Wine Futures: Pricing and Allocation as Levers against Quality Uncertainty

Tim Noparumpa
tim@cbs.chula.ac.th
Chulalongkorn Business School
Chulalongkorn University
Bangkok, Thailand 10330

Burak Kazaz
bkazaz@syr.edu
Whitman School of Management
Syracuse University
Syracuse, NY 13244 USA

Scott Webster
scott.webster@asu.edu
W.P. Carey School of Business
Arizona State University
Tempe, AZ 85287 USA

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This study examines the impact of using wine futures in order to mitigate the winemaker's risk stemming from quality uncertainty. In each vintage, a winemaker harvests grapes and crushes them in order to make wine. A premium wine sits in barrels for eighteen to twenty-four months. During the aging process, tasting experts take samples and establish a *barrel score*; this barrel score often indicates the expert's perception of whether the wine will be a superior wine. Based on the barrel score, the winemaker can sell some or all of her/his wine in the form of wine futures and in advance of bottling. The winemaker makes three decisions: (1) the price to sell her/his wine futures, (2) the quantity of wine futures to be sold in advance, and (3) the amount of wine to be kept for retail and distribution. The wine continues to age for one more year after barrel samples. The tasting experts then provide a *bottle score* upon the bottling of the wine. At the time the winemaker determines the price and quantity of wine futures, this unrealized bottle score represents the uncertainty that influences the market price of the wine.

This study makes two contributions to the optimization of pricing and quantity decisions and offers insightful recommendations for practicing managers. First, it develops a stochastic optimization model that integrates uncertain consumer valuations of wine both in the form of futures and in bottle, and the uncertainty associated with bottle scores. Second, it provides an empirical analysis using data collected from Bordeaux wineries engaging in wine futures. The empirical analysis demonstrates that wine futures can be used as price and quantity levers to mitigate the negative consequences of quality uncertainty. The results provide clues as to how other markets (e.g. Italy and the U.S.) can establish similar wine futures markets in order to help their small and artisanal winemakers.

Keywords: *Stochastic optimization*, *wine futures, futures pricing, quality uncertainty*

1. Introduction

This study shows how wine futures can be used as pricing and quantity levers in order to mitigate the negative consequences of quality uncertainty in the process of winemaking. Selling wine in the form of wine futures refers to the winemaker's decision to offer her/his wine in advance and prior to the completion of the winemaking process. Fine wine often requires a long aging process for the liquid resting in barrels, e.g. eighteen to twenty-four months for most Bordeaux style wines. Thus, a winemaker has her cash tied up in this inventory for a long period of time before the wine gets bottled and distributed for retail. Wine futures can offer the winemaker the opportunity to collect some of this cash investment earlier and transfer a proportion of the risk stemming from uncertain bottle reviews to consumers.

The paper builds a stochastic optimization model in order to assist a winemaker in her decisions regarding the proportion of wine to be sold in advance in the form of wine futures and the price of wine futures. Consequently, the model determines the proportion of the wine that should be distributed for retail sale in later periods. The uncertainty in the life of a fine wine producer arises from the critical reviews of tasting experts. These experts review the wine while it is still aging in barrels and provide a score that indicates projections regarding the quality of the wine. Potential buyers rely on this information in order to determine whether to purchase wine futures. The same tasting experts provide a second review when the winemaking process is completed and the wine is bottled. This bottled wine review can differ from the review provided in the barrel phase. The model in this paper model helps the winemaker to mitigate the negative consequences of the uncertainty stemming from as-yet unknown bottle reviews.

We begin the discussion with the description of the winemaking process.

1.1. Winemaking Process and the Tasting Reviews

A fine wine producer in the US and in Europe harvests grapes in September and/or October. After crushing grapes and shuffling the juice in a tank (wood, steel, or concrete), red wines are then transferred to oak barrels; this marks the beginning of the aging process. The wine continues its aging process in barrels for eighteen to twenty-four months.

Tasting experts visit these fine wine producers six to eight months after harvest (in March and April). These tasting experts provide their reviews and assign a *barrel score*, often out of 100 points. The most influential and widely-distributed magazine *Wine Spectator*, for example, describes its 100-point scoring system as follows: A classic (great) wine receives a score between 95 to 100, and an outstanding wine (a wine of superior character and style) 90 to 94, a very good wine (a wine with special qualities) 85 to 89 points, a good wine (well-made wine) 80 to 84 points, a mediocre wine (a drinkable wine that may have minor flaws) 75 to 79. A wine that receives a score 74 or below is not recommended by *Wine Spectator*.

The same tasting expert provides another score, called *bottle score*, when the wine completes its aging process and gets bottled. This bottle score can differ from barrel score, and is the primary source of the risk for a fine wine producer. This work develops a stochastic optimization model that uses the barrel scores in order to mitigate the uncertainty in bottle reviews.

It is known that premium French wines have been sold in the form of wine futures since the 17th century. “En primeur” is the French concept of selling wine while it is still aging in the barrel. En primeur is translated into English as “wine futures” indicating financial contracts with standardized terms. These wine futures are traded in an electronic exchange market called the London International Vintner’s Exchange, or shortly known as “Liv-ex.” This electronic platform is similar to NASDAQ, however, only highly sought-after fine wines are traded both in the form of wine futures and in bottle in Liv-ex. Figure 1 demonstrates a screenshot of the trading platform in Liv-ex. Merchants, brokers, retailers, and consumers make up the buyers of wine futures in Liv-ex.

Tasting reviews have significant impact on the quality perception of wine. *Wine Spectator* is the most widely distributed magazine in the wine industry and has a significant impact on the quality perception of wine. Masset et al. (2015) demonstrates that a 10% increase in barrel scores provided by *Wine Spectator* leads to a 4% increase in futures price.

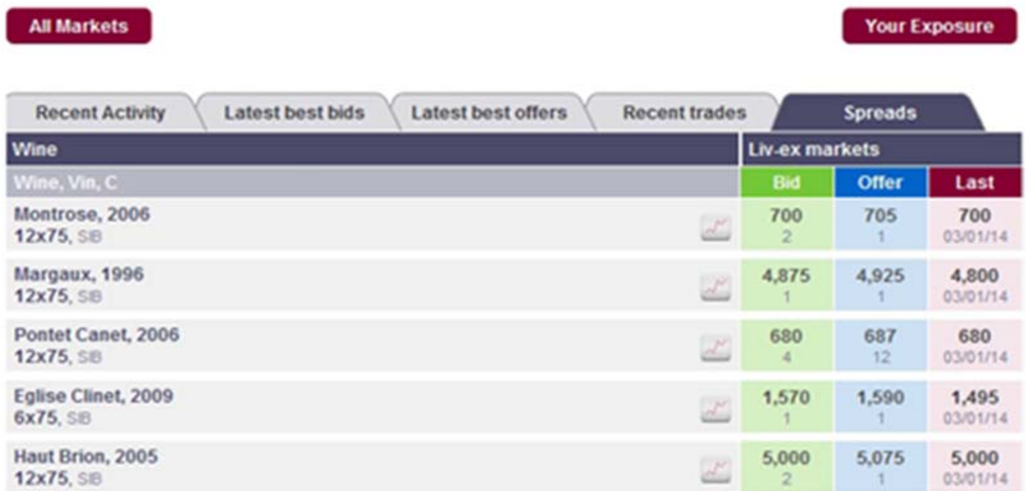

Figure 1. A screenshot of Liv-ex trading platform.

The winemaker and wine futures consumers exhibit distinct properties that differ from the common description of risk aversion in (the industrial organization theory of) economics literature. According to the industrial organization theory, (large) firms can diversify their risk and do not need to behave in a risk-averse manner. The same theory indicates that individual consumers would exhibit a risk-averse behavior as they possess limited resources and cash. However, consumers in the wine industry are affluent collectors and/or financially-healthy merchants and distributors. The empirical analysis in Noparumpa et al (2015a) does not support a risk-averse behavior on the part of wine futures consumers. Therefore, the consumers of wine futures in this study are considered to be risk-neutral in order to reflect the true operating environment in this industry. Because winemakers are often small in size with limited financial resources, they exhibit a risk-averse behavior. These unique features are incorporated into the empirical analysis as well.

This paper develops a stochastic optimization model that maximizes the percentage profit improvement from using wine futures as price and quantity levers in the presence of bottle score uncertainty. It demonstrates that these two decisions, futures quantity and futures price, serve as effective levers against quality uncertainty. Section 2 reviews the corresponding literature. Section 3 introduces the model; Section 4 presents its analysis. Section 5 provides an empirical analysis using data from Bordeaux wineries as well as one of the US artisanal winemakers. Section 6 presents the conclusions.

2. Literature Review

There are three streams of literature related with this study.

2.1. Pricing and Quantity Decisions under Uncertainty

Supply chain and operations management literature focuses primarily on pricing and quantity decisions under uncertainty. Specifically, the *Price-Setting Newsvendor Problem* (PSNP) investigates the problem of determining a selling price and a production quantity (or inventory level) under demand uncertainty: Van Mieghem and Dada (1999), Petruzzi and Dada (1999), Dana and Petruzzi (2001), Federgruen and Heching (1999, 2002) and Kocabıyıkoğlu and Popescu (2011) are examples of studies that examined these two critical decisions under stochastic demand. These studies, however, assume that supply and quality are deterministic, and thus, supply and quality fluctuations do not influence pricing and quantity decisions. This work differs from these earlier publications in three ways: (1) It incorporates quality uncertainty into the joint pricing and quantity decisions under uncertainty; (2) it develops two new levers with advance selling quantity (i.e., the amount of futures to be sold) and the advance selling price (futures price) as levers to mitigate quality uncertainty; and, (3) it examines a risk-averse winemaker (firm) who is interested in transferring a proportion of her quality risk to consumers. Kazaz and Webster (2015) incorporate supply uncertainty into PSNP, and develop a new elasticity measure leading to unique optimal solutions in the problem of determining price and quantity under supply and demand uncertainty; however, their study does not feature a retail market analysis. Finally, this study shows that advance pricing through futures prices and advance allocation are financially viable risk mitigation techniques for winemakers with a significant amount of cash tied up in inventory that may diminish in value.

In addition to the PSNP literature, there is a growing body of literature that examines the impact of supply uncertainty. Jones et al. (2001), Kazaz (2004), and Kazaz and Webster (2011), Noparumpa et al. (2015b) demonstrate the benefits of using a secondary source of supply in order to mitigate the negative consequences of supply uncertainty. Rather than utilizing a secondary source, this work focuses on the use of advance selling as a lever against uncertainty. Moreover, we examine quality uncertainty rather than supply uncertainty. In this problem, the quality of the final product can fluctuate during the course of the aging process.

2.2. Advance Selling

Marketing literature demonstrates the benefits of advance selling as consumers get the opportunity to purchase goods or services before the time of consumption. Gale and Holmes (1992, 1993), Shugan and Xie (2000, 2005), Xie and Shugan (2001), Fay and Xie (2010), Boyaci and Özer (2010), Tang and Lim (2013), Cho and Tang (2013) show that advance selling is a method where a firm can discriminate its consumer base through differential pricing. These studies demonstrate that advance selling helps a firm to manage fluctuations in demand. This work differs from these studies by introducing quality uncertainty at the time of consumption.

2.3. Wine Tasting

A wide majority of the economics literature on wine pricing has focused on the influence of weather fluctuations in growing seasons. Ashenfelter (2010) and Ashenfelter et al. (1995), for example, focus on the impact of climactic conditions on the quality and price of aged wines. There is a growing literature examining various aspects of the influence in wine tasting. Ali et al. (2008), Ashenfelter and Jones (2013), Stuen et al. (2015), Bodington (2015), and Olkin et al. (2015) are examples of studies that investigate the impact of wine tasting experts in creating the perception of quality. Masset et al. (2015) examine the influence of various tasting experts on futures prices. However, these publications do not develop a stochastic optimization model for the winemaker in order to determine quantity (the amount of wine to be sold in the form of futures) or price (price of wine futures); thus, they do not emphasize building levers to mitigate quality uncertainty.

2.4. Contribution over Noparumpa et al. (2015a)

This paper is similar to Noparumpa et al. (2015a) where they also build an analytical model based on tasting expert reviews. It departs from the earlier publication in three dimensions. First, this work removes the assumption of risk-averse consumers, and considers risk-neutral buyers of wine futures. The considerations of risk-neutral consumers is reflective of the operating environment as the ultimate buyers of futures, as explained before, constitute an affluent customer base. Thus, this study leads to more accurate estimations of the benefits that can be obtained by optimizing the winemaker's pricing and quantity decisions at the futures stage. Second, the emphasis is on the research question associated with identifying and measuring the financial benefit from using a stochastic optimization model. Noparumpa et al. (2015a) do not even report on the benefit of their analytical model. Third, this study employs barrel and bottle scores from *Wine Spectator* and Noparumpa et al. (2015) relies on Robert Parker's reviews.

In sum, this study integrates marketing, economics and supply chain management by studying the price and quantity decisions in the form of wine futures. From a marketing perspective, we show that a futures price can act as a lever to discriminate buyers through futures and retail prices. From an economics perspective, the pricing decision helps the winemaker to extract additional surplus from consumers. From a supply chain management perspective, selling wine in advance of bottling enables the winemaker to transfer the risk of holding inventory that fluctuates in value due to quality-rating uncertainty to buyers of wine futures; it also helps the winemaker to recover some of her cash investment.

3. The Model

This section presents the modeling approach useful to a facing quality-rating uncertainty and seeking an optimal supply policy in the spot and futures market. Both the futures price and the wine supply in the futures market are endogenous. We develop a two-stage stochastic programming model in order to formulate the problem for the winemaker. Figure 2 depicts the timeline of events and decisions. At the end of grape harvest (September of calendar year t), the winemaker obtains a certain amount of wine described by Q of wine from vintage t. After the wine ages for eight to ten months, tasting experts (e.g. Robert Parker Jr. of *The Wine Advocate*, James Molesworth of *Wine Spectator*, Jancis Robinson of *Financial Times*) visit the winery in order to taste the wine. The tasting expert provides a barrel score in May of calendar year $t + 1$ that gets revealed to the winemaker and consumers through a publication. We denote the realized barrel score assigned by the tasting expert with s_1. The realization of the barrel score marks the beginning of stage 1 in the model. The winemaker then makes the following three decisions based on the realized barrel score:

(1) The price of wine futures, denoted p_f, which determines the demand for wine futures, denoted $d_f(p_f)$,

(2) the quantity of wine to be sold as futures, denoted q_f,

(3) the quantity of wine that is reserved for retail distribution, denoted q_r.

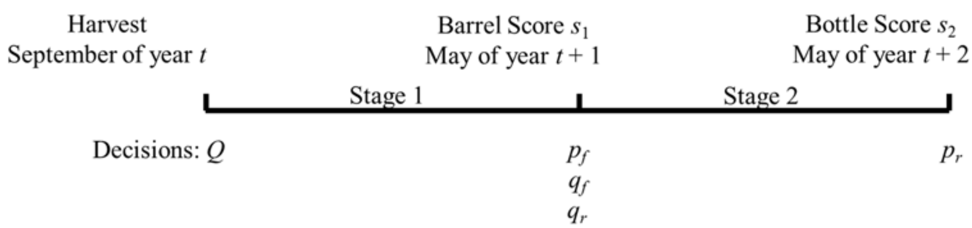

Figure 2. Model specifications, stages in the model, and the timeline of decisions.

In stage 1, the winemaker sells a quantity of wine in the form of futures equivalent to $\min\{d_f(p_f), q_f\}$ at the unit price of p_f. Thus, the winemaker collects a revenue of $p_f \min\{d_f(p_f), q_f\}$ in stage 1. The remaining portion of wine is distributed for retail sale in the second-stage of the model; we denote this quantity $q_r = Q - \min\{d_f(p_f), q_f\}$. Although the quantity decisions might be in integer values in reality, the model utilizes continuous values, and can be perceived as an approximation to the ideal amount of wine that should be sold in the form of wine futures.

At the end of the aging process, in May of calendar year $t + 2$, the wine gets bottled and goes through another review of the wine-tasting experts. The random bottle score is expressed as $\tilde{s}_2$, and its realization as s_2. Because the barrel score provides an indication of the final bottle score s_2, the random variable $\tilde{s}_2$ follows a conditional probability density function $f(s_2 \mid s_1)$. We assume that the expectation of the bottle score in May of calendar year $t + 2$ when the barrel score is revealed in May of calendar year $t + 1$ is equal to the barrel score, i.e., $E[\tilde{s}_2 \mid s_1] = s_1$.

At the end of Stage 2 of the model, the wine is sold at a retail price p_r that is influenced by the random bottle score that gets revealed in May of calendar year $t + 2$ as well as the barrel score that is revealed in May of calendar year $t + 1$. Without loss of generality, we normalize the bottle price of retail wine to be equivalent to the bottle rating of the wine; specifically, we have $p_r = p_r(s_2) = s_2$. It follows from $E[\tilde{s}_2 \mid s_1] = s_1$ that the expected retail price in May of calendar year $t + 1$ is equal to the barrel score: $E[p_r(\tilde{s}_2 \mid s_1)] = s_1$. As a consequence, the winemaker collects a revenue equivalent to $E[p_r(\tilde{s}_2 \mid s_1)](Q - \min\{d_f(p_f), q_f\})$ in stage 2.

The revenues collected in stage 2 are discounted to May of calendar year $t + 1$ through the winemaker's attitude towards risk under uncertainty. We adopt the risk-adjusted discount rate that is common in the finance literature (e.g., Samuelson 1963). The value of the risk-adjusted discount rate, denoted ϕ, depends on the risk of selling a bottle of wine at an uncertain retail price in the future. The higher the uncertainty in bottle price and the more risk-averse the winemaker is, the lower the value of ϕ. If the winemaker is risk-neutral, for example, then $\phi = (1+ r)^{-1}$. The winemaker's risk-adjusted expected profit for a given set of first-stage decisions (p_f, q_f) can then be expressed as follows:

$$\Pi(p_f, q_f) = p_f \min\{d_f(p_f), q_f\} + \phi E[p_r(\tilde{s}_2 \mid s_1)](Q - \min\{d_f(p_f), q_f\}). \quad (1)$$

3.1. The Model

We develop a model that maximizes the benefits from using the optimal choices of futures price and quantity of wine to be sold in the form of wine futures. We describe the winemaker's present choice of futures price and quantity with p_f^0 and q_f^0, respectively. For the futures price p_f^0, the demand for wine futures is $d_f(p_f^0)$. Thus, the present profit level for the winemaker can be expressed as:

$$\Pi(p_f^0, q_f^0) = p_f^0 \min\{d_f(p_f^0), q_f^0\} + \phi E[p_r(\tilde{s}_2 \mid s_1)](Q - \min\{d_f(p_f^0), q_f^0\}).$$

This model maximizes the benefits exceeding the present level of profitability. We describe the percentage of profit improvement through the proposed modeling approach as:

$$\Delta\Pi(p_f, q_f) = (\Pi(p_f, q_f) - \Pi(p_f^0, q_f^0))/\Pi(p_f^0, q_f^0). \quad (2)$$

We can now express the model as follows:

$$\max_{(p_f, q_f) \geq 0} \ \Delta\Pi(p_f, q_f) \quad (3)$$

s.t.

$$q_f \leq Q. \quad (4)$$

It is important to observe that the winemaker's current choice of (p_f^0, q_f^0) can differ from the optimal decisions in the price and quantity pair (p_f, q_f). Specifically, the winemaker might have chosen a futures price to be higher (or lower) than the optimal futures price, i.e., $p_f^0 > p_f$ (or $p_f^0 < p_f$) leading to a lower (or higher) wine futures demand than ideal. Similarly, the winemaker's current allotment as futures q_f^0 can be higher or lower than the ideal quantity of futures q_f. Thus, the model in (3) – (4) leads to the highest benefit from a simultaneous optimization of price and quantity decisions for the futures market. In reality, the firm might determine integer values for its quantity decisions, however, the model uses continuous decision variables. Therefore, the results should be perceived as an approximation of the benefits from using the proposed modeling approach.

3.2. Demand for Wine Futures

We next describe how the demand for wine futures, expressed as $d_f(p_f)$, is developed as a function of futures price p_f. We consider the case when each individual in the futures market has idiosyncratic preferences. In May of calendar year $t + 1$, each individual considers utility from three alternatives: purchasing a wine future, purchasing wine at retail, and no purchase. Individuals discount the value gained in May of calendar year $t + 2$ to the value in May of calendar year $t + 1$ using a risk-adjusted discount rate θ. Because the individuals in the futures market correspond to an affluent population, we consider their decisions to be consistent with risk-neutral decisions; then $\theta = (1+ r)^{-1}$ where r is the risk-free rate over the time-period from May of calendar year $t + 1$ to May of calendar year $t + 2$. The utilities of a random member of the futures market associated with these alternatives are as follows:

$$U_f = \theta E\left[\tilde{s}_2 \mid s_1\right] + \varepsilon_f - p_f = \theta s_1 + \varepsilon_f - p_f$$

$$U_r = \theta E\left[\tilde{s}_2 \mid s_1\right] + \varepsilon_r - \theta E\left[p_r\left(\tilde{s}_2\right) \mid s_1\right] = \varepsilon_r$$

$$U_0 = \varepsilon_0$$

where ε_f, ε_r, and ε_0 are i.i.d. Gumbel random variables with zero mean and scale parameter β. Gumbel distribution describing the error terms in a multinomial logit model is widely used in literature examining the problems in the retail industry. There are several publications that provide ample empirical support; these include McFadden (2001), Talluri and van Ryzin (2004), and Vulcano et al. (2010).

We first explain the utility expressions U_r and U_0 associated with the retail purchase and no-purchase alternatives. For an individual in the futures market, the value of ε_r is the difference between her valuation of retail wine and the retail price (in the dollar equivalent in May of calendar year $t + 1$). The underlying assumption is that this difference does not depend on the realized bottle score s_2 (or equivalently, due to the deterministic relationship between bottle score and the bottle price). Due to this assumption, each individual knows with certainty her utility (or surplus) from a retail purchase. Similarly, the value of ε_0 is the individual's utility from not purchasing a future or a bottle at retail, which is also known with certainty.

We now turn our attention to the expression for U_f, which is the difference between an individual's valuation of a future and the futures price p_f. An individual's valuation of a future is

$$\theta E\left[\tilde{s}_2 \mid s_1\right] + \varepsilon_f .$$

The bottle price is uncertain, though its expected value is known as s_1. We describe the market size for wine futures as $M(s_1)$, which is a non-decreasing function of the barrel score s_1 (i.e., $M'(s_1) \geq 0$). A higher barrel score increases the market size as a consequence of the hype it creates. The demand for wine futures can now be determined by the multinomial logit (MNL) model:

$$d_f\left(p_f\right) = M\left(s_1\right)P\left[U_f > \max\left\{U_r, U_0\right\}\right] = M\left(s_1\right)\left[\frac{e^{\left(\theta s_1 - p_f\right)/\beta}}{2 + e^{\left(\theta s_1 - p_f\right)/\beta}}\right]. \tag{5}$$

4. Analysis

We begin the analysis by establishing the optimal price and quantity coordination in the profit function (1) in the absence of the futures quantity constraint (4). For a given futures price p_f, the following lemma establishes the optimal futures quantity which is equivalent to the demand established in (5); thus, (5) also describes the desirable amount of wine that should be allocated as wine futures.

Lemma 1. *For a given futures price* p_f*, the futures quantity that maximizes* (1) *is* (a) $q_f^* = d_f(p_f)$ *when* $p_f \geq \phi E[p_r(\tilde{s}_2 \mid s_1)]$; (b) $q_f^* = 0$ *when* $p_f < \phi E[p_r(\tilde{s}_2 \mid s_1)]$.

Lemma 1 indicates that the winemaker sells some of the wine in the form of wine futures as long as the futures price p_f is greater than or equal to the expected retail price discounted to the beginning of the problem, i.e., $q_f^* = d_f(p_f)$ only when $p_f \geq \phi E[p_r(\tilde{s}_2 \mid s_1)]$. Otherwise, the winemaker would sell all wine in the retail market, corresponding to Stage 2 of the model.

Aydin and Porteus (2008) show that, in the MNL model, the first-order condition with respect to price yields the optimal price in the absence of a constraint as in (4). From equation (5), the futures price can be described as a function of demand for wine futures. Alternatively from Lemma 1, the futures price can be expressed in terms of a corresponding optimal futures amount when the winemaker offers a positive amount of futures. Equating $q_f^* = d_f(p_f)$ and inverting (5) provide the following futures price expression for a given futures quantity.

Lemma 2. *For a given futures quantity* q_f ($\leq Q$), *the futures price that maximizes* (1) *is*

$$p_f^*\left(q_f\right) = \theta s_1 + \beta \ln\left[\frac{M\left(s_1\right) - q_f}{2q_f}\right]. \tag{6}$$

Substituting (6) into (1), the profit function in (1) can now be expressed in terms of a single decisions variable.

$$\Pi(q_f) = \Pi(p_f^*(q_f), q_f) = \left\{\left(\theta - \phi\right)s_1 + \beta \ln\left[\frac{M\left(s_1\right) - q_f}{2q_f}\right]\right\}q_f + \phi s_1 Q\,. \tag{7}$$

We substitute (7) into the objective function in (3), and analyze the constrained MNL model subject to inequality (4). We next develop the closed-form expressions for the optimal price, quantity, and profit for the model in (3) – (4). These expressions utilize the Lambert W function $W(z)$ in Corless et al. (1996) where $W(z)$ describes the value of w satisfying $z = we^w$. Let us define r^0 =

$$\frac{e^{(\theta-\phi)s_1/\beta - W\left(\frac{e^{(\theta-\phi)s_1/\beta}}{2e}\right)}}{2e + e^{(\theta-\phi)s_1/\beta - W\left(\frac{e^{(\theta-\phi)s_1/\beta}}{2e}\right)}}$$ as the optimal proportion of the wine futures market that buys wine in the form of wine futures in the absence of a supply constraint. Recall that the total market size for wine futures consumers is described as $M(s_1)$. In the absence of a supply constraint, then the demand for wine futures is equal to $r^0 \times M(s_1)$.

Proposition 1. *The optimal futures price and futures quantity that maximize* (3) *subject to* (4) *are*

$$p_f^* = \begin{cases} \phi s_1 + \beta\left[1 + W\left(\frac{e^{(\theta-\phi)s_1/\beta}}{2e}\right)\right] & \text{when } r^0 \le \frac{Q}{M(s_1)} \\ \theta s_1 + \beta \ln\left[\frac{M(s_1) - Q}{2Q}\right] & \text{when } r^0 > \frac{Q}{M(s_1)} \end{cases} \tag{8}$$

$$q_f^* = \begin{cases} M(s_1)\left(\frac{e^{(\theta-\phi)s_1/\beta - W\left(\frac{e^{(\theta-\phi)s_1/\beta}}{2e}\right)}}{2e + e^{(\theta-\phi)s_1/\beta - W\left(\frac{e^{(\theta-\phi)s_1/\beta}}{2e}\right)}}\right) & \text{when } r^0 \le \frac{Q}{M(s_1)} \\ Q & \text{when } r^0 > \frac{Q}{M(s_1)} \end{cases} \tag{9}$$

and the optimal expected profit in (3) *is*

$$\Pi^* = \begin{cases} M(s_1)\left[\beta W\left(\frac{e^{(\theta-\phi)s_1/\beta}}{2e}\right) + \phi s_1 \frac{Q}{M(s_1)}\right] & \text{when } r^0 \le \frac{Q}{M(s_1)} \\ Q\left(\theta s_1 + \beta \ln\left[\frac{M(s_1) - Q}{2Q}\right]\right) & \text{when } r^0 > \frac{Q}{M(s_1)} \end{cases}. \tag{10}$$

We next provide a sensitivity analysis on the optimal values of the futures price, quantity, and expected profit. We begin the discussion with the influence of the relationship between the consumers' and the winemaker's risk-adjusted discount rates, θ and ϕ, respectively; note that these parameters represent the consumers' and winemaker's risk perception. For example, higher variations in bottle scores imply bigger risk for the winemaker, leading to smaller values of ϕ; thus, the impact of variation in s_2 can be analyzed through decreasing values of ϕ. It is stated earlier that the wine industry is a unique market where the winemakers' risk concern is higher than that of the consumers. Departing from Noparumpa et al. (2015a), we focus on the representative case where $\theta > \phi$.

Higher values of risk aversion for the winemakers is represented with smaller values of ϕ, correspondingly increasing values of $\theta - \phi$. Higher degrees of risk aversion cause the winemaker to allocate a higher percentage of wine for the futures market. This behavior is commonly observed in practice. Small Bordeaux wineries with smaller overall profitability and higher risk concerns (e.g. Evangile, Clos Fourtet, Troplong Mondot, and Cheval Blanc) allocated more than 25% of their wine as futures on average between 2006 and 2011. During the same time interval, smaller risk winemakers such as Cos d'Estournel and Leoville Poyferre sold less than 15% of their wine on average early in the form of wine futures. The most profitable winemakers with a higher degree of fluctuations in returns, Pavie and Angelus, sold approximately 20% of their wine in the form of futures.

The behavior of the optimal futures price and expected profit, however, are not monotone in ϕ and $\theta - \phi$; and they can feature an increasing or a decreasing behavior depending on the parameter values.

How should a higher barrel score influence the winemaker's allocation of wine to be sold as futures? In this model, the amount of wine allocated for futures (q_f^*) increases in s_1. Similarly, higher barrel scores lead to a higher price of wine futures (p_f^*), and an increased level of optimal expected profit. In this case, the winemaker prefers early cash over the alternative of holding inventory in order to exploit the retail market customers. This result is a consequence of the following two conditions: (1) The assumption of no bias with $E[\tilde{s}_2 \mid s_1] = s_1$, and (2) risk-neutral buyers and risk-averse winemakers, i.e., $\theta > \phi$.

5. Empirical Analysis with Bordeaux Winery Data

This section provides an empirical analysis of the stochastic optimization model presented in Sections 3 and 4. The analysis considers twelve winemakers from the Bordeaux region, six from the Right Bank and six from the Left Bank wine growing districts. The data used in the analysis is collected from several sources.

Liv-ex is the largest source of fine wine data in the world, and the firm provided all the information regarding the wineries included in the analysis and their futures trades involving futures prices and quantities traded. The wineries included in the analysis are: Angelus (Right Bank), Cheval Blanc (Right Bank), Clos Fourtet (Right Bank), Cos d'Estournel (Left Bank), Ducru Beaucaillou (Left Bank), Duhart Milon (Left Bank), Evangile (Right Bank), Leoville Poyferre (Left Bank), Mission Haut Brion (Left Bank), Pavie (Right Bank), Pichon Lalande (Left Bank) and Troplong Mondot (Right Bank). The data includes the futures of vintages from 2006 to 2011. For the twelve wineries included in the study, there have been 307,909 cases traded in the form of futures in a total of 32,869 futures transactions.

Barrel and bottle scores indicate the quality of the wine. The data for the barrel and bottle scores, and the production quantities, are collected from the most influential wine magazine, *Wine Spectator*.

5.1. Wine Futures as a Quantity Lever

This stochastic optimization model uses wine futures as a quantity lever as the winemaker sells a proportion of the wine in the form of wine futures. In this section, we develop a regression model in order to predict the percentage of wine allocated as futures based on *Wine Spectator*'s barrel scores. The regression analysis helps demonstrate the robustness of this optimization model.

We describe the percentage of wine allocated as futures with r_{jt} and barrel scores with s_{1jt} for winery j and vintage t, the mean and standard deviations of the percentage of wine sold as futures and barrel scores with $\overline{r}_j$, σ_{α_j} and the mean and standard deviations of barrel scores with $\overline{s}_{1j}$ and $\sigma_{s_{1j}}$, respectively. We normalize the values of the ratio of wine allocated as futures and barrel scores and describe them as follows: $\hat{r}_{jt} = \dfrac{r_{jt} - \overline{r}_j}{\sigma_{r_j}}$ and $\hat{s}_{1jt} = \dfrac{s_{1jt} - \overline{s}_{1j}}{\sigma_{s_{1j}}}$.

The first analysis regresses the normalized values of percentage of wine allocated as futures ($\hat{r}_{jt}$) based on the normalized values of Wine Spectator's barrel tasting scores ($\hat{s}_{1jt}$). Table 1 provides the results of this regression analysis, and shows that barrel score is a statistically significant variable at less than 1%. Thus, we conclude that barrel score explains a fairly large portion of the amount of wine that should be allocated as wine futures. Figure 3 shows how well this regression model fits between the actual and forecasted percentage allocation.

Parameter	Coefficient	(*p-value*)
Intercept	3.48×10^{-16}	(1)
Barrel Score ($\hat{s}_{1jt}$)	0.73	$(2.16 \times 10^{-13})^{***}$
Adjusted R^2	0.53	

Table 1. Summary of regression results for the normalized values of wine allocated as futures versus the normalized values of barrel scores. *** implies that the variable is significant at 0.01 level.

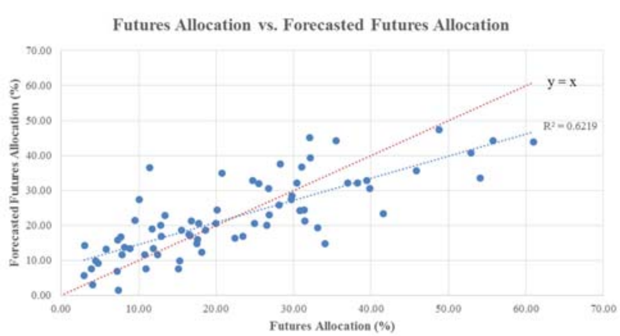

Figure 3. The fit between the normalized actual and forecasted futures allocation.

Figure 4 demonstrates the impact of barrel scores on each winery's percentage allocation decision during each vintage. For each vintage, given the Wine Spectator barrel score, it shows each winery's actual allocation (labeled as "Futures Allocation") and the percentage of wine that should have been allocated according to the statistical analysis reported in Table 1 (labeled as "Forecast Futures Allocation"). Figure 5 shows, during each vintage, how each winemaker allocated its wine for the futures market and what the regression-based model suggested as the percentage to be sold as futures based on the barrel scores.

5.2. Wine Futures as a Price Lever

This stochastic optimization model describes that wine futures can be used as a price lever in order to mitigate quality uncertainty stemming from the randomness in bottle reviews of the tasting experts. In this section, we develop a regression model in order to predict the futures price using *Wine Spectator*'s barrel scores. The regression analysis once again helps demonstrate the robustness of this optimization model.

Using the same twelve wineries, we denote the futures price for winery j and its vintage t from 2006 to 2011 by f_{jt}, the mean and standard deviations of the futures prices for winery j with $\overline{f}_j$ and σ_{f_j}, respectively, and the normalized futures price with $\hat{f}_{jt} = \frac{f_{jt} - \overline{f}_j}{\sigma_{f_j}}$.

The results of the regression analysis is presented in Table 2. It shows that the barrel score is a statistically significant variable at less than 1%. The adjusted R^2 of 0.70 indicates that the barrel score explains a fairly large portion of the decision regarding futures prices. Figure 6 shows the fit of this regression model by comparing the actual futures price with the forecasted futures price.

Parameter	Coefficient	(*p-value*)
Intercept	3.63×10^{-16}	(1)
Barrel Score ($\hat{s}_{1jt}$)	0.841	$(2.18 \times 10^{-20})^{***}$
Adjusted R^2	0.70	

Table 2. Summary of regression results for the normalized values of futures prices versus the normalized values of barrel scores. *** implies that the variable is significant at 0.01 level.

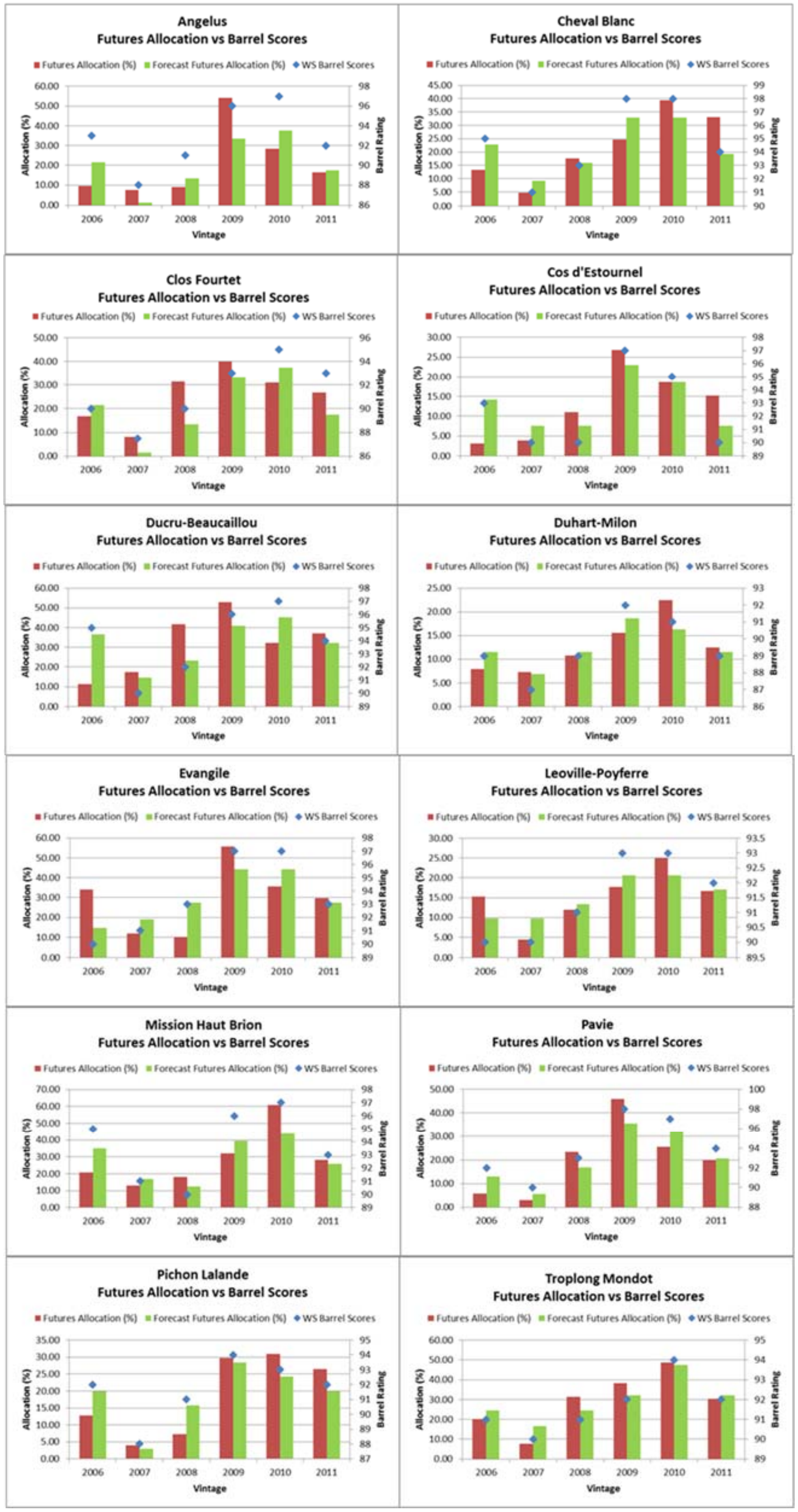

Figure 4. Actual and forecasted percentage of wine allocated for futures predicted from the regression model vs. barrel scores from *Wine Spectator*.

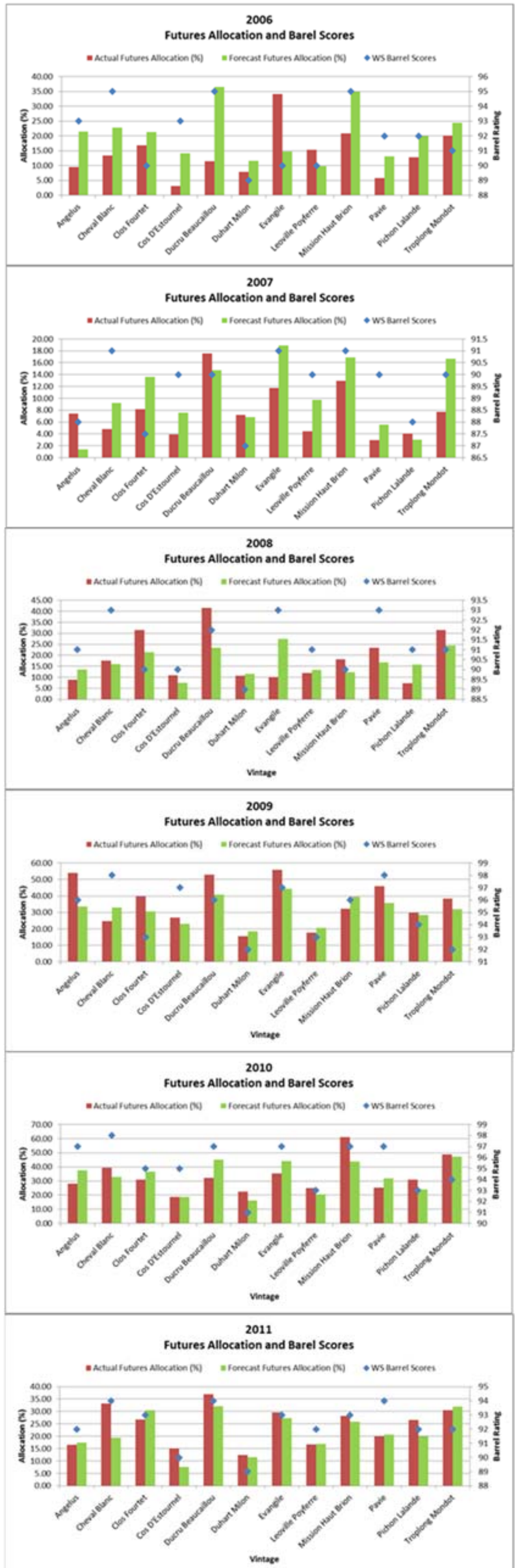

Figure 5. Actual and forecasted futures allocation percentage of Bordeaux wineries vs. barrel scores during each vintage.

Figure 6. The fit between the normalized actual and forecasted futures prices.

Figure 7 demonstrates the impact of barrel scores on each winery's futures price decision during each vintage. For each vintage, given the *Wine Spectator* barrel score, it shows each winery's actual futures price decision (labeled as "Futures Price") and the futures price forecasted based on the statistical analysis reported in Table 2 (labeled as "Forecast Futures Price").

Table 3 presents the correlation coefficient values between the Wine Spectator barrel scores (s_1), the allocation percentages assigned by winemakers (r), the futures price (p_f), and the forecasts using the regression models for the allocation (r_{jt}) and for the futures price (f_{jt}) decisions. Table 3 demonstrates that the barrel score (s_1) shows a 64% positive correlation with the winemaker's allocation decision (r) and a 62.1% positive correlation with the futures decision (p_f). These correlation values are significant. While the percentage of wine allocated for the futures market and the futures price exhibit relatively lower correlation (32.6%), this statistical analysis leads to strong fit with a 78.9% positive correlation between the amount of wine allocated for the futures market and its estimate. We obtain a strong fit for the futures price using *Wine Spectator*'s barrel scores, and this can be viewed from 97.5% positive correlation between the futures price and its estimate. As a consequence, we conclude that there is a strong relationship between the barrel scores, the percentage of wine allocated for the futures market and the futures price. In conclusion, the statistical analysis provides for the foundation for using barrel scores in the stochastic optimization model.

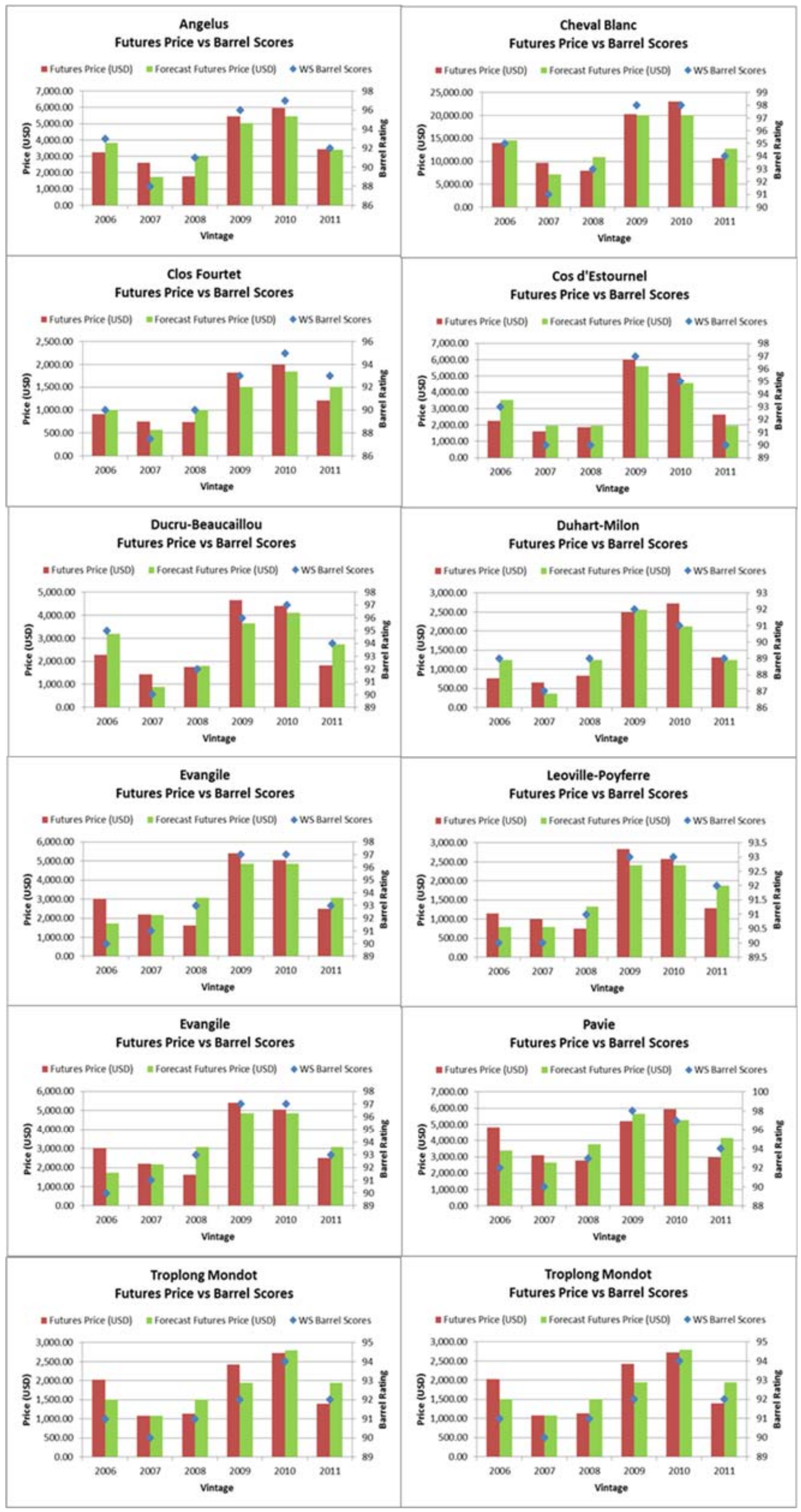

Figure 7. Actual futures price of wine, and forecasted futures price predicted from the regression model vs. barrel scores from *Wine Spectator*.

	Barrel Score (s_1)	Allocation (r)	Futures Price (p_f)	Forecast Allocation (r_{jt})	Forecast Futures Price (f_{jt})
Barrel Score (s_1)	1				
Allocation (r)	0.644	1			
Futures Price (p_f)	0.621	0.326	1		
Forecast Allocation (r_{jt})	0.824	0.789	0.380	1	
Forecast Futures Price (f_{jt})	0.634	0.303	0.975	0.384	1

Table 3. The correlation coefficients barrel scores, futures allocation percentage, forecasted futures allocation percentage, futures price, and forecasted futures price.

5.3. Financial Benefit from the Proposed Stochastic Optimization Model

The analysis in this section compares the firm's actual allocation quantity for wine futures and the futures price (p_f^0, q_f^0) provided by Liv-ex.com with the optimal choices (p_f^*, q_f^*) developed from solving the model presented in (3) – (4).

Table 4 presents the financial benefit from utilizing the stochastic optimization model in the twelve Bordeaux winemakers during the 2006 and 2011 vintages. In the empirical analysis, we estimate consumers' valuation of fine wine using the risk-free rate in order to reflect the structure of this market that is populated with the affluent customer base. We describe consumer's valuation with $\theta = (1 + r_f)^{-1}$ where r_f is the risk-free rate. Using the European Central Bank interest rate of 0.025, we have $\theta =$ 0.97561.

We estimate the winemaker's preference, the risk-adjusted discount rate ϕ, using a Capital Asset Pricing Model (CAPM) perspective. We describe the winemaker's preference as $\phi = (1+ r_f + \gamma(r_m - r_f))^{-1}$ where r_m is the market return, $r_m - r_f$ is the risk premium, and γ is the winemaker's risk measure following the Capital Asset Pricing Model (CAPM) approach. We estimate $r_m = 0.104262504$ through the average annual market returns in the Liv-ex 100 index from 2006 to 2013 describing the most sought after 100 wines in the world; it is important to note that the vintages of the most sought after 100 wines do not exist in our data set. We estimate each winemaker's risk premium through the covariance between the returns of the specific winemaker and the market returns (defined as $COV(r_j, r_m)$) divided by the variance in market returns (defined as $VAR(r_m)$), i.e., $\gamma = COV(r_j, r_m)/VAR(r_m)$. Market size is also provided by Liv-ex. We estimate the consumer heterogeneity parameter β in the Gumbel distribution by inverting the Bordeaux winemaker's allocation percentages; because most of these wineries cater to the same variety of consumer, we use the average value corresponding to $\beta = 24$.

Table 4 demonstrates that the proposed stochastic optimization model is expected to improve profits of the twelve Bordeaux winemakers by 4.10%. On average, the minimum improvement is 1.46% and the maximum is 7.12%; and the overall minimum is 0.62% and the overall maximum is 11.69%.

In sum, we conclude that the proposed stochastic optimization model is financially beneficial for the Bordeaux winemakers in determining their optimal futures price and futures allocation as it can improve their profits by more than 4%.

Winemaker	ϕ	Minimum ΔΠ	Maximum ΔΠ	Average ΔΠ
Angelus	0.96936308	1.83	9.64	4.75
Cheval Blanc	0.86918809	1.34	10.59	5.18
Clos Fourtet	0.88701179	1.91	6.98	5.29
Cos d'Estournel	0.87673835	0.88	4.72	3.01
Ducru Beaucaillo	0.88961788	2.44	9.11	5.94
Duhart Milon	0.79816123	1.06	2.51	1.58
Evangile	0.85688923	2.74	11.69	7.57
Leoville Poyferre	0.9082983	0.47	2.29	1.47
Mission Haut Brion	0.94221522	2.76	8.22	4.55
Pavie	0.97247639	0.62	8.88	4.04
Pichon Lalande	0.84258235	0.74	6.71	3.26
Troplong Mondot	0.83791897	0.69	4.08	2.54
Weighted Average		**1.46**	**7.12**	**4.10**

Table 4. The financial benefit from the stochastic optimization model with $\theta = 0.97561$; $\beta = 24$.

5.4. Financial Impact from A Wine Futures Market

We next present the benefit from establishing a futures market for winemakers. As stated earlier, the US wine industry does not have a futures market. What would be the benefit from establishing a wine futures market in the US? While this is hard to demonstrate in precision, we attempt in identifying potential benefits by comparing the optimal profit obtained from solving the proposed stochastic optimization in in (3) – (4) with the optimal profit that can obtained from setting the futures quantity equal to zero, i.e., $q_f = 0$. Note that when there is no futures market, the firm has to sell all of its wine in the retail market; we describe the profit that can be obtained in the absence of a futures market by Π^0. The profit in the absence of a futures market is calculated by substituting $q_f = 0$ in (1); this provides $\Pi^0 = \phi s_1 Q$. The percentage impact of wine futures on the profit of the winemaker is then described as follows:

$$\Delta\Pi^0 = (\Pi(p_f^*, q_f^*) - \Pi^0)/\Pi^0 \times 100\%. \quad (11)$$

The directional impact of a higher barrel score (s_1) on $\Delta\Pi^0$ is not monotone, and is parameter-dependent. We can observe from (11) that $\Delta\Pi^0$ is higher for a highly risk-averse winemaker with smaller values of ϕ.

Table 5 demonstrates the financial benefit that can be obtained from having a futures market. Using the 2006 – 2011 vintages of the twelve wineries employed in the empirical analysis, and it estimates the financial benefit from having a futures market to be 7.82% on average. The average percentage improvement in profits from the presence of a futures market ranges from 3.19% to 17.19%. The minimum financial benefit occurs at the low barrel scores as observed at Leoville Poyferre with a 1.08% profit improvement; the highest benefit is observed with high barrel scores at

Cheval Blanc with a 23.57% profit improvement. It is important to note here that Table 5 shows that the financial benefit from the presence of a futures market for the Bordeaux wineries is 7.82%, and this number is smaller than the estimate of 10.10% provided in Noparumpa et al. (2015). There are two differences in our study when compared with Noparumpa et al. (2015). First, this study considers risk-neutral consumers, rather than risk-averse consumers, reflecting the operating environment in the wine industry. Thus, we believe that this is a better estimate representing the wine futures market. Second, we use barrel and bottle scores established by *Wine Spectator*, the most widely distributed magazine in the wine industry, and Noparumpa et al. (2015) relies on Robert Parker scores. Table 6 provides the correlation between the barrel scores and bottle scores establishes by Robert Parker and *Wine Spectator* for the twelve wineries used in the earlier analysis during the same vintages of 2006 – 2011. It is evident that there is strong correlation between the tasting expert reviews, the correlation coefficient between the barrel scores of Robert Parker and *Wine Spectator* for the twelve winemakers in this study is 80.3% during the 2006 – 2011 vintages. In conclusion, Table 5 demonstrates that the wine futures market creates a significant financial benefit to the Bordeaux winemakers.

Winemaker	**Minimum r**	**Maximum r**	**Average r**	**Minimum $\Delta\Pi^0$**	**Maximum $\Delta\Pi^0$**	**Average $\Delta\Pi^0$**
Angelus	9.88	62.29	27.83	3.23	18.65	8.61
Cheval Blanc	7.58	68.20	32.57	2.81	23.57	11.58
Clos Fourtet	11.05	48.88	34.07	4.12	17.21	12.19
Cos d'Estournel	4.98	32.76	18.68	1.79	11.28	6.73
Ducru Beaucaillo	15.58	66.90	40.54	5.35	22.75	14.09
Duhart Milon	8.23	23.13	13.45	3.61	9.74	5.75
Evangile	16.10	84.20	56.50	5.97	30.02	17.19
Leoville Poyferre	3.07	14.79	9.23	1.08	5.03	3.19
Mission Haut Brion	16.29	58.23	29.52	5.36	17.99	9.42
Pavie	3.46	57.11	27.03	1.10	16.67	7.74
Pichon Lalande	4.83	39.63	22.25	1.93	14.93	8.59
Troplong Mondot	6.17	34.21	22.34	2.44	12.99	9.06
Weighted Average			**21.90**			**7.82**

Table 5. The financial benefit from the presence of a wine futures market in winemaker profits with $\theta = 0.97561$; $\beta = 24$.

Table 5 also demonstrates how futures quantity is a beneficial lever in mitigating the winemaker's quality uncertainty. The analysis shows that these wineries would benefit by using wine futures as a quantity lever: They should allocate on average 21.90% of their wine as futures, with a minimum of 9.23% and a maximum of 56.50% on average. If they get low barrel scores, the twelve winemakers allocate less wine for wine futures; the minimum occurs at Leoville Poyferre with a 3.07% of wine dedicated to wine futures. High barrel scores are desirable, and when a winery receives a high barrel score, it can reserves more wine for the futures market. This is exemplified in Evangile who allocated

84.20% of its production up for sale in the form of wine futures. We conclude that selling wine while aging in the barrel in the form of wine futures provides a good quantity lever to these winemakers interested in reducing the negative consequences of bottle score uncertainty.

	Robert Parker Barrel Score	Robert Parker Bottle Score	*Wine Spectator* Barrel Score	*Wine Spectator* Bottle Score
Robert Parker Barrel Score	1			
Robert Parker Bottle Score	0.905	1		
Wine Spectator Barrel Score	0.803	0.774	1	
Wine Spectator Bottle Score	0.752	0.731	0.860	1

Table 6. The correlation coefficients between the barrel scores and the bottle scores established by Robert Parker and *Wine Spectator* for the same twelve wineries used in this study during the 2006 – 2011 vintages.

While Liv-ex is a beneficial electronic exchange platform for trading wine, many small and artisanal winemakers cannot benefit from the presence of this market. Wineries that are traded in Liv-ex are established winemakers with a recognized brand name and image. We argue that artisanal and boutique wineries would particularly benefit from establishing a futures market. In the US, most winemakers are small and do not possess the brand recognition of Bordeaux winemakers. Similarly, few Italian winemakers are traded in Liv-ex, and a majority of winemakers in this country have limited resources to negate the financial consequences from poor reviews. We expect these small and artisanal winemakers to allocate a higher percentage of their wine to be sold in the form of wine futures; specifically, the quantity lever would be used significantly. Similarly, we expect them to reduce their futures price significantly, and therefore, they would engage in using futures as a price lever. These arguments are demonstrated in Table 7 through the analysis of Heart & Hands Wine Co., a small and artisanal winemaker in the Finger Lakes region in the State of New York. Heart & Hands Wine Co. is gaining significant reputation for its stellar Pinot Noir and is in the process of becoming a popular winemaker. We estimate the US consumers' valuation by using the risk-free rate of return based on the 12-month US Treasury Bond; we have $r_f = 0.0012$, leading to $\theta = (1 + r_f)^{-1} = 0.998801$. We again utilize the CAPM approach in order to estimate the winemaker's risk preference; we have $\phi = (1 + r_f + \gamma(r_m - r_f))^{-1} = 0.76595$. Because consumers in the US, and particularly for this small winemaker, are more homogenous compared to the Bordeaux winemakers, we describe consumer heterogeneity through a Gumbel distribution with mean of zero and a smaller dispersion parameter at $\beta = 10$. We use the scores established by *Wine Spectator* in this analysis; it is also important to note that Robert Parker and The Wine Advocate does not provide reviews of the small and artisanal winemakers such Heart & Hands Wine Co.

Table 7 demonstrates that wine futures offer financially more beneficial price and quantity levers for the small and artisanal winemakers than the Bordeaux wineries. Heart & Hands Wine Co. improves its profit by 12.51% on average with a minimum financial benefit of 11.33% and a maximum financial benefit of 14.99%. This winery has consistently lower scores than Bordeaux wineries, and the proposed model recommends to allocate a significantly larger percentage of its wine as futures: 47.61%. Thus, the quantity lever of wine futures is an extremely important risk mitigation tool for small and boutique winemakers.

Varietal	**Vintage**	***r***	**$\Delta\Pi^0$**
Pinot Noir Barrel Reserve	2007	45.96	11.91
	2008	37.41	12.55
	2009	45.03	11.33
	2010	46.89	11.93
Riesling	2008	55.92	14.15
	2009	59.11	14.79
	2010	55.27	13.90
	2011	59.60	14.99
Average		**47.61**	**12.51**

Table 7. The financial benefit from the presence of a wine futures market at Heart & Hands Wine Co. using parameters $\theta = 0.998801$; $\phi = 0.76595$, $\beta = 10$.

6. Conclusions

This paper develops a stochastic optimization model and establishes the use of wine futures as a price and quantity lever in order to mitigate quality uncertainty. The winemaker financially benefits from the use of wine futures, but more importantly, reduces the negative consequences of uncertain tasting expert reviews that get established when the wine is bottled. Selling some of her wine in advance, the winemaker recuperates her cash investment in a liquid that is uncertain in value; the firm can use this money to reinvest in business, improve quality, and expand her growth initiatives.

The study makes two sets of contributions. First, we develop an analytical model that helps winemakers improve their profits. The proposed model incorporates uncertain consumer valuations of wine futures and bottled wine and the random bottle score that is assigned to the wine at the end of the production process. The analysis leads to closed-form expressions for the optimal futures price, futures quantity and the expected profit.

Second, we test the model by illustrating how it benefits the winemakers. We show that the proposed stochastic model can improve the profits of Bordeaux winemakers by 4.10% on average. We also estimate the financial benefits from using the futures market for these Bordeaux winemakers: The futures market helps improve their profits by 7.82% on average. Thus, the model makes a substantial contribution to their bottom line profits. Finally, establishing a futures market in other regions, e.g. the US and Italy, can be extremely beneficial for the small and artisanal winemakers. Using one small winery from the

Finger Lakes region in the US, we demonstrate that this small winemaker would sell a higher percentage of their wine with deeper discounts benefiting her more than the Bordeaux winemakers. Thus, establishing a futures market would enable small and artisanal winemakers to utilize these price and quantity levers to create a healthy and sustainable growth opportunity.

This study also sheds light into the benefits from price efficiency over the traditional practice of market-clearing price mechanisms. It is often believed that winemakers, as well as many retailers, use market-clearing prices in order to sell out the inventory of short selling season items. Wine for a specific vintage can be perceived as a short selling season item, because winemakers need to replace the shelf space and limited storage space (for barrels dedicated to aging the wine) with the upcoming vintage's bottles and barrels. This paper demonstrates that, by using price as a lever, winemakers can increase their expected profits.

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Appendix

Proof of Lemma 1. Taking the derivative of (1) with respect to q_f provides the result.

$$\partial\Pi(p_f, q_f)/\partial q_f = \begin{cases} p_f - \phi E\left[p_r\left(\tilde{s}_2 | s_1\right)\right] & \text{if } q_f < d_f\left(p_f\right) \\ 0 & \text{if } q_f \geq d_f\left(p_f\right) \end{cases}.$$

Because $E[\tilde{s}_2 \mid s_1] = s_1$, the expected retail price in May of calendar year $t + 1$ is equal to the barrel score, i.e., $E[p_r(\tilde{s}_2 \mid s_1)] = s_1$. When $p_f \geq \phi E[p_r(\tilde{s}_2 \mid s_1)]$, the derivative is positive for $q_f < d_f(p_f)$, and is equal to zero for $q_f \geq d_f(p_f)$. Thus, increasing q_f to $d_f(p_f)$ provides a positive improvement in the expected profit. When $p_f \geq \phi E[p_r(\tilde{s}_2 \mid s_1)]$, the winemaker sells all of the wine in Stage 2 in the retail market. ❒

Proof of Lemma 2. We have $E[p_r(\tilde{s}_2 \mid s_1)] = s_1$, and we take the natural log of $q_f = d_f(p_f)$ where $d_f(p_f)$ is expressed as in (5). Thus,

$$q_f = d_f(p_f) = M(s_1)\left[\frac{e^{(\theta s_1 - p_f)/\beta}}{2+e^{(\theta s_1 - p_f)/\beta}}\right] \Rightarrow \frac{q_f}{M(s_1)}\left(2+e^{(\theta s_1 - p_f)/\beta}\right) = e^{(\theta s_1 - p_f)/\beta} \quad \Rightarrow \frac{2q_f}{M(s_1)-2q_f} = e^{(\theta s_1 - p_f)/\beta}.$$

Taking the natural logarithm of both sides provides:

$$\ln\left[\frac{2q_f}{M(s_1)-2q_f}\right] = \beta\left(\theta s_1 - p_f\right).$$

Rearranging the terms, we obtain the futures price expression in (6).

$$p_f\left(q_f\right) = \theta s_1 - \beta \ln\left[\frac{2q_f}{M(s_1)-q_f}\right] = \theta s_1 + \beta \ln\left[\frac{M(s_1)-q_f}{2q}\right]. ❒$$

Lemma A1. *Maximizing the objective function in* (3) *is equivalent to maximizing the expected profit expression in* (1).

Proof of Lemma A1: The objective function in (3) can be rewritten as follows:

$\Delta\Pi(p_f, q_f) = (1/\Pi(p_f^0, q_f^0))(\Pi(p_f, q_f) - \Pi(p_f^0, q_f^0)) \times 100\%$.

Because the values of p_f^0 and q_f^0 are given, the expected profit expression for the winemaker's current profit level, described with $\Pi(p_f^0, q_f^0)$, is constant. Thus, maximizing $\Delta\Pi(p_f, q_f)$ is equivalent to maximizing the expected profit expression $\Pi(p_f, q_f)$ in (1). ❒

Proof of Proposition 1: From Lemma A1, we know that maximizing $\Delta\Pi(p_f, q_f)$ in (3) is equivalent to maximizing the expected profit $\Pi(p_f, q_f)$ in (1). Thus, we focus on the properties of (1). Moreover, we know that $\Pi(p_f, q_f)$ can be expressed as a single decision variable function as in (7). Thus, it is sufficient to show that $\Pi(q_f)$ is concave in q_f. Following the proof of Theorem 1 in Li and Huh (2011); it can be shown that $\Pi''\left(q_f\right) < 0$. Using the first-order condition and (6), we have the futures price can be expressed as follows:

$$p_f\left(q_f\right) = \phi s_1 + \frac{\beta M(s_1)}{M(s_1)-q_f} = \beta + \phi s_1 + \frac{\beta q_f}{M(s_1)-q_f}.$$

Using the approach described in the derivations of Proposition 1 of Noparumpa et al (2015a), the optimal unconstrained futures quantity can be obtained as follows:

$$q_f^0 = M(s_1)\left(\frac{e^{(\theta-\phi)s_1/\beta - W\left(\frac{e^{(\theta-\phi)s_1/\beta}}{2e}\right)}}{2e + e^{(\theta-\phi)s_1/\beta - W\left(\frac{e^{(\theta-\phi)s_1/\beta}}{2e}\right)}}\right).$$

Iff $q_f^0 \le Q$, then $q_f^* = q_f^0$, and the optimal profit is equivalent to the unconstrained optimal profit, and

$$p_f^* = \phi s_1 + \beta\left[1 + W\left(\frac{e^{(\theta-\phi)s_1/\beta}}{2e}\right)\right].$$

If $q_f^0 \geq Q$, then the supply constraint is binding, i.e., $q_f^* = Q$. In this case, the optimal price is obtained by substituting $q_f^* = Q$ in (6), and the optimal profit is obtained by substituting the revised price expression into (1). ❐