Product semantics and wine portfolio optimisation

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Abstract: Semantics is an important aspect of product design. Quantitative models of product semantics can enhance product decisions and positively contribute to a product's market position. This paper demonstrates the value of linking product semantics, design, pricing and manufacturing decisions in a wine-making optimisation problem. A manufacturing model of the wine-making process allows manipulation and optimisation of wine flavours. Wine bottle shapes are designed using conjoint analysis to convey semantic messages of wine flavour. The shape and flavour models are combined to maximise profitability of a portfolio of wines with different flavours, price points, quantities produced, and matching bottles. Semantics are shown to enhance the portfolio, including profitability.

Keywords: product semantics; design optimisation; wine; interdisciplinary design; multi-disciplinary design; conjoint analysis.

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1 Introduction

User emotions play an important role in product design. Assessing quantitatively the significance of emotions on the overall design of a product, specifically in financial terms, is an important step in establishing product semantics as a valuable element in product development. Product semantics have been defined as

> "the study of the symbolic qualities of the man-made forms in the context of their use, and the application of this knowledge to industrial design." (Krippendorff and Butter, 1984)

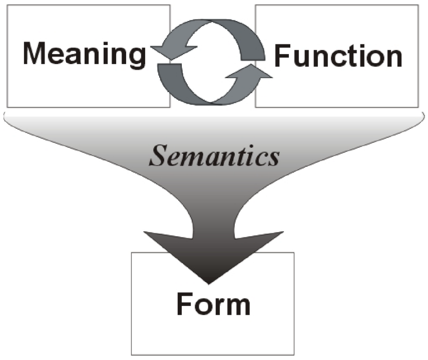
Product semantics lie within the larger realms of industrial design and ergonomics, which are considered to be 'link' disciplines that intersect with the product design process at various points (Aoussat et al., 2000).

Krippendorff (1995) argues that the emphasis in product design has shifted from functionalism, where form follows function (Eco, 1980 from Lin et al., 1996), to product semantics, where form follows meaning. Yet, product semantics can contribute to both 'form follows function' and 'form follows meaning'. As Lin assert,

> "in semantic terms, the symbolic meanings of objects include connotation and denotation, which are both essential to successful products. Denotation is relevant to the relationship of the symbol and the referent …. Connotation is relevant to the relationship of the symbol and the properties or adjectives of the referent." (Lin et al., 1996)

If the symbolic communication of objects includes connotation (form follows meaning) and denotation (form follows function), then product semantics arguably address both meaning and function, as illustrated in Figure 1.

Figure 1 Product semantics can communicate both function and meaning



Petiot and Yannou suggest that

> "to improve attractiveness, a well-designed product should not only satisfy requirements, defined objectively, but should also satisfy consumers' psychological needs, by essence subjective." (Petiot and Yannou, 2004)

They argue that not all psychological needs are purely subjective. The need to interpret knowledge found in the world and translate it to the mind is a psychological need that humans experience every day. The need itself is objective, not subjective – every human requires this ability. Product semantics can address this objective need and hence provide an objective, quantifiable contribution to product design.

Norman (1988) asserts that there are two types of knowledge about objects: knowledge stored in the head, referred to as 'in-head knowledge', and knowledge stored in the world, referred to as 'in-world knowledge', In-world knowledge is accessible and readily retrievable, while in-head knowledge is not readily retrievable and can require learning and memorisation in order to be stored. However, in-world knowledge requires interpretation and can be unaesthetic in design – such as labels and instruction manuals (Norman, 1988). Products with semantics specifically designed to articulate in-world knowledge can add aesthetically-pleasing in-world knowledge to products, in some instances eliminating the need for labels and instruction manuals. Product semantics can be 'sign vehicles' that act as symbolic communication tools for a product's design (Eco, 1980 from Lin et al., 1996; Hsu et al., 2000). Besides trying "to explain which messages a product expresses or represents (Petiot and Yannou, 2004)", semantics can explain, inform, and even enhance actual product features. Brunswik (1952) argues that a product model should link 'subjective quality' controlled by the subject's perceptions, and the 'design elements' represented by the physical characteristics that define the product.

In this spirit, this paper attempts to use product semantics to communicate wine flavours through a wine bottle's shape, allowing the consumer to interpret both the function of the wine (will the wine go well with red meat?) and the meaning of wine (does bringing this wine to a dinner party imply that I am thoughtful or frivolous?). Furthermore, such semantics are placed within a quantitative decision-making model in order to demonstrate the power of such quantification within a model-based design process. Product semantics can improve the competitiveness of a product (Bloch, 1995; Hsiao and Wang, 1998). However, methodologies for quantifying this improvement in terms of sales benefits and balancing it with other factors in the product design process remain undeveloped (Chuang et al., 2001). Mathematical design optimisation is effective at capturing such trade-offs, provided designs can be modelled in a quantitative manner (Papalambros and Wilde, 2000). The model-based design process in this paper uses a design optimisation approach to maximise economic benefit, including product semantics as a quantified link between manufacturing costs and product demand.

Section 2 describes a general approach for wine-making optimisation, consisting of modelling the semantics of bottle shapes, formulating wine recipes, and populating a winery's portfolio. Section 3 describes how to formulate and optimise a wine portfolio, making use of the models in Section 2. The results demonstrate the value contributed by the quantification of semantics. Clearly, the reality of wine making and purchasing is much more complex than what is presented here. Initial capital investment and practical availability of grape varietals may overshadow the effects included in the proposed decision model. Nevertheless, the work presented is a good starting point for a quantitative approach to a highly complex product development process.

2 Wine-making optimisation

Selecting a wine portfolio to produce and market involves artistic, manufacturing, and business decisions. The optimisation model described in this section addresses three decisions of the wine-making process: designing semantic wine bottles, formulating wine recipes, and populating the winery's portfolio. The latter two decisions are included in the optimisation so as to elucidate the impact of product semantics on overall design.

Wine bottle shape designs are optimised to convey a semantic message of the wine's flavour-theme. The effectiveness of the semantic properties of the bottle is part of the wine's overall desirability, which also depends on manufactured qualities. Different bottles are designed for different wine formulations within a portfolio, thereby enhancing the distinctiveness of the individual products within the product family.

Wine recipe formulation involves grape blending, manufacturing steps, and resulting wine qualities (i.e., sweetness and other flavours). The formulation must specify the proportions of grape varieties to be used and manufacturing process variables. The resulting formulations will have certain wine qualities grouped by their thematic flavours and placed in wine bottles that semantically communicate these flavour themes to the consumer. Grape and manufacturing costs and sales income are linked to maximise profitability.

The wine portfolio design balances manufacturing resource limitations, demand for various wine formulations, financial considerations, and the product cannibalisation that may occur by marketing too-similar products. The portfolio model separates wine formulations and price points so that no two wines taste too similar or cost the same amount.

The wine formulation, bottle design, and portfolio design models are now discussed in more detail. When combined and optimised, they offer a holistic approach to the wine development process with particular attention to the role semantics play in the final portfolio design.

2.1 Modelling semantic bottle shapes

When consumers begin the selection process for a bottle of white wine, they have certain preferences that they are looking to satisfy in their wine purchase. They may want a wine that goes well with fish or they may be buying a bottle of wine for a barbeque. They may know that they like sweet wines but not dry wines. However, most wine bottles have little or no visual indication of the flavours the consumer will experience upon drinking the wine. Typically, the consumer is presented with an artfully designed bottle and label that merely state the type and origin of the grape used, and the year and location of manufacture of the wine. Wine is a product that relies on a great deal of Norman's 'in-head' knowledge cited above.

There is little time to convey wine qualities in the brief moment that the typical consumer spends on selecting a bottle of wine. The typical consumer is not likely to have much in-head knowledge about wines, especially ones not previously tried, and so wineries must rely on subtle marketing messages in the wine's packaging. In a less-than-a-minute decision time frame, product semantics play an important role. If the message the winery attempts to convey in the packaging is not the same as the one the consumer interprets, the result can have a negative impact on the particular wine and possibly on the winery's entire portfolio. For example, a supermarket shopper quickly picks a bottle of white wine to go with dinner, thinking that it looks like it will taste 'sweet'. Upon drinking the wine, the consumer discovers the wine is actually very dry and does not like the taste. Now that the consumer has plenty of time to study the wine name and packaging over the course of dinner, it is possible that the consumer will feel misled and remember the wine and maker negatively. Therefore, 'in-world knowledge' must be semantically conveyed by wine bottles with a clear, intentional message about the flavour qualities of the wine. The flavour qualities, referred to as 'flavour-themes', studied in this model are 'Sweet and Fruity', 'Dry and Crisp' and 'Nutty and Oaky'.

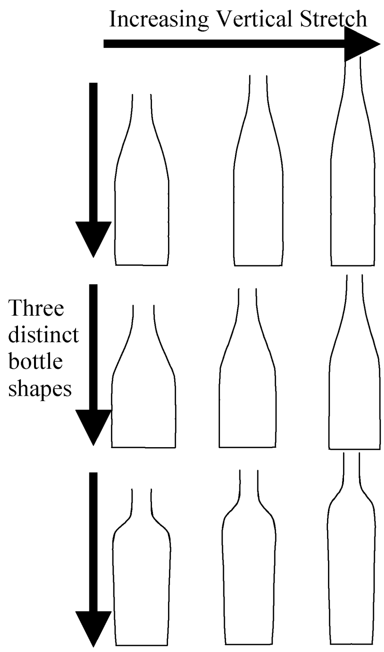
There are various factors that influence the appearance of a wine product. Large wine companies have departments dedicated to designing labels, foils, closures, carton cases, and bottles. Of any design change that goes into a bottle of wine, the design of a bottle is by far the most expensive. A new mould can cost several hundreds of thousands of dollars. Companies often consider economies of scale when designing a new bottle, expecting to use one bottle across several brands. We have focused on the optimisation of bottle shape because the great investment it demands also represents the greatest opportunity for reaping the benefits of optimisation. Because it is the most expensive and labour-intensive process within the overall aesthetic design process, bottle design is seen as a starting point for the rest of the aesthetic design of the bottle. Once it has been designed, there is no reason why the concepts of semantic enhancement could not be applied to the colours and shapes of labels, size and materials of corks, characteristics of foils, and colours of glass.

Within the overall model, a subsystem optimisation was developed to design semantically-shaped wine bottles. This subsystem optimisation began with a conjoint survey that explored the consumer's interpretation of flavours associated with pre-defined bottle shapes and proportions. The purpose of the semantically-designed wine bottles was to give an accurate portrayal of the predominate flavours of the wine within each bottle, adding to consumer satisfaction and aiding in the wine selection process. This added customer satisfaction is modelled as an enhancement to the desirability of the wine, which is a function of both the qualities of the wine formulation and the correct pairing of the flavour-theme of the wine with the shape of the wine bottle. Then, in populating the optimal wine portfolio, profitability increases as wines are paired with semantically enhancing bottles.

2.1.1 Identifying semantic shapes

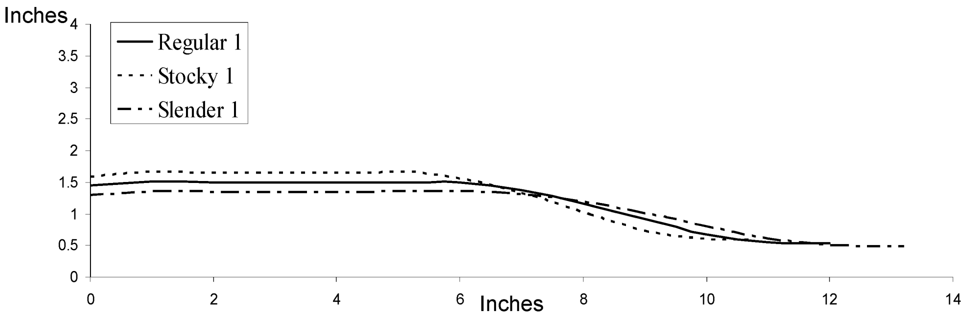
For this study, the semantic effects of both general bottle shape and specific bottle proportions were studied. Conjoint analysis was chosen as the investigative method. A discrete choice survey was created to investigate the semantic implications of nine specified bottle shapes. The survey focused on two different factors – bottle shape and vertical stretch – expressed in a single line drawing of a bottle. Although more complex three-dimensional representations could be used, the two-dimensional representation is assumed to convey sufficiently the actual three-dimensional one, due to rotational symmetry (and the need to keep the present demonstration reasonably simple). The multiple choice answers to the survey were line drawings of bottles that were combinations of three different bottle shapes combined with three different levels of vertical stretch; see Figure 2 for a picture of the bottle shapes and levels of vertical stretch included in the discrete choice survey.

Figure 2 The nine bottles shown in the discrete choice survey



Three real bottles with distinctive shapes were selected from a local wine store as the basis for the shapes included in the survey. The three bottles were selected in the following manner: one was selected for its distinctively long and slender shape, one was selected with the help of a wine merchant as being a 'traditional' shape for a chardonnay bottle, and one was selected, also with the help of a wine merchant, as being a traditional shape for robust wine such as a merlot, a shape that more chardonnays are now adopting. Measurements of the radius of these bottles were taken at one-inch increments from the bottom to the top of the bottle and graphed, as shown by the solid line in Figure 3. Then these measurements were mathematically manipulated to give the vertically stretched and vertically compressed bottle shapes, and re-graphed, as shown by the dashed lines in Figure 3. In order to determine the level of stretching and compression to be presented in the survey, a variety of wine bottles, wine shelving, and store displays were measured. The minimum and maximum diameters and heights presented went slightly beyond what is offered in the typical wine shop. The middle level was the actual dimensions of the bottle measured. All of the graphs were then converted into spline curves, and mirror-imaged to look like line drawings of wine bottles, while keeping the original proportions.

Figure 3 Measurements of actual bottles are manipulated to create stretched and compressed bottle shapes for discrete choice survey

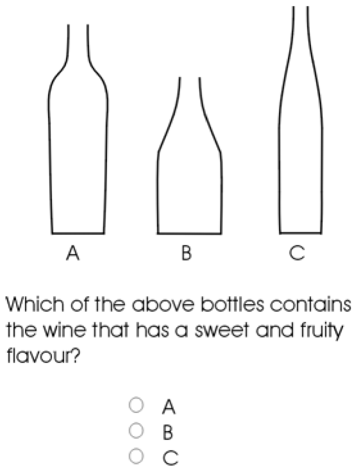


2.1.2 Administering the survey

Three identical surveys were constructed, one for each flavour-theme 'sweet and fruity', 'dry and crisp' and 'nutty and oaky'. The surveys were orthogonally balanced with 18 questions for two factors (shape and vertical stretch) at three levels each. The dependent variable was vertical stretch and the independent variable was bottle shape. The survey was a full-factorial survey, so any interaction between the two variables, or factors, was accounted for in the final analysis of the survey results. Each of the 18 questions in the three surveys asked the consumer to identify which of three bottles pictured contains the wine that is, for example, the most 'sweet and fruity'. See Figure 4 for a sample survey question.

The three surveys were administered via the internet at zoomerang.com to a population of convenience sample of graduate students, family members, and friends that had all familiarity with purchasing wine. One third of respondents were requested to complete the Sweet and Fruity survey, one third were requested to complete the Dry and Crisp survey, and one third were requested to complete the Nutty and Oaky survey. Respondents were also given the option to complete the other two surveys after completing the first. Most respondents only took one survey. Since the results are anonymous, it is impossible to tell how many, if any, respondents took multiple surveys. Any order effects amongst the respondents who took multiple surveys should have been counteracted by the fact that they most likely began with different surveys. There were 23 full responses to the 'sweet and fruity' survey, 18 to the 'dry and crisp', and nine to the 'nutty and oaky'.

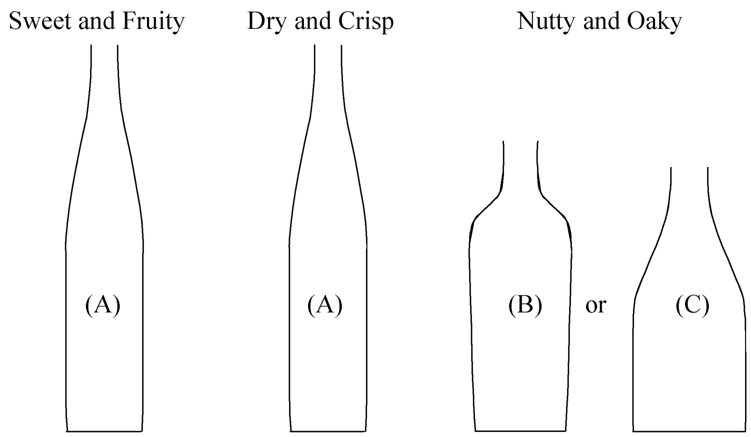
Figure 4 Sample discrete choice survey question



2.1.3 Survey results

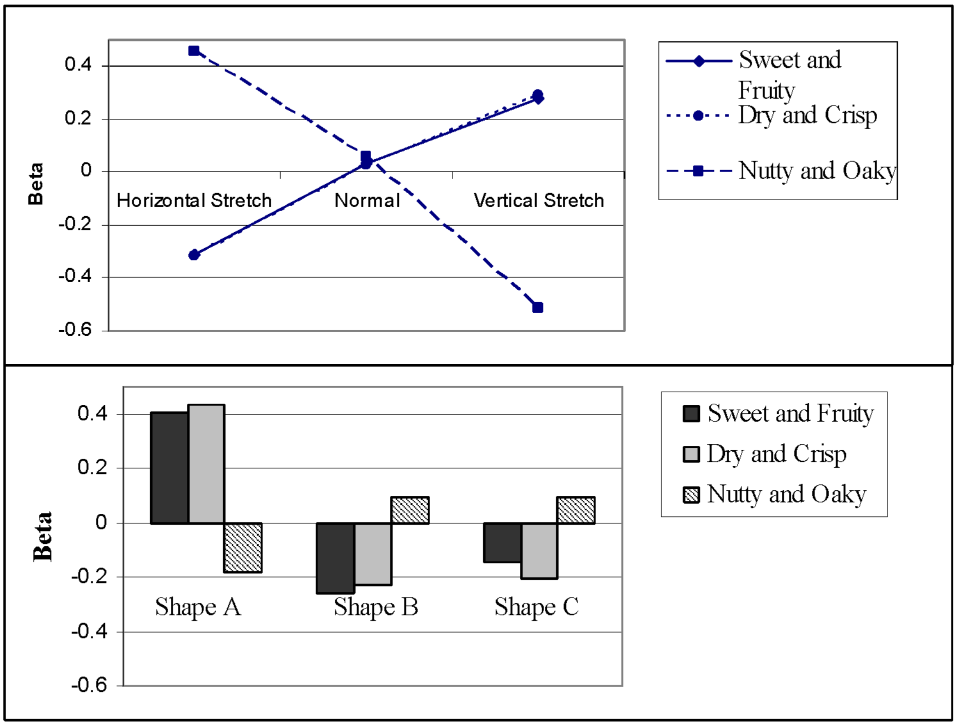
Conjoint analysis revealed unanticipated results: the bottle shape consumers identified most strongly as 'sweet and fruity' was the same bottle shape that consumers identified most strongly as 'dry and crisp'. This is bottle Shape A in Figure 5, with a beta value of 0.40 for 'sweet and fruity' and 0.43 for 'dry and crisp'. Conversely, for 'nutty and oaky', consumers almost equally preferred either bottle shapes shown as B or C in Figure 5.

Figure 5 Semantic bottles indicated by results of discrete choice survey



Similarly, the vertical stretch value that consumers identified most strongly as 'sweet and fruity' was the same as the one they identified most strongly as 'dry and crisp'. This is the maximum stretch, as shown in Figure 5(A). For both 'sweet and fruity' and 'dry and crisp', the stretch preference is almost linear – the more the bottle shape is vertically stretched, the stronger the preference. Conversely, the proportionality most preferred for 'nutty and oaky' wines is the least vertically stretched bottle. The strongest beta value seen in the entire survey is the non-preference for vertically stretched 'nutty and oaky' bottles, with a beta value of –0.51. Figure 6 shows the beta values for the factors that resulted from conjoint analysis of the discrete choice survey.

Figure 6 Beta values indicate that survey respondents believe both sweet and fruity and dry and crisp wines are packaged in bottle Shape A with vertical stretch, and that nutty and oaky wines are packaged in bottle Shape B or Shape C with horizontal stretch (see online version for colours)



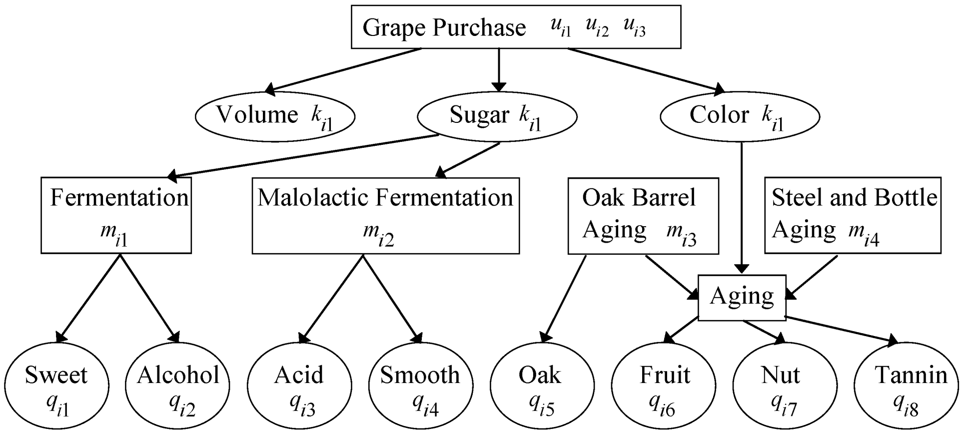
The fact that the same bottle was identified as semantically expressing both 'sweet and fruity' and 'dry and crisp', may be due to the fact that the bottle shape was only represented as an outline, and not as a three-dimensional shaded shape or physical model. It may be that a more rigorous survey, including actual bottles or realistic 3-D bottle pictures and more levels of bottle shapes, would reveal that these two flavours are actually associated with different bottle shapes.

Along these lines, another obvious next step would be to test the link between the words 'sweet and fruity' and the flavour of an actual wine that tastes sweet and fruity. The same should be done for the other two flavour themes. Next, the link between the actual wine flavour and the bottle shapes could be investigated. The combination of these three surveys could reveal an explanation as to why flavour themes were paired with the same bottle shape. If it is discovered that these two flavour themes are indeed paired by consumers with the same bottle shape, then it will be necessary to investigate adding more semantic messages to the bottle in order for the consumer to semantically distinguish between these two flavour-themes.

2.2 Modelling the wine formulation

The model focuses on the key formulation and manufacturing processes, beginning with purchasing the grapes and ending with aging the wine in its bottle, as depicted in Figure 7. The model here is limited to the formulation of a chardonnay portfolio but it can be expanded to other types of wines. The details of the model are included in the Appendix.

Figure 7 Overview of the formulation and processing model. Variables are represented as rectangles, functions are represented as ovals



Many wineries purchase grapes because they do not own vineyards or to supplement their own production. Modern technology allows wineries to analyse grape quality chemically before making a purchase but, traditionally, grape colour has been used as a proxy for desired quality. The model includes colour as a subjective measure that reflects grape quality, which in turn influences grape cost and the aging characteristics of the wine. Grape cost is also significantly influenced by the grape's sugar content. The model includes the option of purchasing three types of chardonnay grapes, with characteristics denoted in the model as k_{xk}^{G}, where the subscript k ($k = 1, 2, 3$) denotes one of the three grape varietals, and the subscript x with values 1, 2, 3, denotes volume of liquid as a percent of total, amount of sugar measured in the Brix scale, and colour, respectively. Colour is measured on a relative scale where a value of 100 denotes ideal grape colour for a given variety and each increment or decrease of one unit represents an undesired deviation from the ideal colour by 1%. The characteristics of the three grapes available for purchase in this model are detailed in Table 1. Grapes of type $k = 1$ are the most expensive due to their exceptional quality. However, they are not as sweet or juicy as grapes of type $k = 2$. Grapes of type $k = 3$ are inexpensive and very juicy but are neither very sweet nor high-quality. In addition to grape characteristics, the model includes the cost g_k of purchasing the quantity of grape k required to make one bottle of wine. The model considers the purchasing decision as the proportion of the pre-specified total amount of grapes purchased that should be distributed to each type of grape, where u_k represents the percentage of the total grape purchase of grape k by volume.

Table 1 Characteristics of the three chardonnay grapes available for purchase in model

Grape characteristic (k^G_{xk})	*k = 1*	*k = 2*	*k = 3*
$x = 1$ (% Liquid volume)	85.3%	96.0%	98.7%
$x = 2$ (Brix sugar scale)	22.5	24.5	21.0
$x = 3$ (Colour rating)	102	72	55
Cost per Bottle (g_k)	$4.22	$3.40	$2.09

The chardonnay manufacturing model includes fermentation, malolactic fermentation, oak barrel aging, and steel and bottle aging. These processes are the main contributors to wine flavour and market price, and can be controlled by the winemaker, see Figure 7. The variable m_j is the number of days spent in a processing step ($j = 1, 2, 3, 4$). Fermentation affects sweetness and alcohol level. Malolactic fermentation determines acidity and smoothness. Oak barrel aging affects the distinctive oak flavour of the chardonnay. Steel barrel and bottle aging determine total age and influence fruit and nut flavours. The grape blend also plays a role in the quality of the resulting wine. Sweeter grapes lead to a potentially sweeter or more alcoholic wine. Higher quality grapes provide the potential for fruitier and more complex wines with better nut and wood flavours. Therefore, the quality characteristics of a wine are functions of the number of days the wine spends in each processing step and the grape blend.

The quality characteristics for a wine as modelled in this study are: sweetness, alcohol intensity, acidity, smoothness, oak, fruitiness and nut/oak flavour. The equations for these quality characteristics were determined mainly by fitting curves to charts found in wine-making books, as listed in the reference section, and are included in the Appendix.

Each of these qualities represents a ‘dimension’ of the desirability of the wine. Total desirability of the wine is expressed as the sum $d^Q_{iq}(u_{ik}, m_{ij}, b_i)$ of these dimensions, discussed further in Section 3.4.

Due to purchase and processing costs, achieving the targets for each quality characteristic is not necessarily the most profitable formulation. Furthermore, there are trade-offs among the seven different wine qualities represented in the model. For example, a wine can not be both smooth and acid at the same time. Therefore, each wine formulation will have some quality characteristics that contribute the majority of the wine’s flavour. This concept is summarised in the model as flavour-themes, defined as ‘sweet and fruity’, ‘dry and crisp’ and ‘nutty and oaky’, which correspond to the flavour-themes studied for semantic impact in the wine bottles.

3 Wine portfolio optimisation

The purpose of the portfolio model is to demonstrate the potential impact of semantics on the design and profitability of a product line. In reality, a winery would not design its entire portfolio simultaneously. Whether designed incrementally or simultaneously, in a portfolio of chardonnays, each wine must be sufficiently distinct in price and flavour to create a defined market position. The maker must also consider the quantity of each wine in the portfolio to be manufactured and appropriately distribute manufacturing capacity in the winery.

3.1 Summary of portfolio model

Several assumptions have been included in the model in order to simplify calculations. The model assumes that every bottle of wine produced will be sold at full price. The demand function used to predict the number of wine bottles the market will buy has a cap that is based on information from the Adams Wine Handbook (2001). The cap on demand for a particular bottle is based on its market price. Also, the number of different chardonnay formulations produced by the winery, the parameter n, is set to $n = 9$. Competition from other wineries in the marketplace has been accounted for with additional assumptions in the model.

The functions in the portfolio model serve to ensure wine formulations taste different from one another, to fix price points and bottle quantities based on the demand for the formulation, to assign flavour-themed bottles, and to calculate profitability. Profitability, for the purpose of this study, is defined as revenue less manufacturing and raw material costs. It does not include, for example, marketing and distribution budgets, thus the computed profitability is typically too large. Nevertheless, it is consistently defined amongst the optimisation scenarios compared in the results of Section 3.5 allowing for a useful comparison.

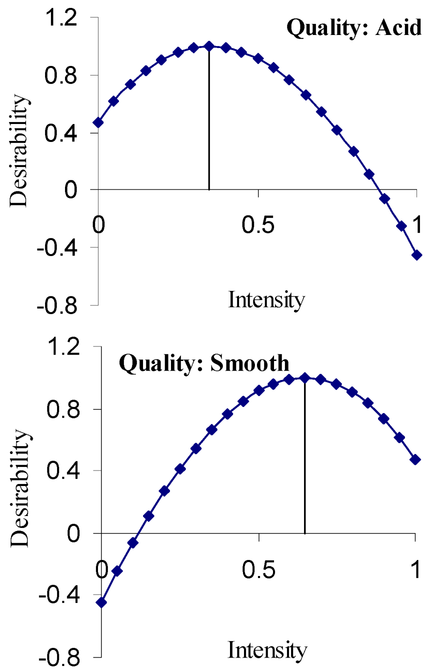
The objective function of the model maximises the profitability of the chardonnay portfolio while treating wine prices, production quantities, grape proportions, and manufacturing processes as variables. Inputs (fixed parameters) include grape quality characteristics and costs, manufacturing costs, calibrating coefficients for wine desirability and processing-related constraints. The model is summarised in equation form in the Appendix.

3.2 Wine desirability

Wine desirability is presented as a combination of the wine's abilities to meet the targeted values for the following qualities: sweet, alcohol, acid, smooth, oak, fruit, nut, and tannin. A 'desirability enhancement' that comes from matching the flavour-theme of the wine to a semantically designed wine bottle is also included. The equations that determine desirability are detailed in the Appendix, with all terms defined in Table 4. Equation (49) calculates individual desirability based on a single quality, such as sweetness. Equation (50) calculates a weighted sum of the individual desirabilities.

A graphical representation of desirable qualities is shown in Figure 8, which depicts the desirability curves for 'acid' and 'smooth' qualities. Each quality is associated with a desirability curve. These curves are derived from industry guidelines, and all range between 0 and 1 in quality intensity. On each curve, there is a targeted quality value. This value corresponds to '1' in desirability, the highest possible value. The difference between a wine formulation's quality and the targeted quality value contributes to the overall desirability of the wine – the smaller the better. For example, the targeted quality value for acidity is 0.35. If a wine has an acid intensity of exactly 0.35 then it receives a maximum desirability of 1 for this quality. Some targeted quality values are traded-off with others. For example, 'acid' and 'smooth' have an inverse relationship – a wine can not have both optimal acidity and smoothness, since both of these values are controlled by the same process, malolactic fermentation. The longer the wine is allowed to ferment malolactically, the smoother it gets.

Figure 8 Desirabilities of smoothness and acidity are traded-off in model (see online version for colours)

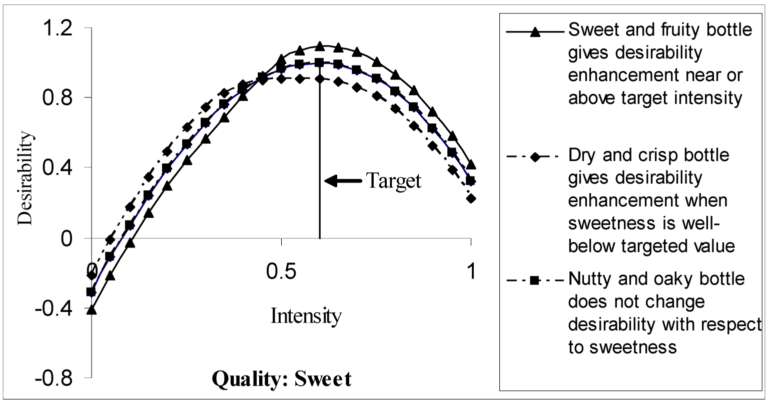


3.3 Semantic desirability enhancement

The semantic desirability enhancement is modelled as a bonus to desirability when the wine formulation's flavour-theme is matched to the bottle's semantic message. The enhancement is assumed to come from communicating in-world knowledge about the flavours of the wine to the consumers, in order to simplify the purchasing decision and ensure they will not be disappointed or unpleasantly surprised with the wine's flavours. Conversely, clashing wine flavour and semantic message decreases the modelled desirability of the wine.

With the semantic messages of the three flavour-themes in mind, the desirabilities of the following qualities are affected: sweet, acid, smooth, oak, fruit and nut. In the portfolio optimisation model, the desirability curves of the individual qualities are modified by the wine's bottle. Figure 9 shows a semantic desirability enhancement of 10% for the quality 'sweet'. If a wine with a sweetness intensity near or above the targeted sweetness of 0.6 is placed in a 'sweet and fruity' bottle, the wine receives a 0.1 merit point in the portion of the overall desirability function related to flavour of sweet. Alternatively, if a 'dry and crisp' wine is placed in a bottle that does not indicate dryness and crispness, it receives a 0.1 penalty in the portion of the overall desirability function related to that quality. If a sweet wine is placed in a 'nutty and oaky' bottle, it receives neither a penalty nor a merit based on the wine's sweetness. Desirability curve augmentations similar to the one pictured in Figure 9 were created for each of the six effected quality characteristics.

Figure 9 Semantic desirability enhancement of 10% on the quality of sweetness (see online version for colours)



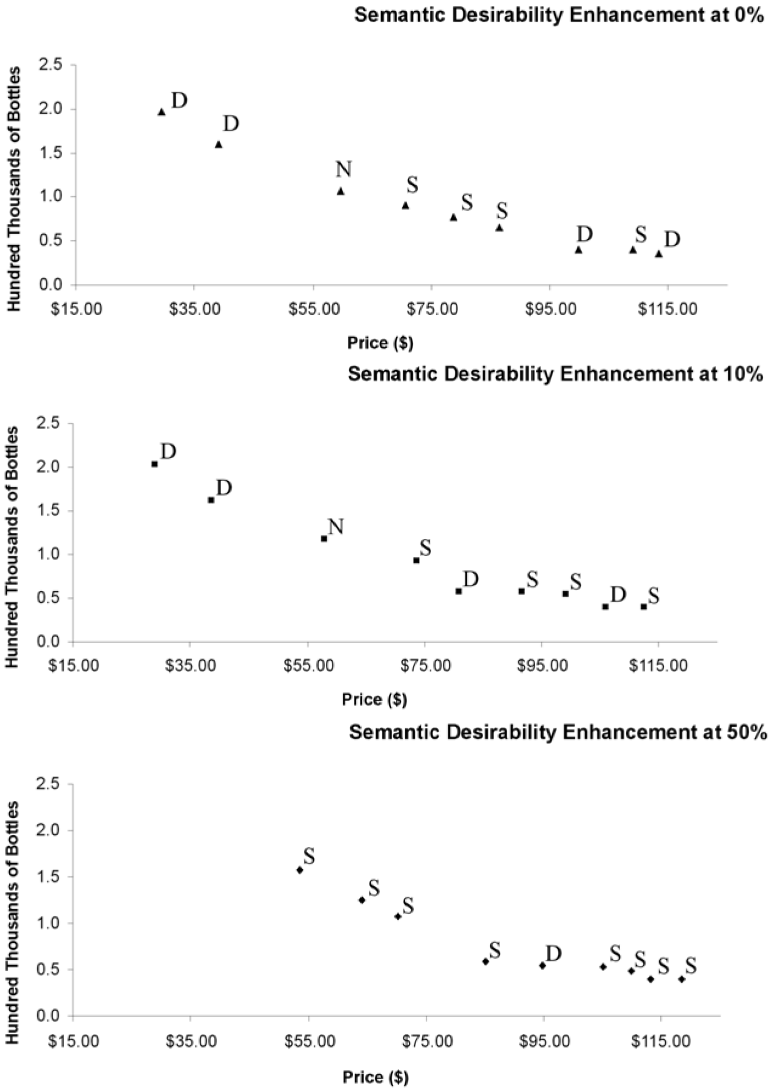
Correctly setting the semantic desirability enhancement level within the model is a difficult task. Setting the enhancement level requires an accurate prediction of how much more appealing the wine will be when placed in a semantically enhancing bottle. This value could perhaps be set through 'willingness to pay' marketing studies. For the purposes of this study, the semantic desirability enhancement is set as a parameter that is set at values of 0%, 10% and 50% to test the effectiveness of including semantically designed wine bottles.

3.4 Portfolio optimisation results

This section summarises the results obtained by solving the portfolio optimisation problem, including the impact of assuming different semantic enhancement parameter values (scenarios). Inclusion of bottle semantic enhancement into the portfolio optimisation affected all variables in the model including the grape proportions, process step variables, prices, and quantities of each of the nine wines in the portfolio. Therefore, the semantic enhancement level affected the formulations and quantities of wine produced, as well as the overall profitability of the wine portfolio, as illustrated in Figure 10.

Table 2 lists the grape proportions and processing step days for the optimal chardonnay portfolio with a semantic enhancement level of 10%. Grape u_2 is used in the largest quantity in all but one of the nine formulations. Grape u_2 is the most expensive but also the highest quality grape available. In the lowest-priced formulation, grape u_3 is used in a slightly larger quantity than u_2. In both the 0% and 10% semantic enhancement scenarios, the two lowest-priced wines are dry and crisp, followed by one nutty and oaky wine at a price point just over $55. Above this price point, the distribution of flavours and quantities varies between the two enhancement scenarios, although pricing ranges and intervals remain similar. It can be concluded that semantic desirability enhancement level makes more of an impact on the other design attributes of the higher-end, lower-quantity formulations in the portfolio than it does on the attributes of the more mass-market formulations.

Figure 10 Semantic enhancement level affects optimal wine portfolio pricing, formulations, and quantities. 'D' denotes a dry and crisp wine, 'S' denotes a sweet and fruity wine and 'N' denotes a nutty and oaky wine



At the 50% semantic enhancement level, all but one of the wine formulations in the optimal portfolio has a flavour-theme of sweet and fruity. This is because the most expensive grapes and processing options produce the wines with the most desirable sweetness and fruit flavours. When the desirability of the sweet and fruity flavour-theme is enhanced by a large amount, these expensive alternatives become preferable in the model. The 50% enhancement level allows the winery to reduce its production by over 100,000 bottles, as compared to the 10% or 0% enhancement levels, while increasing overall winery profitability by 12%. It is interesting to think about the trade-offs that would need to be considered under this scenario between the unmodelled costs associated with the production-level of bottles and the unmodelled semantic design costs necessary to achieve such high levels of desirability enhancement.

Table 2 Summary information of wine portfolio with 10% semantic desirability enhancement

Wine i	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*
u_1	0.00	0.00	0.03	0.10	0.00	0.10	0.10	0.06	0.08
u_2	0.45	0.70	0.90	0.90	0.90	0.90	0.90	0.90	0.90
u_3	0.55	0.30	0.07	0.00	0.10	0.00	0.00	0.04	0.02
m_1 (days)	11.04	11.69	10.63	10.47	15.96	12.54	8.91	6.64	7.65
m_2 (days)	3.28	4.23	8.72	8.86	3.26	6.07	13.80	4.34	6.02
m_3 (days)	46.73	32.59	116.11	115.10	49.70	50.35	165.76	77.63	77.88
m_4 (days)	121.45	133.99	47.04	232.29	153.43	493.01	374.14	190.95	305.72
Price (USD)	\$29	\$39	\$58	\$74	\$81	\$92	\$99	\$106	\$112
Quantity (thousands)	2022.40	1613.60	1179.80	922.60	574.30	571.60	543.90	391.40	402.10

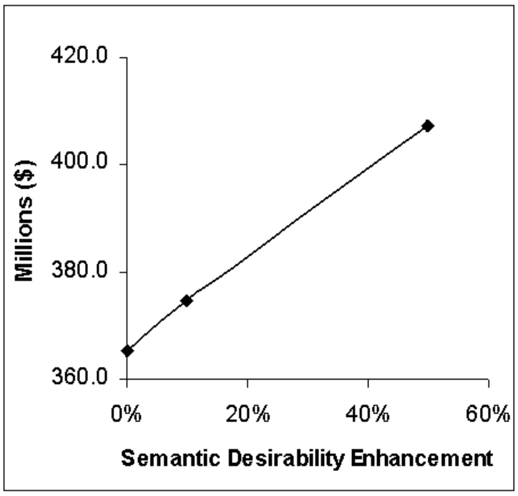
The model predicts a sizeable increase in profitability with the inclusion of semantically designed bottles, as shown in Table 3. As noted previously, the actual profitability is overestimated since overhead and other costs are not included, and neither is mark-up between retail and wholesale pricing. A 10% a semantic desirability enhancement leads to a \$1.14 profit increase per bottle, while a 50% increase leads to a \$6.15 profit increase per bottle.

Table 3 Optimal wine portfolios with semantic desirability enhancement levels of 0%, 10% and 50% have different characteristics

Semantic desirability enhancement	*0%*	*10%*	*50%*
Retail sales minus manufacturing costs ('Profit')	\$365,300,000	\$374,550,000	\$407,400,000
Profit increase due to semantic design	–	\$9.25 Million or \$1.14 per bottle	\$42.1 Million or \$6.15 per bottle
Price range	\$29 – \$113	\$29 – \$112	\$53 – \$118
Total number of bottles	8117400	8221700	6844100
Number of sweet and fruity wine formulations	4	4	8
Number of dry and crisp wine formulations	4	4	1
Number of nutty and oaky wine formulations	1	1	0

The relationship between semantic enhancement level and increased profitability is linear for these three enhancement scenarios, as shown in Figure 11, even though the wine price range does not increase between the 0% and 10% semantic desirability enhancement levels, and different wines are featured in each scenario (not merely the same wine formulations at increased prices). This linear relationship could be used to predict increased profitability at any semantic enhancement level between 0% and 50%.

Figure 11 The relationship between semantic desirability enhancement level and profitability

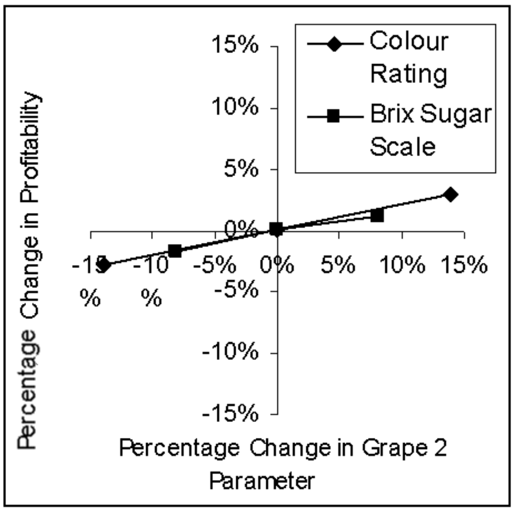


3.5 Sensitivity analysis of grape parameters

The qualities of the grapes available for purchase are exemplary of the parameters that will experience the most change on a seasonal basis. Of the three grapes described in Table 1, Grape 2 ($k = 2$) is the one that is predominantly used in the wine formulations at the optimal point.

An analysis of the sensitivity of the model to the Brix sugar scale and colour rating of Grape 2 produced nearly linear results, as shown in Figure 12. A 14% increase (decrease) in the colour rating caused a 3% increase (decrease) in overall model profitability. Manipulating grape 2's Brix sugar scale parameter produced a very similar trend.

Figure 12 The increase/decrease in profitability is linear with respect to changes in the parameters of Grape 2



The costs of raw materials, grapes, are also highly susceptible to seasonal fluctuations. The model is relatively insensitive to fluctuations in the costs of purchasing grapes. Fluctuations of grape cost increasing and decreasing by \$0.25, or 7%, were investigated, causing only a 0.5–1% difference in profitability. This suggests it is possible to create desirable portfolios of wine despite fluctuations in the costs of raw materials. However, according to the model, it will be necessary to slightly change price points and adjust formulations.

4 Conclusion

This study has demonstrated the potential benefits of using a concurrent approach to designing a wine portfolio, wine formulations, and accompanying wine bottle shapes. However, there is much work still to be done in order to make the results market-ready. In modelling semantic bottle shapes, there are opportunities to make the results more detailed, rigorous, and robust. For example, the attributes and levels of shapes shown in the survey can be determined through a technique such as the grid repertory method. Using actual wine-tastings and 3-D bottle models in conjunction with the administration of the survey would improve the accuracy of the results. Including more subjects and querying their knowledge of wines may bring latent class segmentation of the survey results to light. The bottle model can also take into consideration bottle design limitations, due to such things as packaging and shipping requirements. A greater number of flavour adjectives and the relative importance of these flavours can be further investigated.

The desirability enhancement functions used to link semantic bottle shapes to the overall desirability of the wine can be refined through marketing studies that attempt to place a value on repeat customers. ‘Willingness to Pay’ studies can be performed with consumers to get a sense of how they might value a semantically designed bottle.

Within the wine portfolio model, the weighting of price and quality in the cannibalisation function can be further investigated, and the model can be improved overall by including the effects of competition in a more detailed manner than merely a cap on the number of bottles sold. Both static and dynamic factors could be included, for example, the model could be posed over a multi-period scenario using game theory functions. The model can be expanded to include other varietals besides chardonnays. With input from an actual winery, more work can be done to validate and improve the wine formulation model, which in the present demonstration was based on industry tradebooks. In fact, wineries may already have such working models that could be readily incorporated into our approach. In general, working with a winery to hone the capabilities of the model would be a worthwhile future pursuit.

There is a long standing debate on the objective of winemaking: Should winemakers do their best to provide a wine that will cater to the drinker’s preferences or should they provide the wine that best represents what nature provided during a particular season in a particular place? If a winemaker is with the first camp, optimisation of wine flavours as presented in this paper should be of interest. On the other hand, if the winemaker believes that wine and its terroir are inexorably bound, optimising to a particular flavour may be less appealing. The concepts presented in the paper with regard to bottle design can be applied to either school of thought: one may design a bottle for a wine with a particular flavour target or for a particular vintage and territory.

Previous studies have documented emotional and semantic responses to design but there has been little work on linking these semantic responses with other quantitative design properties at an integrative level. This study investigated the trades-offs between enhancing product semantics and other product features in a quantitative manner. It demonstrated that the level of semantic enhancement of a product affects the profitability of the product as well as the design of the product's other features – in this case, wine formulations, quantities and pricing.

The level of semantic enhancement, represented as an enhancement to desirability, had far-reaching effects on the other aspects of the product's design. Hence, it is important that future work in product semantics strives to quantify the worth of semantically designed product features in a manner comparable to the values of other product features. Detailed studies that investigate costs and time commitments associated with semantic design and the impact of increased manufacturing costs can help to build a basis for comparisons with other product design processes.

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Appendix: Mathematical nomenclature and models

Wine formulation model

Table 4 Model quantities and nomenclature

Variables	
b_i	Number of bottles of formulation i produced (i = 1, 2, …, n)
m_{ij}	Number of days of processing step j used for formulation i (j = 1, 2, 3, 4)
p_i	Selling price of formulation i (i = 1, 2, …, n)
u_{ik}	Proportion of grape k used in formulation i (i = 1, 2, …, n), (k = 1, 2, 3)
Functions	
$a(u_{ik}, m_{ij}, b_j)$	Total liquid put in to the bottles of wine that are sold (litres)
$h_i(p_i, u_{ik}, m_{ij}, b_j)$	Maximum demand for formulation i
$c_i^B(u_{ik}, m_{ij}, b_i)$	Cost per bottle of producing label i (USD)
$c_k^G(u_k)$	Cost of purchasing a grape of type k (USD)
c_j^M	Cost of manufacturing process j (USD)
$d_i(u_{ik}, m_{ij}, b_i)$	Desireability of formulation i
$d_{iq}^Q(u_{ik}, m_{ij}, b_i)$	Desireability of a wine quality characteristic q
$f(p_i, u_{ik}, m_{ij}, b_i)$	Profit as defined by retail sales minus manufacturing cost (USD)
$k_{ix}(u_{ik})$	Characteristic x of aggregated grape purchase for formulation i (% Liquid, Brix sugar scale, Colour rating)
$l_j(m_j)$	Percentage of volume lost process j
$q_{iq}(u_{ik}, m_{ij})$	Quality of characteristic q for formulation i (1, 2, …, 7)
$j_i(u_{ik})$, $z_i(m_{i1})$, $i_i(u_{ik})$, $\rho_i(u_{ik}, m_{ij})$, $\sigma_i(u_{ik}, m_{ij})$, $\omega(u_{ik})$, $\eta(m_{ij})$	Intermediate simplifying wine formulation functions
$\delta p(p_i)$, $\delta d(u_{ik}, m_{ij}, b_i)$, $\delta pd(p_i, u_{ik}, m_{ij}, b_i)$, $\delta q_q(u_{ik}, m_{ij})$, $\delta qt(u_{ik}, m_{ij})$, $\tau(p_i)$, $C_t(p_i, u_{ik}, m_{ij}, b_i)$, $C_{ti}(p_i, u_{ik}, m_{ij}, b_i)$, $C_{tj}(p_i, u_{ik}, m_{ij}, b_i)$	Cannibalisation functions

Table 4 Model quantities and nomenclature (continued)

Parameters	
c^W	Fixed cost to produce a label of wine (USD)
g_k	Market price of grape k (USD)
k^G_{xk}	Characteristic x of grape k (% Liquid, Brix sugar scale, Colour rating)
n	Number of wine formulations in the portfolio
o_j	Cost of one unit processed on manufacturing step j (USD)
r_{zq}	Coefficient that adjusts desirability of a wine with respect to bottle shape (z = 1, 2, …, 7)
s	Semantic desireability enhancement (%)
t_q	Target intensity of quality characteristic q
v^G_k	Maximum proportion of grape k
v^M_j	Maximum amount of manufacturing step j allowed or available (days)
v^c	Maximum cost allowed for producing the wine (USD)
v^l_j	Percent volume lost per unit of manufacturing on process j
w_q	Importance weight of quality characteristic q
y	Production capability of winery (bottles)
ς^C	Manufacturing costs not explicitly modelled (USD)

$$j_i(u_{ik}) = k_{i2} - \frac{(2k_{i2})^4}{10^{6.3}} \tag{1}$$

$$z_i(m_{i1}) = \frac{-0.3}{0.1(m_{i1}) + 0.175} + 1.16 \tag{2}$$

$$i_i(u_{ik}) = (0.569)j_i + (5.67\times10^{-3})j_i^2 - (1.13\times10^{-4})j_i^3 + (1.34\times10^{-6})j_i^4 \tag{3}$$

$$\rho_i(u_{ik}, m_{ij}) = z_i i_i = \text{ alcohol level} \tag{4}$$

$$\alpha_i = i_i(1 - z_i) \tag{5}$$

$$\begin{aligned}\sigma_i(u_{ik}, m_{ij}) = 0.9872 + (6.01\times10^{-3})\alpha_i + (3.09\times10^{-5})\alpha_i^2 \\ -(1.16\times10^{-6})\alpha_i^3 + (1.51\times10^{-8})\alpha_i^4\end{aligned} \tag{6}$$

$$\omega_i(u_{ik}) = \frac{((k_{i3} - 100)/5)^2}{100} \tag{7}$$

$$\eta_i = 0.6 - \frac{\left(\left(\sum_j m_{ij} \big/ 365\right) - 7\right)^2}{15.6025} + \frac{\left(\sum_j m_{ij} \big/ 365\right)^{4.46}}{90000} - \omega. \tag{8}$$

The functions below specify the quality characteristics for a wine as modelled in this study: sweetness, alcohol intensity, acidity, smoothness, oak, fruitiness and nut/oak flavour:

$$\text{Sweetness: } q_{i1}(u_{ik}, m_{ij}) = \frac{\sigma_i - 0.964}{0.066}. \tag{9}$$

$$\text{Alcohol Intensity: } q_{i2}(u_{ik}, m_{ij}) = \frac{(\rho_i / 100) - 0.1}{0.05}. \tag{10}$$

$$\text{Acidity: } q_{i3}(m_{i2}) = \frac{0.3}{(m_{i2}/12) + 0.217}. \tag{11}$$

$$\text{Smoothness: } q_{i4}(m_{i2}) = 1 - \frac{0.3}{(m_{i2}/12) + 0.217}. \tag{12}$$

$$\text{Oak: } q_{i5}(m_{i3}) = 1 - \frac{1}{(0.01)m_{i3} + 1}. \tag{13}$$

$$\text{Fruitiness: } q_{i6}(u_{ik}, m_{ij}) = \left(1.1 - \frac{\left(\left(\sum_j m_{ij} \middle/ 365\right) - 3\right)^2}{17.64} - \frac{\left(\left(\sum_j m_{ij} \middle/ 365\right)\right)^{6.5}}{100000} - \omega \right) \times \left(\frac{1}{1 + e^{\left(0.2 \sum_j m_{ij} - 1730\right)}} \right). \tag{14}$$

$$\text{Nut/Wood Flavour: } q_{i7}(u_{ik}, m_{ij}) = \left(\eta_i - \frac{\eta_i}{1 + e^{\left(\left(8\left(\sum_j m_{ij}\right) / 365\right) - 40\right)}} \right) \times \left(\frac{1}{1 + e^{0.15\left(\left(\sum_j m_{ij}\right) - 3510\right)}} \right). \tag{15}$$

Portfolio model

Maximise profit, where profit is the price minus the cost multiplied by the amount sold, minus costs of formulation manufacturing lines.

$$\text{Max } f(p_i, u_{ik}, m_{ij}, b_i) = \left(a \sum_i b_i (p_i - c_i^b)\right) - c^W n. \tag{16}$$

Amount sold is the volume of liquid collected from the grapes minus the amount lost during manufacturing.

$$a(u_{ik}, m_{ij}, b_i) = k_1 \sum_{ij} \left(1 - l_{ij}\right). \tag{17}$$

Cost per bottle is the sum of grape purchasing costs and manufacturing costs, plus manufacturing costs that were not explicitly modelled.

$$c_i^{\,B} = \varsigma^c + \sum\nolimits_{ik} c_{ik}^G + \sum\nolimits_j c_{ij}^M. \tag{18}$$

Total grape cost is determined by the purchase price of each of three available types of grapes multiplied by the proportion of each purchased.

$$c_{ik}^G = g_{ik} u_{ik}. \tag{19}$$

Manufacturing cost is determined by the cost of the process multiplied by the amount of that process used.

$$c_{ij}^M = o_j m_{ij}. \tag{20}$$

The desirability for each wine quality is determined by the difference between target and actual quality, and modified by match between semantic bottle shape and the wine's flavour-theme.

$$d_{iq}^Q(u_{ik}, m_{ij}, b_i). \tag{21}$$

The qualities of a wine formulation are a function of manufacturing processes and the characteristics of the grapes.

$$q_{iq}(u_{ik}, m_{ij}). \tag{22}$$

The characteristics of the grapes to be processed are determined by the proportions of the grapes purchased.

$$k_x = \sum\nolimits_k k_{xk}^G u_k. \tag{23}$$

The volume lost in a manufacturing process is determined by the amount of that process utilised.

$$l_{ij} = v_{ij}^L m_{ij}. \tag{24}$$

Subject to constraints:

The sum of the proportions of purchased grapes must sum to 100%.

$$h_1 : \; 1 - \sum\nolimits_k u_{ik} = 0. \tag{25}$$

The proportion purchased of any grape can not be less than 0%.

$$g_1 : \; -u_{ik} \le 0. \tag{26}$$

The amount of each type of grape purchased must not exceed a pre-specified amount.

$$g_2 : \; \sum\nolimits_i u_{ik} - v_k^G \le 0. \tag{27}$$

Negative manufacturing is not permitted.

$$g_3 : -m_{ij} \leq 0. \quad (28)$$

The amount of processing used can not exceed a pre-specified amount.

$$g_4 : m_{ij} - v_j^M \leq 0. \quad (29)$$

Percentage loss can not exceed 100%.

$$g_5 : l_j - 1 \leq 0. \quad (30)$$

Percentage loss can not be less than 0%.

$$g_6 : -l_j \leq 0. \quad (31)$$

The cost of producing the wine must not be higher than a pre-specified amount.

$$g_7 : c_i^B - v^C \leq 0. \quad (32)$$

The number of bottles made for specific wine formulation must be less than the demanded quantity for that formulation.

$$g_8 : b_i - h_i \leq 0. \quad (33)$$

The price for a bottle of any wine formulation must be more than the cost per bottle for that formulation.

$$g_9 : c_i^B - p_i \leq 0. \quad (34)$$

The total number of bottles made by the winery must be less than the total capacity of the winery.

$$g_{10} : \sum_i b_i - y \leq 0. \quad (35)$$

Negative production is not allowed.

$$g_{11} : -b_i \leq 0. \quad (36)$$

The price per bottle must be between \$4 and \$150.

$$g_{12} : 4 - p_i \leq 0 \quad (37)$$

$$g_{13} : p_i - 150 \leq 0. \quad (38)$$

Calculating demand

The equations express how demand is affected by differences in price, quality and flavours among various wines, and they are used to modify price, quantities and qualities of the wines in the portfolio. These functions were developed from an equation that calculated the total cannibalisation between each pair of wines. A subsequent equation was used to assign the cannibalisation among two wines to capture the fact that a cheaper wine would be preferred if two wines had the same qualities. Also, if two wines were priced similarly, the better wine would lose less of its potential demand through cannibalisation than the inferior wine. The cannibalisation equations for wine formulations *i* and *j* are:

$$\delta p = \sqrt{\left(\frac{(p_i - 4)}{146} - \frac{(p_j - 4)}{146}\right)^2} \quad (39)$$

$$\delta d = \sqrt{(d_i - d_j)^2} \quad (40)$$

$$\delta pd = \sqrt[4]{\delta p \delta d} \quad (41)$$

$$\delta q_q = \left(-2 + \frac{3}{1.5 + 10\mathrm{e}^{100\left(\sqrt{(q_{iq} - q_{jq})^2} - 0.1\right)}}\right)(-0.5) \quad (42)$$

$$\delta qt = \sum_{q=1}^{7} t_q \delta q \quad (43)$$

$$\tau = \left(\frac{0.5}{1 + \mathrm{e}^{((p_i - p_j)/(2-84))/8}}\right) + 0.5 \quad (44)$$

$$C_t = 1 - (\tau(\delta pd) + \delta qt(1 - \tau)) \quad (45)$$

$$C_{ti} = \left(1 - \frac{1}{1 + \mathrm{e}^{((p_i - 4)/146 - (p_j - 4)/146 - d_i + d_j)(20/3)}}\right) C_t \quad (46)$$

$$C_{tj} = C_t - C_{ti}. \quad (47)$$

The *δpd* function evaluates cannibalisation between wines *i* and *j* based on their price and overall quality. If two wines are similar in price and quality there will be a great deal of cannibalisation between them. The *δqt* function expresses cannibalisation between wines *i* and *j* based on difference in flavours. The τ function determines the relative weighting between 'price and quality' and 'flavour' within the cannibalisation function. This function is meant to model cannibalisation between two similarly high-priced wines with similar quality but different flavour. Under this scenario, flavour differentiation dominates the cannibalisation equation: there will be little cannibalisation between the two wines even if they have similar price and quality.

The C_t value is the total percentage cannibalisation that will occur between the two wines. The C_{ti} function splits this cannibalisation between wine *i* and wine *j*. There are $(n - 1)$ of these values calculated for each label (comparing that label to all others). The total cannibalisation in percentage for each label is calculated using a geometric average of these values as:

$$C_i = \sqrt[(n-1)]{\prod_{j=1}^{n-1} (1 - C_{ti})}. \quad (48)$$

This value is the percentage of the demand for a particular wine that remains after the effects of cannibalisation due to the presence of the other wines.

Wine desirability

In equation form, desirability is expressed as:

$$d_{iq}^{Q}(u_{ik}, m_{ij}, b_i) = (1 - 4(q_{iq} - t_q)^2 + 6(0.5 - t_q)(0.98(q_{iq} - t_q))^3) + \left(r_{1q} + \frac{r_{2q}}{r_{3q} + r_{4q} e^{r_{5q}(q_{iq} + r_{6q})}} \right) \tag{49}$$

$$d_i(u_{ik}, m_{ij}, b_i) = \sum_q d_{iq} w_q . \tag{50}$$