Model Predictive Control of Stem Water Potential in Grapevines: A Simulation Study

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Abstract: Vines for wine production are commonly cultivated under regulated deficit irrigation, i.e. the vines (*Vitis vinifera*) are maintained in a state of mild-sever, controlled drought stress in order to enhance the quality of the yield and the wine. The plant water status can be estimated via measurements of the Stem Water Potential (SWP) using Scholander pressure chamber. The objective of the present work was to demonstrate the application of Model Predictive Control (MPC) for managing grapevine irrigation via midday Stem Water Potential at two levels: (1) MPC was used to determine SWP reference values for the whole season, and (2) MPC was used to estimate twice a week the irrigation required to achieve the desired SWP.

Keywords: MPC; Dynamic crop model; Irrigation; Precision agriculture.

1. INTRODUCTION

Wine quality is defined by a combination of sensory properties: Jackson (2007) visual properties (color, clarity), taste, flavor and mouth feel, scent\odor. These sensations correlate to the combination of the different chemical ingredients of the wine. Alcohol\sugar content, organic acids content, phenolic compounds (which are the main factor in wine flavour), anthocyanidin content (a group of polyphenols that are pigment molecules, the main factor on wine colour), ester content (molecules which are main factor for wine scent). Grapevines consists mostly of water that serves as a solvent for organic and inorganic solutes Keller (2015). Plant water status is also an important and a limiting factor of plant photosynthetic activity, due to water loss caused by stomatal transpiration. If the plant has insufficient amount of water for maintaining its water status, the leaf stomata close and photosynthetic activity is reduced, and in critical states even disabled, thus, limiting the plant's growth. Absolute closure of the leaf stomata may cause heat accumulation in the leaf which may lead to defoliation or even plant mortality. On the contrary to most agricultural crops that optimally grow under non-stress conditions, it is well known that *Vitis vinifera* vines grown for wine production benefit from mild, controlled, water stress that improves berries and must characteristics. For instance, Merli *et al.* (2016) describes an improvement in the berry composition due to drought stress achieved by non-irrigation practice applied to cv. Sangiovese vines. Castellarin *et al.* (2007) examined the effect of water stress at different fruit's development stages on the phenolic content of the berry. Leeuwen *et al.* (2004) examined the effect of water and nitrogen stress on cv. sauvignon blanc grapes' properties.

Due to the importance of plant water stress to the generation of important qualitative berry ingredients, and on the other hand the increase of yield due to irrigation, many articles addressed the subject of irrigation methods for grapevines in order to find a proper balance between the two Munitz *et al.* (2018); Netzer *et al.* (2019). In practice, wine grapevines are grown without irrigation or while applying so-called deficit irrigation, which maintains the vine in a controlled state of stress in order to enhance the grapes quality. There are two main sub-methods of deficit irrigation: Sustained deficit irrigation- The irrigation dosage is a constant proportion of the estimated crop evapotranspiration (ET_c); Regulated deficit irrigation – the irrigation dosage is proportional to ET_c but the factor ratio changes at different phenological stages of the berries. Two main physiological states which are highly correlated to the grapevine's water stress status are midday stem water potential (SWP, ψ_{stem}) and predawn leaf water potential (LPW, ψ_l) (Choné *et al.* (2001); Williams (2012)). Some work was done on using these measures as a basis for regulated deficit irrigation treatments (Girona *et al.* (2006); Acevedo-Opazo, Ortega-Farias and Fuentes (2010)). However, due to the limitations of the methods currently available for measuring these states, which are destructive, slow and labor-intensive, their practical use is limited, mostly restricted to research purposes.

The objective of the present study was to demonstrate the application of the Model Predictive Control (MPC) concept for managing grapevine irrigation via Stem Water Potential at two levels:

- Strategic level: Determination of optimal reference/target values for midday stem water potential / predawn leaf potential, assuming that the growing season is split into N periods during which the SWP reference value remains constant
- Tactical level: Determination of the optimal irrigation schedule for a seven-day period, so as to reach to reference SWP value.

In both cases a mathematical model describing the vines and berries development is required. Only a handful number of grapevines models have been published (Wermelinger, Baumg and Gutierrez (1991); Bindi *et al.* (1997); Lakso and Poni. (2005); Lakso, Intrigliolo and Eissenstat (2008); Cola *et al.* (2014); Miras-Avalos *et al.* (2017), (2018); Nogueira Júnior *et al.* (2018)). Most of these are not suitable for optimal control application and predict “only” variables such as canopy cover, number of leaves, number or weight of berries, etc., but not “quality features”, such as sugar content, phenols or anthocyanidin, which are critical in determining wine quality.

2. MODEL OVERVIEW

The present study was conducted with the model STICS (Simulateur mulTIdisciplinaire pour les Cultures Standard) Brisson *et al.* (2008), which is a generic plant model that has been adapted to grapevines. This model includes most of the vegetative states, soil-plant-air dynamics and many different agrotechnical treatments. In particular, Valdés-Gómez *et al.* (2009) examined the model performances for different irrigation strategies and showed that the model is capable of generating good estimation for some of the plant's and soil states. The model has been calibrated for a number of grapevine varieties and soil types De Cortazar-Atauri *et al.* (2009). The present study was conducted with the parameter set corresponding to *Vitis Vinifera* cv. Syrah, and the properties of a loamy-sand soil from a vineyard located in the mountain region (430 m above sea level) near Dolev, Israel.

STICS does not predict any indicator of berry quality, which is critical since it determines the price winemakers pay for berries. Since in-depth modifications of the model to include such predictions was beyond the scope of the present study, for the sake of the present computations we assumed a simple function to represent the berry quality in relation to the berry's size and sink to source ratio (calculated using yield per area and grapevine's Leaf area index value at harvest):

$$K_{Quality} = \frac{\beta_1 \cdot K_{\textbf{Trophic Ratio}}\left(R_{sis} = \dfrac{y_{\textbf{LAI at harvest}}}{y_{\textbf{yield}}}\right)}{1+\beta_2\left(y_{berryWeight} - y_{berryWeight,ref}\right)}$$

Where $K_{Quiality}$ is a unit less factor representing the effect of yield quality on net profit per weight.

R_{sis} – Harvest's source to reproductive-sink ratio.

β_1, β_2 - weighting coefficients.

$K_{\textbf{Trophic Ratio}}$ - a function of the desired of sink / source ratios, where y_{yield} is the fresh yield weight per area, which correlates with the reproductive sink and $y_{LAI\ \textbf{at harvest}}$ is leaf area index (LAI) at harvest, which correlates with the source. This model is based on Kliewer and Dokoozlian (2005).

$$K_{\textbf{Trophic Ratio}}\left(R_{SIS}\right) = \begin{cases} R_{SIS} > 1.22 & C_3\left(R_{SIS}\right) = \dfrac{1}{1+\beta_3\left(R_{SIS}-1.22\right)^2} \\ 0.65 \le R_{SIS} \le 1.22 & C_3\left(R\right) = 1 \\ R_{SIS} < 0.65 & C_3\left(R_{SIS}\right) = \dfrac{1}{1+\beta_4\left(0.65-R_{SIS}\right)^2} \end{cases}$$

β_3, β_4 - weighting coefficients.

3. PROBLEMS FORMULATION

2.1 Strategic level

The objective at this stage is to determine the sequence of SWP reference value that maximize the expected profit defined as the difference between the value of the harvest and the irrigation costs.

$$\max_{\underline{X}} F_{SO} = f_{Payoff}\left(y_{yield}, y_{berryWeight}, y_{tss}, y_{LAI\ \textbf{at harvest}}\right) - \ldots$$
$$\ldots - f_{\textbf{Irrigation Costs}}\left(\underline{Y}_{irri}\right)$$

where

$$f_{Payoff} = K_{payoff}\left(y_{yield}, y_{tss}\right) \cdot K_{Quality}\left(y_{yield}, y_{berryWeight}, y_{LAI\ \textbf{at harvest}}\right)$$

K_{payoff} – a lookup chart based on the Israel Wine Board payoff charts.

y_{yield} : fresh yield weight per area

y_{tss} : Total soluble solids content in yield, units are °Brix [1 gram soluble solids/100 gram of solvent liquid]

$y_{LAI\ \textbf{at harvest}}$: grapevine leaf area index at harvest

$f_{\textbf{Irrigation Costs}}\left(\underline{Y}_{irri}\right)$: Total seasonal irrigation costs, a function of the seasonal irrigation dosages vector $\underline{Y}_{irri}$.

$$f_{\textbf{Irrigation Costs}}\left(\underline{Y}_{irri}\right)=\begin{cases}\sum \underline{Y}_{irri}\le Q_0 & D_0\sum \underline{Y}_{irri}\\ Q_0\le\sum \underline{Y}_{irri}\le Q_1 & D_0\cdot Q_0+D_1\left(\sum \underline{Y}_{irri}-Q_0\right)\\ \mathrm{M} & \mathrm{M}\\ \sum \underline{Y}_{irri}\ge Q_{n-1} & D_0\cdot Q_0+\sum_{ii=1}^{n-1}D_{ii}\cdot\left(Q_{ii}-Q_{ii-1}\right)+D_n\left(\sum \underline{Y}_{irri}-Q_{n-1}\right)\end{cases}$$

where:

D_{ii}: price coefficient for water between quanta quota ii and quota ii+1;

$Q_{ii}[m^3]$: the allowable water quota for price up till D_{ii}

The growing season was divided into three periods corresponding to the three major development stages of the berry development along the season (Stage I – from flowering until bunch closure, Stage II- from bunch closure to veraison, Stage III – from veraison until harvest) and the decision variables consisted of the SWP at the beginning of each stage and on the last day of the season (altogether four values). Daily reference values were obtained by linear interpolation between these values. Irrigation events were determined (indirectly) from the SWP values and corresponded to the irrigation required to achieve the desired SWP taking into account the soil water status, crop demand and expected weather. The optimization was performed using the meteorological conditions recorded at Talmon local meteorological station in 2009-2011. Several years meteorological data was used to account for inherent climate variability and the practical need for the grower to have year-independent SWP reference values. The objective function was calculated using the cumulative (or equivalently average) profits and costs.

Note that an additional set of constraints was included to prevent irreversible physiological damage:

$$\psi_{Stem}\ge\psi_{Stem\_ref}$$

2.2 Tactical level

The problem's objective function is the minimum squared differences of the predicted stem water pressure values ($\underline{\Psi}_{Stem}\left[Mpa\right]$) and the reference stem water pressure values ($\underline{\Psi}_{Stem,ref}\left[Mpa\right]$):

$$\min_U F_{RH1}=\left\|\underline{\Psi}_{Stem}-\underline{\Psi}_{Stem,ref}\right\|_2$$

s.t.

$$\psi_{Stem}\left(t_0\right)=\psi_{Stem,0}$$
$$t_N\le t_0+H-1$$
$$\forall t\in\left[t_0,t_N\right]:0\le u\left(t\right)\le u_{\max}$$

Where

F_{RH1}: problem's objective function (scalar).

H: the prediction horizon.

$$\underline{\Psi}_{Stem}=\begin{bmatrix}\psi_{Stem}\left(t_0+1\right),\psi_{Stem}\left(t_0+2\right),\ldots\\ \ldots,\psi_{Stem}\left(t_0+H-1\right),\psi_{Stem}\left(t_0+H\right)\end{bmatrix}:$$

vector of predicted stem water potential values of the predicted horizon time range.

$$\underline{\Psi}_{Stem,ref}=\begin{bmatrix}\psi_{Stem,ref}\left(t_0+1\right),\psi_{Stem,ref}\left(t_0+2\right),\ldots\\ \ldots,\psi_{Stem,ref}\left(t_0+H-1\right),\psi_{Stem,ref}\left(t_0+H\right)\end{bmatrix}$$

: vector of reference stem water potential values of the predicted horizon time range.

U: the control input vector (decision variable) of the problem. In this case, irrigation dosages

$\psi_{Stem,0}$: model pressure at time t_0 (beginning of the current horizon problem)

$u_{\max}$: maximum irrigation admissible dosage

t_N : time of the last control input

4. RESULTS

4.1 Strategic level

The SWP values that maximize profit were determined iteratively, using the meteorological varibles of 2009-2011. Figure 1 shows the adjustments of the SWP reference values as the number of optimization iterations increase. Figure 2 shows the convergence of the expected profit as a result of these adjustments.

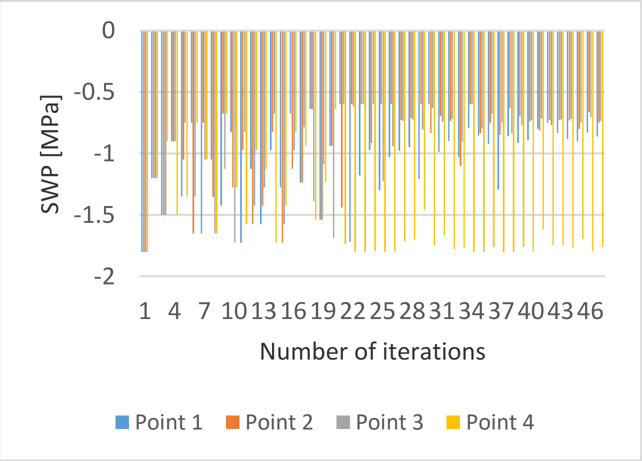

Fig. 1: Convergence of the midday Stem Water Potential optimal reference values computed based on years 2009-2011

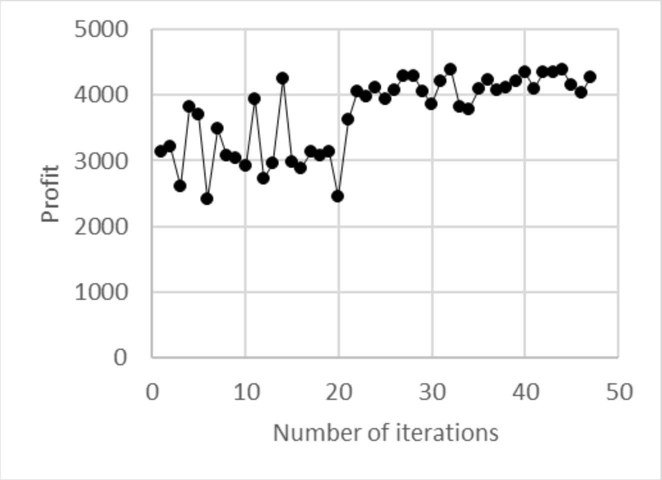

Fig. 2: Convergence of the profit computed based on years 2009-2011

5.2 Tactical level

The objective was to maintain SWP as close as possible to the reference values determined in Section 4.1, despite the temperature forecasts being imperfect. The SWP values corresponding to the highest profit (Iteration number 44) were selected as reference. The irrigation amounts were determined based on synthetic temperature forecasts that were generated by perturbating the actual measurements. In order to reflect the fact that very short-term predictions are more accurate than longer-term ones, the amplitude of the perturbations was time-dependent as described in Table 1.

$$T_{Forecast}\left(t+\Delta t\right) \in N\left(\mu = T_{real}\left(t+\Delta t\right), \sigma^{2}\left(\Delta t\right)\right)\left[°C\right]$$

where:

$T_{Forecast}$ **- Forecast temperature**

T_{real} **- Real temperature**

$t -$ **Present time**

$\Delta t -$ **Time difference from present to predicted day**

$N -$ **Normal gaussian random distribuition**

$\mu -$ **mean**

$\sigma^{2}\left(\Delta t\right) -$ **Time difference dependent standard deviation**

$T_{real}\left(t+\Delta t\right) -$ **Real value of temperature at time $\Delta t + \Delta t$**

Table 1. Mean absolute error of the temperature forecast used in the simulations

Days	2-5	6-10	11-15
Mean absolute error(°C)	1	2	3

The prediction horizon was one week, and it was assumed that irrigation events could take place only on Mondays and Fridays. On each of these days two irrigation decisions were made but only the first one (corresponding to the present day) was implemented.

Figure 3 shows the reference and actual Stem Water Potential., and Figure 4 shows the corresponding irrigation events. During the first 40 days the desired SWP cannot be achieved due to water initially present in the soil (from winter rains). The optimization recommends very small irrigation amounts due to a somewhat unexpected behaviour of the model that predicts marginally lower SWP values (less negative) with such irrigations rather than with no irrigation at all. The behaviour is probably due to some numerical issue in the model and is under investigation. From day 180, when irrigation is actually needed, the MPC controller maintains the SWP very close to its desired value.

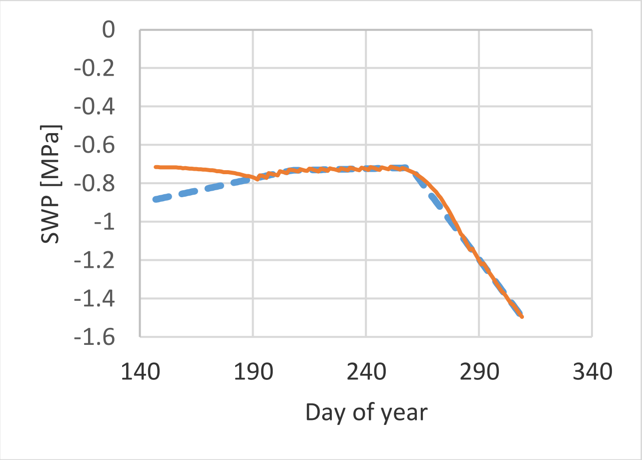

Fig. 3: Stem Water Potential reference values (dashed blue line) and values achieved by implementing the irrigation computed with non-perfect temperature forecasts (continuous red line)

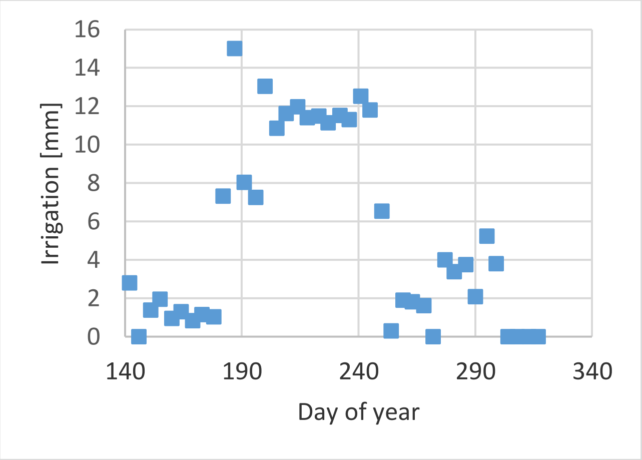

Fig. 4: Irrigation events computed with non-perfect temperature forecasts

6. CONCLUSIONS

Application of the Model Predictive Control concept for determining time-dependent vine stem water potential reference values and managing irrigation to achieve actual SWP values close to the desired one has been demonstrated[1].

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[1] It is important to remark that the resulting reference SWP values are not practical values and are used solely for the purpose of demonstrating the method. For real and applicable SWP values in (vines for wine production) regulated deficit irrigation treatments, see Netzer *et al.* (2019)