A critical process analysis of wine production to improve cost, quality and environmental performance

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Abstract Wine production in South Africa is delocalised, with numerous small-to-medium sized producers within several regions within the Western Cape. Whilst adapting to new technological changes, producers have to respond to pressure from consumers and governments regarding the environmental consequences of winemaking, especially water usage and pollution. To date, no systematic analysis integrating the various aspects of winemaking in South Africa has been done. This study assessed both physical inputs and outputs. A detailed questionnaire was developed to broadly assess these parameters and was submitted to all cellars in South Africa. Case studies were performed at three cellars during the 2002 harvest season to validate the questionnaires and collect missing information. Based on this, and a concurrent project, the following parameters were correlated to the tons of grapes presses per annum: effluent parameters which include chemical oxygen demand, suspended solids, total dissolved solids, sodium adsorption ratio, quantity of effluent; wine produced, water consumed, and electricity consumed. These parameters were used to develop an input/output model. This model may be used by wineries to predict their water and electrical consumption, wine produced and effluent characteristics provided they know the tonnage of grapes pressed per year.

Keywords Input/output correlations; process analysis; wine

Introduction

Wine production generally follows traditional methodologies, however new technologies have resulted in important changes in winemaking over the last few decades. Whilst adapting to these technological changes, producers also have to respond to increased pressure from consumers regarding the quality of the product and the environmental consequences of winemaking, particularly with regard to water usage and chemical pollution. No systematic analysis integrating all the different aspects of the winemaking process in the South African wine industry has thus far been undertaken. This project therefore systematically analyses the process of wine production during cellar operation, from the reception of grapes to the final product ready for bottling. This analysis aimed to assess all of the physical inputs (e.g. cellar infrastructure, energy, chemical and water consumption); problems associated with processing (occurrence of microbial contamination, problems during clarification, stuck and/or sluggish fermentation) and the output in terms of income, product quality and the amount of effluent/waste generated.

Due to a lack of information regarding some aspects of winemaking in South Africa, this proved difficult. A significant amount of information is available in terms of cellar throughput, and hectares under vines, but there is little data on consumption levels of water or electricity, what equipment is used in cellars, the frequency of microbial contamination of the wines or stuck fermentations.
Duarte et al. (1998) analysed the process of wine production in Portugal. Their study analysed parameters such as COD, BOD, TDS etc. and performed a mass balance over a winery. However, their data was specific for one winery only. This study found that that the daily water flow during the harvest was twice that of the first racking period, which is useful to size a wastewater treatment plant.

Rozzi et al. (1998) tried to estimate specific polluting loads for 17 different European wineries. The specific load (gCOD/100 kg grapes.day) ranged from 4.3 to 12. This study concluded that higher polluting loads occurred during the harvest period, and that the polluting load could be correlated to the quantity of grapes harvested. The data showed, however, that there was no clear correlation between the quantity of grapes harvested and the polluting load during the racking season.

Balsari and Airoldi (1998) developed a software package for winery waste management. In order for such a system to work correlations had to be developed. The data presented in this paper showed that both the washing water and the COD of the washing water could be correlated to the quantity of grapes pressed. Their correlations were developed from experimental data collected at various cellars in the Cuneo area in 1995 and 1996.

As such, the objectives of this study were to:

- Develop a questionnaire for submission to wineries that could be used as a basis for further development and data collection.
- Obtain a set of data with input from as many wineries as possible.
- Correlate various parameters with a specific winery input (grapes pressed).
- Develop a mathematical model of a South African winery that could be used as a rough guide to predict various parameters based solely on the tons of grapes pressed per annum.

**Methods**

Data was obtained by the development of a questionnaire that assessed a number of broad parameters. This questionnaire was submitted to 390 cellars in South Africa (mid 2001). Sixty replies were finally returned and these form the basis of much of the data presented in this thesis. Additional data was obtained from the Winetech effluent sampling programs due to both sets of data being incomplete in certain instances. The merging of the data sets allowed for a more meaningful analysis of the information of both databases. The data was analysed and parameters were correlated to the tons of grapes pressed by each cellar. Microsoft Excel 2000 was used for the analysis of the data, and the built-in line fitting functions were used to generate equations as well as regression coefficients.

**Results and discussion**

**Physical inputs**

Physical inputs can be described as the parameters whereby materials/energy enter the process of winemaking. Typical inputs can be defined as grapes, electricity consumption, chemicals and water. All variables have been correlated to tons of grapes pressed per year because this is the main material input.

**Electricity**

Figure 1 shows how many electrical units (kWhr) were consumed per month as a function of the tons of grapes pressed. This data is taken from questionnaire respondents who measure cellar electricity consumption. There are two correlations shown – during harvest and out of harvest. During the harvest, Eq. (1) may be used, where $E_H$ is electrical units per month, and $T$ is the tons pressed per season. This correlation has a co-efficient of regression value of 0.7689, which indicates low level of data scatter.
Equation (2) shows the electricity consumption of the cellars outside of the harvest season. As is expected, the consumption of electricity is lower. Harvest consumption is approximately 2.5 times that of the rest of the year. However, the scatter of the data is greater, so this correlation is not as accurate as the harvest data. This is possibly due to different types of lights and different heating regimes used by cellars in winter. Most cellars use refrigeration in summer, which makes up a large percentage of the energy costs.

\[ E_H = 88.634 \cdot T^{0.8587} \quad (1) \]
\[ E_O = 44.82 \cdot T^{0.811} \quad (2) \]

**Water**

In Figure 2, the consumption of water per year was plotted as a function of the tons pressed per year. The data was split into wineries with water measurement and those without.

\[ W = 4037.5 \cdot T^{0.9243} \quad (3) \]

Equation (3) has relatively low scatter, and can thus be considered accurate. It is interesting to note from this graph that there is difference between real water measurement and guesswork. Estimating seems to undervalue the consumption of water by approximately...
60%. Given that only 20% (Sheridan, 2003) of cellars measure their water, this implies that 80% would underreport their water consumption, or would underestimate it if required to report a value.

**Physical outputs**
Physical outputs may be defined as all of the products leaving the cellar. These include wine, solid waste, lees and wastewater. These variables were correlated to the tonnage pressed, and the following set of graphs was developed.

**Wine**
In Figure 3, the quantity of wine produced was plotted as a function of tons of grapes pressed. There is a strong correlation (Eq. (3)) between tons pressed and wine produced, as is to be expected. Figure 3 may seem trivial, but it allows the correlation of all variables to wine produced, instead of tons pressed. This is useful because wine is ultimately the product that is sold. It can be noticed that there are significant variations between producers. These variations do have a significant economic effect. It is normally expected that those wineries that produce less wine per ton of grapes pressed (those points below the correlation line) make better quality wines. This is not the case in this data set. All three wineries that have data points far below the correlation line tend to make “lower quality” wine. A possible explanation for this is that the pressing equipment is old and not as efficient as the more modern presses.

\[
Wine = 626.24 \cdot T
\]  

**(4)**

**Effluent**
Effluent is defined as the wastewater that is discharged from a cellar during normal and abnormal operation. Abnormal operation could be defined as any problem that occurs during processing. These could include extra busy harvest periods, the accidental release of wine or juice etc. into the drains. For the purposes of this study, the effluent has been quantified according to the following classifications: quantity disposed, effluent quality, chemical oxygen demand (COD), total dissolved solids (TDS) and sodium adsorption ratio (SAR).

![Figure 3](image_url)  
*Figure 3* Wine produced as a function of tons of grapes pressed
Quantity of effluent
From the data gathered, only 5% of respondents measure the quantity of effluent disposed, therefore no meaningful data on the quantity of effluent disposed could be obtained. One cellar measured effluent disposal to be 10% more than their incoming water flow. Since this value would oversize any treatment plant, it was used for the purposes of this study.

\[ \text{Effluent} = 1.1 \cdot \text{Water} \] (5)

Effluent characterisation
In Figure 4, a plot was made to correlate various characteristics of the effluent with the tons pressed by the cellar. It is evident from the graph that as the size of the cellar increases, the quality of the effluent decreases (the concentration of COD and TDS rises).

The COD can be correlated to the quantity of tons pressed with Eq. (6). However, this equation has a very low co-efficient of regression which implies a high level of data scatter and consequent poor predictability.

\[ \text{COD} = 772.2 \cdot T^{0.2753} \] (6)

On the same figure, the TDS has also been plotted as a function of tons pressed. This correlation has an even lower regression co-efficient. This shows that these correlations are not particularly accurate, but they do provide industrial averages. The TDS in solution can be given as a function of the tons pressed, shown in Eq. (7).

\[ \text{TDS} = 380.0 \cdot T^{0.2081} \] (7)

In Figure 5, the SAR (sodium adsorption ratio: defined as

\[ \text{SAR} = \frac{[Na]}{([Ca] + [Mg])^{1/2}} \]

where concentrations are given in mmol/L) of the effluent streams was plotted as a function of the tons of grapes pressed and correlated. It must be noted that from all the data, only one cellar exceeded the permissible limit for the SAR for irrigation of effluent (The legal limit for irrigation of effluent is 3 in South Africa). It does show that the SAR of the effluent increases linearly with respect to tons of grapes pressed per annum. This is given by Eq. (8).

\[ \text{SAR} = 6.10^{-5} \cdot T + 1.0414 \] (8)
Development of an input/output model

Figure 6 is a pictorial representation of a preliminary black box model developed to perform mass balance and financial balance calculations for South African wineries based solely on the tons of grapes pressed.

An input is defined as something that is added to the process. In this case, grapes, water, chemicals and energy are defined as the inputs. Typically, inputs have an associated cost. Outputs are materials/energy that are removed from a process. In this case, the outputs are designed as wine, wastewater, solid waste, lees, energy losses and evaporation losses. Outputs may have associated costs, but may also be value added products. These however, are not exclusive definitions. There are many more inputs and outputs, but for the purposes of this study, the above are the most important.

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**Figure 5** Effluent characterisation – SAR as a function of tons of grapes pressed

**Figure 6** Mathematical model of a winery
Processing parameters are defined as those parameters that can be changed by adjusting or modifying the way wine is made. One example of a processing parameter would be applying pinch technology heat exchange (Ficarella and Laforgia, 1999). Another example would be adjusting the residence times of the drainage sumps to lower the ‘leaching’ of COD from pips and skins into the juice.

Design or equipment parameters are defined as those parameters that are changed by adjusting the equipment in the process. Equipment parameters may be very costly to change but this is not necessarily the rule. The parameters range from fixing the cracks and chips in open fermenters, to replacing mild steel tanks with stainless steel ones.

However, there are parameters that are missing from this model that cannot be so easily quantified, an example of this being the solid waste. No information was obtained so there is no cost that can be assigned to the quantity of solid waste. Similarly, the lees can be sold for tartrate recovery or dumped with the solid waste; this then alters the economics of the model. It was unfortunately not possible to include chemical consumption in this model. Many cellars do not measure chemical usage and there are many different types of chemicals that may be used for the same purpose. The questionnaire sought to obtain this information, but the replies were in many cases were either too vague or omitted. This unfortunately means that there is a missing parameter, which is of great importance.

The missing parameters do not make the model less useful though. Any information that is missing can be added at a later stage and the model can then be improved on. Such is the purpose of this model; it is the first of its type and can be used by later studies or by industry. It can also be used by cellars and fine-tuned for their purposes, according to their own unique set of operating conditions, e.g. for red and white grapes.

The following functions have been defined in the numbered equations during this study:

\[
F_1: \text{Water} = 4037.5 \cdot T^{-0.9243} \\
F_2: E_H = 88.63 \cdot T^{-0.8587} \\
F_3: E_O = 44.82 \cdot T^{-0.811} \\
F_4: \text{COD} = 772.2 \cdot T^{-0.2753} \\
F_5: \text{TDS} = 380.0 \cdot T^{-0.2081} \\
F_6: \text{SAR} = 6 \cdot 10^{-5} \cdot T + 1.0414 \\
F_7: \text{Effluent} = 1.1 \cdot \text{Water} \\
F_8: \text{Wine} = 626.24 \cdot T
\]

Conclusions
It was found that although questionnaires do provide valuable information, they are quite restrictive when seeking detailed and quantifiable data. It meant therefore, that the data obtained from this study had to be complemented by data from other sources, in this case from the Winetech program for ongoing effluent analysis. However, the combined data sets provided a detailed database which can be utilised for further research by both the wine industry and academia.

Various parameters with varying degrees of accuracy were correlated to the tons of grapes pressed per annum and this allowed a preliminary input/output model to be developed. It is possible to use this model to roughly predict certain cellar parameters. Two instances of these parameters include effluent COD and TDS. Considering the lack of measurement of these parameters in the industry, this model proves to be a useful tool when dealing with cellars that require information on their processes but have made no measurements in the past. It enables them to anticipate what the parameters are likely to be, and they can use these parameters as a benchmark when comparing themselves to other cellars. This model
provides an industrial “average” for the abovementioned variables and it is always gratifying to a cellar if they can establish that they use less water than the average cellar of that size.

The model needs refinement though, in terms of quantifying inputs like chemical consumption, but also due to it being a dynamic model. As cellars change their processes to become more environmentally friendly and efficient, the correlations will change and this needs to be reflected in the model. It is also possible that this model bears little resemblance to wineries in other parts of the world where winemaking philosophies and priorities differ.

Based on these results, further research is being performed on the use of constructed wetlands for winery effluent treatment, primarily by identifying those wetland botanical and microbial communities best suited for winery effluent. Using the abovementioned model, the cellars that fall within an (unspecified as yet) effluent strength range will be identified as suitable candidates for the use of this system for treatment of their effluent.

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