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An Optimization Model for Winery Capacity Use

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Abstract

An optimization model to sequence wine flow through the production process is developed. The model is formulated as a mixed integer program and accounts for winemaking specifications, market conditions, grape availability, and tank capacity. An empirical example is provided to demonstrate results and uses of the model.

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Wineries are playing an important role in providing economic opportunities to rural areas (Barham; Dodd, Hood, and Jetty). These wineries result in new employment opportunities, and the popularity of wine trips attracts tourist dollars. Moreover, to the extent grapes provide an alternative crop opportunity; increased agricultural sector profitability may result from the expansion of farmers towards this type of crop (Morris and Brady). Interest in the development of wineries is demonstrated by recent studies examining the economic feasibility of establishing wineries (Pisoni; Dakis et al.; Folwell, Bales and Edwards (2000, 2001), Dillon et al.) These studies characterized operating and investment costs, evaluated financial performance, and performed sensitivity analysis on input and output prices.

The overall purpose of this paper is to present a mathematical model that can improve capacity use within a small winery and thereby enhance efficiency and profitability. Much of the success of the wine industry in the Southeastern United States has been due to the development of regional products and differentiation of these products from wines produced in California or imported wines. The continued growth and development of this industry will depend, to a large degree, on the ability of the industry to produce high quality wines with unique flavor profiles that meet consumer preferences at a competitive price.

The model is designed to capture essential sequencing and capacity use considerations important to wineries regardless of location or size. However, to demonstrate the model, certain assumptions were necessary and many of these

assumptions will differ substantially from one winery to the next. The goal in choosing assumptions or data about the mix of wines, prices of wines or grapes, input costs, etc. was to represent a plausible situation confronting a small to mid-sized winery in the Southeastern United States. There was no attempt to represent any specific winery.

A major assumption relates to the size of the winery used for the empirical example. The example winery is assumed to have an annual production capacity of 80,000 gallons. This size is compelling due to the characteristics that a winery of that size possesses. First, an 80,000-gallon winery is large enough to process substantial wine volume and sell wines on both the retail and the wholesale markets. Second, an 80,000-gallon winery is approaching the upper level of small winery sizes and the dimensionality of the model presented in this paper generally increases with winery size. Hence, the ability to find solutions for an 80,000-gallon winery provides reasonable assurance that solutions can be found for wineries with smaller annual production volumes.

Before describing the formulation of the model, it is useful to provide the reader with some general background related to sources of data used for the empirical example and methods of arriving at assumptions. Specifically, Dillon et al. was used as the major source for assumptions about equipment and tank capacity. The available grape varieties, their prices, and harvest dates are from recently completed enterprise budgets for vineyards in Arkansas (Noguera; Noguera et al.) In some cases, specific data for prices, costs, or winemaking specifications were not readily available from secondary sources and plausible assumptions were developed with assistance of knowledgeable individuals involved in the winemaking business. Where possible, these assumptions were verified to be within ranges of those presented in earlier feasibility studies.

The Model

The model is a mixed integer program that sequences wines (indexed by i) to tanks (indexed by j) through necessary production steps (indexed by k). Types of wines refer to varieties (e.g., Chardonnay) or style (e.g., “Reserve” Chambourcin as distinct from Chambourcin). Tanks are characterized by their volume (e.g., 550 gallon tanks, 1,000 gallon tanks, and so forth). Steps in the production of wines that are important to the sequencing component of the model are those that require the use of tank capacity. Examples include fermentation, stabilization of wines, and holding wines prior to blending and bottling. The number of steps and time required to complete each step can vary depending on the wine being produced and its style.

Assumptions about wines and the timing of steps required for their production are depicted in Figure 1. The varieties in this figure are important to viticulture in the Southeast. However, many regions of the Southeast have climates suitable only for production of a subset of the grapes shown in the figure. The interested reader is directed to Noguera et al. for a discussion of climatic considerations related to wine grape production. Other assumptions reflected in Figure 1 are that:

- (1) The winery uses a centrifuge to clarify wines after fermentation is complete.
- (2) With exception of the sweeter Concord and Muscadine wines, all red wines go through a malolactic fermentation resulting in a longer secondary fermentation step.
- (3) Reserve red wines are aged in oak barrels while all other red wines are held in tanks for several months prior to bottling.

- (4) Chardonnay differs from other white wines in that it goes through a malolactic fermentation and is aged in oak barrels after being stabilized.

Sequencing Constraints

The main component of the model involves a series of sequencing constraints.

First, sufficient capacity must be dedicated to the winemaking step in question. Moreover, when a tank is used, it must be filled to a level that facilitates completion of the step and does not compromise wine quality. For example, during fermentation, head space is required in the tanks. After fermentation, tanks need to be full or nearly full in order to prevent oxidation of the wine. The primary fermentation step for red wines involves fermenting crushed grapes that have yet to be pressed. Hence more volume is required to accommodate the skins, pulp, and seeds that are later removed. These considerations are reflected in the following two capacity constraints.

$$(1) \quad u_{i,k} W_{i,k} \leq \sum_j a_{i,k}^{UP} cap_j X_{i,j,k} \quad \text{for all } i \text{ and for all } k$$

$$(2) \quad u_{i,k} W_{i,k} \geq \sum_j a_{i,k}^{LOW} cap_j X_{i,j,k} \quad \text{for all } i \text{ and for all } k$$

In equations 1 and 2, $W_{i,k}$ is the volume (gallons) of wine in tanks for step k . The coefficient $u_{i,k}$ is a scale-up coefficient for wine i in step k (for example, to accommodate the primary fermentation step for red wines). The coefficients $a_{i,k}^{UP}$ and $a_{i,k}^{LOW}$ take a value between 0 and 1 and refer to the maximum and the minimum tank fill level respectively for wine i and process k . The coefficient cap_j specifies the capacity, in gallons, of tanks of type j . Finally, $X_{i,j,k}$ is an integer variable indicating the number of tanks of type j

used for wine i during process k . Assumptions about tank fill levels used in the example model are presented in Table 1. A scale-up coefficient of 1.19 was used for the primary fermentation step for red wines and was equal to 1.00 for all other steps.

Second, wine moves between the different steps of the production process in a proscribed order. These transitions are enforced by equation 3:

$$(3) \quad \delta_{i,k+1}^A (W_{i,k} + \delta_{i,k}^S S_{i,k}) = \delta_{i,k+1}^A (W_{i,k+1} + \delta_{i,k+1}^S S_{i,k+1}) \quad \text{for all } i \text{ and for all } k \leq K-1.$$

In equation 3, $\delta_{i,k}^A$ is a parameter taking the value of one if step k is applicable to the i^{th} wine and taking a value of zero otherwise. To illustrate refer again to Figure 1 which depicts a total of four steps for red wines, three steps for reserve red wines and white wines, and two steps for Chardonnay. For red wines, $\delta_{i,k}^A = 1$ for $k = 1, 2, 3$, and 4. For reserve red wines and white wines, $\delta_{i,k}^A = 1$ for $k = 1, 2$, and 3 and $\delta_{i,k}^A = 0$ for $k = 4$; and for Chardonnay, $\delta_{i,k}^A = 1$ for $k = 1$ and 2 and $\delta_{i,k}^A = 0$ for $k = 3$ and 4.

Also in equation 3, $\delta_{i,k}^S$ is a coefficient taking the value of one if surplus storage is allowable for the i^{th} wine during process k and takes a value of zero otherwise, and the variable $S_{i,k}$ is the volume of wine in surplus storage for process k . It is assumed in the example model that once fermentation is complete, small amounts of wine can be stored in surplus containers (e.g., drums).

Third, capacity can be used for only one wine at any time. Equation 4 enforces this requirement for tank capacity:

$$(4) \quad \sum_i \sum_k \text{flow}_{i,t,k} X_{i,j,k} \leq n_j \quad \text{for all } t \text{ and for all } j$$

In this equation, t indexes time, n_j is the number of tanks of type j and $flow_{i,t,k}$ is a coefficient taking the value of one if the i^{th} wine requires the k^{th} step at time t and a value of zero otherwise. For the example model, the $flow_{i,t,k}$ coefficients reflect the timing of steps as presented earlier in Figure 1. Harvest dates used in the example model reflect grape producing regions in Arkansas and are from Noguera. The number of tanks and their capacities are from Dillon et al. and are presented in Table 2.

Similar to equation 4, equation 5 restricts the use of surplus storage capacity.

$$(5) \quad \sum_i \sum_{k \in K'} flow_{i,t,k} S_{i,k} \leq z \quad \text{for all } t$$

In the example model total surplus storage capacity is assumed to be 5,000 gallons and $S_{i,k}$ is given an upper limit of 200 gallons for any given wine or process.

Objective function

The objective function depends on the length of the planning horizon. In the short term, availability of grapes will be largely fixed and the model could be used to reflect the efficiency of sequencing a fixed volume of different wines through the necessary steps in a manner that minimizes an input such as labor. For longer term planning horizons, the model can facilitate selection of varieties to be included in the product mix by maximizing profits subject to the configuration of a winery's, capacity, the sequencing constraints described above, and constraints reflecting market conditions confronting the winery.

The example model reflects an intermediate term planning horizon, the winery is assumed to have some flexibility in terms of the types of wines that will be produced but faces a fixed configuration of tanks. The objective function is to maximize returns above variable costs and is given by:

$$(6) \quad \sum_i p_i^R Q_i^R + \sum_i p_i^W Q_i^W - \sum_i c_i^{GRAPE} W_{i,1} - \sum_i \sum_j \sum_k c_{i,k}^{TANK} X_{i,j,k} - \sum_i \sum_k c^{STORE} S_{i,k}$$

where p_i and Q_i , are the discounted wine price above specified costs and the wine quantity per gallon, respectively. The superscript R refers to the retail market and the superscript W to the wholesale market. The coefficient c_i^{GRAPE} is the cost of grapes (converted to a per gallon equivalent) for wine i. The coefficient $c_{i,k}^{TANK}$ assigns a fixed cost to the use of tanks. This favors larger tanks because per gallon costs decline as tank size increases. Finally the coefficient c^{STORE} is a cost, per gallon, of using surplus storage.

The total of sales at the retail market and wholesale market for any given wine is restricted by,

$$(7) \quad Q_i^R + Q_i^W \leq \sum_K \delta_{i,k}^L W_{i,k} + \sum_k \delta_{i,k}^L S_{i,k} \quad \text{for all } i$$

where the coefficient $\delta_{i,k}^L$ takes the value of one if the process k is the last process for wine i and the value of zero otherwise.

Table 3 presents prices, sales schedules, and cost information for wines represented in the model. Net discounted prices were obtained by taking observed prices subtracting out material and grape costs, and then computing a weighted average discounted price over the sales schedule for the wine in question.

Other constraints

The sequencing constraints described earlier are the most general aspect of the model, and it is relatively straightforward to add additional steps or change coefficients to reflect the situation confronting a given winery. However, wineries will differ substantially in terms of the mix of products that is best suited to their market environment and the volume that can be sold through the winery's retail sales floor. It will generally be necessary to have constraints that restrict solutions to conform to market realities. Moreover, resource limitations not addressed explicitly in the sequencing constraints above can be added to the model to reflect capacity limitations in other pieces of winery equipment, labor availability, or other constraining factors.

Additional marketing and resource availability constraints used in the example model include the following:

- A maximum of 24,000 gallons could be sold through the winery's retail sales floor. Of this red wines can account for at most 14,000 gallons and white wines can account for at most 14,000 gallons.
- At least 5 percent of the volume of any wine produced is reserved for sale on the retail sales floor.
- Production of Chardonnay must be at least 3,300 gallons.
- Wines are constrained by upper limits as shown in the last column of Table 3.

Solution for the Example Model.

The example model was solved using the CPLEX solver available through GAMS software.

Table 4, presents a summary of the mix of wines suggested by the solution to the model. High value wines in the solution are reserved for the retail sales floor, where margins are the highest. Examples include the reserve red wines and white wines such as Viognier, and Vignoles. However, with few exceptions, most high value wines are produced at substantially less than the upper limits imposed on the model. This demonstrates the importance of capacity use in maximizing returns to the winery. The best illustration of this is that the upper limits are binding for Seyval and for Red and White Muscadine wines. These are relatively lower margin wines, and the solution suggests they be sold primarily through the wholesale market. However, these are the earliest and latest maturing grapes available to the winery. Hence their production has lower opportunity cost in terms of crowding out alternative wines.

One feature of the solution is that it can be used to represent a schematic of tank use such as that presented in Figure 2. Figure 2 would suggest that an alternative configuration of tanks could possibly improve profitability. With exception of one 440 gallon tank, which is never used, most small to midsized tanks are used fairly intensively. Conversely, one of the largest 10,000 gallon tanks is used for only two weeks of the production period. This suggests that the assumptions used for upper limits on the wines are not well suited to the assumptions about configuration of tanks. There are few wines in the example with upper limits large enough to take advantage of the 10,000 gallon tanks.

One straightforward extension of the model would be to specify the number of tanks (n_j from equation 4) to be a decision variable rather than a coefficient. The model would then be used to choose the tank configuration that would best conform to limits on grape availability or wine sales.

Finally, the model can be used to provide production plans for any wine in the solution. Figure 3 presents two examples. In the examples, Chardonnay is fermented in a 6,100 gallon tank and is transferred to 5,500 gallon tank for the remaining two steps in the process. Chambourcin begins in one of the two 6,800 gallon tanks, is transferred to a 4,400 gallon tank for secondary fermentation, and is stabilized in one 3,800 gallon tank and one 250 gallon tank before being transferred to barrels for aging.

Summary

This paper presents a model related to the optimal use of winery capacity. A few reasonably parsimonious constraints reflect the sequencing problem. An empirical example of a winery with an 80,000 gallon annual production capacity was used to demonstrate how the model can be used in planning production over a given season and in making longer term plans related to the mix of wines or configuration of the winery's tank capacity.

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Table 1. Tank Fill Limits Assumed for Example Model

Step	Maximum (%)	Minimum (%)
Red Wines		
Primary Fermentation	75	70
Secondary Fermentation	99	90
Cold Stabilization	100	100
Hold in Tanks	100	100
White Wines		
Fermentation	95	90
Cold Stabilization	100	100
Hold in Tanks	100	100

Table 2. Tank Availability for Example Winery

Tank size (gallons)	Number of tanks
250	8
330	2
440	2
550	6
880	2
1,000	2
1,500	1
2,500	1
3,300	1
3,800	1
4,400	1
4,800	2
5,500	2
6,100	2
6,800	2
8,800	2
10,000	2

Source: Dillon et al. 1994

Table 3. Marketing Assumptions Used in the Example Model

Variety	Retail Price (\$/gal)	Wholesale Price (\$/gal)	Sales Schedule (% per year)				Grape Cost (\$/ton)	Materials Cost (\$/gal) ^A	Upper Limit (gal)
			Year 2	Year 3	Year 4	Year 5			
Reserve Red Wines									
Chambourcin	58.04	31.92		70	5	5	850	8.4	4,314
Cynthiana	60.57	33.31		70	5	5	850	8.4	1,200
Cabernet Franc	70.66	38.86		70	5	5	1,400	8.4	1,200
Cabernet Sauvignon	70.66	38.86		70	5	5	1,600	8.4	1,200
Merlot	70.66	38.86		70	5	5	1,500	8.4	1,200
Red Wines									
Chambourcin	40.63	22.35	80	15	5		750	4.03	10,066
Cynthiana	42.4	23.32	80	15	5		750	4.03	2,800
Cabernet Franc	49.46	27.2	80	15	5		1,000	4.03	2,800
Cabernet Sauvignon	49.46	27.2	80	15	5		1,000	4.03	2,800
Merlot	49.46	27.2	80	15	5		1,000	4.03	2,800
Concord	31.34	17.24	80	15	5		300	4.03	7,360
Red Muscadine	37	20.35	80	15	5		400	4.33	8,000
White Wines									
Seyval	40.02	22.01	80	20			450	4.59	4,960
Vidal	39.62	21.79	80	20			510	4.59	8,000
Vignoles	45.42	24.98	80	20			725	4.59	4,000
Cayuga	35.78	19.68	80	20			475	4.79	4,000
Chardonel	35.78	19.68	80	20			700	4.79	8,000
Traminette	35.78	19.68	80	20			700	4.79	8,000
Chardonnay	41.64	22.9		70	25	5	1,100	6.37	4,000
Viognier	45.42	24.98	80	20			1,200	5.35	4,000
White Riesling	44.01	24.21	80	20			1,000	4.59	4,000
Catawba	21.6	11.88	80	20			450	4.03	2,000
Niagara	30.89	16.99	80	20			375	4.03	2,000
White Muscadine	37	20.35	80	20			400	4.03	8,000

A. Materials cost includes cooperage (if applicable), bottles, corks, capsules, and labels. See Kolympiris for additional details.

Table 4. Production Volumes Suggested by Solution to the Example Model

	Total Production (gal)	Retail Sales (gal)	Wholesale Sales (gal)	Upper Limit (gal)
Reserve Red Wines				
Chambourcin	4,250	4,250	-	4,314
Cynthiana	-	-	-	1,200
Cabernet Franc	901	901	-	1,200
Cabernet Sauvignon	693	693	-	1,200
Merlot	1,089	1,089	-	1,200
Red Wines				
Chambourcin	9,900	6,330	3,570	10,066
Cynthiana	-	-	-	2,800
Cabernet Franc	-	-	-	2,800
Cabernet Sauvignon	-	-	-	2,800
Merlot	-	-	-	2,800
Concord	6,732	337	6,395	7,360
Red Muscadine	8,000	400	7,600	8,000
White Wines				
Seyval	4,960	2,016	2,944	4,960
Vidal	8,000	400	7,600	8,000
Vignoles	2,330	2,330	-	4,000
Cayuga	-	-	-	4,000
Chardonel	5,700	285	5,415	8,000
Traminette	8,000	400	7,600	8,000
Chardonnay	3,373	169	3,204	4,000
Viognier	4,000	4,000	-	4,000
White Riesling	-	-	-	4,000
Catawba	-	-	-	2,000
Niagara	-	-	-	2,000
White Muscadine	8,000	400	7,600	8,000

Figure 1. Timing and Winemaking Steps used in the Example Model.

	15-Jul	22-Jul	29-Jul	5-Aug	12-Aug	19-Aug	26-Aug	2-Sep	9-Sep	16-Sep	23-Sep	30-Sep	7-Oct	14-Oct	21-Oct	28-Oct	4-Nov	11-Nov	18-Nov	25-Nov	2-Dec
Reserve Red Wines																					
Chambourcin								Primary Fermentation			Secondary Fermentation					Cold Stabilization					
Cynthiana									Primary Fermentation		Secondary Fermentation					Cold Stabilization					
Cabernet Franc								Primary Fermentation			Secondary Fermentation					Cold Stabilization					
Cabernet Sauvignon								Primary Fermentation			Secondary Fermentation					Cold Stabilization					
Merlot								Primary Fermentation			Secondary Fermentation					Cold Stabilization					
Red Wines																					
Chambourcin								Primary Fermentation			Secondary Fermentation					Cold Stabilization				Hold	
Cynthiana									Primary Fermentation		Secondary Fermentation					Cold Stabilization				Hold	
Cabernet Franc								Primary Fermentation			Secondary Fermentation					Cold Stabilization				Hold	
Cabernet Sauvignon								Primary Fermentation			Secondary Fermentation					Cold Stabilization				Hold	
Merlot								Primary Fermentation			Secondary Fermentation					Cold Stabilization				Hold	
Concord								Primary Fermentation		Secondary Fermentation		Cold Stabilization				Hold					
Red Muscadine												Primary Fermentation	Secondary Fermentation			Cold Stabilization				Hold	
White Wines																					
Seyval		Fermentation																			
Vidal																					
Vignoles																					
Cayuga																					
Chardonnay																					
Traminette																					
Chardonnay																					
Viognier																					
White Riesling																					
Catawba																					
Niagara																					
White Muscadine																					

Figure 2. Use of Tanks by Week as Suggested by the Solution to the Example Model.

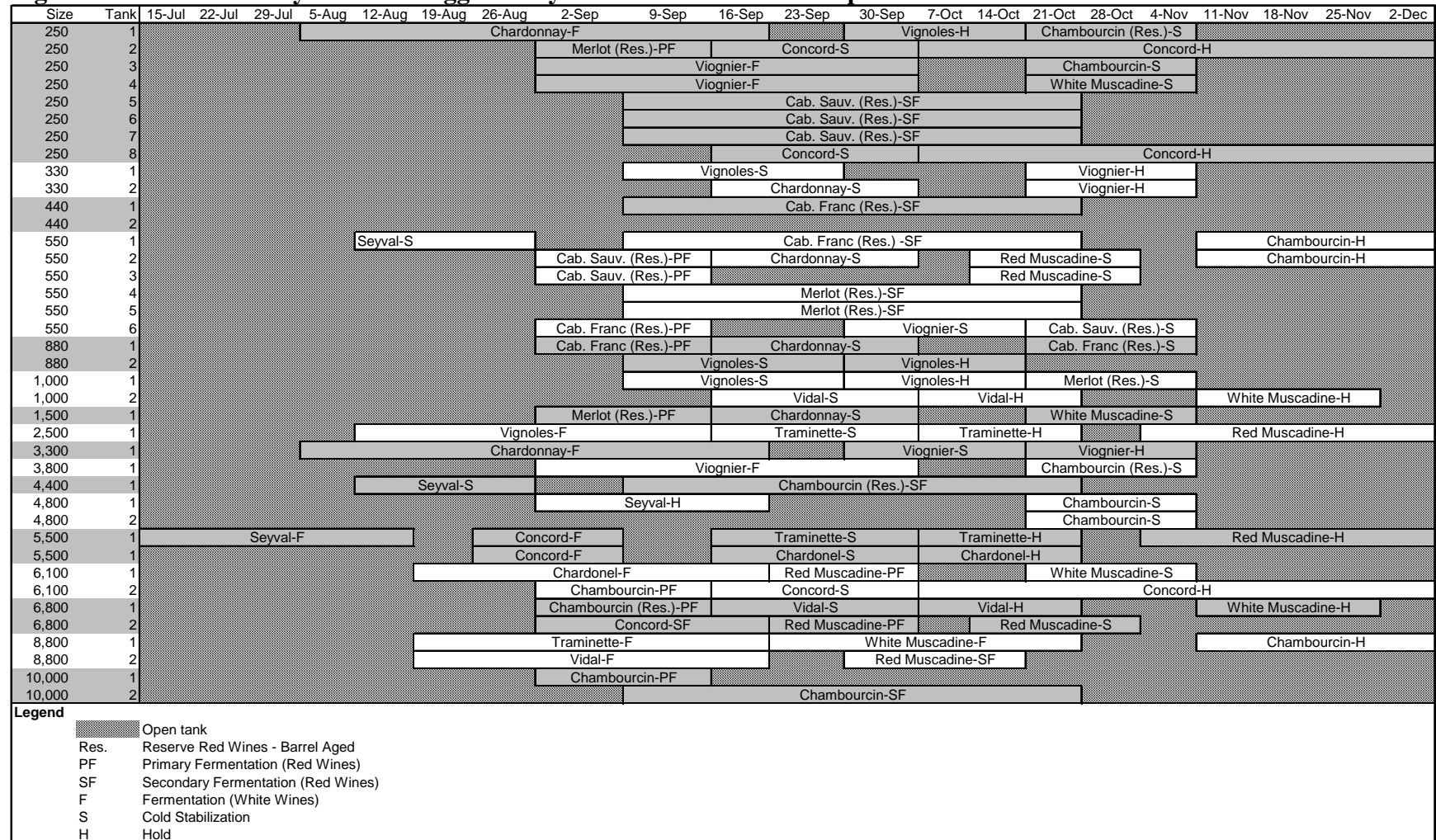


Figure 3. Production Plans Resulting from the Solution.

Tank Size	Number of Tanks	19-Aug	26-Aug	2-Sep	9-Sep	16-Sep	23-Sep	30-Sep	7-Oct	14-Oct	21-Oct	28-Oct	4-Nov
6,100	1	Chardonel (White Wine)											
		Fermentation											
5,500	1						Cold Stabilization			Hold			
		Chambourcin (Reserve Red Wine)											
6,800	1	Primary Fermentation											
4,400	1						Secondary Fermentation						
3,800	1										Cold Stabilization		
250	1										Cold Stabilization		