\}$ when $y_1 = 0$. Combined with $P\left[\tilde{z}_f \leq z_{f\alpha}\right] = P\left[\tilde{z}_b \leq z_{b\alpha}\right] = \alpha$, they imply that $P[\Pi(x_1, 0, w, m, x_2^0, y_2^0, \tilde{z}_f, \tilde{z}_b) < -\beta] \leq \alpha$ for all $(w, m) \in \Omega$ for any $x_1 \leq \min\{x_1^H(0), x_1^V\}$. As a consequence, VaR constraints (2.6) and (2.12) are satisfied by (x_2^0, y_2^0) and $(x_1, 0)$ decisions for $x_1 \leq \min\{x_1^H(0), x_1^V\}$. ❑

Lemma 2.A11. *Suppose that* (2.23) *holds, and* $\left(\tilde{z}_f, \tilde{z}_b\right)$ *follow a bivariate normal distribution. Then* $P[\Pi(x_1, y_1, w, m, x_2^0, y_2^0, \tilde{z}_f, \tilde{z}_b) < -\beta] \leq \alpha$ *for all* $(w, m) \in \Omega$ *for any* $0 < y_1 < B$ *and* $x_1 \leq \min\{x_1^H(y_1), x_1^V\}$. *This means that* (x_2^0, y_2^0) *and* (x_1, y_1) *decisions such that* $0 < y_1 < B$ *and* $x_1 \leq \min\{x_1^H(y_1), x_1^V\}$ *satisfy both* (2.6) *and* (2.12).

Proof of Lemma 2.A11.

Note first that $y_1 \neq 0$. $\Pi(x_1, y_1, w, m, x_2^0, y_2^0, \tilde{z}_f, \tilde{z}_b \mid (w, m) \in \Omega1 \cup \Omega3)$ has only $\tilde{z}_b$ term. Combined with $P\left[\tilde{z}_b \le z_{b\alpha}\right] = \alpha$, and lemmas 2.A6 and 2.A8, it follows that $P[\Pi(x_1, y_1, w, m, x_2^0, y_2^0, \tilde{z}_f, \tilde{z}_b) < -\beta] \le \alpha$ for all $(w, m) \in \Omega1 \cup \Omega3$ for any $0 < y_1 < B$ and $x_1 \le \min\{x_1^H(y_1), x_1^V\}$.

$\Pi(x_1, y_1, w, m, x_2^0, y_2^0, \tilde{z}_f, \tilde{z}_b \mid (w, m) \in \Omega2)$ has both $\tilde{z}_f$ and $\tilde{z}_b$ terms. We first consider the case where $\tilde{z}_f$ and $\tilde{z}_b$ are perfectly positively correlated, i.e., $\tilde{z}_f = k\,\tilde{z}_b$ where $k > 0$. This implies

$$P[\tilde{z}_f \le z_{f\alpha} \;\&\; \tilde{z}_b \le z_{b\alpha}] = P[k\,\tilde{z}_b \le k z_{b\alpha} \;\&\; \tilde{z}_b \le z_{b\alpha}] = P[\tilde{z}_b \le z_{b\alpha}] = \alpha.$$

Together with Lemma 2.A4, it follows that

$$P[\Pi(x_1, y_1, w, m, x_2^0, y_2^0, \tilde{z}_f, \tilde{z}_b) < -\beta] \le \alpha \tag{2.36}$$

for all $(w, m) \in \Omega2$ for any (x_1, y_1). We then consider the less-than-perfect positive correlation case where $(\tilde{z}_f, \tilde{z}_b)$ follow a bivariate normal distribution. The randomness in profit can be expressed as

$$\tilde{Z}_\rho = (x_1 + x_2^0)\,\tilde{z}_f + (y_1 + y_2^0)\,\tilde{z}_b$$

where ρ is the correlation coefficient for $(\tilde{z}_f, \tilde{z}_b)$. As a consequence of bivariate normal distribution, $\tilde{Z}_\rho$, which is the sum of normal random variables, is a normal random variable with

$$E[\tilde{Z}_\rho] = 0 \text{ and } V\left[\tilde{Z}_\rho\right] = \left(x_1 + x_2^0\right)^2 \sigma^2_{\tilde{z}_f} + \left(y_1 + y_2^0\right)^2 \sigma^2_{\tilde{z}_b} + 2\rho\sigma_{\tilde{z}_f}\sigma_{\tilde{z}_b}.$$

From $E[\tilde{z}_f] = E[\tilde{z}_b] = 0$ and $\{z_{f\alpha}, z_{b\alpha}\} < 0$, it follows that $\alpha \le 0.5$. Therefore,

$$\begin{aligned} P[\Pi(x_1, y_1, w, m, x_2^0, y_2^0, \tilde{z}_f, \tilde{z}_b) < -\beta] &= P[\tilde{Z}_\rho < -\beta - \Pi(x_1, y_1, w, m, x_2^0, y_2^0, 0, 0)] \\ &\le P[\tilde{Z}_1 < -\beta - \Pi(x_1, y_1, w, m, x_2^0, y_2^0, 0, 0)] \\ &\le \alpha \end{aligned}$$

for all $(w, m) \in \Omega 2$ for any (x_1, y_1). The first inequality follows from $\alpha \le 0.5$ and the fact that variance is increasing in ρ. The second inequality follows from (2.36), i.e., the case of perfect positive correlation.

As a consequence, VaR constraints (2.6) and (2.12) are satisfied by (x_2^0, y_2^0) and (x_1, y_1) decisions such that $0 < y_1 < B$ and $x_1 \le \min\{x_1^H(y_1), x_1^V\}$. ❑

Proof of Proposition 2.4.

We begin with relaxing (2.6), i.e., $(x_2, y_2) = (x_2^0, y_2^0)$ is feasible. We then show that, when (2.23) holds, constraint (2.6) is nonbinding at the optimal solution to the problem defined in (2.4) – (2.12). From Proposition 2.1, we know that $(x_1, y_1) = (0, 0)$ cannot be optimal. Moreover, $x_1^+ = x_1^H(0) > 0$ (see (2.33)) due to $\beta > 0$ and $1 > f_2(w_H, m_L)$ (follows from $(w_H, m_L) \in \Omega 1$ and (2.1)).

Part (a): When $B \le \min\{x_1^+, x_1^V\}$, then $(x_2, y_2) = (x_2^0, y_2^0)$ and $(x_1, y_1) = (B, 0)$ satisfy both (2.6) and (2.12) following from Lemma 2.A10. This implies that $(x_2^*, y_2^*) = (x_2^0, y_2^0)$ by definition of (x_2^0, y_2^0). It follows from Proposition 2.1 that $(x_1^*, y_1^*) = (B, 0)$.

Part (b): Note that $x_1^V < x_1^H(B - x_1^V)$ when $x_1^V < B \le x_1^+$. Proposition 2.1 and Lemma 2.A11 imply that $(x_2^*, y_2^*) = (x_2^0, y_2^0)$ and $(x_1^*, y_1^*) = (x_1^V, B - x_1^V)$.

Part (c): Note that $x_1^H(y_1)$ is linearly decreasing in y_1 (see (2.33)). As a consequence, when $x_1^+ < x_1^V$, we have $x_1^H(y_1) < x_1^V$ for any $y_1 \ge 0$. Moreover, $E[\Pi(x_1, y_1, \tilde{w}, \tilde{m}, x_2^0, y_2^0, \tilde{z}_f, \tilde{z}_b)]$ is linear in x_1 and y_1 (see proof of Proposition 2.1). Therefore,

$$dE[\Pi(x_1^H(y_1), y_1, \tilde{w}, \tilde{m}, x_2^0, y_2^0, \tilde{z}_f, \tilde{z}_b)]/dy_1 = \partial E[\Pi(x_1, y_1, \tilde{w}, \tilde{m}, x_2^0, y_2^0, \tilde{z}_f, \tilde{z}_b)]/\partial y_1$$

$$-\left[\frac{1-b_3(m_L)-z_{b\alpha}}{1-f_2(w_H, m_L)}\right]\partial E[\Pi(x_1, y_1, \tilde{w}, \tilde{m}, x_2^0, y_2^0, \tilde{z}_f, \tilde{z}_b)]/\partial x_1.$$

Part (c)(i): $dE[\Pi(x_1^H(y_1), y_1, \tilde{w}, \tilde{m}, x_2^0, y_2^0, \tilde{z}_f, \tilde{z}_b)]/dy_1 < 0$ due to (2.24) and Lemma 2.A2. Following from Lemma 2.A10, $(x_2, y_2) = (x_2^0, y_2^0)$ and $(x_1, y_1) = (x_1^+, 0)$ satisfy both (2.6) and

(2.12). Moreover, (2.11) is satisfied due to $x_1^+ < B$. Therefore, together with Proposition 2.1, it follows that $(x_2^*, y_2^*) = (x_2^0, y_2^0)$ and $(x_1^*, y_1^*) = (x_1^+, 0)$.

Part (c)(ii): $dE[\Pi(x_1^H(y_1), y_1, \tilde{w}, \tilde{m}, x_2^0, y_2^0, \tilde{z}_f, \tilde{z}_b)]/dy_1 \geq 0$ due to the reversal of (2.24), and Lemma 2.A2. Note that $x_1^H(B) > 0$ (see (2.9) and (2.33)). Together with $x_1^+ < B$ and the linearity of $x_1^H(y_1)$ in y_1, it follows that the VaR constraint (2.12) at (w_H, m_L) crosses the budget constraint at a single point, i.e.,

$$y_1^s + x_1^H(y_1^s) = B$$

such that

$$y_1^s = \frac{B\left[1 - f_2\left(w_H, m_L\right)\right] - \beta}{\left[b_3\left(m_L\right) + z_{b\alpha} - f_2\left(w_H, m_L\right)\right]} \text{ and } x_1^s = x_1^H\left(y_1^s\right) = \frac{\beta - B\left[1 - b_3\left(m_L\right) - z_{b\alpha}\right]}{\left[b_3\left(m_L\right) + z_{b\alpha} - f_2\left(w_H, m_L\right)\right]}$$

where $\{x_1^s, y_1^s\} > 0$ following from $x_1^+ < B$ and (2.9). Note also that $x_1^s < x_1^+$. Following from Lemma 2.A11, $(x_2, y_2) = (x_2^0, y_2^0)$ and $(x_1, y_1) = (x_1^s, y_1^s)$ satisfy both (2.6) and (2.12). Therefore, together with Proposition 2.1, it follows that $(x_2^*, y_2^*) = (x_2^0, y_2^0)$ and $(x_1^*, y_1^*) = (x_1^s, y_1^s)$.

Part (d): We now examine the case when $x_1^s < x_1^V \leq x_1^+ < B$.

Part (d)(i): When $x_1^V = x_1^+$, it follows from the proof of part (c)(i). When $x_1^V < x_1^+$, $x_1^H(y_1)$ linearly decreasing in y_1 implies that there exists a single y_1^V, i.e.,

$$x_1^H(y_1^V) = x_1^V \text{ such that } y_1^V = \frac{\beta - \dfrac{\left[\beta + z_{b\alpha}B\right]}{\left[1 + z_{b\alpha}\right]} \dfrac{\left[1 - f_2\left(w_H, m_L\right)\right]}{\left[1 - f_2\left(w_H, m_\tau\right)\right]}}{\left[1 - b_3\left(m_L\right) - z_{b\alpha}\right]}$$

where $x_1^V + y_1^V < B$ (i.e., (2.11) is satisfied) due to $x_1^s < x_1^V$, $x_1^+ < B$, and (2.9).

$dE[\Pi(x_1^H(y_1), y_1, \tilde{w}, \tilde{m}, x_2^0, y_2^0, \tilde{z}_f, \tilde{z}_b)]/dy_1 < 0$ due to (2.24) and Lemma 2.A2. Together with Proposition 2.1 and Lemma 2.A11, it follows that $(x_2^*, y_2^*) = (x_2^0, y_2^0)$ and $(x_1^*, y_1^*) = (x_1^V, y_1^V)$.

Part (d)(ii): Since $x_1^s < x_1^V$, it follows from the proof of part (c)(ii).

Part (e): Note that $x_1^V \leq x_1^H(B - x_1^V)$ when $x_1^V \leq x_1^s$. Proposition 2.1 and Lemma 2.A11 imply that $(x_2^*, y_2^*) = (x_2^0, y_2^0)$ and $(x_1^*, y_1^*) = (x_1^V, B - x_1^V)$. ❑

Proof of Proposition 2.5.

Relaxing (2.23) does not affect the feasibility of (x_2^0, y_2^0) in Ω1 and Ω3 (see lemmas 2.A6 and 2.A8). However, (x_2^0, y_2^0) may no longer be feasible in Ω2 (see Lemma 2.A4). From (2.3), the realized profit at α-fractile is

$$\prod(x_1, y_1, w, m, x_2, y_2, z_{f\alpha}, z_{b\alpha})$$

$$= -x_1 - y_1 - f_2(w, m)x_2 - b_2(m)y_2 + [f_3(w, m) + z_{f\alpha}](x_1 + x_2) + [b_3(m) + z_{b\alpha}](y_1 + y_2)$$

which is linear in $z_{f\alpha}$. Following from (2.7), $\partial\prod(x_1, y_1, w, m, x_2, y_2, z_{f\alpha}, z_{b\alpha})/\partial z_{f\alpha} \geq 0$. Therefore, it is sufficient to show that Proposition 2.5 holds at the extreme case such that $z_{f\alpha} \rightarrow -\infty$. The result naturally extends to any other $z_{f\alpha}$, which may or may not satisfy (2.23).

$z_{f\alpha} \rightarrow -\infty$ implies that $x_2^* = -x_1$; otherwise, $\lim_{z_{f\alpha} \rightarrow -\infty} \prod(x_1, y_1, w, m, x_2, y_2, z_{f\alpha}, z_{b\alpha}) = -\infty$.

We partition Ω2 into the following two sets:

$\Omega2_A = \{(w, m): f_3(w, m)/f_2(w, m) \geq 1 > b_3(m)/b_2(m)\}$,

$\Omega2_B = \{(w, m): f_3(w, m)/f_2(w, m) > b_3(m)/b_2(m) \geq 1\}$.

In $\Omega2_A$, $y_2^* = 0$ due to $1 > b_3(m)/b_2(m)$. Thus,

$$\begin{aligned}\prod(x_1, y_1, w, m, x_2^*, y_2^*, z_{f\alpha}, z_{b\alpha} \mid (w, m) \in \Omega2_A) &= [f_2(w, m) - 1]x_1 + [b_3(m) + z_{b\alpha} - 1]y_1 \\ &\geq [f_2(w_H, m_L) - 1]x_1 + [b_3(m_L) + z_{b\alpha} - 1]y_1 \\ &= \Pi(x_1, y_1, w_H, m_L, x_2^0, y_2^0, z_{f\alpha}, z_{b\alpha}) \geq -\beta \quad (2.37)\end{aligned}$$

where the first inequality follows from the fact that $f_2(w_H, m_L)$ and $b_3(m_L)$ are the worst price realizations for $f_2(w, m)$ and $b_3(m)$, respectively, and the last inequality follows from Lemma 2.A5.

We next show that $y_2^* = [B - x_1 - y_1 + f_2(w, m)x_1]/b_2(m)$ given that that $x_2^* = -x_1$ in $\Omega2_B$:

$$\prod(x_1, y_1, w, m, x_2^*, y_2^*, z_{f\alpha}, z_{b\alpha} \mid (w, m) \in \Omega 2_B) = [f_2(w, m) - 1][1 + [b_3(m) + z_{b\alpha} - b_2(m)]/b_2(m)]x_1$$
$$+ [b_3(m) + z_{b\alpha} - 1]y_1$$
$$+ [[b_3(m) + z_{b\alpha} - b_2(m)]/b_2(m)][B - y_1]$$

where

$$[f_2(w, m) - 1][1 + [b_3(m) + z_{b\alpha} - b_2(m)]/b_2(m)]x_1 \geq 0 \tag{2.38}$$

following from $x_1 \geq 0, f_2(w, m) > 1$ (due to the definition of $\Omega 2_B$ and (2.1)), and $[b_3(m) + z_{b\alpha} - b_2(m)]/b_2(m) > -\beta/B > -1$ (due to the definition of $\Omega 2_B$, $\beta < B$, $z_{b\alpha} < 0$, (2.9));

$$[b_3(m) + z_{b\alpha} - 1]y_1 > -\beta \tag{2.39}$$

following from $y_1 \leq B$ and (2.9); and

$$[[b_3(m) + z_{b\alpha} - b_2(m)]/b_2(m)][B - y_1] > -\beta \tag{2.40}$$

following from $y_1 \leq B$ and $[b_3(m) + z_{b\alpha} - b_2(m)]/b_2(m) > -\beta/B > -1$ (due to the definition of $\Omega 2_B$, $\beta < B$, $z_{b\alpha} < 0$, (2.9)). Inequalities (2.38), (2.39) and (2.40) together imply that

$$\prod(x_1, y_1, w, m, x_2^*, y_2^*, z_{f\alpha}, z_{b\alpha} \mid (w, m) \in \Omega 2_B) > -\beta \tag{2.41}$$

where $x_2^* = -x_1$ and $y_2^* = [B - x_1 - y_1 + f_2(w, m)x_1]/b_2(m)$.

Following from (2.37), (2.41), and lemmas 2.A6 and 2.A8,

$$\left(x_2^*(x_1, y_1, w, m), y_2^*(x_1, y_1, w, m)\right) = \begin{cases} (-x_1, 0) & \text{if } (w, m) \in \Omega 1 \cup \Omega 2_A \\ \left(-x_1, \left(B - x_1 - y_1 + f_2(w, m)x_1\right)/b_2(m)\right) & \text{if } (w, m) \in \Omega 3 \cup \Omega 2_B \end{cases}.$$

Thus, $\partial E[\Pi(x_1, y_1, \tilde{w}, \tilde{m}, x_2^*, y_2^*, \tilde{z}_f, \tilde{z}_b)]/\partial y_1 = E[b_3(\tilde{m}) + \tilde{z}_b]$

$$- \iint_{\Omega 1 \cup \Omega 2_A} \phi_w(w)\phi_m(m)dwdm$$

$$- \iint_{\Omega 3 \cup \Omega 2_B} \left(b_3(m)/b_2(m)\right)\phi_w(w)\phi_m(m)dwdm$$

$$= E[b_3(\tilde{m}) + \tilde{z}_b] - 1 - V_c' \tag{2.42}$$

where

$$V_c' = \iint\limits_{\Omega 3\cup\Omega 2_B} \left(\frac{b_3(m)}{b_2(m)} - 1\right)\phi_w(w)\phi_m(m)dwdm$$

which is nonnegative because the integrand is nonnegative by definitions of $\Omega 2_B$ and $\Omega 3$. Also, we have

$$\partial E[\Pi(x_1, y_1, \tilde{w}, \tilde{m}, x_2^*, y_2^*, \tilde{z}_f, \tilde{z}_b)]/\partial x_1$$

$$= E[f_3(\tilde{w},\tilde{m}) + \tilde{z}_f] - \iint\limits_{\Omega 1\cup\Omega 2_A} \phi_w(w)\phi_m(m)dwdm$$

$$- \iint\limits_{\Omega 3\cup\Omega 2_B} \left(b_3(m)/b_2(m)\right)\phi_w(w)\phi_m(m)dwdm$$

$$+ \iint\limits_{\Omega 1\cup\Omega 2_A} \left(f_2(w,m) - f_3(w,m)\right)\phi_w(w)\phi_m(m)dwdm$$

$$+ \iint\limits_{\Omega 3\cup\Omega 2_B} \left(f_2(w,m)\frac{b_3(m)}{b_2(m)} - f_3(w,m)\right)\phi_w(w)\phi_m(m)dwdm$$

$$= E[f_3(\tilde{w},\tilde{m}) + \tilde{z}_f] - 1 - V_c' + V_{l\cup s}' \tag{2.43}$$

where

$$V_{l\cup s}' = \iint\limits_{\Omega 1\cup\Omega 2_A} \left(f_2(w,m) - f_3(w,m)\right)\phi_w(w)\phi_m(m)dwdm$$

$$+ \iint\limits_{\Omega 3\cup\Omega 2_B} \left(f_2(w,m)\frac{b_3(m)}{b_2(m)} - f_3(w,m)\right)\phi_w(w)\phi_m(m)dwdm.$$

Following from the definitions of $\Omega 2_B$ and $\Omega 3$, $w_\tau(m_\tau) = 0$ (see (2.14)), $E[\tilde{w}] = 0$, and the symmetry in $\phi_w(w)$, we have

$$\iint\limits_{\Omega 3\cup\Omega 2_B} \left(f_2(w,m)\frac{b_3(m)}{b_2(m)} - f_3(w,m)\right)\phi_w(w)\phi_m(m)dwdm = 0.$$

Following from the definitions of Ω1 and $\Omega 2_A$, $w_\tau(m) < 0$ for all $m < m_\tau$ (see (2.14)), $E[\tilde{w}] = 0$, and the symmetry in $\phi_w(w)$, we have

$$\iint_{\Omega 1 \cup \Omega 2_A} \left(f_2(w,m) - f_3(w,m)\right)\phi_w(w)\phi_m(m)\,dwdm \geq 0 .$$

Thus, $V_{l\cup s}' \geq 0$. Following from (2.13),

$$\partial E[\Pi(x_1, y_1, \tilde{w}, \tilde{m}, x_2^*, y_2^*, \tilde{z}_f, \tilde{z}_b)]/\partial x_1 - \partial E[\Pi(x_1, y_1, \tilde{w}, \tilde{m}, x_2^*, y_2^*, \tilde{z}_f, \tilde{z}_b)]/\partial y_1 = V_{l\cup s}' \geq 0.$$

Moreover, following from the definitions of Ω2 and Ω3, $V_c' \leq V_c$ (see (2.22)). Recall that (2.17) implies (2.29) is positive (see the proof of Proposition 2.1). Thus, $V_c' \leq V_c$ implies that (2.42) is positive, i.e.,

$$\partial E[\Pi(x_1, y_1, \tilde{w}, \tilde{m}, x_2^*, y_2^*, \tilde{z}_f, \tilde{z}_b)]/\partial y_1 > 0. \ \square$$

2.6.2. Appendix B – Details of Empirical Foundation

Data Collection and Sample Selection

Wine price data is collected from Liv-ex (www.liv-ex.com) which is an online trading platform for licensed members, and the world's largest database for fine wine prices. Our sample is composed of five vintages of wine futures (2007 to 2011) and five vintages of bottled wine (2006 to 2010) of 44 Bordeaux wines that aggregates the price data of 43,837 transactions (10,451 via wine futures) corresponding to a total trade volume of 520,133 bottles.

We refer to the Liv-ex Bordeaux 500 index (shortly, Liv-ex 500) when determining the wines to be examined. This index is composed of the 10 most recent bottled vintages of 50 leading Bordeaux wines. Among those 50 wines, sweet Sauternes wines (Yquem, Climens, Coutet, Suduiraut, and Rieussec) are excluded from the sample since their production process and timeline are different than the traditional Bordeaux wines. Another wine, Bahans/Clarence Haut

Brion, is also excluded from the analysis due to missing price data. Therefore, the final sample is composed of 44 of the 50 leading Bordeaux winemakers that make up the Liv-ex 500 index.

The weather information is gathered for the Merignac station serving as the main weather station for Bordeaux from TuTiempo.net. Daily maximum temperatures are collected for each growing season (i.e., May 1 – August 31) for the years from 2006 to 2012. We then calculate the average growing season temperature for every year.

The effects of market fluctuations on fine wine prices are captured through the Live-ex Fine Wine 100 index (shortly, Liv-ex 100). The percentage change in Liv-ex 100 index over each growing season (i.e., May 1 – August 31) is obtained for the years from 2008 to 2012. It is important to note that the 100 most sought-after wines belong to older vintages than the vintages used in our sample, and therefore, there is no overlap of wines with our sample.

One might intuit that our Liv-ex 100 index can be replaced with another market variable describing the movements in financial markets. However, we find Liv-ex 100 to be a strong indicator that is distinct from traditional financial indices. This can be seen from the correlation coefficients between the Liv-ex 100 index and the three popular financial indicators during same time period with our data involving futures and bottle prices between 2007 and 2014: The correlation coefficient with the Standard & Poor 500 index is –0.03, with the Financial Times 100 index is 0.11, with the Dow Jones index is 0.04 whereas the correlation coefficients between these three financial indices range from 0.92 to 0.99. The details of this correlation analysis can be seen in Table 2.4. Thus, Liv-ex 100 is not an arbitrarily chosen market indicator.

	Liv-ex 100	S&P 500	FTSE 100	Dow Jones
Liv-ex 100	1			
S&P 500	-0.0316	1		
FTSE 100	0.1054	0.9178	1	
Dow Jones	0.0368	0.9932	0.9221	1

Table 2.4. Correlation coefficients among Liv-ex 100, S&P 500, FTSE 100, and Dow Jones between 2007 and 2014.

Models 1A and 1B: Futures Price Evolution

We describe the futures price of vintage $t - 1$ for winemaker j in May of year t (stage 1), in September of year t (beginning of stage 2), and in May of year $t + 1$ (end of stage 2) with $f_1^{j,t-1}$, $f_2^{j,t-1}$, and $f_3^{j,t-1}$, respectively. As in Noparumpa et al. (2015), we strip out the variations in price levels across different winemakers (i.e., some wines are always sold at much higher prices) and use the standardized prices expressed as $\hat{f}_i^{j,t-1} = (f_i^{j,t-1} - \bar{f}_i^{\,j})/\sigma_{f_i^j}$ where $\bar{f}_i^{\,j}$ and $\sigma_{f_i^j}$ represent the mean and the standard deviation of the futures price of winemaker j in stage $i = \{1, 2, 3\}$.

For the futures of vintage $t - 1$, we denote the average temperature difference between the new growing season (of calendar year t) and the wine's own growing season by w_t. A positive (negative) w_t implies that the new growing season is relatively warmer (colder) than the growing season of the futures.

Our choice of an absolute weather change measure (as opposed to percentage change) is consistent with Ashenfelter (2008) who uses an absolute measure of weather in his analysis. Unlike temperature, which conforms to a range that is relatively universal over each season, market indices may grow and shrink significantly over time, and thus percentage change is a more meaningful indicator than absolute change. We denote the percentage change in Liv-ex 100 index over the new growing season (of calendar year t) by m_t. A positive (negative) m_t implies that the market conditions are improved (worsened) over the new growing season.

We develop the following linear regression models designated as Model 1A and Model 1B, respectively, where $t = \{2008, 2009, 2010, 2011, 2012\}$ and $j = \{1, 2, \ldots, 44\}$:

$$(\hat{f}_2^{j,t-1} - \hat{f}_1^{j,t-1}) = \gamma_0 + \gamma_1 w_t + \gamma_2 m_t + \varepsilon_{j,t} \tag{2.44}$$

$$(\hat{f}_3^{j,t-1} - \hat{f}_2^{j,t-1}) = \eta_0 + \eta_1 w_t + \eta_2 m_t + \varepsilon_{j,t}. \tag{2.45}$$

The results are tabulated in Table 2.1 in section 2.3.1. When presenting the results in section 2.3.1, we drop the superscripts from the futures prices and the subscripts from w and m for notational simplicity because the analytical model given in section 2.3.2 examines the distributor's investment decision in futures of vintage t – 1 of a single winemaker (i.e., an arbitrary j) in May of an arbitrary year t. Therefore, the subscripts/superscripts j and t are not necessary in the presentation of the analytical model in section 2.3.2.

Models 2A and 2B: Bottle Price Evolution

We describe the bottle price of vintage t – 2 for winemaker j in May of year t (stage 1), in September of year t (beginning of stage 2), and in May of year t + 1 (end of stage 2) with $b_1^{j,t-2}$, $b_2^{j,t-2}$, and $b_3^{j,t-2}$, respectively. As in Noparumpa et al. (2015), we strip out the variations in price levels across different winemakers (i.e., some wines are always sold at much higher prices) and use the standardized prices expressed as $\hat{b}_i^{j,t-2} = (b_i^{j,t-2} - \bar{b}_i^j)/\sigma_{b_i^j}$ where $\bar{b}_i^j$ and $\sigma_{b_i^j}$ represent the mean and the standard deviation of the bottle price of winemaker j in stage $i = \{1, 2, 3\}$.

For the bottles of vintage t – 2, we denote the average temperature difference between the new growing season (of calendar year t) and the wine's own growing season by w_t. A positive (negative) w_t implies that the new growing season is relatively warmer (colder) than the growing season of the bottles.

We denote the percentage change in Liv-ex 100 index over the new growing season (of calendar year t) by m_t. A positive (negative) m_t implies that the market conditions are improved (worsened) over the new growing season.

We develop the following linear regression models designated as Model 2A and Model 2B, respectively, where t = {2008, 2009, 2010, 2011, 2012} and j = {1, 2, …, 44}:

$$(\hat{b}_2^{j,t-2} - \hat{b}_1^{j,t-2}) = \theta_0 + \theta_1 w_t + \theta_2 m_t + \varepsilon_{j,t} \tag{2.46}$$

$$(\hat{b}_3^{j,t-2} - \hat{b}_2^{j,t-2}) = \lambda_0 + \lambda_1 w_t + \lambda_2 m_t + \varepsilon_{j,t}. \tag{2.47}$$

The results are tabulated in Table 2.2 in section 2.3.1. When presenting the results in section 2.3.1, we drop the superscripts from the bottle prices and the subscripts from w and m for notational simplicity because the analytical model given in section 2.3.2 examines the distributor's investment decision in bottles of vintage t – 2 of a single winemaker (i.e., an arbitrary j) in May of an arbitrary year t. Therefore, the subscripts/superscripts j and t are not necessary in the presentation of the analytical model in section 2.3.2.

CHAPTER 3: CAPACITY PLANNING AS A BUFFER AGAINST SUPPLY CHAIN DISRUPTIONS

3.1. Introduction

This essay examines a firm's capacity planning decisions as a mitigation strategy against supply chain disruptions. Our work is motivated by a risk assessment project conducted at the world's largest office supplies firm. Business customers constitute the largest portion of the firm's revenues, and the firm operates a delivery supply chain to serve its business customers. Figure 3.1 illustrates the firm's delivery supply chain. There are 31 fulfillment centers located in the US, and they are responsible for delivering orders within the next business day. Specifically, orders placed before 5:00pm (in regional time) are delivered the next day before 5:00pm. Thus, the firm utilizes quick delivery as its winning criterion in competition with other office supply providers (e.g. Amazon.com). Fulfillment centers carry approximately 80,000 different products (SKUs), but delivers a total of more than 2 million products through its vendor shipments. These products are sorted, bundled, and wrapped at the fulfillment centers before being shipped out to the customers. If a disruption affects operations at a fulfillment center, that facility temporarily loses its capability to serve its customers until it recovers from the disruption. As a consequence, the firm might fail to deliver the orders the next day.

For a firm standing out with the next-day delivery promise, late deliveries may cause significant consequences. Therefore, the firm needs to react quickly, and divert the orders of the disrupted facility to the functional facilities. However, this kind of a reactive approach proves useful in preventing late deliveries only if the functional facilities have sufficient excess capacity to serve as the backup. Therefore, the firm should take a proactive approach by determining its capacity needs in advance before a disruption occurs.

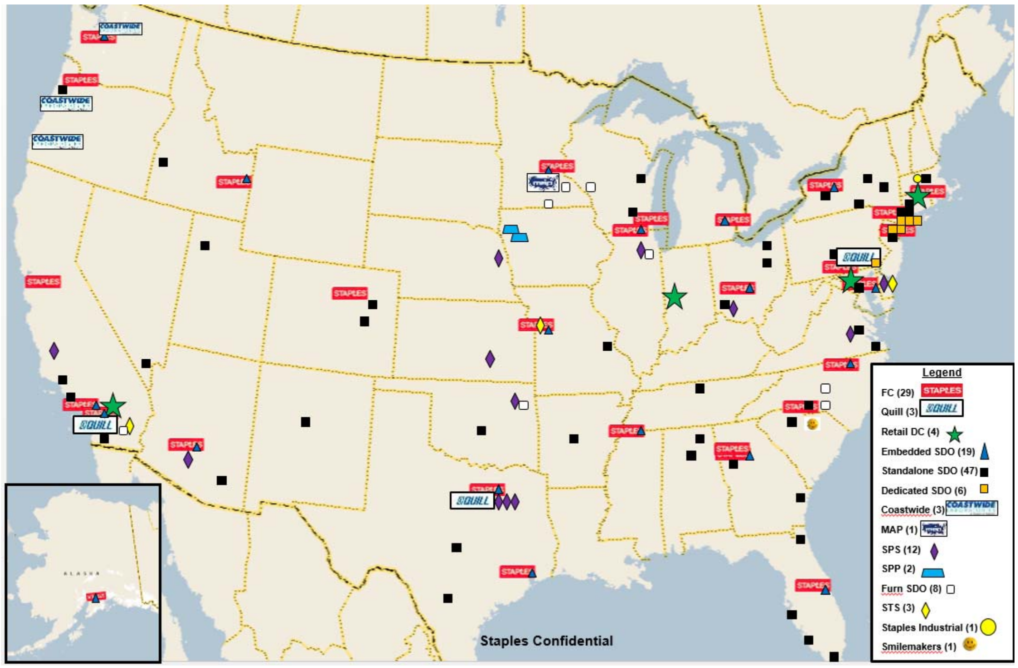
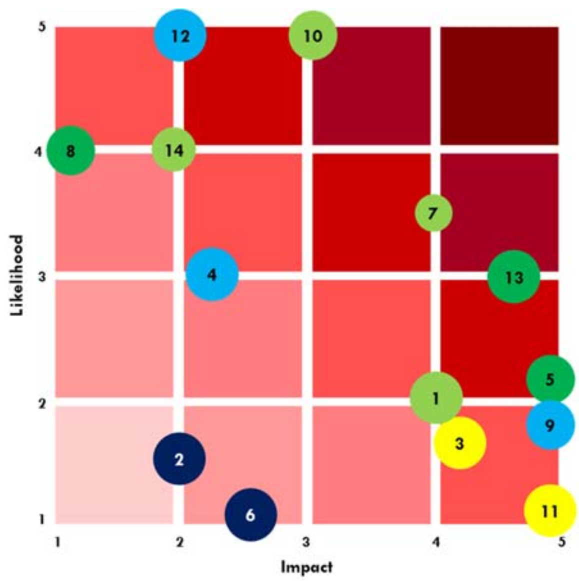


Figure 3.1. Illustration of the delivery supply chain.

We formulate the capacity planning problem for the delivery supply chain of the above-mentioned office supplies company using a two-stage model. The firm determines the capacity expansion amount in each fulfillment center (FC) in stage 1. After observing the disruption, corresponding to stage 2 of our model, the firm determines how best to allocate backup capacity in order to deliver the orders arriving at the disrupted FC. In stage 2, our model considers the length of disruption as random, and the firm complies with a chance constraint that limits the probability of late deliveries exceeding a threshold to be less than a tolerable probability.

Our study utilizes capacity planning, rather than inventory planning, as a proactive measure because of the characteristics of a delivery supply chain. The operations at a fulfillment center (e.g., sorting, bundling, and wrapping) require agility and flexibility since each customer order consists of a unique combination of multiple products. Therefore, satisfying those unique combinations through the safety stock (inventory planning) is not practically possible when the operations at a fulfillment center are disrupted. As a result, the firms needs to utilize the excess capacity of its functional facilities to satisfy the orders of the disrupted facility. Therefore, capacity planning serves as a buffer against disruptions in a delivery supply chain unlike inventory planning, which may serve as a buffer in a manufacturing supply chain.



ID	Risk	I	L	V	S
1	Bomb Threat	4	2	4	5
2	Break In	2	1.5	1	5
3	Chemical Plant	4.1	1.7	5	5
4	Crime	2.2	3	2	5
5	Earthquake	5	2.1	3	5
6	Fire	2.5	1	1	5
7	Flood	4	3.5	3.5	2
8	Gas Leak	1	4	3	4
9	Hurricane	5	1.9	1.7	4
10	IT disruption	3	5	4	5
11	Nuclear Plant	5	1	5	5
12	Power Outage	2	5	2	5
13	Tornado	4.4	3.1	3	5
14	Weather	2	4	3.5	3.5

I = Impact L = Likelihood V = Vulnerability S = Speed of onset

- Dot color reflects vulnerability: Very Low, Low, Medium, High, Very High
- Dot size reflects speed of onset

Figure 3.2. Heat map for the disruption categorization.

Our work focuses on two types of disruptions: (1) Low impact and high likelihood (we will refer to these disruptions shortly as low-impact disruptions) and (2) high impact and low likelihood (we refer to these disruptions as high-impact disruptions). Figure 3.2 provides the heat map that we developed for our motivating firm when categorizing multiple disruptions. We understand from our conversations with the executives at firm that their contingency backup plans primarily account for low-impact disruptions (power outage, gas leak, etc.). Typically, fulfillment centers are paired based on geographic distance to serve each other as primary backup in case of a disruption. However, several of those paired facilities are located very close to each other, thus, it is possible that they both can be affected by a high-impact disruption occurring in the region (e.g., earthquake, hurricane, etc.). When such nearby facilities become nonfunctional at the same time, our model utilizes a third fulfillment center, which is located far away from the paired (nearby) facilities, to satisfy the orders. Thus, our work sheds light on the commonly ignored effects of high-impact disruptions.

One might expect that geographic proximity should anchor the decision on where to add capacity, i.e., the firm should be economically better off by adding more capacity at the paired facilities, which are located in closer proximity, rather than adding capacity at the distant facility. However, our work suggests the opposite under several conditions, and characterizes those conditions. This is an important result because it would motivate establishing an omni-channel backup system for a firm operating multiple channels that are not linked to each other. For example, our motivating firm operates a second distribution network that is called the retail supply chain where the distribution centers are responsible for serving the retail stores alone. Even though the distribution centers have greater amounts of excess capacity, they currently do not communicate with the fulfillment centers. However, our work provides the motivation for establishing a backup link between these two channels by justifying that the readily available excess capacity at a distribution center can be used to back up a fulfillment center even if these facilities are not located close to each other.

Our work shows how capacity planning is influenced by risk aversion. Since the firm has a next-day delivery promise, late deliveries may have a greater impact in the long-run than the immediate financial loss observed. Thus, we incorporate a chance constraint (similar to a value-at-risk measure) to capture the likelihood of late deliveries exceeding a tolerable amount under the presence of disruption length uncertainty. When a disruption occurs, its duration is typically uncertain, and a disruption lasting longer may lead to more late deliveries. One might intuit that, as risk aversion increases, the firm should increase its total capacity expansion. However, our work shows that there can be a substitution effect between the capacity decisions as risk aversion increases such that increasing capacity at the distant facility may lead to a decrease in the capacity at one or both of the paired (nearby) facilities. As a further consequence of the substitution effect, we find that the firm's total capacity expansion may decrease as risk aversion increases. This rather surprising result stems from the flexibility of the distant facility as it can serve both of the paired (nearby) facilities.

In sum, this essay makes five main contributions. First, our work utilizes capacity planning (rather than inventory planning) as a buffer against disruptions in a delivery supply chain. Second, our work examines both low-impact and high-impact disruptions together where the latter is commonly overlooked. Third, we find that geographic proximity may not anchor the decision on where to expand capacity. Fourth, we find that, as risk aversion increases, there may be a substitution effect between the capacity decisions at the distant facility and the paired (nearby) facilities. Fifth, we show that the firm's total capacity expansion may decrease as risk aversion increases.

The reminder of the essay is organized as follows. Section 3.2 reviews the relevant literature. Section 3.3 presents the two-stage model, and it is analyzed in Section 3.4. Section 3.5 presents our conclusions and managerial insights.

3.2. Literature Review

Earlier literature mainly focuses on two types of levers against supply chain disruptions: (1) Inventory, and (2) flexible sourcing. There are many papers that examine the use of inventory as a mitigation strategy (Xia et al. 2004, Qi et al. 2009, Yang et al. 2009 and 2012, Atan and Snyder

2012, Dong and Tomlin 2012, DeCroix 2013, Tang et al. 2014, Dong et al. 2015). These studies consider manufacturing supply chains. The firm typically determines the inventory level, and then utilizes the safety stock if operations at the manufacturing facility are disrupted. Inventory planning proves useful in a manufacturing setting because manufacturing operations are identical across multiple customer orders for the same product. This enables the firm to accumulate some safety stock to be used in case of a disruption. We differ from these papers as our work focuses on a delivery supply chain where the operations (e.g. sorting, bundling, and wrapping) are rather unique across customer orders. Thus, increasing inventory levels at a fulfillment center does not protect the firm if the disruption halts the operations.

Flexible sourcing is another strategy in order to mitigate the supply chain disruptions. Sourcing from multiple locations are examined in various settings by Gurler and Parlar (1997), Berger et al. (2004), Tomlin and Wang (2005), Berger and Zeng (2006), Tomlin (2006), Tang (2006), Ruiz-Torres and Mahmoodi (2007), Yan and Liu (2009), Meena et al. (2011), Qi (2013). Ang et al. (2016) add a multi-tier structure to aforementioned papers. Their work studies the sourcing decisions in a supply network where the tier 2 suppliers are prone to disruption. These papers often focus on the coordination of multiple vendors. Our work also features an example of flexible sourcing which is the vendor shipment that is exercised when the backup capacity is not sufficient to recover the entire demand. However, vendor shipment is not a preferable alternative for our motivating firm as it puts emphasis on the next-day delivery. In addition to being highly costly, vendor shipments cannot satisfy the delivery commitments of the firm.

Chen and Graves (2014) and Acimovic and Graves (2015) examine the decisions made at the fulfillment centers of an online retailer. The former focuses on a transportation problem where a sparsity constraint exists. The latter focuses on minimizing the outbound transportation cost through a proactive approach. However, neither paper features any sort of disruption risk. Our work employs a proactive capacity planning approach at fulfillment centers in the presence of disruption risk, and these decisions are coupled with a reactive contingency transportation planning.

Serpa and Krishnan (2016) study the strategic role of insurance in a multi-firm setting in the presence of operational failures. The likelihood of these operational failures can be controlled by the firms' efforts. They show that insurance can be used as a commitment mechanism to improve the firms' efforts, reducing the likelihood of the operational failures. In our work, disruptions are not stemming from operational failures at the firm, thus, the disruption likelihood is considered to be exogenous.

Simchi-Levi et al. (2015) make an important practical contribution in addition to the aforementioned analytical papers. Their work examines the financial impact of a generic disruption (i.e., low likelihood and high impact) at different nodes of an automotive supply chain. However, the scope of mitigation strategy is the use of inventory like the previous studies. We depart from this paper in several aspects: (1) Our work focuses on a delivery supply chain (where the nodes can serve each other as backup without featuring a precedence relationship) instead of a manufacturing supply chain (where the nodes cannot backup each other due to precedence relationships); (2) our work uses mitigation through capacity planning instead of inventory planning; (3) our model addresses a low-impact disruption in addition to a high-impact disruption; (4) Length of disruption is a static parameter in Simchi-Levi et al. (2015) whereas our model introduces randomness into the length of disrupted operations; (6) Simchi-Levi et al. (2015) study the impact when the disruption occurs, and thus, focuses on reactive operations; our work, on the other hand, examines the expected impact before the disruption actually occurs, and can be perceived as a proactive approach.

3.3. The Model

The firm's problem is formulated using a two-stage program under disruption risk. The objective in stage 1 is to minimize the sum of the two costs: The capacity expansion cost and the expected cost from executing a contingency plan over the next one-year period (by determining the capacity expansion decisions). A contingency plan is implemented in stage 2 if a disruption occurs; the objective in stage 2 is to minimize the cost of executing the contingency plan (by determining the backup allocation decisions that are capped by stage-1 decisions).

Stage-1 capacity decisions are made under disruption risk that would halt operations at fulfillment centers (from here on we refer to as FCs). The disruption risks are classified as follows: (1) low impact and high likelihood (we will refer to these disruptions shortly as low-impact disruptions), and (2) high impact and low likelihood (we refer to these disruptions as high-impact disruptions). We develop a stylized model that examines three FCs such that FC1 and FC2 are located close to each other, and FC3 is located far away from FC1 and FC2. Because FC1 and FC2 are located in closer proximity, one serves the other as the primary backup facility in case of a low-impact disruption (e.g., gas leak). The implication of serving as a backup facility is that the demand at the nonfunctional FC is diverted to the functional FC. The probability of a low-impact disruption occurring at FC1 (FC2) over the one-year period is denoted by $p_{L,1}$ ($p_{L,2}$). The probability of a low-impact disruption occurring at FC1 and FC2 at the same time is assumed to be negligible. However, a high-impact disruption (e.g., earthquake, hurricane) may affect both FC1 and FC2 because of their geographic proximity; thus, we assume that both FC1 and FC2 become nonfunctional at the same time due to a high-impact disruption with a probability of p_H over the one-year period. It is important to note that $\{p_{L,1}, p_{L,2}\} > p_H$ in light of the disruption definitions (i.e., high vs. low likelihood). In case of a high-impact disruption, the demand of FC1 and FC2 are diverted to FC3, which is assumed to be out of the impact region due to the fact that it is sufficiently far away from FC1 and FC2. Furthermore, FC3 is capable of serving FC1 (FC2) as the secondary backup facility in case of a low-impact disruption if the primary backup FC2 (FC1) does not have sufficient excess capacity to recover the entire demand of FC1 (FC2).

In stage 1, the firm determines the amount of capacity expansion, denoted K_i, at fulfillment center i (shortly, FC i) where $i \in \{1, 2, 3\}$. The unit cost of capacity expansion (amortized per year) is denoted by c_K. Each FC is primarily responsible for serving its own customer demand, denoted D_i, and has a beginning capacity K_i^0 such that $D_i \le K_i^0$ (i.e., each FC has a sufficient initial capacity to satisfy its own customer demand). In order to eliminate several trivial scenarios, we assume that the primary backup facility does not have sufficient excess capacity at the beginning (i.e., the beginning capacity net of its own demand) to recover the entire demand of the nearby facility, i.e., $\{K_1^0, K_2^0\} < D_1 + D_2$. Similarly, we assume that FC3 does not have sufficient excess capacity at the beginning to recover the entire demand of FC1 and FC2 at the same time, i.e., $K_3^0 < D_1 + D_2 + D_3$. Note that $\{K_i, K_i^0, D_i\}$ represent the daily amounts.

In stage 2, one of the following four events occurs, and the firm determines the allocation of daily backup capacity, limited with the capacity expansion decisions made in stage 1, at the functional FC(s) in order to fulfill the demand at the nonfunctional FC(s):

Event 1: A low-impact disruption hits FC1 for a random duration $\tilde{t}_L$ (in days) with an expectation of $E[\tilde{t}_L] = \bar{t}_L$. The firm determines the daily backup amount $B_{i,1}$ from FC i to recover the daily demand at FC1 at a unit cost of $c_{i,1}$ where $i \in \{2, 3\}$. Note that $c_{2,1} < c_{3,1}$

due to the fact that FC2 is closer than FC3. The goal is to minimize the expected cost of implementing the contingency plan, denoted $\psi_{L,1}(\cdot)$, subject to a chance constraint that limits the probability of late deliveries exceeding a threshold to be less than a tolerable probability.

<u>Event 2</u>: A low-impact disruption hits FC2 for a random duration $\tilde{t}_L$ (in days) with an expectation of $E[\tilde{t}_L] = \bar{t}_L$. The firm determines the daily backup amount $B_{i,2}$ from FC i to recover the daily demand at FC2 at a unit cost of $c_{i,2}$ where $i \in \{1, 3\}$. Note that $c_{1,2} < c_{3,2}$ since FC1 is closer than FC3. The goal is to minimize the expected cost of implementing the contingency plan, denoted $\psi_{L,2}(\cdot)$, subject to a chance constraint that limits the probability of late deliveries exceeding a threshold to be less than a tolerable probability.

<u>Event 3</u>: A high-impact disruption hits both FC1 and FC2 for a random duration $\tilde{t}_H$ (in days) with an expectation of $E[\tilde{t}_H] = \bar{t}_H$. Note that $\tilde{t}_H$ has first-order stochastic dominance over $\tilde{t}_L$ in light of the disruption definitions (i.e., high vs. low impact). The firm determines the daily backup amount $B_{3,j}$ from FC3 to recover the daily demand at FC j at a unit cost of $c_{3,j}$ where $j \in \{1, 2\}$. The goal is to minimize the expected cost of implementing the contingency plan, denoted $\psi_H(\cdot)$, subject to a chance constraint that limits the probability of late deliveries exceeding a threshold to be less than a tolerable probability.

<u>Event 4</u>: No disruption occurs with a probability of $1 - p_{L,1} - p_{L,2} - p_H$. A contingency plan is not needed; thus, it has zero cost in stage 2. As a result, this event is simply excluded from the analysis.

The cost of implementing the contingency plan involves three types of costs: (1) Additional transportation cost stemming from on-time delivery through the use of backup fulfillment centers; (2) the cost of late deliveries associated with the firm's promise of delivering within the next business day; and, (3) the cost of satisfying demand through vendor shipments. We next describe each cost individually.

A firm's capability of executing a contingency backup plan may be restricted by its level of preparedness. If a firm is not well prepared in advance for a disruption (e.g., absence of a rigorous plan to execute the contingency actions), the backup capacity may not be effectively utilized. This may cause late deliveries even if the firm has sufficient excess capacity. We denote the firm's level of preparedness as T. The preparedness affects the on-time delivery performance of the backup actions, i.e., T portion of the backup allocation is delivered on-time, and $1 - T$ portion is delivered late where $0 \leq T \leq 1$. For every unit of late delivery, the firm incurs an additional cost of c_L. The cost of on-time deliveries is denoted by $OC(\cdot)$, and the cost of late deliveries is denoted by $LC(\cdot)$.

If the firm's maximum backup capacity, which is capped by stage-1 decisions, is not sufficient to recover the entire demand of the nonfunctional FC(s), then the remaining demand is fulfilled through a vendor. Vendor deliveries are late, and incur a unit cost of $c_V + c_L$. The cost of vendor deliveries is denoted by $VC(\cdot)$. As a result, the cost of contingency plan is composed of three terms: (1) the cost of on-time deliveries $OC(\cdot)$, (2) the cost of late deliveries $LC(\cdot)$, and (3) the cost of vendor deliveries $VC(\cdot)$. It is defined that $\{c_{2,1}, c_{1,2}, c_{3,1}, c_{3,2}\} < c_V$ since vendor shipment is the most costly backup alternative.

The firm's risk consideration is modeled using a chance constraint similar to a value-at-risk measure in stage 2. According to this risk constraint, the firm limits the probability of late deliveries exceeding a tolerable threshold when a disruption occurs. The tolerable thresholds β_L and β_H are defined for low-impact disruptions (Events 1 and 2) and high-impact disruptions

(Event 3), respectively. Furthermore, we define $\beta_L \leq \beta_H$ implying that the firm may have a greater tolerance to a high-impact disruption due to the fact that customers might regret less about the late deliveries due to a natural disaster. The tolerable probability is denoted by α. In the firm motivating our problem, the values of β_L, β_H and α come strictly from the firm's promises to its business customers.

The model is mathematically expressed as follows:

Stage 1:

$$\min_{K_1, K_2, K_3} \Psi(K_1, K_2, K_3) = c_K(K_1 + K_2 + K_3)$$
$$+ p_{L,1}\psi_{L,1}(B_{2,1}, B_{3,1} \mid K_2, K_3) + p_{L,2}\psi_{L,2}(B_{1,2}, B_{3,2} \mid K_1, K_3) + p_H\psi_H(B_{3,1}, B_{3,2} \mid K_3) \quad (3.1)$$

subject to

$$\{K_1, K_2, K_3\} \geq 0 \quad (3.2)$$

Stage 2:

Event 1: A low-impact disruption occurs at FC1

$$\min_{\{B_{2,1}, B_{3,1}\} \geq 0} \psi_{L,1}(B_{2,1}, B_{3,1} \mid K_2, K_3) = [OC(B_{2,1}, B_{3,1}) + LC(B_{2,1}, B_{3,1}) + VC(B_{2,1}, B_{3,1})]E[\tilde{t}_L] \quad (3.3)$$

subject to

$$B_{2,1} \leq \min\{K_2^0 + K_2 - D_2, D_1\} \quad (3.4)$$

$$B_{3,1} \leq \min\{K_3^0 + K_3 - D_3, D_1\} \quad (3.5)$$

$$P[[(B_{2,1} + B_{3,1})(1 - T) + (D_1 - B_{2,1} - B_{3,1})^+]\tilde{t}_L > \beta_L] \leq \alpha \quad (3.6)$$

where

$$OC(B_{2,1}, B_{3,1}) = (c_{2,1}B_{2,1} + c_{3,1}B_{3,1})T \quad (3.7)$$

$$LC(B_{2,1}, B_{3,1}) = [(c_{2,1} + c_L)B_{2,1} + (c_{3,1} + c_L)B_{3,1}](1 - T) \quad (3.8)$$

$$VC(B_{2,1}, B_{3,1}) = (c_V + c_L)(D_1 - B_{2,1} - B_{3,1})^+ \quad (3.9)$$

<u>Event 2:</u> A low-impact disruption occurs at FC2

$$\min_{\{B_{1,2}, B_{3,2}\}\geq 0} \psi_{L,2}(B_{1,2}, B_{3,2} \mid K_1, K_3) = [OC(B_{1,2}, B_{3,2}) + LC(B_{1,2}, B_{3,2}) + VC(B_{1,2}, B_{3,2})]E[\tilde{t}_L] \quad (3.10)$$

subject to

$$B_{1,2} \leq \min\{K_1^0 + K_1 - D_1, D_2\} \quad (3.11)$$

$$B_{3,2} \leq \min\{K_3^0 + K_3 - D_3, D_2\} \quad (3.12)$$

$$P[[(B_{1,2} + B_{3,2})(1 - T) + (D_2 - B_{1,2} - B_{3,2})^+]\,\tilde{t}_L > \beta_L] \leq \alpha \quad (3.13)$$

where

$$OC(B_{1,2}, B_{3,2}) = (c_{1,2}B_{1,2} + c_{3,2}B_{3,2})T \quad (3.14)$$

$$LC(B_{1,2}, B_{3,2}) = [(c_{1,2} + c_L)B_{1,2} + (c_{3,2} + c_L)B_{3,2}](1 - T) \quad (3.15)$$

$$VC(B_{1,2}, B_{3,2}) = (c_V + c_L)(D_2 - B_{1,2} - B_{3,2})^+ \quad (3.16)$$

<u>Event 3:</u> A high-impact disruption occurs at FC1 and FC2

$$\min_{\{B_{3,1}, B_{3,2}\}\geq 0} \psi_H(B_{3,1}, B_{3,2} \mid K_3) = [OC(B_{3,1}, B_{3,2}) + LC(B_{3,1}, B_{3,2}) + VC(B_{3,1}, B_{3,2})]E[\tilde{t}_H] \quad (3.17)$$

subject to

$$B_{3,1} \leq \min\{K_3^0 + K_3 - D_3, D_1\} \quad (3.18)$$

$$B_{3,2} \leq \min\{K_3^0 + K_3 - D_3, D_2\} \quad (3.19)$$

$$B_{3,1} + B_{3,2} \leq K_3^0 + K_3 - D_3 \quad (3.20)$$

$$P[[(B_{3,1} + B_{3,2})(1 - T) + (D_1 + D_2 - B_{3,1} - B_{3,2})^+]\,\tilde{t}_H > \beta_H] \leq \alpha \quad (3.21)$$

where

$$OC(B_{3,1}, B_{3,2}) = (c_{3,1}B_{3,1} + c_{3,2}B_{3,2})T \quad (3.22)$$

$$LC(B_{3,1}, B_{3,2}) = [(c_{3,1} + c_L)B_{3,1} + (c_{3,2} + c_L)B_{3,2}](1 - T) \quad (3.23)$$

$$VC(B_{3,1}, B_{3,2}) = (c_V + c_L)(D_1 + D_2 - B_{3,1} - B_{3,2})^+ \quad (3.24)$$

The unit backup cost between the nearby facilities (i.e., FC1 and FC2) is assumed to be equal in both directions, and are therefore, relabeled as c_{12}, i.e., $c_{12} = c_{1,2} = c_{2,1}$ in the remaining part of the analysis. The unit backup cost from the distant facility (i.e., FC3) to FC1 is assumed to be equal to that to FC2, and is relabeled as c_3, i.e., $c_3 = c_{3,1} = c_{3,2}$ in the remaining part of the analysis. Furthermore, it is assumed that $c_3 - c_{12} < c_V - c_3$; this implies that the marginal benefit of recovering one order from the vendor to the distant FC (i.e., FC3) is greater than that from the distant FC to the nearby FC (i.e., FC1 or FC2). Finally, it is assumed that the probability of a low-impact disruption at FC1 is equal to that at FC2; thus, the probability of a low-impact disruption is relabeled as p_L, i.e., $p_L = p_{L,1} = p_{L,2}$ in the remaining part of the analysis. It is important to note that $c_3 - c_{12} < c_V - c_3$ and $p_{L,1} = p_{L,2}$ are useful for eliminating several redundant scenarios in the mathematical analysis that do not bring additional insight.

3.4. Analysis

This section presents the analytical results obtained from the model presented in Section 3.3.

3.4.1. Optimal Stage-2 Policies

The cost structure defined in the model section (i.e., $c_{12} < c_3 < c_V$) prioritizes the backup shipment alternatives in the following order: (1) the nearby FC, (2) the distant FC, and (3) the vendor. Note that the nearby FC alternative is not available in case of a high-impact disruption (Event 3). On the other hand, the distant FC and the vendor alternatives are available in each disruption (Events 1, 2, and 3).

Stage 2 is composed of three events, and the optimal policy for each event is presented in the following proposition.

Proposition 3.1. *For given* (K_1, K_2, K_3),

(*a*) *if Event* 1 *occurs in stage* 2, *then*

(i) *if* $K_2^0 + K_2 - D_2 > D_1$, *then* $(B_{2,1}^*, B_{3,1}^*) = (D_1, 0)$;

(ii) *if* $K_2^0 + K_2 - D_2 \le D_1$, *then* $B_{2,1}^* = K_2^0 + K_2 - D_2$, *and*

(1) *if* $K_3^0 + K_3 - D_3 > D_1 - K_2^0 - K_2 + D_2$, *then* $B_{3,1}^* = D_1 - K_2^0 - K_2 + D_2$;

(2) *if* $K_3^0 + K_3 - D_3 \le D_1 - K_2^0 - K_2 + D_2$, *then* $B_{3,1}^* = K_3^0 + K_3 - D_3$;

(b) *if Event* 2 *occurs in stage* 2, *then*

(i) *if* $K_1^0 + K_1 - D_1 > D_2$, *then* $(B_{1,2}^*, B_{3,2}^*) = (D_2, 0)$;

(ii) *if* $K_1^0 + K_1 - D_1 \le D_2$, *then* $B_{1,2}^* = K_1^0 + K_1 - D_1$, *and*

(1) *if* $K_3^0 + K_3 - D_3 > D_2 - K_1^0 - K_1 + D_1$, *then* $B_{3,2}^* = D_2 - K_1^0 - K_1 + D_1$;

(2) *if* $K_3^0 + K_3 - D_3 \le D_2 - K_1^0 - K_1 + D_1$, *then* $B_{3,2}^* = K_3^0 + K_3 - D_3$;

(c) *if Event* 3 *occurs in stage* 2, *then*

(i) *if* $K_3^0 + K_3 - D_3 > D_1 + D_2$, *then* $(B_{3,1}^*, B_{3,2}^*) = (D_1, D_2)$;

(ii) *if* $K_3^0 + K_3 - D_3 \le D_1 + D_2$, *then* $(B_{3,1}^*, B_{3,2}^*) \in \{(B_{3,1}, B_{3,2}): B_{3,1} + B_{3,2} = K_3^0 + K_3 - D_3\}$.

In Proposition 3.1(a)(ii)(2), 3.1(b)(ii)(2), and 3.1(c)(ii), the total backup capacity is not sufficient to recover the entire demand at the nonfunctional FC(s). Therefore, the remaining portion of the demand is fulfilled through the vendor. However, in the other conditions, the entire demand can be backed up without any vendor shipment.

3.4.2. Optimal Stage-1 Policies – Risk Neutral

We begin the analysis by characterizing the first-order conditions. The next proposition makes use of the following notation to denote the expected marginal benefits of capacity expansion:

$$N_S = p_L \overline{t}_L (c_3 - c_{12})$$

$$N_L = p_L \overline{t}_L (c_V - c_{12} + c_L T)$$

$$F_S = p_H \overline{t}_H (c_V - c_3 + c_L T)$$

$$F_M = (p_L \overline{t_L} + p_H \overline{t_H})(c_V - c_3 + c_L T)$$

$$F_L = (2p_L \overline{t_L} + p_H \overline{t_H})(c_V - c_3 + c_L T)$$

where N_S and N_L (such that $N_S < N_L$) represent the small and large benefit, respectively, of capacity expansion at the nearby functional FC in case of a low-impact disruption (either Event 1 or Event 2). The value of N_S is the expected benefit of recovering one order from the distant FC to the nearby FC. The value of N_L is the expected benefit of recovering one order from the vendor to the nearby FC. On the other hand, F_S, F_M, and F_L (such that $F_S < F_M < F_L$) represent the small, moderate, and large benefit, respectively, of capacity expansion at the distant FC. Expanding capacity at the distant FC recovers the orders from the vendor. The value of F_S is the expected benefit in Event 3 only. The value of F_M is the expected benefit in either Event 1 or Event 2 in addition to Event 3. The value of F_L is the expected benefit in all three events.

Proposition 3.2. *The first-order conditions for* K_1, K_2, *and* K_3 *are as follows*:

$$\partial\Psi(K_1, K_2, K_3)/\partial K_1 = \begin{cases} c_K & \text{if } D_1 + D_2 - K_1^0 < K_1 \\ c_K - N_S & \text{if } D_1 + D_2 + D_3 - K_3^0 - K_1^0 - K_3 < K_1 \leq D_1 + D_2 - K_1^0 \\ c_K - N_L & \text{if } K_1 \leq D_1 + D_2 + D_3 - K_3^0 - K_1^0 - K_3 \end{cases}$$

$$\partial\Psi(K_1, K_2, K_3)/\partial K_2 = \begin{cases} c_K & \text{if } D_1 + D_2 - K_2^0 < K_2 \\ c_K - N_S & \text{if } D_1 + D_2 + D_3 - K_3^0 - K_2^0 - K_3 < K_2 \leq D_1 + D_2 - K_2^0 \\ c_K - N_L & \text{if } K_2 \leq D_1 + D_2 + D_3 - K_3^0 - K_2^0 - K_3 \end{cases}$$

$$\partial\Psi(K_1, K_2, K_3)/\partial K_3 = \begin{cases} c_K & \text{if } D_1 + D_2 + D_3 - K_3^0 < K_3 \\ c_K - F_S & \text{if } \max\{D_1 + D_2 + D_3 - K_3^0 - K_1^0 - K_1, D_1 + D_2 + D_3 - K_3^0 - K_2^0 - \\ & \quad K_2\} < K_3 \leq D_1 + D_2 + D_3 - K_3^0 \\ c_K - F_M & \text{if } \min\{D_1 + D_2 + D_3 - K_3^0 - K_1^0 - K_1, D_1 + D_2 + D_3 - K_3^0 - K_2^0 - \\ & \quad K_2\} < K_3 \leq \max\{D_1 + D_2 + D_3 - K_3^0 - K_1^0 - K_1, D_1 + D_2 + D_3 - \\ & \quad K_3^0 - K_2^0 - K_2\} \\ c_K - F_L & \text{if } K_3 \leq \min\{D_1 + D_2 + D_3 - K_3^0 - K_1^0 - K_1, D_1 + D_2 + D_3 - K_3^0 - \\ & \quad K_2^0 - K_2\}. \end{cases}$$

The above proposition states that the capacity expansion decisions have a piecewise linear impact on the stage-1 objective function. Let us first consider the effect of K_1. FC1 serves as a primary backup if FC2 gets disrupted (Event 2). In case of Event 2, FC3 can also serve FC2 as a secondary backup. If the combined excess capacity at FC1 and FC3 is not sufficient to fulfill the entire demand at FC2, then increasing K_1 has a marginal benefit of N_L (i.e., the third region of $\partial\Psi(\cdot)/\partial K_1$) as it recovers from the vendor. Otherwise, increasing K_1 has a marginal benefit of N_S (i.e., the second region of $\partial\Psi(\cdot)/\partial K_1$) as it recovers from the distant FC. However, if K_1 is very large, then FC1 can back up the entire demand by itself (i.e., the first region of $\partial\Psi(\cdot)/\partial K_1$); thus, the marginal benefit of any further expansion becomes zero.

Similar interpretations apply to the effect of K_2. Let us now consider the effect of K_3. FC3 can serve as a primary backup (in case of Event 3) as well as a secondary backup (in cases of Event 1 and Event 2). If the combined capacity at FC3 and the nearby functional facility is not sufficient to fulfill the entire demand at the nonfunctional FC in both Event 1 and Event 2, then increasing K_3 has a marginal benefit of F_L (i.e., the fourth region of $\partial\Psi(\cdot)/\partial K_3$) as it recovers from the vendor in both events in addition to Event 3. If the combined capacity at FC3 and the nearby functional facility is not sufficient to fulfill the entire demand at the nonfunctional FC in either Event 1 or Event 2, then increasing K_3 has a marginal benefit of F_M (i.e., the third region of $\partial\Psi(\cdot)/\partial K_3$) as it recovers from the vendor in one of those events in addition to Event 3. Otherwise, increasing K_3 has a marginal benefit of F_S (i.e., the second region of $\partial\Psi(\cdot)/\partial K_3$) as it recovers from the vendor in Event 3 only. However, if K_3 is very large, then FC3 can back up the entire demand ($D_1 + D_2$) in Event 3 (i.e., the first region of $\partial\Psi(\cdot)/\partial K_3$); thus, the marginal benefit of any further expansion becomes zero.

It is important to note that the second and third conditions for both $\partial\Psi(\cdot)/\partial K_1$ and $\partial\Psi(\cdot)/\partial K_2$ depend on K_3. Similarly, the second, third, and fourth conditions for $\partial\Psi(\cdot)/\partial K_3$ depend on both K_1 and K_2. Therefore, the optimal stage-1 decisions depend on the ranking of $\{N_S, N_L, F_S, F_M, F_L, c_K\}$.

Lemma 3.1. *The marginal benefits* $\{N_S, N_L, F_S, F_M, F_L\}$ *can be ranked as follows*:

(*a*) $F_S \leq N_S < F_M \leq N_L < F_L$; (*b*) $N_S < F_S \leq N_L < F_M < F_L$; (*c*) $N_S < N_L < F_S < F_M < F_L$.

In order to solve the generalized version of this problem, we introduce two new conditions: $(K_1^0 - D_1) + (K_3^0 - D_3) < D_2$ and $(K_2^0 - D_2) + (K_3^0 - D_3) < D_1$. These conditions imply that, at the beginning, e.g., $(K_1, K_2, K_3) = (0, 0, 0)$, the functional FCs do not have sufficient excess capacity to fulfill the entire demand at the nonfunctional FC in either Event 1 or Event 2. A similar condition for Event 3 is already introduced in Section 3.3, i.e., $K_3^0 - D_3 < D_1 + D_2$. In the absence of these conditions, the regions where we observe $\{N_L, F_M, F_L\}$ may disappear; thus, the problem would become a sub-problem of the current version of our main problem.

The following proposition characterizes the optimal stage-1 decisions.

Proposition 3.3. *For a risk-neutral firm, the optimal stage-1 decisions* (K_1^N, K_2^N, K_3^N) *are*:

(*a*) *if* $\{N_S, N_L, F_S, F_M, F_L\} < c_K$, *then*

$$(K_1^N, K_2^N, K_3^N) = (0, 0, 0);$$

(*b*) *if* $\{N_S, N_L, F_S, F_M\} < c_K \leq F_L$, *then*

$$(K_1^N, K_2^N, K_3^N) = (0, 0, \min\{D_1 + D_2 + D_3 - K_3^0 - K_1^0, D_1 + D_2 + D_3 - K_3^0 - K_2^0\});$$

(*c*) *if* $F_S \leq N_S < \{F_M, c_K\} \leq N_L < F_L$, *then*

(*i*) *if* $F_L + c_K > 2N_L$ *and* $K_1^0 > K_2^0$, *then*

$$(K_1^N, K_2^N, K_3^N) = (0, K_1^0 - K_2^0, D_1 + D_2 + D_3 - K_3^0 - K_1^0);$$

(*ii*) *if* $F_L + c_K > 2N_L$ *and* $K_1^0 \leq K_2^0$, *then*

$$(K_1^N, K_2^N, K_3^N) = (K_2^0 - K_1^0, 0, D_1 + D_2 + D_3 - K_3^0 - K_2^0);$$

(*iii*) *if* $F_L + c_K \leq 2N_L$, *then*

$$(K_1^N, K_2^N, K_3^N) = (D_1 + D_2 + D_3 - K_3^0 - K_1^0, D_1 + D_2 + D_3 - K_3^0 - K_2^0, 0);$$

(*d*) *if* $N_S < \{N_L, F_S\} < c_K \leq F_M < F_L$ *or* $N_S < F_S \leq c_K \leq N_L < F_M < F_L$, *then*

$$(K_1^N, K_2^N, K_3^N) = (0, 0, \max\{D_1 + D_2 + D_3 - K_3^0 - K_1^0, D_1 + D_2 + D_3 - K_3^0 - K_2^0\});$$

(*e*) *if* $N_S < N_L < c_K \leq F_S < F_M < F_L$ *or* $N_S < c_K \leq \{N_L, F_S\} < F_M < F_L$, *then*

$$(K_1^N, K_2^N, K_3^N) = (0, 0, D_1 + D_2 + D_3 - K_3^0);$$

(*f*) *if* $F_S \leq c_K \leq N_S < F_M \leq N_L < F_L$, *then*

$$(K_1^N, K_2^N, K_3^N) = (D_1 + D_2 - K_1^0, D_1 + D_2 - K_2^0, 0);$$

(*g*) *if* $c_K \leq \{N_S, N_L, F_S, F_M, F_L\}$, *then*

$$(K_1^N, K_2^N, K_3^N) = (D_1 + D_2 - K_1^0, D_1 + D_2 - K_2^0, D_1 + D_2 + D_3 - K_3^0).$$

Proposition 3.3(a) indicates that the firm does not invest in any additional capacity when its marginal cost is greater than the marginal benefits. Thus, vendor shipment is needed in all three events.

Proposition 3.3(b) indicates that the firm buys additional capacity at FC3 up to an amount such that the functional FCs have sufficient total excess capacity to fulfill the entire demand at the nonfunctional FC in either Event 1 or Event 2 (i.e., vendor shipment is not needed in one of these two events). Note that vendor shipment is still needed in Event 3.

Before proceeding with the results given in Proposition 3.3(c), we explain the implication of the condition $F_L + c_K > 2N_L$. Recall that the excess capacities at FC2 and FC3 are utilized in Event 1, the excess capacities at FC1 and FC3 are utilized in Event 2, and the excess capacity at FC3 is utilized in Event 3. Thus, the first unit invested in K_3 recovers one order from the vendor to the distant FC in all three events with a net benefit of $F_L - c_K$. Alternatively, the firm may invest one unit in K_1 and one unit in K_2; this investment recovers one order from the vendor to the nearby FC in events 1 and 2 with a net benefit of $2(N_L - c_K)$. Thus, the tradeoff is between (1) recovering one order from the vendor to the distant FC in three events, and (2) recovering one order from the vendor to the nearby FC in two events. If $F_L + c_K > 2N_L$ holds, it means that the firms is better off with the first alternative, thus, invests in K_3 up to the point where the region of F_L disappears. Otherwise, the firm is better off with the second alternative, thus, invests in K_1 and K_2 up to the point where the region of N_L disappears.

When $F_L + c_K > 2N_L$ holds, propositions 3.3(c)(i) and 3.3(c)(ii) show that the firm invests in the same amount of capacity at FC3 as in Proposition 3.3(b); furthermore, the firms buys capacity at either FC1 or FC2 up to an amount such that the functional FCs have sufficient total excess capacity to fulfill the entire demand at the nonfunctional FC in both Event 1 and Event 2 (i.e., vendor shipment is not needed in these two events). However, when $F_L + c_K > 2N_L$ does not hold, the firm invests in K_1 and K_2 as seen in Proposition 3.3(c)(iii). Similar to Proposition 3.3(c)(i) and 3.3(c)(ii), vendor shipment is not needed in Event 1 or Event 2. However, the total capacity expansion given in Proposition 3.3(c)(iii) is greater than that in propositions 3.3(c)(i) and 3.3(c)(ii).

Proposition 3.3(d) presents the same amount of total capacity expansion as in propositions 3.3(c)(i) and 3.3(c)(ii). Thus, vendor shipment is not needed in Event 1 or Event 2. However, unlike proposition 3.3(c)(i) and 3.3(c)(ii), the firm invests in capacity only at FC3. Note that vendor shipment is still needed in Event 3.

Proposition 3.3(e) states that the firm buys capacity at FC3 up to an amount such that FC3 has sufficient excess capacity to fulfill the total demand at FC1 and FC2 in Event 3 (i.e., vendor shipment is not needed in Event 3). This also implies that vendor shipment is not needed in Event 1 or Event 2.

Proposition 3.3(f) states that the firm buys capacity at FC1 and FC2 up to amounts such that one can completely recover the demand at the other FC. Thus, vendor shipment is not needed in Event 1 or Event 2. However, vendor shipment is still needed in Event 3 since $K_3^N = 0$.

Proposition 3.3(g) indicates that the firm makes a maximum amount of capacity investment when the cost is less than the marginal benefits. This means that FC1 and FC2 can recover each other completely in Event 1 and Event 2, whereas FC3 can recover the total demand at FC1 and FC2 completely in Event 3. Thus, no vendor shipment is needed in any event under this condition.

Proposition 3.3 implies that geographic proximity does not anchor the decision on where to add capacity when $K_3^N > 0$. In those conditions, the firm is economically better off by adding capacity at the distant facilities rather than at a nearby facility.

3.4.3. Optimal Stage-1 Policies under Risk Aversion

The risk constraints in stage 2 (see equations (3.6), (3.13), and (3.21)) measure the probability of late deliveries exceeding the tolerable amount (β_L in Events 1 and 2, and β_H in Events 3). Late delivery is caused by two factors: (1) the $(1 - T)$ portion of the backup allocation from the functional FC(s); and, (2) the vendor shipments. Vendor shipments can be eliminated in all events through capacity expansion decisions (i.e., $K_3 = D_1 + D_2 + D_3 - K_3^0$ as in propositions 3.3(e) and 3.3(g)). However, the $(1 - T)$ portion of the backup allocation remains to be late, thus, cannot be eliminated through capacity expansion decisions unless $T = 1$. As a consequence, depending on the values of several parameters (e.g. low values of T), the problem may be infeasible. The following lemma shows the necessary conditions to guarantee that the problem is feasible. The conditions given in this lemma are assumed to hold in the rest of the analysis. The values of $t_{L,1-\alpha}$ and $t_{H,1-\alpha}$ denote the realizations of $\tilde{t}_L$ and $\tilde{t}_H$ at fractile $1 - \alpha$, i.e., $P[\tilde{t}_L > t_{L,1-\alpha}] = P[\tilde{t}_H > t_{H,1-\alpha}] = \alpha$.

Lemma 3.2. *When* $K_3 = D_1 + D_2 + D_3 - K_3^0$, (*a*) *Equation* (3.6) *in Event 1 is satisfied if and only if* $D_1(1 - T)t_{L,1-\alpha}/\beta_L \leq 1$ *holds*; (*b*) *Equation* (3.13) *in Event 2 is satisfied if and only if* $D_2(1 -$

$T)t_{L,1-\alpha}/\beta_L \leq 1$ holds; (*c*) *Equation* (3.21) *in Event 3 is satisfied if and only if* $(D_1 + D_2)(1 - T)t_{H,1-\alpha}/\beta_H \leq 1$ *holds*. *Therefore, when these three conditions hold, the problem is feasible*.

From the above lemma, it follows that the risk constraints are never binding when the risk-neutral stage-1 decisions (K_1^N, K_2^N, K_3^N) can recover all the vendor shipments in all events as in propositions 3.3(e) and 3.3(g). Thus, the optimal risk-averse stage-1 decisions (K_1^A, K_2^A, K_3^A) are the same as the risk-neutral decisions for the conditions presented in propositions 3.3(e) and 3.3(g). The remark below summarizes this result.

Remark 3.1. $(K_1^A, K_2^A, K_3^A) = (K_1^N, K_2^N, K_3^N)$ *if* $N_S < N_L < c_K \leq F_S < F_M < F_L$ *or* $N_S < c_K \leq \{N_L, F_S\} < F_M < F_L$ *or* $c_K \leq \{N_S, N_L, F_S, F_M, F_L\}$.

For the remaining risk-neutral decisions, at least one of the risk constraints may be violated. The following proposition identifies the conditions under which each risk constraint is violated. Note that $R^{i,j}$ denotes j^{th} condition for Event i.

Proposition 3.4. *Given the optimal risk-neutral stage-1 decisions* (K_1^N, K_2^N, K_3^N):

(*a*) *The risk constraint* (3.6) *in Event 1 is violated when*

(*i*) $(K_2^N, K_3^N) = (0, 0)$ *and* $R^{1,1} = [D_1 - (K_2^0 - D_2 + K_3^0 - D_3)T]t_{L,1-\alpha}/\beta_L > 1$; *or*

(*ii*) $(K_2^N, K_3^N) = (0, D_1 + D_2 + D_3 - K_3^0 - K_1^0)$ *and* $K_1^0 > K_2^0$ *and*

$R^{1,2} = [D_1(1 - T) + (K_1^0 - K_2^0)T]t_{L,1-\alpha}/\beta_L > 1$;

(*b*) *The risk constraint* (3.13) *in Event 2 is violated when*

(*i*) $(K_1^N, K_3^N) = (0, 0)$ *and* $R^{2,1} = [D_2 - (K_1^0 - D_1 + K_3^0 - D_3)T]t_{L,1-\alpha}/\beta_L > 1$; *or*

(*ii*) $(K_1^N, K_3^N) = (0, D_1 + D_2 + D_3 - K_3^0 - K_2^0)$ *and* $K_1^0 \leq K_2^0$ *and*

$R^{2,2} = [D_2(1 - T) + (K_2^0 - K_1^0)T]t_{L,1-\alpha}/\beta_L > 1$;

(*c*) *The risk constraint* (3.21) *in Event 3 is violated when*

(*i*) $K_3^N = 0$ *and* $R^{3,1} = [D_1 + D_2 - (K_3^0 - D_3)T]t_{H,1-\alpha}/\beta_H > 1$; *or*

(ii) $K_3^N = D_1 + D_2 + D_3 - K_3^0 - K_1^0$ *and* $R^{3,2} = [(D_1 + D_2)(1 - T) + K_1^0 T]t_{H,1-\alpha}/\beta_H > 1$; *or*

(iii) $K_3^N = D_1 + D_2 + D_3 - K_3^0 - K_2^0$ *and* $R^{3,3} = [(D_1 + D_2)(1 - T) + K_2^0 T]t_{H,1-\alpha}/\beta_H > 1$.

If the risk-neutral decisions violate at least one of the risk constraints, then the firm should increase at least one of the capacity decisions compared to the risk-neutral benchmark in order to comply with the violated risk constraint(s). The following proposition characterizes the capacity expansion decisions that are required to comply with the risk constraints. We denote $K^{R,i}$ as the minimum total capacity expansion required to comply with the risk constraint in Event i.

Proposition 3.5. (a) *If the risk constraint* (3.6) *in Event 1 is violated*, *then the optimal risk-averse stage-1 decisions* (K_2^A, K_3^A) *must satisfy that*

$$K_2^A + K_3^A \geq K^{R,1} = [1/T][D_1 - \beta_L/t_{L,1-\alpha}] - (K_2^0 - D_2 + K_3^0 - D_3);$$

(b) *If the risk constraint* (3.13) *in Event 2 is violated*, *then the optimal risk-averse stage-1 decisions* (K_1^A, K_3^A) *must satisfy that*

$$K_1^A + K_3^A \geq K^{R,2} = [1/T][D_2 - \beta_L/t_{L,1-\alpha}] - (K_1^0 - D_1 + K_3^0 - D_3);$$

(c) *If the risk constraint* (3.21) *in Event 3 is violated*, *then the optimal risk-averse stage-1 decision* K_3^A *must satisfy that*

$$K_3^A \geq K^{R,3} = [1/T][D_1 + D_2 - \beta_H/t_{H,1-\alpha}] - (K_3^0 - D_3).$$

In order to keep the analysis focused, we consider the case when the firm uses a single tolerable loss amount β such that $\beta = \beta_L = \beta_H$. This leads to the result presented in the following lemma.

Lemma 3.3. *If* $\beta_L = \beta_H$, *then* (a) $\{R^{1,1}, R^{2,1}\} < R^{3,1}$, $R^{1,2} < R^{3,2}$, *and* $R^{2,2} < R^{3,3}$;

(b) $\{K^{R,1}, K^{R,2}\} < K^{R,3}$.

Lemma 3.3(a) states that the risk constraint (3.21) in Event 3 is the governing risk constraint. Lemma 3.3(b) states that the firm's minimum total capacity expansion required to comply with the risk constraint (3.21) in Event 3 is greater than that to comply with the risk constraints in events 1 and 2. Thus, the risk-averse firm should determine the capacity expansion decisions based on the governing risk constraint, which is (3.21) in Event 3.

The following proposition characterizes the optimal risk-averse stage-1 decisions.

Proposition 3.6. *For a risk-averse firm, the optimal stage-1 decisions* (K_1^A, K_2^A, K_3^A) *are*:

(*a*) *if* $\{N_S, N_L, F_S, F_M, F_L\} < c_K$, *then*

(*i*) *if* $R^{3,1} \leq 1$, *then* $(K_1^A, K_2^A, K_3^A) = (K_1^N, K_2^N, K_3^N) = (0, 0, 0)$;

(*ii*) *if* $R^{3,1} > 1$, *then* $(K_1^A, K_2^A, K_3^A) = (0, 0, K^{R,3})$;

(*b*) *if* $\{N_S, N_L, F_S, F_M\} < c_K \leq F_L$, *then*

(*i*) *if* $\max\{R^{3,2}, R^{3,3}\} \leq 1$, *then*

$$(K_1^A, K_2^A, K_3^A) = (K_1^N, K_2^N, K_3^N) = (0, 0, \min\{D_1 + D_2 + D_3 - K_3^0 - K_1^0, D_1 + D_2 + D_3 - K_3^0 - K_2^0\});$$

(*ii*) *if* $\max\{R^{3,2}, R^{3,3}\} > 1$, *then* $(K_1^A, K_2^A, K_3^A) = (0, 0, K^{R,3})$;

(*c*) *if* $F_S \leq N_S < \{F_M, c_K\} \leq N_L < F_L$, *then*

(*i*) *if* $F_L + c_K > 2N_L$ *and* $K_1^0 > K_2^0$, *then*

(1) *if* $R^{3,2} \leq 1$, *then* $(K_1^A, K_2^A, K_3^A) = (K_1^N, K_2^N, K_3^N) = (0, K_1^0 - K_2^0, D_1 + D_2 + D_3 - K_3^0 - K_1^0)$;

(2) *if* $R^{3,2} > 1$, *then*

(2.1) *if* $K^{R,3} \leq D_1 + D_2 + D_3 - K_3^0 - K_2^0$, *then*

$$(K_1^A, K_2^A, K_3^A) = (0, D_1 + D_2 + D_3 - K_3^0 - K_2^0 - K^{R,3}, K^{R,3});$$

(2.2) *if* $K^{R,3} > D_1 + D_2 + D_3 - K_3^0 - K_2^0$, *then* $(K_1^A, K_2^A, K_3^A) = (0, 0, K^{R,3})$;

(*ii*) *if* $F_L + c_K > 2N_L$ *and* $K_1^0 \leq K_2^0$, *then*

(1) *if* $R^{3,3} \leq 1$, *then* $(K_1^A, K_2^A, K_3^A) = (K_1^N, K_2^N, K_3^N) = (K_2^0 - K_1^0, 0, D_1 + D_2 + D_3 - K_3^0 - K_2^0)$;

(2) *if* $R^{3,3} > 1$, *then*

(2.1) *if* $K^{R,3} \leq D_1 + D_2 + D_3 - K_3^0 - K_1^0$, *then*

$$(K_1^A, K_2^A, K_3^A) = (D_1 + D_2 + D_3 - K_3^0 - K_1^0 - K^{R,3}, 0, K^{R,3});$$

(2.2) *if* $K^{R,3} > D_1 + D_2 + D_3 - K_3^0 - K_1^0$, *then* $(K_1^A, K_2^A, K_3^A) = (0, 0, K^{R,3})$;

(*iii*) *if* $F_L + c_K \leq 2N_L$, *then*

(1) *if* $R^{3,1} \leq 1$, *then*

$$(K_1^A, K_2^A, K_3^A) = (K_1^N, K_2^N, K_3^N)$$
$$= (D_1 + D_2 + D_3 - K_3^0 - K_1^0, D_1 + D_2 + D_3 - K_3^0 - K_2^0, 0);$$

(2) *if* $R^{3,1} > 1$, *then*

(2.1) *if* $K^{R,3} \leq \{D_1 + D_2 + D_3 - K_3^0 - K_1^0, D_1 + D_2 + D_3 - K_3^0 - K_2^0\}$, *then*

$$(K_1^A, K_2^A, K_3^A) =$$
$$(D_1 + D_2 + D_3 - K_3^0 - K_1^0 - K^{R,3}, D_1 + D_2 + D_3 - K_3^0 - K_2^0 - K^{R,3}, K^{R,3});$$

(2.2) *if* $D_1 + D_2 + D_3 - K_3^0 - K_1^0 < K^{R,3} \leq D_1 + D_2 + D_3 - K_3^0 - K_2^0$, *then*

$$(K_1^A, K_2^A, K_3^A) = (0, D_1 + D_2 + D_3 - K_3^0 - K_2^0 - K^{R,3}, K^{R,3});$$

(2.3) *if* $D_1 + D_2 + D_3 - K_3^0 - K_2^0 < K^{R,3} \leq D_1 + D_2 + D_3 - K_3^0 - K_1^0$, *then*

$$(K_1^A, K_2^A, K_3^A) = (D_1 + D_2 + D_3 - K_3^0 - K_1^0 - K^{R,3}, 0, K^{R,3});$$

(2.4) *if* $K^{R,3} > \{D_1 + D_2 + D_3 - K_3^0 - K_1^0, D_1 + D_2 + D_3 - K_3^0 - K_2^0\}$, *then*

$$(K_1^A, K_2^A, K_3^A) = (0, 0, K^{R,3});$$

(*d*) *if* $N_S < \{N_L, F_S\} < c_K \leq F_M < F_L$ *or* $N_S < F_S \leq c_K \leq N_L < F_M < F_L$, *then*

(*i*) *if* $\min\{R^{3,2}, R^{3,3}\} \leq 1$, *then*

$$(K_1^A, K_2^A, K_3^A) = (K_1^N, K_2^N, K_3^N)$$
$$= (0, 0, \max\{D_1 + D_2 + D_3 - K_3^0 - K_1^0, D_1 + D_2 + D_3 - K_3^0 - K_2^0\});$$

(*ii*) *if* $\min\{R^{3,2}, R^{3,3}\} > 1$, *then* $(K_1^A, K_2^A, K_3^A) = (0, 0, K^{R,3})$;

(*e*) *if* $N_S < N_L < c_K \leq F_S < F_M < F_L$ *or* $N_S < c_K \leq \{N_L, F_S\} < F_M < F_L$, *then*

$$(K_1^A, K_2^A, K_3^A) = (K_1^N, K_2^N, K_3^N) = (0, 0, D_1 + D_2 + D_3 - K_3^0);$$

(*f*) *if* $F_S \leq c_K \leq N_S < F_M \leq N_L < F_L$, *then*

(i) *if* $R^{3,1} \leq 1$, *then* $(K_1{}^A, K_2{}^A, K_3{}^A) = (K_1{}^N, K_2{}^N, K_3{}^N) = (D_1 + D_2 - K_1{}^0, D_1 + D_2 - K_2{}^0, 0)$;

(ii) *if* $R^{3,1} > 1$, *then* $(K_1{}^A, K_2{}^A, K_3{}^A) = (D_1 + D_2 - K_1{}^0, D_1 + D_2 - K_2{}^0, K^{R,3})$;

(g) *if* $c_K \leq \{N_S, N_L, F_S, F_M, F_L\}$, *then*

$$\begin{aligned}(K_1{}^A, K_2{}^A, K_3{}^A) &= (K_1{}^N, K_2{}^N, K_3{}^N)\\ &= (D_1 + D_2 - K_1{}^0, D_1 + D_2 - K_2{}^0, D_1 + D_2 + D_3 - K_3{}^0).\end{aligned}$$

In propositions 3.6(e) and 3.6(g), the governing risk constraint (3.21) never becomes binding, and thus, the optimal decisions are the same as the risk-neutral ones (recall Remark 3.1).

When $R^{3,j} \leq 1$ for $j \in \{1, 2, 3\}$, the governing risk constraint (3.21) is not violated by the risk-neutral decisions, the risk-neutral decisions remain intact (see Proposition 3.4(c)). This corresponds to the conditions given in propositions 3.6(a)(i), 3.6(b)(i), 3.6(c)(i)(1), 3.6(c)(ii)(1), 3.6(c)(iii)(1), 3.6(d)(i), and 3.6(f)(i).

In the remaining parts of this proposition, the risk-neutral decisions violate the governing risk constraint (3.21), and therefore, the firm needs to set $K_3{}^A = K^{R,3}$ ($> K_3{}^N$) in order to comply with the risk aversion. Note that, as risk aversion increases (i.e., lower β and/or α), the value of $K^{R,3}$ increases. This implies that the firm increases the capacity expansion at FC3 as risk aversion increases. One might intuit that the firm should not change the capacity expansion decisions at FC1 and FC2 as they are not directly affected by the governing risk constraint (see Proposition 3.5(c)), and thus, the total capacity expansion should increase as the risk aversion increases. However, the following proposition presents the conditions where this intuition is not valid.

Proposition 3.7. *As risk aversion increases*, *for every unit of increase in FC3 capacity expansion*, (a) *the firm decreases the capacity expansion by one unit at both FC1 and FC2 in Proposition* 3.6(c)(iii)(2.1); (b) *the firm decreases the capacity expansion by one unit at either FC1 or FC2 in propositions* 3.6(c)(i)(2.1), 3.6(c)(ii)(2.1), 3.6(c)(iii)(2.2), *and* 3.6(c)(iii)(2.3).

The above proposition identifies the conditions where we observe a substitution effect, i.e., increasing capacity investment at the farther FC (i.e., FC3) leads to a decrease in capacity investment at the nearby FC(s) (i.e., FC1 and FC2). Increasing capacity at FC3 by one unit brings a benefit through recovering one unit of vendor shipment by FC3. However, this diminishes the benefit provided by the last unit of capacity added at FC1 and FC2, causing an overinvestment. Therefore, the firm is economically better off by taking back that expansion at FC1 and/or FC2. Mathematically, increasing K_3 by one unit decreases the marginal benefit of the last unit in K_1 and K_2 from N_L to N_S (see Proposition 3.2). Since $N_S < c_K \leq N_L$ holds in Proposition 3.6(c), the firm is better off by taking back the last unit in K_1 and K_2 for every unit of increase in K_3 until K_1 and K_2 reach zero. For the conditions given in Proposition 3.7(a), the rate of substitution is two units because both $K_1^A > 0$ and $K_2^A > 0$. For the conditions given in Proposition 3.7(b), the rate of substitution is one unit because either $K_1^A = 0$ or $K_2^A = 0$.

Proposition 3.8. *As risk aversion increases*, *the total capacity expansion* (*i.e.*, $K_1^A + K_2^A + K_3^A$) (*a*) *decreases under Proposition* 3.7(a); (*b*) *remains the same under Proposition* 3.7(b).

The above proposition describes an intriguing result that increasing the degree of risk aversion may lead to a decrease in total capacity expansion. This is highlighted in Proposition 3.8(a), and the finding relies on the substitution effect described in Proposition 3.7. Let us consider the case when the firm prefers making a capacity expansion at both FC1 and FC2 ($K_1^N > 0$ and $K_2^N > 0$) but not at FC3 ($K_3^N = 0$) in the risk neutral setting. At a low degree of risk aversion, the firm has to make a small amount of investment at FC3 ($K_3^A = K^{R,3}$) to comply with the governing risk constraint. However, the firm has to deduct the same amount from the investment at both FC1 and FC2 due to the substitution effect. As a consequence, the total capacity expansion decreases as risk aversion increases until the investment at either FC1 or FC2 drops to zero (either $K_1^A = 0$ or $K_2^A = 0$). At a moderate degree of risk aversion, the firm increases investment at FC3 while decreasing investment at FC1 or FC2 (whichever has a positive investment amount) as risk aversion increases. At a high degree of risk aversion, the firm takes back the entire investments at FC1 and FC2 ($K_1^A = 0$ and $K_2^A = 0$). Thus, increasing risk aversion only leads to an increase in investment at FC3. This leads to a non-monotone impact on the total capacity expansion in Proposition 3.6(c)(iii)(2): Increasing risk aversion (equivalent to increasing $K^{R,3}$) causes a decrease in the total capacity expansion at low risk aversion (i.e., Proposition 3.6(c)(iii)(2.1)), does not affect the total capacity expansion at moderate risk aversion (i.e., Proposition 3.6(c)(iii)(2.2) or 3.6(c)(iii)(2.3)), and causes an increase in the total capacity expansion at high risk aversion (i.e., Proposition 3.6(c)(iii)(2.4)).

3.5. Conclusions

We have examined a firm's capacity expansion decisions in a delivery supply chain to mitigate the negative effects of disruptions. The firm's risk preference is modeled with a chance constraint in the presence of disruption length uncertainty.

Our work makes five main contributions. First, this study uses capacity planning as a proactive measure against supply chain disruptions. Unlike inventory planning which may help overcoming some production failures in a manufacturing chain, capacity planning brings agility and flexibility to the delivery supply chain. Therefore, it serves as buffer against disruptions.

Second, our work captures different disruption characteristics by incorporating (1) low-impact and high-likelihood disruptions, and (2) high-impact and low-likelihood disruptions. This provides a more comprehensive analysis of supply chain disruptions.

Third, we show that geographic proximity does not necessarily serve as an anchor when determining the location of capacity expansion. This is an important result because it would motivate establishing an omni-channel backup system for a firm operating multiple channels that are not linked to each other.

Fourth, our work shows that there can be a substitution effect between the capacity decisions at the distant facility and the nearby facilities. We characterize the conditions where this effect is observed. Furthermore, we find that the rate of substitution decreases as risk aversion increases.

Fifth, as a further consequence of the substitution effect, we find that the firm's total capacity expansion may decrease as risk aversion increases around low risk aversion. After an initial decrease, the total capacity expansion may remain the same at moderate risk aversion that is followed by an increase at high risk aversion. This type of non-monotone impact stems from the flexibility of the distant facility.

Our findings have significant implications for our motivating firm as our contingency backup recommendations based on an extended version of our stylized model are being implemented at the firm. Furthermore, the firm shows interest in initiating an omni-channel backup structure as we show that geographic proximity is not necessarily the anchor.

3.6. Appendix

Proof of Proposition 3.1.

(a) $\partial\psi_{L,1}(B_{2,1}, B_{3,1} \mid K_2, K_3)/\partial B_{2,1} \geq 0$ and $\partial\psi_{L,1}(B_{2,1}, B_{3,1} \mid K_2, K_3)/\partial B_{3,1} \geq 0$ when $(D_1 - B_{2,1} - B_{3,1})^+ = 0$. However, when $(D_1 - B_{2,1} - B_{3,1})^+ > 0$, we have $\partial\psi_{L,1}(B_{2,1}, B_{3,1} \mid K_2, K_3)/\partial B_{2,1} < \partial\psi_{L,1}(B_{2,1}, B_{3,1} \mid K_2, K_3)/\partial B_{3,1} < 0$ following from $c_{12} < c_3 < c_V$. Thus, the firm first uses $B_{2,1}$, and then $B_{3,1}$ until $(D_1 - B_{2,1} - B_{3,1})^+ = 0$ or until the constraints (3.4) and (3.5) become binding.

(b) $\partial\psi_{L,2}(B_{1,2}, B_{3,2} \mid K_1, K_3)/\partial B_{1,2} \geq 0$ and $\partial\psi_{L,2}(B_{1,2}, B_{3,2} \mid K_1, K_3)/\partial B_{3,2} \geq 0$ when $(D_2 - B_{1,2} - B_{3,2})^+ = 0$. However, when $(D_2 - B_{1,2} - B_{3,2})^+ > 0$, we have $\partial\psi_{L,2}(B_{1,2}, B_{3,2} \mid K_1, K_3)/\partial B_{1,2} <$

$\partial\psi_{L,2}(B_{1,2}, B_{3,2} \mid K_1, K_3)/\partial B_{3,2} < 0$ following from $c_{12} < c_3 < c_V$. Thus, the firm first uses $B_{1,2}$, and then $B_{3,2}$ until $(D_2 - B_{1,2} - B_{3,2})^+ = 0$ or until the constraints (3.11) and (3.12) become binding.

(c) $\partial\psi_H(B_{3,1}, B_{3,2} \mid K_3)/\partial B_{3,1} \geq 0$ and $\partial\psi_H(B_{3,1}, B_{3,2} \mid K_3)/\partial B_{3,2} \geq 0$ when $(D_1 + D_2 - B_{3,1} - B_{3,2})^+ = 0$. However, when $(D_1 + D_2 - B_{3,1} - B_{3,2})^+ > 0$, we have $\partial\psi_H(B_{3,1}, B_{3,2} \mid K_3)/\partial B_{3,1} = \partial\psi_H(B_{3,1}, B_{3,2} \mid K_3)/\partial B_{3,2} < 0$ following from $c_3 = c_{3,1} = c_{3,2} < c_V$. Thus, the firm uses $B_{3,1}$ and $B_{3,2}$ indifferently until $(D_1 + D_2 - B_{3,1} - B_{3,2})^+ = 0$ or until the constraints (3.18), (3.19), and (3.20) become binding. ❑

Proof of Proposition 3.2.

The first-order conditions are developed using the optimal stage-2 decisions given in Proposition 3.1. $\partial\Psi(K_1, K_2, K_3)/\partial K_1 = c_K$ follows from Proposition 3.1(b)(i). $\partial\Psi(K_1, K_2, K_3)/\partial K_1 = c_K - N_S$ follows from Proposition 3.1(b)(ii)(1). $\partial\Psi(K_1, K_2, K_3)/\partial K_1 = c_K - N_L$ follows from Proposition 3.1(b)(ii)(2).

$\partial\Psi(K_1, K_2, K_3)/\partial K_2 = c_K$ follows from Proposition 3.1(a)(i). $\partial\Psi(K_1, K_2, K_3)/\partial K_2 = c_K - N_S$ follows from Proposition 3.1(a)(ii)(1). $\partial\Psi(K_1, K_2, K_3)/\partial K_2 = c_K - N_L$ follows from Proposition 3.1(a)(ii)(2).

$\partial\Psi(K_1, K_2, K_3)/\partial K_3 = c_K$ follows from Proposition 3.1(c)(i). $\partial\Psi(K_1, K_2, K_3)/\partial K_3 = c_K - F_S$ follows from propositions 3.1(c)(ii), 3.1(a)(ii)(1) and 3.1(b)(ii)(1). $\partial\Psi(K_1, K_2, K_3)/\partial K_3 = c_K - F_M$ follows from one of the following two combinations: (1) Propositions 3.1(a)(ii)(1) and 3.1(b)(ii)(2); or (2) propositions 3.1(a)(ii)(2) and 3.1(b)(ii)(1). $\partial\Psi(K_1, K_2, K_3)/\partial K_3 = c_K - F_L$ follows from propositions 3.1(a)(ii)(2) and 3.1(b)(ii)(2). ❑

Proof of Lemma 3.1.

It is trivial that $N_S < N_L$ and $F_S < F_M < F_L$. Furthermore, $N_L < F_L$ and $N_S < F_M$ following from $c_3 - c_{12} < c_V - c_3$. Note that $N_S \lozenge F_S$ if and only if $N_L \lozenge F_M$ where $\lozenge \in \{>, =, <\}$. Thus, if $N_S \geq F_S$, then we have $F_S \leq N_S < F_M \leq N_L < F_L$ as presented in part (a). Otherwise, we have $N_S < \{F_S, N_L\} < F_M < F_L$ as presented in parts (b) and (c). ❑

Proof of Proposition 3.3.

(a) $\{\partial\Psi(K_1, K_2, K_3)/\partial K_1, \partial\Psi(K_1, K_2, K_3)/\partial K_2, \partial\Psi(K_1, K_2, K_3)/\partial K_3\} > 0$. Thus, $(K_1^N, K_2^N, K_3^N) = (0, 0, 0)$.

(b) Following from Proposition 3.2, for $K_3 \leq \min\{D_1 + D_2 + D_3 - K_3^0 - K_1^0 - K_1, D_1 + D_2 + D_3 - K_3^0 - K_2^0 - K_2\}$, we have $\partial\Psi(K_1, K_2, K_3)/\partial K_3 = c_K - F_L \leq 0$. Thus, $K_3^N = \min\{D_1 + D_2 + D_3 - K_3^0 - K_1^0 - K_1, D_1 + D_2 + D_3 - K_3^0 - K_2^0 - K_2\}$ whereas $(K_1^N, K_2^N) = (0, 0)$.

(c) Since we have $c_K \leq N_L < F_L$ in this condition, the optimal decision depends on whether one unit of K_3 with a net benefit of $F_L - c_K$ is more beneficial than that of one unit of K_1 and K_2 together with a net benefit of $2(N_L - c_K)$. Let us first consider the case when $F_L + c_K > 2N_L$ as in parts (i) and (ii), i.e., the firm prefers one unit of K_3 over two units of K_1 and K_2.

(c)(i) Following from Proposition 3.2, for $K_3 \leq \min\{D_1 + D_2 + D_3 - K_3^0 - K_1^0 - K_1, D_1 + D_2 + D_3 - K_3^0 - K_2^0 - K_2\}$, we have $\partial\Psi(K_1, K_2, K_3)/\partial K_3 = c_K - F_L < 0$. Thus, $K_3^N = D_1 + D_2 + D_3 - K_3^0 - K_1^0 - K_1$ since $K_1^0 > K_2^0$. Similarly, following from Proposition 3.2, for $K_2 \leq D_1 + D_2 + D_3 - K_3^0 - K_2^0 - K_3^N = K_1^0 - K_2^0$, we have we have $\partial\Psi(K_1, K_2, K_3)/\partial K_2 = c_K - N_L \leq 0$. Thus, $K_2^N = K_1^0 - K_2^0$. Consequently, $K_1^N = 0$.

(c)(ii) Symmetric to part (c)(i) with $K_1^0 \leq K_2^0$.

(c)(iii) We now consider the case when $F_L + c_K \leq 2N_L$, i.e., the firm prefers two units of K_1 and K_2 over one unit of K_3. Following from Proposition 3.2, for $K_1 \leq D_1 + D_2 + D_3 - K_3^0 - K_1^0 - K_3^N = D_1 + D_2 + D_3 - K_3^0 - K_1^0$, we have $\partial\Psi(K_1, K_2, K_3)/\partial K_1 = c_K - N_L \leq 0$. Similarly, for $K_2 \leq D_1 + D_2 + D_3 - K_3^0 - K_2^0 - K_3^N = D_1 + D_2 + D_3 - K_3^0 - K_2^0$, we have $\partial\Psi(K_1, K_2, K_3)/\partial K_2 = c_K - N_L \leq 0$. Thus, $(K_1^N, K_2^N) = (D_1 + D_2 + D_3 - K_3^0 - K_1^0, D_1 + D_2 + D_3 - K_3^0 - K_2^0)$ whereas $K_3^N = 0$.

(d) First, note that $F_L + c_K > 2N_L$ is always satisfied due to the ranking given in this part. Furthermore, we have $N_L < F_M$ in this condition. This implies that the firm prefers one unit of K_3 over one unit of K_1 or K_2. Following from $c_K \leq F_M < F_L$ and Proposition 3.2, for $K_3 \leq \max\{D_1 + D_2 + D_3 - K_3^0 - K_1^0 - K_1, D_1 + D_2 + D_3 - K_3^0 - K_2^0 - K_2\}$, we have $\partial\Psi(K_1, K_2, K_3)/\partial K_3 \in \{c_K - F_M, c_K - F_L\} \leq 0$. Thus, $K_3^N = \max\{D_1 + D_2 + D_3 - K_3^0 - K_1^0 - K_1, D_1 + D_2 + D_3 - K_3^0 - K_2^0 - K_2\}$ whereas $(K_1^N, K_2^N) = (0, 0)$.

(e) First, note that $F_L + c_K > 2N_L$ is always satisfied due to the ranking given in this part. Furthermore, we have $N_L < F_M$ in this condition. This implies that the firm prefers one unit of K_3 over one unit of K_1 or K_2. Following from $c_K \leq F_S < F_M < F_L$ and Proposition 3.2, for $K_3 \leq D_1 + D_2 + D_3 - K_3^0$, we have $\partial\Psi(K_1, K_2, K_3)/\partial K_3 \in \{c_K - F_S, c_K - F_M, c_K - F_L\} \leq 0$. Thus, $K_3^N = D_1 + D_2 + D_3 - K_3^0$ whereas $(K_1^N, K_2^N) = (0, 0)$.

(f) We have $F_M \leq N_L$ in this condition. This implies that the firm prefers one unit of K_1 or K_2 over one unit of K_3. Following from $c_K \leq N_S < N_L$ and Proposition 3.2, for $K_1 \leq D_1 + D_2 - K_1^0$, we have $\partial\Psi(K_1, K_2, K_3)/\partial K_1 \in \{c_K - N_S, c_K - N_L\} \leq 0$. Similarly, for $K_2 \leq D_1 + D_2 - K_2^0$, we have $\partial\Psi(K_1, K_2, K_3)/\partial K_2 \in \{c_K - N_S, c_K - N_L\} \leq 0$. Thus, $(K_1^N, K_2^N) = (D_1 + D_2 - K_1^0, D_1 + D_2 - K_2^0)$ whereas $K_3^N = 0$.

(g) Following from $c_K \leq \{N_S, N_L, F_S, F_M, F_L\}$ and Proposition 3.2, we have $\partial\Psi(K_1, K_2, K_3)/\partial K_1 \leq 0$ for $K_1 \leq D_1 + D_2 - K_1^0$; $\partial\Psi(K_1, K_2, K_3)/\partial K_2 \leq 0$ for $K_2 \leq D_1 + D_2 - K_2^0$; and $\partial\Psi(K_1, K_2, K_3)/\partial K_3 \leq 0$ for $K_1 \leq D_1 + D_2 + D_3 - K_3^0$. Thus, $(K_1^N, K_2^N, K_3^N) = (D_1 + D_2 - K_1^0, D_1 + D_2 - K_2^0, D_1 + D_2 + D_3 - K_3^0)$. ❑

Proof of Lemma 3.2.

(a) When $K_3 = D_1 + D_2 + D_3 - K_3^0$, we have $B_{2,1}^* + B_{3,1}^* = D_1$ following from Proposition 3.1. As a consequence, Equation (3.6) becomes $P[D_1(1 - T)\tilde{t}_L > \beta_L] \le \alpha$. This is satisfied if and only if $D_1(1 - T)t_{L,1-\alpha}/\beta_L \le 1$ holds.

(b) When $K_3 = D_1 + D_2 + D_3 - K_3^0$, we have $B_{1,2}^* + B_{3,2}^* = D_2$ following from Proposition 3.1. As a consequence, Equation (3.13) becomes $P[D_2(1 - T)\tilde{t}_L > \beta_L] \le \alpha$. This is satisfied if and only if $D_2(1 - T)t_{L,1-\alpha}/\beta_L \le 1$ holds.

(c) When $K_3 = D_1 + D_2 + D_3 - K_3^0$, we have $B_{3,1}^* + B_{3,2}^* = D_1 + D_2$ following from Proposition 3.1. As a consequence, Equation (3.21) becomes $P[(D_1 + D_2)(1 - T)\tilde{t}_H > \beta_H] \le \alpha$. This is satisfied if and only if $(D_1 + D_2)(1 - T)t_{H,1-\alpha}/\beta_H \le 1$ holds. ❑

Proof of Remark 3.1.

When $N_S < N_L < c_K \le F_S < F_M < F_L$ or $N_S < c_K \le \{N_L, F_S\} < F_M < F_L$ holds, it follows from Proposition 3.3(e) that $K_3^N = D_1 + D_2 + D_3 - K_3^0$. Similarly, when $c_K \le \{N_S, N_L, F_S, F_M, F_L\}$ holds, it follows from Proposition 3.3(g) that $K_3^N = D_1 + D_2 + D_3 - K_3^0$. The rest follows from the proof of Lemma 3.2. ❑

Proof of Proposition 3.4.

(a)(i) When $(K_2^N, K_3^N) = (0, 0)$, we have $B_{2,1}^* = K_2^0 - D_2$ and $B_{3,1}^* = K_3^0 - D_3$ following from Proposition 3.1. As a consequence, Equation (3.6) is violated if $P[[(K_2^0 - D_2 + K_3^0 - D_3)(1 - T) + (D_1 + D_2 + D_3 - K_3^0 - K_2^0)]\tilde{t}_L > \beta_L] > \alpha$. This is equivalent to $[D_1 - (K_2^0 - D_2 + K_3^0 - D_3)T]t_{L,1-\alpha}/\beta_L > 1$.

(a)(ii) When $(K_2^N, K_3^N) = (0, D_1 + D_2 + D_3 - K_3^0 - K_1^0)$ and $K_1^0 > K_2^0$, we have $B_{2,1}^* = K_2^0 - D_2$ and $B_{3,1}^* = D_1 + D_2 - K_1^0$ following from Proposition 3.1. As a consequence, Equation (3.6) is violated if $P[[(D_1 - K_1^0 + K_2^0)(1 - T) + (K_1^0 - K_2^0)]\tilde{t}_L > \beta_L] > \alpha$. This is equivalent to $[D_1(1 - T) + (K_1^0 - K_2^0)T]t_{L,1-\alpha}/\beta_L > 1$.

(b) This is symmetric to Part (a).

(c)(i) When $K_3^N = 0$, we have $B_{3,1}^* + B_{3,2}^* = K_3^0 - D_3$ following from Proposition 3.1. As a consequence, Equation (3.21) is violated if $P[[(K_3^0 - D_3)(1 - T) + (D_1 + D_2 + D_3 - K_3^0)]\tilde{t}_H > \beta_H] > \alpha$. This is equivalent to $[D_1 + D_2 - (K_3^0 - D_3)T]t_{H,1-\alpha}/\beta_H > 1$.

(c)(ii) When $K_3^N = D_1 + D_2 + D_3 - K_3^0 - K_1^0$, we have $B_{3,1}^* + B_{3,2}^* = D_1 + D_2 - K_1^0$ following from Proposition 3.1. As a consequence, Equation (3.21) is violated if $P[[(D_1 + D_2 - K_1^0)(1 - T) + K_1^0]\tilde{t}_H > \beta_H] > \alpha$. This is equivalent to $[(D_1 + D_2)(1 - T) + K_1^0T]t_{H,1-\alpha}/\beta_H > 1$.

(c)(iii) This is symmetric to part (c)(ii). ❑

Proof of Proposition 3.5.

(a) Violating the risk constraint (3.6) implies that $D_1 - B_{2,1}^* - B_{3,1}^* > 0$. Thus, following from Proposition 3.1, we have $B_{2,1}^* = K_2^0 + K_2 - D_2$ and $B_{3,1}^* = K_3^0 + K_3 - D_3$. In order to comply with the risk constraint (3.6), (K_2^A, K_3^A) must satisfy that

$$P[[(K_2^0 + K_2^A - D_2 + K_3^0 + K_3^A - D_3)(1 - T) + (D_1 + D_2 + D_3 - K_3^0 - K_2^0 - K_3^A - K_2^A)]\tilde{t}_L > \beta_L] \leq \alpha$$

which is equivalent to $K_2^A + K_3^A \geq K^{R,1} = [1/T][D_1 - \beta_L/t_{L,1-\alpha}] - (K_2^0 - D_2 + K_3^0 - D_3)$.

(b) This is symmetric to part (a).

(c) Violating the risk constraint (3.21) implies that $D_1 + D_2 - B_{3,1}^* - B_{3,2}^* > 0$. Thus, following from Proposition 3.1, we have $B_{3,1}^* + B_{3,2}^* = K_3^0 + K_3 - D_3$. In order to comply with the risk constraint (3.21), K_3^A must satisfy that

$$P[[(K_3^0 + K_3^A - D_3)(1 - T) + (D_1 + D_2 + D_3 - K_3^0 - K_3^A)]\tilde{t}_H > \beta_H] \leq \alpha$$

which is equivalent to $K_3^A \geq K^{R,3} = [1/T][D_1 + D_2 - \beta_H/t_{H,1-\alpha}] - (K_3^0 - D_3)$. ❑

Proof of Lemma 3.3.

The proof follows immediately from $\beta_L = \beta_H$. Also, note that $t_{H,1-\alpha} > t_{L,1-\alpha}$ due to the first-order stochastic dominance. ❑

Proof of Proposition 3.6.

In parts (e) and (g), $(K_1^A, K_2^A, K_3^A) = (K_1^N, K_2^N, K_3^N)$ following from Remark 3.1. In parts (a)(i), (b)(i), (c)(i)(1), (c)(ii)(1), (c)(iii)(1), (d)(i), and (f)(i), $(K_1^A, K_2^A, K_3^A) = (K_1^N, K_2^N, K_3^N)$ following from Proposition 3.4(c) and Lemma 3.3.

In parts (a)(ii) and (b)(ii), $K_3^A = K^{R,3} > K_3^N$ following from propositions 3.4(c), 3.5(c) and Lemma 3.3. Furthermore, $(K_1^A, K_2^A) = (K_1^N, K_2^N) = (0, 0)$ since $\{N_S, N_L\} < c_K$.

In part (c)(i)(2), $K_3^A = K^{R,3} > K_3^N$ following propositions 3.4(c), 3.5(c) and Lemma 3.3. However, $K_2^A < K_2^N$ because increasing K_3 by one unit shifts $\partial\Psi(K_1, K_2, K_3)/\partial K_2$ from $c_K - N_L \leq 0$ to $c_K - N_S > 0$ for one unit of K_2 (see Proposition 3.2). Thus, in part (c)(i)(2.1), K_2^A is such that $K_2^A + K_3^A = K_2^N + K_3^N$. In part (c)(i)(2.2), however, K_2^A reaches zero, and thus, $K_2^A + K_3^A > K_2^N + K_3^N$. Note that $K_1^A = K_1^N = 0$. Part (c)(ii)(2) is symmetric to part (c)(i)(2).

In part (c)(iii)(2), $K_3^A = K^{R,3} > K_3^N$ following propositions 3.4(c), 3.5(c) and Lemma 3.3. However, $K_1^A < K_1^N$ and $K_2^A < K_2^N$ because increasing K_3 by one unit shifts $\partial\Psi(K_1, K_2, K_3)/\partial K_1$ from $c_K - N_L \leq 0$ to $c_K - N_S > 0$ for one unit of K_1, and shifts $\partial\Psi(K_1, K_2, K_3)/\partial K_2$ from $c_K - N_L \leq 0$ to $c_K - N_S > 0$ for one unit of K_2 (see Proposition 3.2). Thus, in part (c)(iii)(2.1), K_1^A and K_2^A are such that $K_1^A + K_2^A + K_3^A < K_1^N + K_2^N + K_3^N$. In parts (c)(iii)(2.2) and (c)(iii)(2.3), either K_1^A or K_2^A reaches zero. In part (c)(iii)(2.4), both K_1^A and K_2^A reach zero.

In part (d)(ii), $K_3^A = K^{R,3} > K_3^N$ following propositions 3.4(c), 3.5(c) and Lemma 3.3. Furthermore, $(K_1^A, K_2^A) = (K_1^N, K_2^N) = (0, 0)$ due to $N_L < F_M$.

In part (f)(ii), $K_3^A = K^{R,3} > K_3^N$ following propositions 3.4(c), 3.5(c) and Lemma 3.3. Furthermore, $(K_1^A, K_2^A) = (K_1^N, K_2^N) = (D_1 + D_2 - K_1^0, D_1 + D_2 - K_2^0)$ due to $c_K \leq N_S < N_L$. ❑

Proof of Proposition 3.7.

Risk aversion increases by decreasing α and/or β. Decreasing α and/or β lead to an increase in $K_3^A = K^{R,3}$. When we have $N_S < c_K \leq N_L$, increasing K_3 by one unit shifts $\partial\Psi(K_1, K_2, K_3)/\partial K_1$ from $c_K - N_L \leq 0$ to $c_K - N_S > 0$ for one unit of K_1, and shifts $\partial\Psi(K_1, K_2, K_3)/\partial K_2$ from $c_K - N_L \leq 0$ to $c_K - N_S > 0$ for one unit of K_2 (see Proposition 3.2). Thus,

(a) when both $K_1^A > 0$ and $K_2^A > 0$, increasing K_3^A by one unit leads to one unit decrease in K_1^A and K_2^A each. This corresponds to the case presented in Proposition 3.6(c)(iii)(2.1);

(b) when either $K_1^A > 0$ or $K_2^A > 0$, increasing K_3^A by one unit leads to one unit decrease in K_1^A or K_2^A. This corresponds to the cases presented in propositions 3.6(c)(i)(2.1), 3.6(c)(ii)(2.1), 3.6(c)(iii)(2.2), and 3.6(c)(iii)(2.3). ❑

Proof of Proposition 3.8.

The proof follows immediately from the proof of Proposition 3.7. ❑

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EDUCATION

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PhD in *Supply Chain Management* — July 2016
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MA in *Economics* — December 2014

Bilkent University, Ankara, Turkey
MS in *Finance* — September 2010
Thesis title: Stock-market reactions to mergers of non-financial Turkish firms
BS in *Industrial Engineering* — May 2008

PUBLICATIONS & WORKING PAPERS

Hekimoglu, M.H., B. Kazaz, S. Webster. 2016. Wine analytics: Fine wine pricing and selection under weather and market uncertainty. Under revision after being invited for a fourth-round review at *Manufacturing & Service Operations Management*.

Hekimoglu, M.H., J. Park, B. Kazaz. 2016. Omni-channel as a buffer against supply chain disruptions. Working paper. Target journal: *Manufacturing & Service Operations Management*.
[This paper is based on our risk assessment study examining the impact of supply chain disruptions in the Staples retail and delivery supply chains; the outcome of this work is being implemented at Staples].

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Hekimoglu, M.H., B. Tanyeri. 2011. Stock-market reactions to mergers of non-financial Turkish firms. *Iktisat Isletme ve Finans* **26**(308) 53-70.

INDUSTRY PROJECT

Staples, Framingham, MA, September 2014 – May 2015
- developed a new capacity planning under disruption risk for the Staples supply chain (including internal business continuity risks, and external disruption risks)
- the end result of this project is implemented at the company
- received a grant in the amount of $50,000 (with J. Park and B. Kazaz)

TEACHING EXPERIENCE

Primary Instructor at Syracuse University

Introduction to Supply Chain Management (SCM 265)
- undergraduate core course
- Spring 2014, Spring 2015, and Spring 2016
- more than 50 students in each of my sections
- topics include demand forecasting, inventory management, material requirements planning, operations scheduling, project management, quality management, and waiting line theory
- used a book of short case studies rather than a traditional textbook in order to underline the importance and the practicality of the concepts/tools covered
- one of the early adopters of the *ResponseWare* technology at Syracuse University that is a solution that allows students to use their smartphones, tablets, or laptops to respond to interactive questions that show up on the classroom screen

Teaching Assistant at Syracuse University

Introduction to Supply Chain Management (SCM 265)
- undergraduate core course
- Fall 2011, Spring 2012, Spring 2013, Fall 2013, and Fall 2015

Global Supply Chain Management (SCM 477)
- undergraduate elective course
- Fall 2012 and Fall 2014

Global Supply Chain Strategy (SCM 777)
- MBA elective course
- Fall 2012

Introduction to Management Science (SCM 403)
- undergraduate elective course
- Spring 2013

Principles of Management Science (SCM 702)
- MBA elective course
- Spring 2013

Supply Chain and Logistics Management (SCM 701)
- MBA elective course
- Fall 2013

Creatively Growing Your Business: A Design Thinking Approach (SCM 400/600)
- undergraduate/MBA elective course
- Fall 2014

Teaching Assistant at Bilkent University

Introduction to Management Science (MAN 256)
- undergraduate core course
- Spring 2009 and Spring 2010

Data Models and Decisions (MBA 553)
- MBA core course
- Fall 2008 and Fall 2009

Decision Analysis (MAN 451)

- undergraduate elective course
- Fall 2009

Corporate Finance (MAN 321)
- undergraduate core course
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Capital Markets and Institutions (MAN 421)
- undergraduate elective course
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CONFERENCE PRESENTATIONS

Wine analytics: Fine wine pricing and selection under weather and market uncertainty
POMS, Orlando, FL, May 2016
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INFORMS, San Francisco, CA, November 2014
POMS, Atlanta, GA, May 2014
INFORMS, Minneapolis, MN, October 2013

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