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Why Do Distilleries Produce Multiple Ages of Whisky?

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Abstract Unlike many other vintage goods, distilleries often opt to mature their stocks to different ages, selling a heterogeneous line of products which vary in quality. We develop a theoretical model to examine the maturation decisions of a whisky distillery and find that it is possible for a profit-maximizing distillery to produce multiple ages of whisky under perfect competition. Based on an analysis of retail whisky prices, we find evidence suggesting that most distilleries that produce multiple ages of whisky do not operate under perfect competition. However, a hedonic estimation of whisky prices does not find any strong link between a distillery's size and its ability to influence market prices, suggesting that distilleries may achieve market power through brand recognition.

Key words: Vintage goods, maturation, price analysis, whisky, whiskey

1. Introduction

When modeling the decisions of profit-maximizing firms, researchers tend to assume that any time between the onset of manufacturing and the final sale of a good is irrelevant. In fact, a similar assumption is likely what lead to the discovery of aged spirits. Producers would distill alcohol and then store it in wooden casks for later consumption, only to discover afterward that storage had actually matured the spirit and created a more palatable good. Whisky[1] was first produced in the British Isles several hundred years ago. Now, thanks to emigration, the relative affordability of grain, and growing international demand, there are competitive industries in the United States, Canada, Japan, and even India, all of which produce whisky using various combinations of barley, corn, rye, and wheat.

Considering the age and value of the whisky industry, it is surprising that there has been little analysis of its multi-period production to date. Goodhue, LaFrance, and Simon (2009) identify several goods whose quality improves over time: wine, timber, aged cheese, and cultured pearls, as well as livestock and most agricultural crops more generally. Wine and timber, whose maturation can take decades, have received the most attention in the context of

[1] Both "whisky" and "whiskey" are acceptable spellings, though the usage somewhat depends on the spirit's origin. Because our analysis focuses on Scotch whisky, we opt to use "whisky" throughout the paper, except in cases in which "whiskey" is more appropriate given the context.

dynamic production, though their maturation processes, the traits of the final goods, and even the general business decisions of their respective producers are not perfectly relatable to whisky. Unlike whisky, wine continues to improve once it is bottled, hence the maturation decision of wine can also be described as a dynamic problem faced by the consumer or investor, not necessarily the producer. And timber, a major topic of study in resource economics, accrues value primarily because trees gain biomass with age. Whisky, on the other hand, accrues value because quality improves, and will sell at a higher price when it is eventually bottled.

Perhaps the most interesting difference between whisky and wine or timber is that whisky distilleries consistently produce a product line in which the primary distinguishing factor within their own brand is product age. We find that the existing literature on both wine and timber does not satisfactorily explain this behavior. Conventional wisdom with respect to wine maturation is that quality increases overtime before eventually peaking. And because many exogenous factors that influence the quality of wine can vary between years (i.e., weather), the "peak" quality of a particular vintage can be difficult to predict *ex ante*. Analyses such as Jaeger (1981) therefore grant that it may be optimal to uncork bottles of the same vintage at different points in time, but only as a method of experimentation to determine peak quality. Goodhue, LaFrance, and Simon (2009) offered a recent analysis of the maturation decisions of a winery. They explicitly assume that there is a unique optimal maturation age for their theoretical analysis. Wohlgenant (1982) is somewhat exceptional in that his dynamic analysis of a winery's behavior allows for the possibility of multiple maturation ages from a single vintage. He models the pricing decision of a producer with an inventory of wines from various years. However, his model considers the total value of the inventory, and each vintage accrues value at a fixed rate from additional storage. Consequently, the actual age of stock sold is obfuscated by the model's format.

While wine economics tends to ignore the possibility of multiple optimal maturation ages, this topic has been analyzed somewhat in the context of timber harvesting. Recent work by Salo and Tahvonen (2002 and 2003), and Uusivuori and Kuuluvainen (2005) have analyzed uneven-aged management of forests. However, these analyses tend to question the existence of and convergence towards a steady state with an even distribution of age classes. The existing market conditions and characteristics of a timber stand that would give rise to multiple optimal maturation ages remain largely unanalyzed.

The purpose of this paper is to explore the decisions of whisky distilleries and attempt to determine what existing market conditions lead many distilleries to produce multiple ages of whisky. In Part 2, we provide an overview of the production process of Scotch whisky, then setup a basic theoretical model of a profit-maximizing distillery. Using some of the conditions from the theoretical model, we are able to estimate the minimum discount rates of various Scottish distilleries based on their products and retail prices in Part 3. We also employ a basic hedonic model of whisky prices to determine how age influences product price and search for evidence of market power among distilleries. Part 4 identifies areas of future study and concludes.

2. Modeling Whisky Production

2.A. Overview

Throughout the paper we will focus on Scotch whisky, though the analysis could easily be extended to other aged spirits, such as bourbon or rum. One of the key differences between Scotch and other whiskies is that Scotch whisky must be made from malted barley, whereas others (such as bourbon) are mostly made from corn. We will also refer to the spirit as "whisky" regardless of its actual age, though Scotch whisky cannot actually be sold as such until it has

been aged for at least three years. In fact, the spirit must satisfy several conditions in order to legally be sold as "Scotch whisky", one of which is its minimum maturation age. Additional conditions include bottling the whisky at a strength of no less than 40 percent alcohol by volume and no additives are permitted, the sole exception being caramel coloring E150a. We provide a general overview of the production of single malt Scotch whisky here to further elucidate the process.

Single malt Scotch whisky is made with only two ingredients: water and barley. The barley is malted during the initial phase of production by first steeping it in water, then allowing it to dry and germinate, at which point it is considered green malt. The seeds are next kilned, which halts the germination process and prevents the plant from using its stored sugars. Many distilleries in Scotland toast the green malt with furnaces powered by peat during this phase. Peat, which is decayed organic vegetable matter from bog plants, imparts the smokiness traditionally associated with Scotch whisky. Originally, peat was the primary fuel source available for most distilleries, though the advent of railroads provided distilleries with more affordable coke and coal for their furnaces. Consequently, distilleries now have much greater control over how much peat they use during the kilning process, and many distilleries' flavor profiles are only lightly peated.

After kilning, the malt is sent through rollers to crack and grind the malt, producing grist. The grist is then mixed with hot water, which completes the conversion of the malt's starches into maltose. The resulting liquid is called wort, and it is sent to a large vat called a washback. Yeast is next added to the wort, and it soon begins feasting on the sugars, converting them into alcohol and carbon dioxide over the next two to four days. After fermentation, the wort is considered wash, and it is ready for distillation. Scotch whisky is distilled in a pot still to purify and concentrate the spirit. Pot stills are large, copper containers that taper at the top into

a slender neck. Pot stills perform distillation in batches; most distilleries distill the spirit twice. Elsewhere, such as Ireland, the spirit must be distilled three times.

After distillation the spirit is a "new-make", which is essentially just un-aged whisky and typically around 70 percent alcohol by volume. The new-make is filled into oak casks and the maturation process finally begins. During the maturation process, the wood mellows the whisky, imparts some of its flavor to the spirit, and gives it its color. Generally, older whiskies are smoother and more complex than younger whiskies, as they have been in close contact with the wood for more years. Cask sizes are typically between 180 and 500 liters, with smaller casks being able to enhance the maturation process because of the greater surface area to volume ratio. Because many oak casks are reused, their original contents also add some character to the whisky. While almost all Scotch whisky is aged in casks that previously held bourbon, distilleries often use ex-sherry or rum casks, which impart their own particular flavors.

After several years of storage, the whisky evaporates and the alcohol content typically declines, though to what extent is determined by the climate and the type of warehouse used for storage.[2] Whiskies can be bottled at cask strength, which is typically around 55 percent alcohol by volume, though most whiskies are diluted to 40 percent alcohol by volume. Although whisky must be matured for at least three years, distilleries are not required to include the whisky's age on the label. If the whisky's age is not included on the label, it is known as a "no age statement" whisky. Standard bottlings with an age statement range from about 10 to 40 years old, though both younger and older whiskies are sometimes available. Unlike wine, whisky will not improve with age once it has been bottled.

[2] The evaporation rate is colloquially known as "the angel's share". In Scotland, it is approximately 2 percent per year.

A distillery will typically produce a "core range" of whiskies, which means that it will consistently bottle and sell the same types of whiskies from year to year, though these whiskies will each possess unique traits to differentiate themselves within the range. The primary distinguishing factor is often age, though distilleries can employ various techniques during the production process to create a whisky that is tangibly different in a way other than additional maturation. Examples include alternating the intensity of roasting or peating the malt, maturing whisky in an ex-sherry or rum cask, or bottling at cask strength. The ages in a distillery's core range also tend towards certain numbers. For example many distilleries produce a 10 or 12 year old as their youngest whisky with an age statement, though producing both of these ages (or an 11 or 13 year old) is very uncommon. The next youngest whisky produced will typically be between 14 and 16 years old, if another is produced at all. Ages of additional bottlings tend to increase in fixed increments, for example five or ten years. Most distilleries produce three or fewer whiskies, though some distilleries have a core range with more than ten different whiskies.

2.B. Optimal Maturation

Goodhue, LaFrance, and Simon (2009) used a model to analyze the production and aging decisions of a profit-maximizing winery when the firm's output had no impact on the market price of its good. We use a similar model here, with several minor differences. Goodhue, LaFrance, and Simon's model accounts for total quantity of output and includes a convex cost function for the production of its un-aged wines. Since our research pertains to the question of why a distillery would produce multiple ages of whisky, we instead normalize the quantity of un-aged whisky to 1 and omit distillation costs. However, we do include bottling costs, since we wish to distinguish between the marginal revenue of a bottle and its net marginal revenue later

in our analysis. We also model time discretely, since distilleries only label their whiskies' ages in whole increments.

Let a denote the age of whisky, where $a = 0, \ldots, M$ and M is the maximum maturation age beyond which whisky loses its value. We assume that M is finite but sufficiently large so as to not restrict the optimal solution. We next normalize the quantity of new-make produced in a year and examine the distillery's decision to mature portions of the batch to different ages. Let x_a be the percent of the new-make to be aged for a years before bottling. Whisky steadily evaporates during its time in storage, so let the evaporation rate of whisky be ε. Then if x_a was initially distilled, only the amount $x_a(1-\varepsilon)^a$ will be left after maturation.

Production costs are incurred during three different phases of a whisky's lifetime. We assume that the distillery has already decided to produce some whisky, and this quantity is normalized to 1, hence we omit fixed distillation costs. After distillation, the whisky is placed in wood casks and left to mature. Marginal storage costs are c_S, and given a discount factor of δ, the present value of total storage costs is $\sum_{a=1}^{M}\sum_{v=0}^{a-1}\delta^v c_S x_a$. Note that storage costs are a function of the initial amount of casked whisky and do not decrease with the volume of whisky therein. Storage costs are also constant, which is consistent with the modeling assumptions of Krasker (1979), Jaeger (1981), and Goodhue, LaFrance, and Simon (2009) with respect to wine storage. After sufficient maturation, whisky is taken out of its casks and bottled. Marginal bottling costs are c_B, and the present value of total bottling costs is $\sum_{a=0}^{M}\delta^a c_B x_a(1-\varepsilon)^a$.

After the whisky has been matured and bottled, it is finally ready to be sold. Assume that a whisky that has been aged for a years sells at a price of p_a. While price will naturally reflect consumers' preferences for quality, and product quality increases with age, it is not

necessary to assume any further relationship between price and age.[3] In this case, the present value of total revenue is $\sum_{a=0}^{M} \delta^a p_a x_a (1-\varepsilon)^a$. Combining revenue with the separate cost functions, we find that the present value of producer surplus from a year's batch of new-make is

$$\sum_{a=0}^{M} \delta^a p_a x_a (1-\varepsilon)^a - \sum_{a=1}^{M} \sum_{v=0}^{a-1} \delta^v c_S x_a - \sum_{a=0}^{M} \delta^a c_B x_a \, (1-\varepsilon)^a$$

subject to

$$1 \geq \sum_{a=0}^{M} x_a,$$

$$x_a \geq 0, \quad a = 0, \dots, M.$$

To find the profit-maximizing combination of maturation ages, we next obtain the Lagrangian $\mathcal{L} = \sum_{a=0}^{M} \delta^a p_a x_a (1-\varepsilon)^a - \sum_{a=1}^{M} \sum_{v=0}^{a-1} \delta^v c_S x_a - \sum_{a=0}^{M} \delta^a c_B x_a \, (1-\varepsilon)^a + \lambda(1 - \sum_{a=0}^{M} x_a)$ and the corresponding first order conditions

$$\partial \mathcal{L} / \partial x_0 = p_0 - c_B - \lambda \leq 0,$$

$$\partial \mathcal{L} / \partial x_i = \delta^i p_i (1-\varepsilon)^i - \sum_{v=0}^{i-1} \delta^v c_S - \delta^i c_B (1-\varepsilon)^i - \lambda \leq 0, \quad i = 1, \dots, M,$$

$$x_i \, \partial \mathcal{L} / \partial x_i = 0, \quad i = 0, \dots, M,$$

$$\lambda \geq 0,$$

$$\lambda \left(1 - \sum_{a=0}^{M} x_a \right) = 0.$$

We next use these basic first order conditions to examine the conditions under which a distillery would find it profit-maximizing to produce multiple ages of whisky. Let x_j^* be the

[3] If consumers are heterogeneous with respect to utility of quality, prices may naturally be discontinuous with respect to quality (age). Many countries also regulate the minimum number of years the spirit must aged before it can legally be sold as "whisky". In that case, distilleries are still able to sell the younger spirit, though without the name "whisky" the product price may be significantly different.

optimal amount of whisky to be matured for j years before being bottled and sold, and assume $x_j^* > 0$, $j > 0$. Without loss of generality, let $j < k$, where k identifies a second, older age that the distillery also produces, $x_k^* > 0$. We begin with the first order conditions for $x_j^* > 0$ and $x_k^* > 0$ and identify lower- and upper-bounds that the price ratio p_k/p_j must adhere to if production with multiple maturation ages is profit-maximizing.

PROPOSITION 1) If $x_j^* > 0$, $x_k^* > 0$, $j < k$, then

$$\frac{p_k}{p_j} > 1.$$

PROOF: By setting the first order conditions equal to each other and eliminating redundant terms, we find

$$\delta^j p_j (1-\varepsilon)^j - \delta^j c_B (1-\varepsilon)^j = \delta^k p_k (1-\varepsilon)^k - \sum_{v=j}^{k-1} \delta^v c_S - \delta^k c_B (1-\varepsilon)^k.$$

Since $\delta > 0$, we know that $\sum_{v=j}^{k-1} \delta^v c_S > 0$. This means that

$$\delta^j (1-\varepsilon)^j \left(p_j - c_B\right) < \delta^k (1-\varepsilon)^k (p_k - c_B).$$

Because $(1-\varepsilon) < 1$ and $\delta < 1$, $\delta^j (1-\varepsilon)^j > \delta^k (1-\varepsilon)^k$. Thus, it must be the case that $p_j < p_k$.

This result is driven by the additional storage costs incurred from aging the whisky for longer, and the fact that discounting and losses from evaporation tend to make marginal profits from younger whiskies more attractive. Although one may be tempted to naturally impose the condition $p_0 < \cdots < p_M$, this may not necessarily be the case, even though price should generally increase with quality, and quality is strongly correlated with age. No distillery produces every age of whisky, so the validity of this assumption cannot easily be checked. However,

Proposition 1 strongly indicates that older whiskies that are produced should always be more expensive, which makes intuitive sense.

PROPOSITION 2) If $x_j^* > 0$, $x_k^* > 0$, $0 < j < k$, then

$$\frac{p_k}{p_j} < \frac{\sum_{v=0}^{k-1} \delta^v}{\left(\sum_{v=0}^{j-1} \delta^v\right)(\delta^{k-j})(1-\varepsilon)^{k-j}}$$

PROOF: If we take the first order conditions for x_j^* and x_k^* and solve for c_S, we find

$$\frac{1}{\sum_{v=0}^{j-1} \delta^v}\left(\delta^j p_j (1-\varepsilon)^j - \delta^j c_B (1-\varepsilon)^j - \lambda\right) = \frac{1}{\sum_{v=0}^{k-1} \delta^v}\left(\delta^k p_k (1-\varepsilon)^k - \delta^k c_B (1-\varepsilon)^k - \lambda\right).$$

Because $j < k$, $\delta^j c_B (1-\varepsilon)^j / \sum_{v=0}^{j-1} \delta^v > \delta^k c_B (1-\varepsilon)^k / \sum_{v=0}^{k-1} \delta^v$ and $\lambda / \sum_{v=0}^{j-1} \delta^v \geq \lambda / \sum_{v=0}^{k-1} \delta^v$, thus

$$\frac{\delta^j p_j (1-\varepsilon)^j}{\sum_{v=0}^{j-1} \delta^v} > \frac{\delta^k p_k (1-\varepsilon)^k}{\sum_{v=0}^{k-1} \delta^v}.$$

The above expression can then be rearranged to find the upper limit on the price ratio.

Even though Proposition 1 establishes that older whiskies must fetch a higher price, Proposition 2 identifies their upper-bound. If the price ratio were to violate this upper-bound, then $x_j^* > 0$ would not be optimal, as the producer could earn greater profits by shifting production to an older whisky. Note that if $\delta = 1$, the distillery does not discount future values and the ratio simplifies to $k/j(1-\varepsilon)^{k-j}$, which is simply the ratio of ages weighted by the evaporation losses that occur between years j and k. With discounting, the price ratio is the ratio between the present value of marginal storage costs weighted by both evaporation losses and time preferences between years j and k. It is worth noting that this condition was derived assuming that the distillery knows with certainty that prices will be stable throughout time.

Krasker (1979), Jaeger (1981), and Ashenfelter (2008)[4] demonstrate how uncertainty with respect to future vintage quality can influence wine prices over time. But because whisky is produced in a more controlled environment, it is much less sensitive to weather patterns, hence quality uncertainty is not a significant issue with respect to aging whisky. On the other hand, both demand and input prices can fluctuate, and Jaeger (1981) and Wohlgenant (1982) found evidence suggesting that such uncertainty can influence the production and maturation decisions of a winery. For whisky, the price of barley has the greatest potential to fluctuate unpredictably from year to year, though this element of uncertainty would not affect the distillery's decision to mature a batch of new-make to multiple ages according to our model. It may then be the case that distilleries offer a diverse product line to hedge against uncertainty with respect to product price, though most distilleries have been in operation for decades, if not longer, and likely have precise expectations of future product prices. In any event, Propositions 1 and 2 establish that a distillery can find multiple maturation ages to be profit-maximizing without uncertainty or imperfect competition.

Proposition 2 has several important applications. If the evaporation rate is known, it can be used to estimate the minimum discount rate of the distillery. This can serve as a litmus test to determine whether the distillery operates under perfect competition, as an excessively high minimum discount rate would lead us to believe that the distillery has some control over price through the quantity it supplies. Alternatively, if the evaporation and discount rates are both known, we can use the upper-bound to test the hypothesis that the distillery operates under perfect competition in a more straightforward manner. Proposition 2 therefore allows us to explore the possibility that the distillery does not operate under perfect competition using only

[4] Ashenfelter's empirical work on the relationship between vintage quality and wine prices actually began over a decade earlier, in a newsletter titled *Liquid Assets – The International Guide to Fine Wines*. We refer the reader to Storchmann (2012) for a more thorough overview on the subject.

observed prices, the evaporation rate, and the discount rate. No further information about quantity is necessary, neither is further information in regards to the distillery's costs.

3. Analyzing Whisky Prices

3.A. Estimating Distilleries' Discount Rates

It is known that whisky matured in Scotland incurs annual evaporation losses of 2 percent, $\varepsilon = 0.02$, during the aging process. However, distilleries' time preferences are not readily known, so constructing the upper-bound as described by Proposition 2 and directly testing observed price ratios is not a viable option, as the appropriateness of a selected discount rate is somewhat subjective. Instead, we opt to use observed retail prices to estimate distilleries' discount rates. To do so, we collect data on single malt whisky prices to construct price ratios, then solve for the discount rate r, where $\delta = 1/(1 + r)$, for which the price ratio would exactly equal the upper bound. Because the price ratio must be strictly less than the upper bound, the calculated discount rate identifies the distillery's minimum discount rate.

Although there are approximately eighty distilleries operating in Scotland, we employ some selective criteria in our analysis that precludes many of them. First, we are only interested in distilleries that have been active for at least the past twenty years. This is because there are many distilleries that were either only recently founded or were previously mothballed and have only recently resumed production. We ignore these distilleries because their stocks may not yet be mature enough to sell older whiskies, or young distilleries may produce multiple ages to explore the profitability of various ages, or they may even sell a portion of their immature stock to raise revenue during their initial years of operation. We also only consider whiskies in a distillery's core range, and for which age is the primary distinguishing factor across products. Limited and special editions, travel retail products, and special whiskies (e.g.,

those with rum cask finishes) are also omitted from our analysis. We must obviously also exclude distilleries which only produce one age of whisky.

Without access to producer-end prices, we must rely on retail data for our analysis. We acknowledge that this somewhat influences our interpretation of observed price ratios, as consumer-end prices will include markups not paid to producers, and hence should not influence the distillery's decision to produce multiple ages of whisky. But in the case of markups that occur at a fixed rate, this has no impact on our analysis. Let P_i be the retail price of a bottle of whisky aged i years and p_i be the price paid to the producer. Let $P_i = (1 + v)p_i$, where v represents a price markup such as the Value Added Tax. Our observed price ratio is $P_k/P_j = (1 + v)p_k/(1 + v)p_j = p_k/p_j$, which is unbiased. On the other hand, retail prices may include a constant markup, which does bias the price ratio. Let $P_i = p_i + s$, where s is a fixed price markup such as shipping costs. Then our observed price ratio is $P_k/P_j = (p_k + s)/(p_j + s) < p_k/p_j$. Consequently, price ratios constructed from retail data may be downward-biased, which means that any calculated minimum discount rate r from P_k/P_j will also be downward-biased.

We collect price data from Master of Malt, one of the largest online retailers of single malt whisky in the world. We chose this retailer for several reasons. First, because it is one of the largest retailers, it is expected that differences between their prices and producer-end prices will be low. Their available stock of whiskies is also extensive, which is a relative strength compared to many other online inventories because we require at least two observations per distillery, and many other retailers either do not carry a particular brand, or will not have many of the various whiskies from a particular distillery available. Because Master of Malt is based in the UK, shipping charges between producers and the retailer are expected to be low and their prices will not include additional charges from importation, a distinct advantage over using

price data from a US-based retailer. Prices do include the Value Added Tax, though as previously discussed, this has no significant impact on price ratios. Our dataset includes whiskies from twenty-four Scottish distilleries. On average each distillery has about three observed prices. Table 1 includes further summary statistics on the data.

Table 1. *Summary Statistics – Retail Prices*

	Count	Mean	Median	Std. Dev.	Min.	Max
Price (pounds)	72	91.24	46.26	145.59	23.9	895
Age (years)	72	17.46	15.5	7.17	10	40

After assembling the price ratios, we solve for δ and r. Because many distilleries had observations for more than just two whiskies, most distilleries had more than one estimated minimum discount factor. For example, a distillery with four observations would have six different price ratios and as many as six different estimates for δ and r. But because the ratio establishes the minimum discount rate, we can simplify our results by finding the maximum value of all calculated r's for each distillery, as this identifies the minimum discount rate that satisfies Proposition 2 for all observed price ratios for a particular distillery. Figure 1 depicts the distribution of minimum discount rates for the twenty-four distilleries based on our data.[5]

[5] Some distilleries bottle their whiskies at slightly different strengths across ages. We also constructed a dataset which adjusted for alcohol content, though these results were not substantially different.

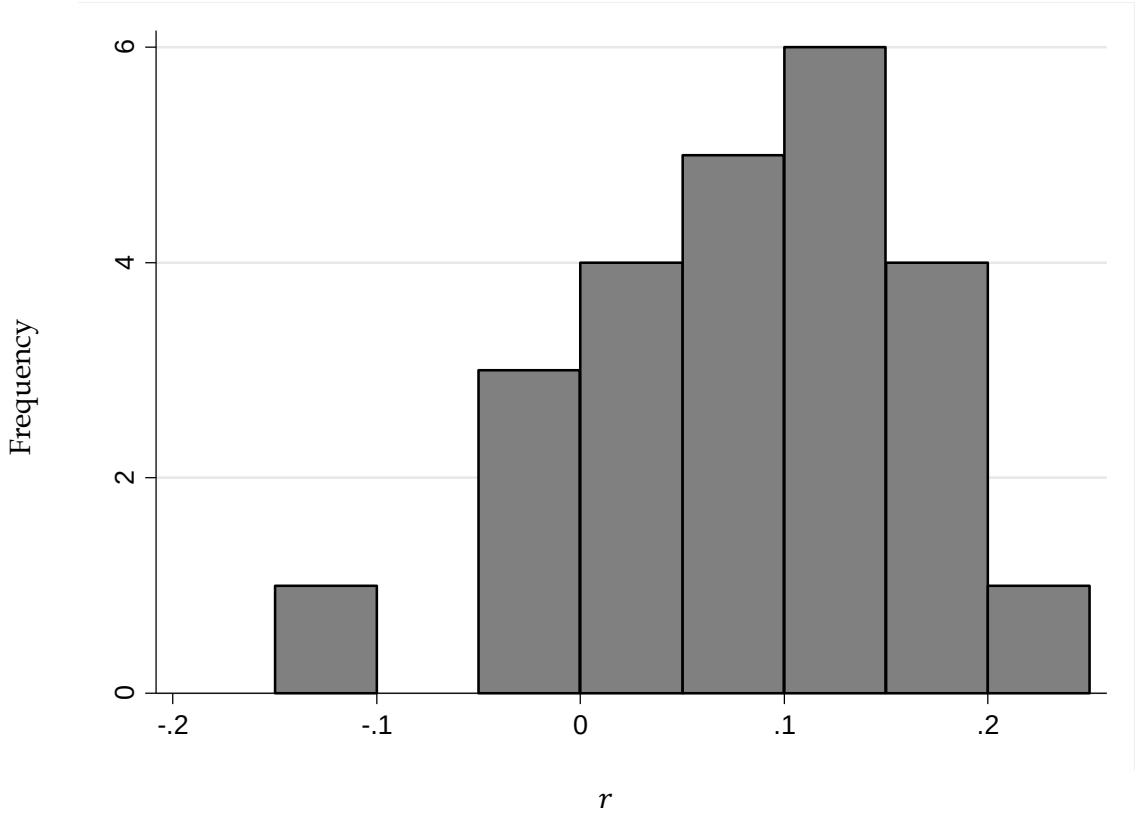

Figure 1. *Minimum Discount Rates*

According to our data, eleven of the sampled distilleries must have a discount rate of at least 0.1, or else their decision to produce some of their younger whiskies could not be described as profit-maximizing. Depending on the difference between producer-end and retail prices, retail prices may also bias the minimum discount rate downward because of price markups not faced by the producer. We can therefore only identify eleven distilleries with a discount rate of at least 0.1, though the actual number may be higher.

Figure 1 also identifies four distilleries with a minimum discount rate that is negative. This does not actually mean that these distilleries have irrational time preferences, merely that we cannot rule out the possibility that their discount rate is exceptionally low or even zero. Only seven of the original twenty-four distilleries could have a discount rate between 0 and 0.05. The discount rate is supposed to represent a distillery's preferences with respect to future

values, and since producing whisky is inherently a time-intensive process, it was not expected that most distilleries would be impatient.

There are several possible explanations that may account for such high minimum discount rates for so many distilleries. One possibility is that our use of retail prices introduces possible outliers. Note that the mean price for a bottle of whisky is considerably higher than the sample's median price, while the mean age is also higher than the median. It may therefore be the case that the older, more expensive whiskies are somehow biasing our estimates upwards. But we should emphasize that all products selected are within each distillery's core range, and are therefore standard bottlings. There are simply some distilleries that chose to produce both very old whiskies that retail for hundreds of pounds and significantly younger whiskies that retail for much less. However, our sample only includes four distilleries that produce a whisky that is at least 30 years old, and only two of those distilleries have an estimated minimum discount rate greater than 0.1. To account for the possibility that older whiskies created an upward bias, Figure 2 depicts the distribution of observed price ratios and their corresponding minimum discount rates.[6]

[6] We also conducted a sensitivity analysis of r with respect to ε. We found that if the evaporation rate were increased from 2 to 5 percent, almost half of the sampled distilleries would still have a minimum discount rate greater than 0.05.

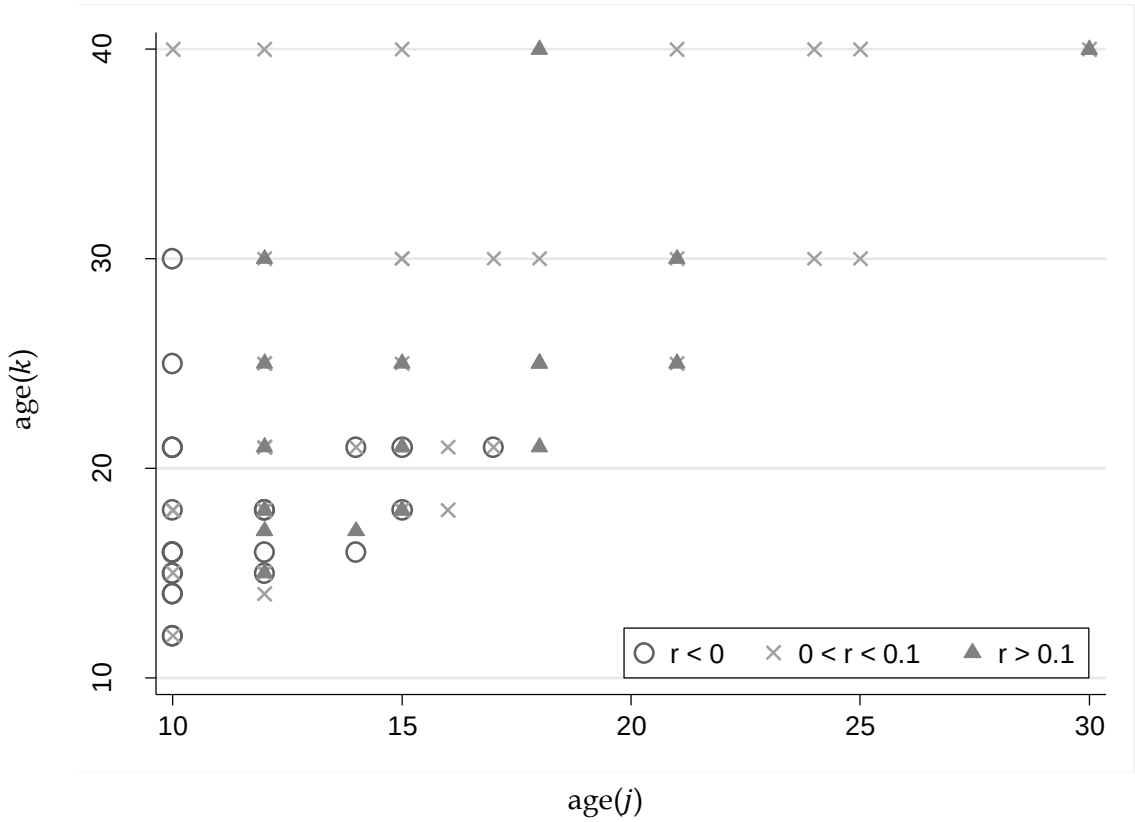

Figure 2. *Price Ratios and Minimum Discount Rates*

The distribution of minimum discount rates is clearly influenced by the older, more expensive whiskies, though the exact relationship between age and r is unclear. Most of the low values of r were calculated for observations in which both whiskies included were less than 21 years old. Higher minimum discount rates have a much wider distribution. It was expected that low minimum discount rates would be concentrated among price ratios where both whiskies were relatively young, yet we also expected that high minimum discount rates would be concentrated among price ratios between very old and very young whiskies, and this is decidedly not the case. Many of the calculated minimum discount rates that exceed 0.1 are found between mid-ranged whiskies and young whiskies, whereas many of price ratios that include a whisky aged at least 30 years lead to an estimated r that is between 0 and 0.1. For example, our data include an observation for a price ratio P_{40}/P_{10}. Given these observed prices

and an evaporation rate of 2 percent, we estimate that the distillery must have a discount rate of at least 0.018, which appears to be reasonable. In fact, of the twenty observed price ratios with at least one whisky aged 30 years or more, only four calculated r's exceed 0.1. The inclusion of exceptionally old whiskies is therefore not the source of upward-bias in our r estimates.

An alternative explanation is the possibility of imperfect competition. There are approximately 80 active distilleries in Scotland, the largest of which accounts for less than 4 percent of total industry capacity. Under perfect competition, we imposed the assumption that that p_a was fixed. Instead, we will consider the implications of market power when the distillery's output can impact its product price. In this case, the price the distillery faces for a whisky aged a years is $p_a(x_a)$, where $p_a(x_a)$ is decreasing in the quantity produced and is at least once differentiable. If we were to setup the Lagrangian again and analyze its first order conditions, we would find multiple maturation ages can still be optimal ($x_j^* > 0$, $x_k^* > 0$, $0 < j < k$), provided that

$$\frac{p_k(x_k^*)}{p_j(x_j^*)} < \frac{\sum_{v=0}^{k-1} \delta^v}{\left(\sum_{v=0}^{j-1} \delta^v\right)(\delta^{k-j})(1-\varepsilon)^{k-j}} + \frac{\sum_{v=0}^{k-1} \delta^v}{\delta^k (1-\varepsilon)^k}\left(\frac{1}{p_j}\right)\left(\frac{\delta^j p_j'(x_j^*) x_j^* (1-\varepsilon)^j}{\left(\sum_{v=0}^{j-1} \delta^v\right)} - \frac{\delta^k p_k'(x_k^*) x_k^* (1-\varepsilon)^k}{\left(\sum_{v=0}^{k-1} \delta^v\right)}\right).$$

Proposition 2 was useful because it only required the evaporation rate and observed prices, but estimating δ and r using the new upper-bound requires knowledge of x_a^* and the marginal change in price, or the elasticities of price for both p_j and p_k. To our knowledge, no such estimations have been done to date, necessitating our omission of the second term in the original estimations. However, the second term has the potential to bias estimates of δ and r if it is omitted. For example, if $\delta^j p_j'(x_j^*) x_j^* (1-\varepsilon)^j / \sum_{v=0}^{j-1} \delta^v > \delta^k p_k'(x_k^*) x_k^* (1-\varepsilon)^k / \sum_{v=0}^{k-1} \delta^v$, the second term will be positive and the true upper-bound will be greater than the specification of

Proposition 2. In this case, estimates of r that are not calculated with the second term will be upward-biased. Consequently, a distillery's market power has the potential to influence our estimated minimum discount rates.

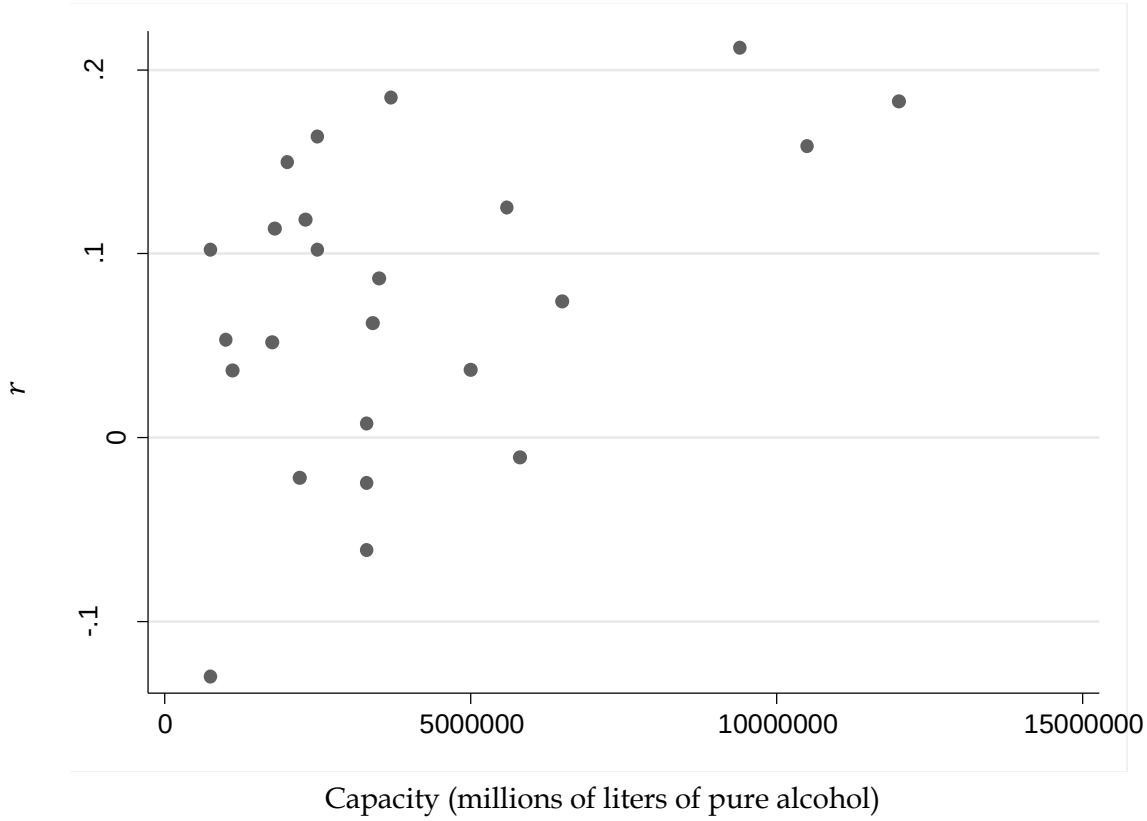

Figure 3. *Distillery Capacity and Minimum Discount Rates*

Figure 3 demonstrates the relationship between a distillery's capacity and its estimated minimum discount rate. There appears to be at least a positive, but weak relationship between distillery capacity and our estimated minimum discount rates. This indicates that larger distilleries tend to have higher estimated minimum discount rates. In fact, four of the eleven distilleries with $r > 0.1$ are among the ten largest Scotch malt whisky brands by world market share. Another of the top ten largest distilleries has a discount rate of at least 0.087 using the specification from Proposition 2. Only one of the ten largest distilleries included had a

minimum discount rate that is reasonably low, $r > 0.008$. The remaining four of the ten largest brands were out of sample. Additional distilleries with $r > 0.1$ either tended to be located in regions with only a few distilleries (e.g. Islay and Campbeltown) or market themselves as "luxury" brands, lending credence to the hypothesis of market power through brand differentiation.[7]

3.B. A Hedonic Model of Whisky Prices

During our theoretical analysis, we made no assumptions in regards to the shape of $\{p_a\}$. This is because the precise relationship between the price of whisky, product traits, and firm market power has not yet been studied. To further understand what factors influence the price of whisky, we therefore assemble a second dataset and perform a hedonic price analysis on single malt Scotch whiskies. We test several different empirical specifications, though the model has the general form

$$price_i = \alpha + \beta' \boldsymbol{X}_i + \gamma' \boldsymbol{Y}_i + e_i,$$

where $price_i$ is the retail price (measured in pounds) of the ith whisky in the dataset. $\boldsymbol{X}_i$ is a vector exogenous variables that are specific to product traits of observation i including age, a dummy variable if the expression is a No Age Statement [NAS] whisky, its alcohol content by volume [ABV], whether the whisky was finished in a sherry cask, and the differences between its age and the ages of the next oldest and youngest whiskies from the distillery's core range. $\boldsymbol{Y}_i$ is a vector of exogenous variables specific to the particular distillery, including distillery capacity and dummy variables for each whisky-producing region in Scotland.

[7] Distilleries with a minimum discount rate of at least 0.10 include Balvenie, Bowmore, Bunnahabhain, Dalmore, Fettercairn, Glenfiddich, Glenlivet, Highland Park, Macallan, Pulteney, and Springbank. Laphroaig was the only top ten brand with a minimum discount rate below 0.05.

Unlike the analysis in 3.A, which required the omission of whiskies that varied from other expressions in a way other than age (e.g., cask strength whiskies), no such restriction is necessary here. We are also able to include data from distilleries with only one observation. However, we do exclude observations from distilleries that have been operating for less than twenty years, as they may still be adjusting their product line to find the profit-maximizing range of expressions. Only whiskies from established distilleries' core range are included. Whiskies specific to the travel retail market, limited editions, and independent bottlings are still omitted. Table 2 details the summary statistics for the data used in our analysis.

Table 2. *Summary Statistics – Price Hedonics*

	Count	Mean	Median	Std. Dev.	Min.	Max
Price (pounds)	149	57.59	41.35	47.95	20.51	264.95
Age (years)	116	15.60	14	5.75	8	40
NAS	149	0.22	0	0.42	0	1
ABV	149	44.03	43	4.47	40	60
Sherry Finish	149	0.28	0	0.45	0	1
Next Youngest (years)	58	4.74	4	2.80	1	15
Next Oldest (years)	71	4.79	4	2.79	1	15
Unique	149	0.38	0	0.49	0	1
Distillery Capacity	149	3610872	3300000	2863231	90000	12000000
Highland	149	0.30	0	0.46	0	1
Speyside	149	0.36	0	0.48	0	1
Lowland	149	0.04	0	0.20	0	1
Island	149	0.11	0	0.32	0	1
Islay	149	0.13	0	0.33	0	1
Campbeltown	149	0.06	0	0.24	0	1

After assembling the dataset, we run various regressions to determine what effect various factors have on product price, including the possibility of market power. We try three different specifications for age while varying the additional exogenous variables included in the model. Models (1-4) include age as a linear variable, whereas models (5-8) include both age and age-squared, and models (9-12) have only age-squared. Models (1), (5), and (9) regress price on

age, a No Age Statement dummy variable, and an intercept. Models (2), (6), and (10) include all of these, and additional variables for the whisky's alcohol by volume and a dummy variable if the whisky was sherry-finished. To examine the possible impacts of market power, and gauge product substitutability within individual brands, models (3), (7), and (11) include distillery capacity, as well as the number of years difference between an observation and the next youngest and oldest whiskies from that distillery's core range, which may serve as substitutes. In the event that the whisky is not comparable to the distillery's other products, we include an additional dummy variable when the product is unique. Lastly, models (4), (8), and (12) include fixed effects for each whisky-producing region in Scotland. Regression results are presented in Table 3.

Table 3. *Regression Results*

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Intercept	-60.38	-104.57	-92.30		-27.48	-71.39	-61.75		8.42	-43.35	-34.00	
(t-stat)	(-8.30)**	(-4.66)**	(-3.79)**		(-1.46)	(-2.61)**	(-2.12)*		(2.17)*	(-1.97)+	(-1.45)	
Age	7.76	7.56	7.65	7.80	3.98	3.46	3.62	3.12				
	(17.74)**	(17.03)**	(10.39)**	(10.52)**	(1.95)+	(1.71)+	(1.60)	(1.39)				
Age^2					0.09	0.10	0.10	0.11	0.19	0.18	0.17	0.18
					(1.90)+	(2.07)*	(1.88)+	(2.19)*	(17.72)**	(17.15)**	(10.48)**	(10.77)**
NAS	106.80	100.45	102.26	102.95	73.91	64.48	66.65	61.49	38.00	32.93	33.13	32.53
	(12.34)**	(11.13)**	(8.57)**	(8.64)**	(3.82)**	(3.31)**	(2.99)**	(2.76)**	(6.24)**	(5.23)**	(4.28)**	(4.25)**
ABV		1.06	1.02	0.65		1.12	1.09	0.72		1.19	1.17	0.78
		(2.08)*	(1.91)+	(1.14)		(2.21)*	(2.06)*	(1.28)		(2.35)*	(2.19)*	(1.39)
Sherry		5.16	4.36	6.40		5.48	4.59	6.83		6.10	5.03	7.21
		(1.03)	(0.87)	(1.24)		(1.12)	(0.93)	(1.35)		(1.24)	(1.01)	(1.42)
Capacity			-0.54	0.38			-0.26	0.82			0.04	1.13
			(-0.68)	(0.41)			(-0.33)	(0.87)			(0.05)	(1.23)
NextYoungest			-0.54	-0.66			-0.03	-0.07			0.97	0.79
			(-0.36)	(-0.45)			(0.02)	(-0.05)			(0.71)	(0.58)
NextOldest			-2.19	-2.23			-2.03	-2.04			-1.83	-1.87
			(-2.39)*	(-2.43)**			(-2.22)*	(-2.23)*			(-2.01)*	(-2.06)*
Unique			-10.68	-9.76			-9.75	-8.73			-8.27	-7.56
			(-1.30)	(-1.18)			(-1.20)	(-1.07)			(-1.02)	(-0.93)
Regional FE	NO	NO	NO	YES	NO	NO	NO	YES	NO	NO	NO	YES
R-squared	0.6880	0.6989	0.7115	0.8880	0.6955	0.7077	0.7187	0.8919	0.6875	0.7017	0.7135	0.8904

**1%, *5%, or +10% significance

Models (1-4) consider the average marginal effect of an additional year of maturation. For whiskies bearing an age statement, the marginal effect of a year is between 7.56 and 7.80 pounds, and all of these coefficients are statistically significant to 1%. Models (5-12), which include a nonlinear term for whiskies' age, perform at least as well, if not better than the first four models. The coefficient for age-squared is also positive, indicating that the price of whisky is likely convex in age.

The average retail price of a No Age Statement whisky is approximately equivalent to a whisky with an age statement of 14 years. This is somewhat high, but not surprising. While some NAS whiskies are affordable entry-level whiskies, others are more complex and subject to innovative production techniques. Considering that most NAS whiskies have no age statement because they are younger than 10 years old, this indicates that either the manufacturing techniques involved in producing many NAS whiskies are either more expensive than standard processes, or that consumers have difficulty comparing the quality of NAS whiskies to those with age statements, and pay a premium. The coefficient for the NAS dummy variable appears to be somewhat correlated with additional factors; as additional variables were introduced the coefficient slightly decreased and lost some statistical significance, but it remained positive and significant at the 1% level.

Including a variable for alcohol by volume generally improved all models' performance, but it does affect the coefficient for the intercept. And because of high correlation (ABV was concentrated between 40 and 46 percent), its introduction to the regressions simultaneously decreased the coefficient of the intercept by about 40, the minimum value of ABV variables, and decreased its precision. According to the various models, whiskies bottled at a higher strength tend to sell for about 1 pound more per percentage point.

Our specifications also include dummy variables to gauge the price effect of sherry maturation and differences in prices attributable to the styles from the various regions. In the case of sherry maturation, we find no statistically significant evidence that it affects product price. We do find that the inclusion of regional fixed effects improves model performance. However, the hypothesis that these coefficients are in fact all equal could not be rejected at the 10% level for models (4), (8), or (12).

Additional variables were also introduced to gauge the market power of a distillery. Although we do not have output data, we use distillery capacity as a proxy, though we find that the coefficient for this variable is small and not statistically significant across models. We also include variables that measure the difference in age between observed whiskies and the next youngest and oldest whiskies from each distillery. We find that the presence of younger whiskies has no statistically significant effect on the price of the next oldest whisky. However, if the whisky is not the oldest expression in the product line, the availability of the next oldest whisky decreases its price. This suggests that there is some substitutability between whiskies from a distillery, but that consumers would prefer to buy the next oldest whisky rather than the next youngest.

4. Conclusion

This paper presents a preliminary analysis of the production decisions of whisky distilleries. Because the final product requires years of maturation, standard production models are inadequate when trying to study the production of multiple ages of whisky. We recognize that there are very few vintage goods and that neither wine nor timber, the two main examples of vintage goods, is a perfect substitute for modeling whisky. The dynamic production models in the forestry literature focus on the increasing quantity of timber available over time, whereas

the quantity of casked whisky decreases over time and simultaneously improves in quality. Wine similarly improves with age, though it tends to be characterized as having a unique optimal maturation age. Whisky distilleries, on the other hand, typically do not age all of their whisky to a uniform age, but will instead bottle amounts after different years of maturation.

We find that the decision to produce multiple maturation ages of whisky can be consistent with perfect competition, and identify natural upper- and lower-bounds on the price ratios of whiskies. Because the evaporation rate of casked whisky is known, we are able to use the upper-bound and observed retail prices to estimate the minimum discount rate of several distilleries. We find that the minimum discount rates for many distilleries are actually quite high. This suggests that the Scotch whisky industry is not perfectly competitive, in spite of the presence of so many active distilleries.

We also perform a basic empirical analysis to determine how maturation, various production techniques, and distillery output affect the retail price of whisky. Although we find that the price of whisky increases with age, models which include age as a linear and a nonlinear term seem to perform equally well. We therefore cannot say whether the price of whisky is strictly convex, convex, or linear with respect to age, though the evidence does at least suggest that the price is not concave with respect to age. We also find that No Age Statement whiskies tend to retail at about the price of a 14 year old whisky, and that bottling whisky at even slightly higher strength should increase the price. Maturing whisky in an ex-sherry cask, on the other hand, does not seem to increase the price of whisky. We also find no evidence that distillery size affects the retail price, though if the distillery produces whiskies with different age statements, the older whiskies will tend to decrease the prices of younger whiskies, suggesting some substitutability within a brand.

Based on our analysis, we find that it is very unlikely that the Scotch whisky industry is perfectly competitive. Instead, it is probable that consumers differentiate many of the different brands, which would create monopolistic competition. This may at least partially explain why distilleries produce multiple ages of whisky, though not necessarily why they choose particular ages, or how many expressions they choose to produce in total. Future work should consider further developing a model with monopolistic competition and product quality. It may be the case that this greatly influences a distillery's decision to produce a line of whiskies of various quality levels. We also anticipate that including the utility maximization decisions of heterogeneous consumers may lend itself to this analysis. The aged spirits considered could likewise be broadened to include other spirits, including Irish whiskey, bourbon, and even rum.

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