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Selling now or later: commercial and storage strategy for wine

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Many types of wine have a unique property in that their quality improves over time, fostering winemakers to store and sell wine later as aged wine. The storage decision is further determined by available storage capacity, as well as multiple players in the aged-wine market. In this paper, we investigate the relationship between the mentioned wine property and storage characteristics, as well as the impact of multiple players in the aged-wine market. We find that optimal storage quantity increases with wines' quality improvement and decreases with storage costs. We find that wines with low quality improvement are highly sensitive to storage costs, while wines with high quality improvement are highly sensitive to storage capacity constraints. When there is an active secondary market for aged wine with other players with their own storage capacities, the optimal market split will depend on their relative competitiveness. As these third-party players become more competitive, a winemaker will choose to store less wine and sell more of the current vintage wine to customers and competitors. In addition, the presence of this type of competition makes the storage quantity of a winemaker more sensitive to storage costs. The storage capacity of competitors helps mitigate the negative effects of the winemaker's storage constraints, leading to a win-win situation. We hope our model formulation will provide a valuable foundation for subsequent wine research.

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Introduction

The quality of certain types of wine improves with aging; that is, the aroma and taste become more pleasant, due to chemical reactions involving its components, such as sugars and acids. Positive attitudes towards wine aging have existed since the times of ancient Greeks and Romans. Aged wine has often been treated as a socio-cultural product reflecting specific geography, identity, and symbolic value. Terroir, regional histories, and localized production practices shape perceptions of its quality and authenticity (Gade 2004; Rainer 2021). Aging of wine amplifies quality signals, contributing to its price differentiation and reinforcing the role of reputation and origin in the market (Combris et al. 1997). Anthropological studies have shown that aged wines function as markers of social distinction and cultural capital, reflecting heritage, expertise, and taste (Demossier 2018; Crenn 2004).

Modern science has developed some mechanisms of aging wine based on the grape properties, such as tannin structure, acidity, and phenolic content, and wine storage environment, such as barrel, temperature, and humidity. Such understanding helps to select the most suitable grape varieties and their vintages for aging and to optimize their aging process. With the improved quality from aging, aged wine can command premium prices. Dimson et al. (2015) identified a positive relationship between age and price of high-quality Bordeaux first-growths during their maturation. Masset et al. (2023) also identified a positive relationship between age and price of wine during the wine maturation phase as an internal component of their pricing model. Fine wine has been an investment option over the last few decades (Sanning et al. 2008; Fogarty 2010). Since 2004, the average price of fine wine has risen by 380%, according to the Liv-ex 1000, which is a cited benchmark for tracking the global price movements of fine wines. The high benefits of wine aging come with a cost. Storage cost of a bottle of wine represents a significant factor in the profitability of aged-wine production, even though it has decreased since 1970 due to a surge in prices of aged wine (Dimson et al. 2015). Storage of wine has stringent requirements with respect to humidity and temperature, and it is rather costly and time-consuming to build new suitable storage capacity. According to Wineware in the UK, the ideal storage temperature for red wine is 12 °C < 19 °C, for white wine 8 °C < 12 °C, and for champagne 5 °C < 8 °C. Even simple residential wine cellars can cost up to $180,000 to build, while the operating cost to maintain permanent temperature conditions needed for the wine aging process can also be high.

While new wine is conventionally made by a unique wine producer, multiple players with storage facilities at their disposal can engage in the aged-wine business, including winemakers and wine merchants, as well as private individuals, collectors, and owners of specialized wine storage spaces for rental purposes.

While there are plenty of secondary sources, such as popular press and academic publications related to wine storage, in order to obtain more profound insights into the ecosystem, we interviewed a sample of one winery owner and one executive of a major wine distributor, both located in Greece and with an international presence. Two consultations were conducted solely to provide contextual background for our study and were not intended to be used to empirically validate our model. The collected information relating to wine storage is summarized below:

Different types of wine exhibit very different properties for aging: some have greatly improved quality over time, and some experience no change. Even for the same winery, yields from different vintages are different in terms of suitability for aging. The quality improvement of wine that does not come from a prestigious winery often is not enough to justify the storage cost.

A storage facility on a commercial scale is very costly and time-consuming to build. Therefore, very few could afford to build their own storage facilities and would rather resort to renting them. There are privately owned storage facilities, where people can rent space to store, and consumers of these storage facilities often engage in peer-to-peer trading. Large wineries with their own storage facilities often prefer to rent out the portion of storage capacity to private wine collectors, instead of storing their own wine.

Based on information collected from our observations and other relevant information, we formulate our research questions and investigate the storage decisions related to wine property, characteristics of storage facilities, and the presence of multiple players in the aged-wine market. In particular, we seek to address three questions:

1. What is the optimal production and storage strategy for a winemaker?
2. How does the wine property interact with characteristics of storage facilities?; and
3. How does a wine property interact with competition in the aged-wine market?

Related literature

Wine as a household good has received much attention in business research. Most of the research has focused on new wine and has not considered quality improvement over time. Chandes and Estampe (2003) outlined the value chain of different wine segments in the case of Bordeaux wine. Thach and Olsen (2006) emphasized the importance of effective partnership relationships with wine distributors. Gergaud and Ginsburgh (2008) indicated that practices, technology, and skills of Bordeaux wine producers have a greater impact on wine quality than natural factors of the Bordeaux region, such as its soil, slope, altitude, and climate. Benfratello et al. (2009) and subsequently Oczkowski and Doucouliagos (2015) pointed to the role of the reputation of winemakers in determining wine prices, highlighting that customers rely on expert opinions about lesser-known wines characterized by weaker reputation and higher uncertainty. Bouzdine-Chameeva and Ninomiya (2011) analyzed the distribution channel for the Bordeaux wine export to the Japanese market. Cholette (2010) discussed postponement strategies in the wine industry.

Not all qualities of wines are sensory, and for that reason, there are information asymmetries in the wine market and uncertainty about improvement in the quality of wines over time. Consumers often rely on reputational signals in their purchase decisions, such as expert opinion and the reputation of producers, besides the intrinsic quality of wines, and see a price as a reflection of expectations about wine's quality improvement over time (Fogarty 2008; Masset et al. 2023). Consumer willingness to pay for experience goods is shaped by expectation formation, signaling, and present – future tradeoffs, which shape wine purchasing decisions under uncertainty (Ariely 2008; Thaler 2016, Behavioral economics). Products with long maturation cycles, symbolic value, and status signaling properties, such as fine wine, exhibit distinct demand patterns driven by scarcity, heritage, and brand reputation (Vigneron and Johnson 2004).

The limited literature available on aged wine is summarized in Table 1. Fogarty (2008) showed that consumers valued easily identifiable objective characteristics of premium Australian wine, such as its age, region, grape variety, and reputation. Sanning et al. (2008) studied returns of a wine portfolio based on detailed

information and viewed it as a financial investment. Storchmann (2012) identified three main topics in the emergence and rise of wine economics from the 1980s to the present day: finance, climate change, and the role of expert opinion. Dimson et al. (2015) also viewed wine as a financial investment, identifying a positive correlation between historic returns on wine and equities, with historic prices of wine peaking simultaneously with other collectables and equities, implying their shared exposure to global asset price cycles. Wine prices have benefited from the global expansion of high-net-worth customers and collectors (Dimson et al. 2015). Breeden and Liang (2017) investigated auction-price dynamics for fine wine, while Oleksy et al. (2021) investigated the role and selection of various trading venues in fine wine trading. Masset et al. (2023) also found that the age of wine contributed positively to its price, being a signal that reflects expected quality improvement over time. In this paper, we focus on the operational side of the wine storage activity.

In modeling, we borrow from the literature of durable goods since it also involves the quality change over time of a certain product. Among the most influential papers, Desai and Purohit (1998) first developed a model of vertical differentiation to compare leasing and selling of durable goods. The work has been extended to investigate the impact of competition (Desai and Purohit 1999). Desai et al. (2004) studied a channel case in which the distribution of used durables is carried out by an agent. The durable-goods literature on secondary markets is particularly relevant for us. Lacourbe (2016) studied the impact of the secondary market when a third party also engaged in the trading of used products. Hendel and Lizzeri (1999) analyzed durability issues in the context of secondary markets. Purohit (1992) investigated secondary markets with potential for product obsolescence. The results suggested that, contrary to common belief, introducing a new product version can make used products of the old version worth more if the upgrade is not well perceived by the market. Desai et al. (2004) showed that, under certain conditions, strategic decentralization through the addition of a retailer in the distribution channel can increase a manufacturer's profits. Levinthal and Purohit (1989) proposed different measures to address problems with multiple versions of a product, aiming to improve product consistency and market efficiency. Yin et al. (2010) investigated the impact of multiple used goods markets, retail, and P2P, in a channel structure, on product upgrade and price of used products.

Model formulation

We employ a model of vertical differentiation with an indefinite time horizon. This type of model has been used extensively in the literature on durable goods (Dhebar 1994). Wine has many similar properties to durable goods that can only be consumed once, with utility that cannot be derived over multiple periods, such as medical disposables, safety equipment, and accessories. Similar to other durable goods, wine can have a long shelf life and remain stable (Waterhouse et al. 2016). We thus adopt a model of vertical differentiation with an indefinite time horizon to make our analysis and results comparable to the literature on durable goods.

A monopolist producer operates over an indefinite number of discrete periods; consumers make their decisions based on their utility in each period. We adopt this monopolist producer model, since it produces a unique wine. An extension in which this unique wine is also handled by other players is also investigated.

Firm and product. A monopolist wine producer introduces wine over an indefinite number of discrete periods. Each unit of wine lasts for two periods. A wine newly introduced has a quality $\lambda^N = 1$, and in the next period, it becomes an aged wine with an improved quality $\lambda^U = 1 + \delta$. For simplicity, we assume all wine will be sold either in the current or next period. This assumption is consistent with the reality that wine improves over time but has a finite life. The firm has to decide how much wine to produce in each period, how much to sell for in the current period, and how much to keep until the next period, which will become an aged wine with higher quality. Each product has a production cost c and a storage cost s. This single appreciation factor is assumed to be constant across multiple periods.

The restrictive assumptions made above are essential to keep the tractability of the analysis and have been used extensively in the literature. This particular model setup is consistent with the durable-goods literature. The infinite time horizon of products with a two-period lifespan is a standard model of intertemporal price discrimination for durable goods, borrowed from papers in the field of economics (Stokey 1981; Waldman 1996). The assumption of a single appreciation factor constant across multiple periods is also a standard assumption in the literature (Moorthy 1984; Desai and Purohit 1998; Hendel and Lizzeri 1999). The limitations of these assumptions are discussed in the final section of our study.

Market structure and consumer strategy. The market space is vertically differentiated. Quality evaluation θ is uniformly distributed in [0,1]. In each period, consumers make their purchase decision based on their utility derived from buying wine, aged or new, available on the market. The utility is defined as $U = \theta \cdot \lambda - p$ when a consumer with quality evaluation θ purchases a unit of wine with quality λ and pays an associated price.

Firm strategy and profit function. In each period indexed as t, the wine producer introduces q_t units of wine to the home market and charges a price of p_t and keeps Q_t units of wine for a future

Table 1 Wine research.

New wine	Production	Goodhue et al. (2009)
	Distribution	Chandes and Estampe (2003)
		Thach and Olsen (2006)
	Quality	Gergaud and Ginsburgh (2008), van Leeuwen and Darriet (2016)
	Pricing	Benfratello et al. (2009), Oczkowski and Doucouliagos (2015)
	Auctions	Kwong (2009)
	Policy and regulations	Meloni and Swinnen (2013)
Aged wine	Quality evolution	Storchmann (2012)
	Investment potential	Sanning et al. (2008), Fogarty (2010), Dimson et al. (2015)
	Pricing	Breeden and Liang (2017), Masset et al. (2023)
	Trade venues	Oleksy et al. (2021)
	Storage quantity decision under capacity constraint	This paper

Table 2 Decision variables.

q_t: quantity of new wine
p_t: price of new wine
Q_t: quantity of aged wine
P_t: price of aged wine

Table 3 Parameters.

θ: quality evaluation
λ: quality of products
δ: appreciation rate of products
α: storage capacity constraint

period at a storage cost s, which will be for sale at a unit price of P_{t+1} in the next period $t+1$. Therefore, the total production in period t is $Q_t + q_t$ at unit production cost c. In each period, the storage quantity Q_t is subject to a storage capacity constraint α and production quantity $Q_t + q_t$. The parameters and decision variables are summarized in Tables 2 and 3.

The profit function for period t can be written as:

$$\Pi_t = (p_t - c) \cdot q_t + (P_t - c - s)Q_{t-1}.$$

Resulting segmentation. The market segmentation of period t, as illustrated in Fig. 1, is consistent with the literature that employs a continuous vertical differentiation model (Moorthy 1984; Tirole 1988; Desai 2001). At the home market, there are two types of products available: old wine with a higher quality $\lambda^U = 1 + \delta$ and a higher price tag P_t, and new wine with a lower quality $\lambda^N = 1$ and a lower price tag p_t. Recall that the utility function is $U = \theta \cdot \lambda - p$. From the properties of the vertically differentiated market space (Tirole 1988), we know that two marginal consumers will determine the segmentation. θ_{1t} is the consumer who is indifferent between aged wine and new wine: $(1+\delta)\cdot\theta_{1t} - P_t = \theta_{1t} - p_t$. θ_{2t} is the consumer who is indifferent between new wine and non-consumption: $\theta_{2t} - p_t = 0$. These two types of marginal consumers segment the home market into three parts: consumers between θ_{1t} and 1 purchase aged wine from the previous period (numbered Q_{t-1}), consumers between θ_{1t} and θ_{2t} purchase new wine (numbered q_t), and consumers below θ_{2t} do not purchase. Therefore, we have $Q_{t-1} = 1 - \theta_{1t}$, $q_t = \theta_{1t} - \theta_{2t}$. Therefore, the segmentation is characterized by these two sets of equations:

$(1+\delta)\cdot\theta_{1t} - P_t = \theta_{1t} - p_t$, $\theta_{2t} - p_t = 0$

$Q_{t-1} = 1 - \theta_{1t}$, $q_t = \theta_{1t} - \theta_{2t}$.

With simple algebra of the equations above, we obtain prices as a function of quantities:

$p_t = 1 - q_t - Q_{t-1}$

$P_t = (1+\delta)(1 - Q_{t-1}) - q_t$

Analysis for monopoly

In this section, we analyze the base case in which a monopoly firm sells directly into a market, both new wine from the current period and aged wine stored from the previous period. We focus on the steady-state equilibrium, in line with existing literature on durable goods using similar models. This simplification has been justified in the literature because it is easy to gain meaningful insights with it (Tirole 1988; Fudenberg and Tirole 1991; Osborne and Rubinstein 1994, Tilson et al. 2009; Hendel and Lizzeri 1999). It is also observed that the wine market tends to converge to a stable equilibrium (Milgrom and Roberts 1994; Vives 1999). We will discuss the limitations of stable equilibrium in the final section of our study.

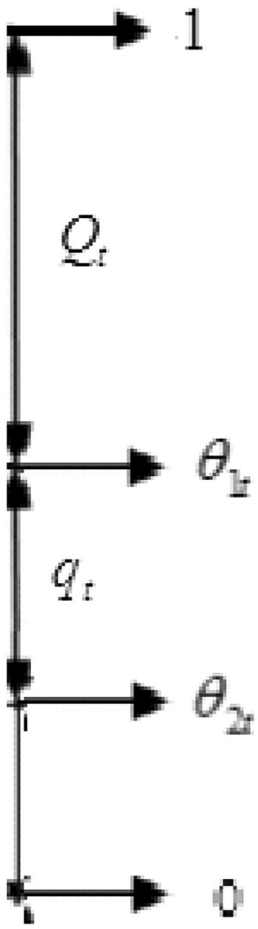

Fig. 1 Consumers' segmentation and decision time frame in a stable equilibrium.

Recall that the profit function of the monopoly firm for period t can be written as:

$$\Pi_t = (p_t - c) \cdot q_t + (P_t - c - s)Q_{t-1}$$

Subject to:

$p_t = 1 - q_t - Q_{t-1}$

$P_t = (1+\delta)(1 - Q_{t-1}) - q_t$

To analyze the long-run equilibrium strategy, we focus on a steady state where quantities and prices are constant across periods. Since quantities do not change over time in the steady-state equilibrium, we take out the notation t in quantity decisions. Hence, profit functions with time index are substituted by a steady-state model where all decision variables are constant over different periods.

Proposition 1: The optimal quantity is characterized as follows:

$Q_t = 0$, $q_t = \frac{1-c}{2}$ if $\delta < s$

$Q_t = \alpha$, $q_t = \frac{1-c}{2} - \alpha$ if $\frac{s}{c} \geq \delta \geq s$ and $\alpha < \frac{1-\frac{s}{\delta}}{2}$

$Q_t = \frac{\delta - s}{2\delta}$, $q_t = \frac{1-c}{2} - \frac{\delta - s}{2\delta}$ if $\frac{s}{c} \geq \delta \geq s$ and $\alpha \geq \frac{1-\frac{s}{\delta}}{2}$

$Q_t = \alpha$, $q_t = 0$ if $\delta \geq \frac{s}{c}$ and $\alpha \leq \frac{1-c}{2}$

$Q_t = \frac{1-c}{2}$, $q_t = 0$ if $\delta \geq \frac{s}{c}$ and $\alpha \geq \frac{1-c}{2}$

Proposition 1, as shown in Fig. 2, illustrates the most basic property of wine: the more it appreciates, the more it should be stored; how much will be stored depends on storage capacity. In zone I of Fig. 2 $\delta < s$, where the appreciation rate is too low, and the value gained is not enough to cover storage cost; it is not worth it to store any wine, and storage capacity does not play any role. In zone II and III $\frac{s}{c} \geq \delta \geq s$, where the appreciation rate is of

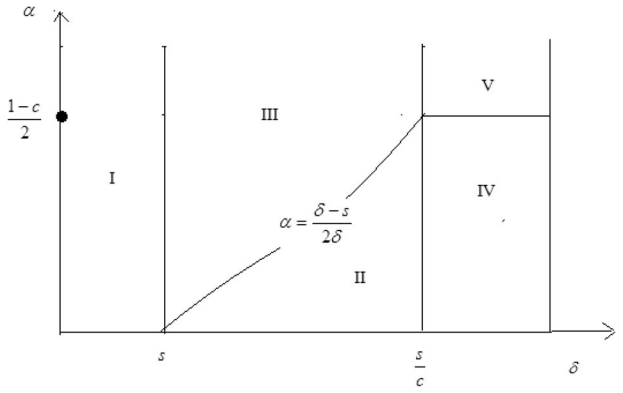

Fig. 2 Optimal solutions in different zones.

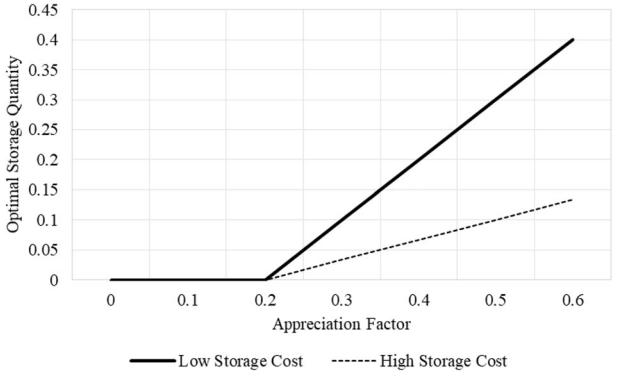

Fig. 3 The impact of the appreciation rate on storage quantity.

moderate value, only part of the wine will be stored, and storage capacity will be fully utilized if $\alpha < \frac{1-\frac{s}{\delta}}{2}$ (zone II) or partially utilized if $\alpha \geq \frac{1-\frac{s}{\delta}}{2}$ (zone III). In zone IV and V $\delta \geq \frac{s}{c}$, the appreciation rate is sufficiently high, and all wine should be stored, and storage capacity will be fully utilized if $\alpha < \frac{1-c}{2}$ (zone IV) or partially utilized if $\alpha \geq \frac{1-c}{2}$ (zone V). Note that in Proposition 1, the threshold concerning how much wine will be stored is defined by storage cost and production cost. When production cost c is low and/or storage cost s is high, $\frac{s}{c}$ shifts to the right and the firm produces a high volume of wine and it is more difficult to store everything; it is also more difficult to store all wine. When production cost c is high and/or storage cost s is low, $\frac{s}{c}$ shifts to the left and the firm produces less, and storage is less costly, and this increases the range where only aged wine is on the market. Figure 3 presents the sensitivity analysis for how decisions on optimal storage quantity change with the appreciation factor for different storage-cost values.

When the appreciation rate is too low, and no wine is stored, storage cost or storage capacity has no impact at all on storage quantity or profit. When the appreciation rate is too high, all wine will be stored, and storage cost has no impact on either quantity or profit. What is more interesting is when the appreciation rate is a moderate value and both new wine and old wine exist. The proof of Proposition 1 is available in Appendix 1: Proof of Proposition 1.

Proposition 2: In zone III, $\frac{\partial^2 Q}{\partial \alpha \partial \delta} < 0$. In zone II, $\frac{\partial \pi^2}{\partial \alpha \partial \delta} \geq 0$.

According to Proposition 2, in zone III, storage capacity is not binding; if storage cost goes up, the quantity of wine to be stored goes down, but the magnitude is reduced by a large amount. Therefore, a highly appreciated wine is not very sensitive to storage cost. In zone II, storage has already reached capacity, and lower capacity hurts profitability; the higher the appreciation rate is, the bigger the profit loss is due to capacity loss. It shows that profit becomes more sensitive to capacity once the appreciation rate goes up. This proposition shows that low appreciation wine and high appreciation wine should be managed differently - high appreciation wine is not very sensitive to storage cost but very sensitive to storage capacity, while low appreciation wine is very sensitive to storage cost but not very sensitive to storage capacity. The proof of Proposition 2 is available in Appendix 2: Proof of Proposition 2. Figure 4 presents the sensitivity analysis for how decisions on optimal storage quantity change with the appreciation factor for different storage capacity constraints.

Secondary market with third-party storage

One particular interesting characteristic of the wine market is that other players are present. As discussed in the introduction, they can be specialist shops, bars and restaurants, and private individuals who possess storage facilities suitable for wine aging. For simplicity, we label this third party as a wine shop. We assume the storage cost of the wine shop is S. In each period, the wine producer sells new wine to the market, part of which will be bought by the wine shop, which will sell it in the next period. The wine shop is a de facto competitor to the wine producer in the aged-wine market. Here, we make a simplifying assumption that the third-party competition is a single firm in order to keep tractability. The potential implications of multiple competitors are discussed later in the study. Prior research has shown that the impact of multiple competitors or a fragmented secondary market (Desai and Purohit 1998; Hendel and Lizzeri 1999).

In each period indexed as t, the producer introduces q_t units of wine to the home market and charges a price of p_t and keeps Q_t units of wine for a future period at a storage cost s, which will be for sale at a unit price of P_t in the next period. It also sells r_t units of wine at the same price of p_t to the wine shop, which will be kept at a storage cost S and will also be for sale at the same unit price of P_t in the next period. Therefore, the total production in period t is $Q_t + q_t + r_t$ at unit production cost c. In each period, the storage quantity Q_t is subject to a storage capacity constraint α.

The profit function for period t of the wine producer can be written as:

$$\Pi_t = (p_t - c) \cdot (q_t + r_t) + (P_t - c - s) Q_{t-1}$$

The profit function for period t of the third-party wine shop can be written as:

$$\Pi_t = (P_t - p_{t-1} - S) r_{t-1}$$

In the previous section, we obtained results based on the relationship between cost structure and capacity of the firm and the appreciation rate. In this section, we are interested in how the results will change with the competitiveness of the wine shop. As in the previous section, to analyze the long-run equilibrium strategy, we focus on a steady state where quantities and prices are constant across periods.

Proposition 3:

$r = 0$ if $S \geq \frac{2s+\delta}{3}$, $Q = 0$ if $S < 2s - \delta$, $r > 0$, $Q > 0$ if $2s - \delta < S < \frac{2s+\delta}{3}$

Proposition 3 illustrates the most basic property of a competitor on the aged-wine market: the more competitive it is, the more wine it will store. If $S \geq \frac{2s+\delta}{3}$, the wine shop is not competitive at all and is unable to capture any wine. The wine producer still dominates both aged-wine and new wine sales. If the wine shop becomes more competitive (but not too competitive) is $2s - \delta < S < \frac{2s+\delta}{3}$, it will capture part of the aged-wine market. If the wine shop becomes too competitive $S < 2s - \delta$, it will

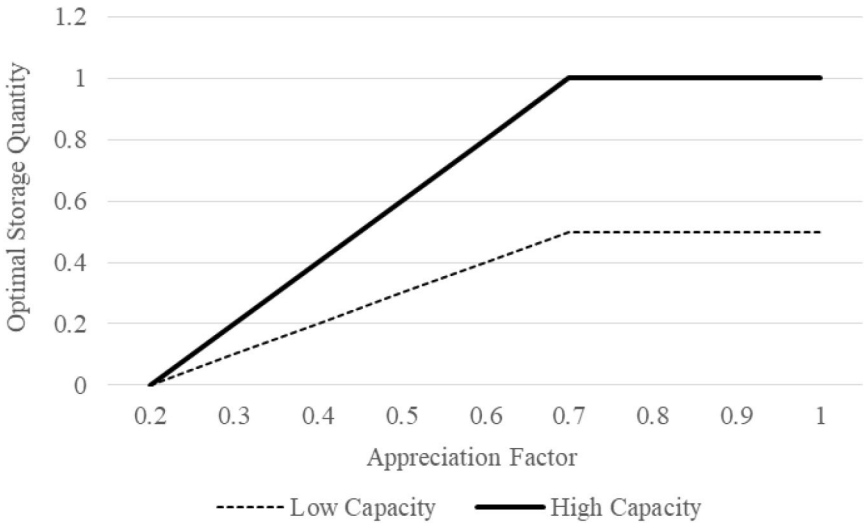

Fig. 4 Impact of storage cost on profit.

Table 4 Comparative statics of the effects of an increase in different parameters on storage decisions.

Parameter	Effect on storage quantity	Explanation of the effect
Appreciation rate	Increase	Incentivizes wine producers to delay the release of aged wine because of future price upside.
Storage cost	Decrease	Increase in the marginal cost of storing each additional unit reduces the incentive to store aged wine.
Capacity	Increase	Incentivizes wines producer to store more, provided that there is a quality appreciation.
Competitiveness of competitors	Decrease	Disincentives wine producers from investing in aged-wine business.

dominate the aged-wine market, and the wine producer no longer stores any wine.

Note that the range in which both firms have aged wine is $2s-\delta<S<\frac{2s+\delta}{3}$. If the appreciation rate gets higher, the total size of the aged-wine market becomes bigger, and this range becomes bigger. Note that the capacity requirement is $\alpha\geq\frac{\delta+S-2s}{2\delta}$, which is less than $\alpha\geq\frac{1-\frac{s}{\delta}}{2}$ if $S<s$. That is, a wine shop can relieve part of the pressure if it has more competitive storage costs. From the solution when capacity is not binding $Q=\frac{S+\delta-2s}{2\delta}$, $q=\frac{S+2s-\delta(1+2c)}{4\delta}$, $r=\frac{2s+\delta-3S}{4\delta}$, we can see that when the wine shop is more competitive, this reduces both aged and new wine carried by the wine producer, but the high appreciation rate causes the quantity change to be less sensitive.

Now we focus on the more interesting case in which both the wine shop and wine producer have positive quantities of aged wine. The closed-form solution similar to that of Proposition 1 is provided in Appendix 3: Proof of Proposition 3.

Proposition 4: when both the wine shop and wine producer store aged wine and the capacity constraint is not binding $\frac{\partial Q}{\partial s}=-\frac{1}{\delta}$; in comparison, in the absence of the wine shop $\frac{\partial Q}{\partial s}=-\frac{1}{2\delta}$.

We can see that with a competitor in the aged-wine market, the storage quantity of the wine producer becomes more sensitive to storage cost. Therefore, an increase in the storage parameter s can force aged wine to move to the storage of a competitor, namely a wine shop. The proof of Proposition 4 is available in Appendix 4: Proof of Proposition 4.

Proposition 5: When both the wine shop and the wine producer store aged wine and the capacity constraint is binding $\frac{\partial q}{\partial\alpha}=-\frac{1}{2}$, in comparison, in the absence of the wine shop $\frac{\partial q}{\partial\alpha}=-1$.

In the absence of third-party storage capability, any decrease in storage capacity of the wine shop translates into an equivalent reduction in aged-wine quantity and an increase in new wine quantity. With the presence of the wine shop, when the storage capacity of the wine producer becomes less, it is possible to use the storage capacity of a third party. Therefore, less wine will have to be consumed as new wine. This allows more wine to achieve appreciation. The proof of Proposition 5 is available in Appendix 5: Proof of Proposition 5. Table 4 summarizes the effects of an increase in selected parameters on optimal storage.

Discussion, conclusions, and further research

Discussion and conclusions. Wine, as an important beverage item, has received moderate attention in business research. Its production, distribution, and storage involve a complicated network of multiple players. In this paper, we focus on the unique property that distinguishes it from other types of products: its value increases over time. This increase in quality can lead to significant price premiums, but also to high costs. It is interesting to see how the storage decision is influenced by the wines' quality improvement potential, market reaction to the quality improvement, costs of the quality improvement, and a capacity constraint. Since the whole ecosystem of wine commerce is too complex to be fully captured, we focus only on components most relevant to the quality improvement, such as specialist wine stores, restaurants, and private customers with their own storage capacities that create competition in the aged-wine market for the wine producer. Our analysis provides the following results:

1. The quantity of wine to be stored increases with the quality improvement potential from storage. If sufficiently low, no

wine will be stored. If it is sufficiently high, all will be stored. If medium, a part will be stored. This result suggests that before any storage decision can be made, a wine producer should assess the aging potential of wine as accurately as possible.

1. Many wine producers only store wines from exceptionally good vintages with high quality improvement potential, while maintaining a continuous presence in the market. Examples of such wine producers include Prestige Cuvée Champagnes such as Dom Pérignon and Cristal, Vintage Port declarations by houses like Taylor's and Fonseca, Barbaresco and Barolo Riserva wines, such as Produttori del Barbaresco, and Reserve selections from leading Napa estates.
2. When wine has a high potential for quality improvement from storage, its storage quantity is not very sensitive to the storage cost. On the contrary, if it is low, a slight increase in storage cost can significantly reduce the quantity of wine to be stored. This implies that for wine with limited aging potential, cost control is of the highest importance; whereas for premium wine with high aging potential, cost control is less of a concern.
3. If the wine has a high potential for quality improvement from storage, a reduction in storage capacity will cause greater profit erosion to the wine producer compared to the wine with a low potential for quality improvement. Therefore, for wines with high aging potential, producers should prioritize securing sufficient storage space over low-cost storage.
4. When there is a wine shop as a competitor in the secondary market for aged wine, its competitiveness determines how the market will be split. If it is very competitive, it will sell all aged wine; if very non-competitive, it will not sell any. Otherwise, it sells a part of the aged wine. Therefore, it is essential to understand the relative competitiveness in order for wine producers to form sales and storage strategies.
5. With the wine shop present in the aged-wine market, the quantity of wine to be stored by the wine producer becomes more sensitive to storage cost because there is an alternative for aged wine. The presence of this alternative would push the wine producer to reduce the cost of its storage.
6. With the wine shop being present in the aged-wine market, the quantity of wine to be stored by the wine producer becomes less sensitive to storage capacity because there is an alternative storage space in the market. Therefore, the presence of external storage possibilities may mitigate the pressure for storage for the wine producer.

Limitations and further research. The model setup of infinite discrete periods and a two-period lifespan is a standard assumption in durable-goods economics, enabling analytical results without compromising the quality of insights. Relaxing this assumption and allowing wine quality to evolve continuously would undermine the analytical tractability of our model without changing the fundamental qualitative findings, including those related to storage costs and aging potential of wine.

The two-period lifespan for wine is an abstraction of a continuous aging process. Although some exceptional wines can remain stable for over a century, the quality appreciation parameter (δ) is simplified in the model and treated as constant for a given wine. In practice, not all wines are suitable for aging, and quality improvements are typically confined to the maturation phase - up to 20 years after the vintage - during which the price of aged wine tends to rise steadily, as documented by Dimson et al. (2015) and Masset et al. (2023). Moreover, vintage-specific factors such as climate conditions introduce substantial variation in wine quality, meaning that age alone does not guarantee higher quality or greater value - an aspect not explicitly captured by the simplified δ parameter.

For tractability, we focused on a stable equilibrium, even though fluctuations in wine quality and production volumes are common in reality. The literature has discussed the impact of such fluctuations, with the central finding being that wine producers would store more in good vintages. Such additional insights, however, do not fundamentally alter the findings obtained in stable equilibrium.

Furthermore, assuming that there is a single wine retailer in the aged-wine market allows us to maintain analytical clarity. Prior research has shown that the impact of multiple competitors or a fragmented secondary market (Desai and Purohit 1998; Hendel and Lizzeri 1999) reduces firms' incentives to invest in the aged-wine business.

While this model provides valuable insights, it relies on several simplifying assumptions required for analytical tractability, which outline potential avenues for future research. Future research could explore multi-period or continuous-time models to capture richer portfolio management strategies for winemakers, considering varied aging trajectories and subsequent aging phases, including the post-maturity phase spanning the period from 20 to 40 years after the vintage, and subsequent antique phase, when prices of wines are determined by their scarcity, rather than quality and vintage-specific attributes. This could also link the abstract appreciation parameter (δ) to measurable enological or sensory indicators, and reinterpret the storage-cost parameter (s) to operational components such as energy, space constraints, and handling, integrating process levers like barrel months or new-oak share.

One of the most important observations emerging from our expert consultations concerns the uncertainty in wine harvests. Both the quantity and quality of vintage yields are highly unpredictable and are largely driven by climate and weather conditions. In extreme cases, adverse climate events can reduce grape yields to nearly zero for certain vintages. Moreover, harvest variation determines whether a given yield is suitable for producing wines with aging potential or wines best consumed immediately. Future research should therefore incorporate these quality and quantity fluctuations into the model. It would also be valuable to introduce additional actors in the wine supply chain to gain further insights into storage decisions under such uncertainty.

Data availability

Data sharing is not applicable to this article, as the study is based on analytical modeling and does not rely on empirical datasets. Expert consultations undertaken during model conceptualization served only as contextual background and did not generate research data.

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Competing interests

The authors declare no competing interests.

Ethical approval

This study develops an analytical modeling framework and does not involve empirical research with human participants or the collection of personal data. Two expert consultations with industry professionals were conducted solely to provide a general contextual understanding during the conceptual development of the study. These consultations did not constitute human-subject research, and no identifiable or personal information was collected or analyzed. Therefore, formal ethical approval was not required. February 27, 2026.

Informed consent

All consulted experts participated voluntarily and were informed about the academic purpose of the discussions. No personal identifiers were recorded, and contributions were treated anonymously. The consultations were conducted exclusively for background contextual understanding and were not used as empirical research data. February 27, 2026.

Additional information

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