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Title
Scheduling Fermentation Tanks Optimally

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Conference Presentation

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Keywords
Math Programming, Scheduling, Assignment, Fermentation Tanks

Research Question
How to scheduling fermentation tanks optimally to minimize wasted space and most effectively use capacity?

Methods
We created a tool that allows winemakers to quickly determine an optimal schedule, a mixed-integer programming model. We use it to set the tank schedule for a test winery.

Results
We fill tanks 72 times over the 70-day season. Only 15% of the 1475 tons of activated capacity was wasted. Demand for tanks was uneven.

Abstract
Scheduling Fermentation Tanks Optimally

Introduction: The Underlying Problem
A winery’s production capability is determined not only by the resources it has available but also how efficiently those resources are used. Fermentation tank capacity can be a critical bottleneck. Tanks are expensive and may represent a scare resource for wineries, especially in years when the grape crop is larger than usual, such as California’s 2014 harvest (Adams 2014). Wineries often acquire these tanks over time and from different sources, resulting in a mix of tank sizes and other attributes. Even for the same varietal, winemakers often ferment grapes from one vineyard separately from another, either because they intend to differentiate the finished products or because they need a varied palette of intermediate products to select from in blending a balanced wine. A winemaker must consider these proscriptions when determining how to allocate lots to tanks.

Fermentation takes a few weeks, but times vary with varietal, ambient temperatures, and other factors, such as residual sugar targets. Given that the grape harvest spans a few months, a tank may be used more than once during the season. Large lots may be split across tanks, but a single tank will never hold more than one lot at the same time. Once the wine has been fermented, it may be held in the tank until it is bottled or moved to other storage facilities. If the wine is to remain in the tank after fermentation is complete, the tank must be filled to a sufficiently high level to avoid oxidation.

Although the winemaker may create a schedule that assigns lots to tanks at the start of the harvest season, this schedule is likely to need revision as the season progresses. Weather patterns affect both the time and the size of the harvest, resulting in significant variations between years. Grape sugar levels and ambient temperatures may also cause fermentation times to deviate from the planned schedule. Tanks must be available when the harvest is ready, and if grapes are harvested earlier or later than is ideal, wine quality suffers (Ferrer et al. 2008). In addition to having to react to changing conditions, winemakers may also have an opportunity to take advantage of unused tank capacity. While some wineries only use grapes harvested from their own vineyards, others source many of their grapes through contracts with outside growers. Procurement is often handled though multi-year contracts, but a significant spot market for grapes may exist. In years when grape production is more bountiful than usual, growers may seek additional markets for their excess grapes, and wineries that have sufficient production capacity may able to purchase these grapes at bargain prices.

Methodology

We created a tool that allows the winemaker to quickly determine an optimal schedule and use new information to update the schedule on the fly, reassigning lots that that can still be changed. This tool was first envisioned during a master’s project done by an employee of a medium sized winery in Napa Valley with 31 wine tanks, varying in capacity from five to 44 tons. Some of these tanks lacked hatches at the tank’s bottom, which would make cleanup after fermenting a red wine too onerous. While winery personnel were not aware of an impending tank shortage, the winery had been acquired by a corporation and was considering consolidating some of the production activities with another winery owned by the same corporation. Could tanks be scheduled better to reduce unnecessary tank usage and perhaps even free tanks for reassignment elsewhere?

We formulated and implemented a mixed integer-programming model, as shown in the appendix. The model is an embellished generalized assignment problem, minimizing the use of tanks while providing fermentation space for all lots of harvested grapes. Assignment problems are a classic applications of operations research, from saving lives through kidney exchanges (Anderson et al. 2015) to saving friendships through allocating season tickets fairly (Grandine 1998). The closest analog wine-related application (Cholette 2007) matches wineries with specialty distributors based on their attributes and preferences.

The first consideration was defining the indices. Clearly, both the set of tanks and the lots of grapes require tracking. Each tank has a capacity and may have restrictions. Each lot has an estimate for harvest date, size, fermentation length, and other attributes that impact assignment.

It may seem necessary to track time explicitly. As harvesting occurs on a daily basis, use of weekly time buckets or anything longer than a 24-hour period would prove too coarse, but three months of daily time buckets dramatically increases the number of variables and inherent model complexity. We avoid increasing model dimensionality by defining a conflict matrix that checks if the harvest of one lot would overlap with the fermentation of another.

Our objective is to minimize the number of tanks used and wasted space in the tanks that are used. A user-defined weight allows for deciding if minimizing wasted space or tanks used is more important: is it preferable to split a 20 ton lot equally between two 10 ton tanks or to assign it to a single 25 ton tank, where 5 tons will be wasted?

The most obvious constraint is that all lots must be assigned. Equation (2) guarantees that sufficient capacity from one or more tanks is allocated to each lot. Others (Kolympiris, Thomsen, and Morris 2006) take a strategic view, allowing the winemaker to determine which lots to harvest. However, we assume that harvesting decisions are exogenous to the tactical problem at hand. As we track both used and wasted space in a tank and penalize the latter, Equations (3) and (4) properly account for all wasted tank space and prevent the model from artificially inflating the volume of used tank space.

Equation (5) prevents timing infeasibilities in tank assignments. We generate these constraints only when the conflict matrix indicates that two lots overlap. In the initial data about half of the lots do. Equation (6) avoids non-temporal mismatches, as tanks with proscriptions will be prevented from having inappropriate lots assigned to them, such as preventing red wines from going into tanks restricted to white wines.

Results, Next Steps, and Conclusion

We produced an optimal schedule for the initial data set: filling tanks 72 times over the 70-day season. Only 15% of the 1475 tons of activated capacity was wasted. While about two-thirds of lots were assigned to one tank only, a

few large lots were split into two or even three tanks. The tanks experienced uneven demand. We filled many of the small and all of the large tanks three times over the season. Yet we used several of the most common, medium sized tanks only once. We also explored what-if scenarios, varying the length of the fermentation process from 21 to 24 days. Capacity usage was tight, and not all lots could be processed had they required more than 24 days.
Constructing and implementing a tool such as this is an iterative process. We plan to improve its functionality and usability based on user feedback from the current subject and operations managers at other wineries. As the end-users are ultimately winemaking professionals, not wine-drinking professors, the tool needs to be easy to use and update and must present results that are simple to understand. It should also be stable, inexpensive, and low-maintenance.
The current subject winery predominantly sources from its own vineyards and has little interest in the grape spot market. However, other potential partners often buy their grapes. We plan to develop an auxiliary model that re-optimizes the current schedule while considers inserting additional lots that become available, should that be both possible and profitable.
While global demand for wine is trending upward, the supply of wine is growing even faster, forcing producers to become even more competitive. Wineries will continue to need to improve their asset utilization, and inefficient usage of tanks increases operating and opportunity costs alike. Relying on business-as-usual scheduling will become less viable as both supply and demand grow evermore stochastic. Being able to re-optimize on the fly during the season will allow wineries to limit problems arising from unanticipated changes and take advantage of unforeseen production opportunities. Tools based on operations research models such as the one we describe can help winemakers in their quest to improve profitability.

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Appendix: Model Formulation
[please see PDF]

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Appendix: Model Formulation

Sets

$t \in \mathbf{T}$ Tanks.
$l \in \mathbf{L}$ Lots of harvested grapes.

Data Parameters

While some wineries may express tank capacities in terms of volume, we follow the original winery's convention of using tons of grapes crushed.

C_t Capacity (tons) of Tank t

$P_t = \begin{cases} 1 \text{ if Tank } t \text{ is Proscribed from use in certain fermentations} \\ 0 \text{ otherwise} \end{cases}$

S_t Setup cost incurred each time Tank t is used

A_l expected Amount (tons) of Lot l

H_l expected Harvest date, measured in days from the start of the season, of Lot l

F_l expected Fermentation length (days) of Lot l

$R_l = \begin{cases} 1 \text{ if Lot } l \text{ is intended to become a Red wine} \\ 0 \text{ otherwise} \end{cases}$

OW user-specified Objective Weight, where $0 \leq OW \leq 1$

Variables

$v_{l,t}$ Volume of Lot l assigned to Tank t

$w_{l,t}$ Wasted space in Tank t leftover from being used for Lot l

$m_{l,t} = \begin{cases} 1 \text{ if Lot } l \text{ is matched to Tank } t \\ 0 \text{ otherwise} \end{cases}$

Pre-solution Calculations

If lots are listed in chronological order of expected harvest, the |**L**| x |**L**| Conflict Matrix will have an upper triangular form.

$\mathrm{CM}_{l1,l2} = \begin{cases} 1 \text{ if } H_{l1} + F_{l1} \geq H_{l2} \mid H_{l1} \leq H_{l2} \; and \; l1 \neq l2 \\ 0 \text{ otherwise} \end{cases}$

Objective Function

Minimize a combination of total tank usage and wasted space within tanks that are used. The user-defined objective weight and setup cost data will influence the solution.

$$\textbf{min } OW \sum_t S_t \sum_l m_{l,t} + (1 - OW) \sum_t \sum_l w_{l,t} \quad (1)$$

Constraints

All of a lot's tonnage must fit in the tank(s) assigned.

$$\sum_t C_t * m_{l,t} \geq A_l \; \forall l \in \mathbf{L} \;\; (2)$$

As the model tracks both volume used and volume wasted within a tank and may penalize the latter, the next two equality constraints enforce that all tank space is accounted for.

$$\sum_t v_{l,t} = A_l \; \forall l \in \mathbf{L} \;\; (3)$$

$$C_t * m_{l,t} = v_{l,t} + w_{l,t} \; \forall l \in \mathbf{L}, \forall t \in \mathbf{T} \; (4)$$

This class of constraints prevents a tank from being assigned to two lots that would have a temporal conflict.

$$m_{l1,t} + m_{l2,t} \leq 1 \; \forall t \in \mathbf{T}, \forall l1, l2 \in \mathbf{L} | \; \mathrm{CM}_{l1,l2} = 1 \; (5)$$

The next class of constraints prevents inappropriate lot assignments to tanks with certain proscriptions.

$$\sum_l R_l * m_{l,t} = 0 \; \forall t \in \mathbf{T} | \; P_t = 1 \; (6)$$

Lastly, non-negativity of the continuous variables must be enforced.

$$v_{l,t} \geq 0, w_{l,t} \geq 0 \quad \forall l \in \mathbf{L}, \forall t \in \mathbf{T} \; (7), (8)$$