A HIERARCHICAL CONTROL SYSTEM FOR MAXIMIZING PROFIT IN GREENHOUSE CROP PRODUCTION

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Abstract

The main objective of greenhouses crop production is to increment the economic profits of the grower by means of finding a trade-off between the improvement of the quantity and quality of the horticultural products and the cost of obtaining adequate climatic conditions using automatic control strategies. This paper shows the development of a hierarchical architecture to control the crop growth in greenhouses based on the inner climate in order to maximize the profit (the difference between the incomes coming from the sale of the final production and its associate costs).

1 Introduction

Agriculture is one of the main economic sectors of the province of Almería (South-East Spain), where the largest concentration of greenhouses of the world is located. Until now, an important presence has been maintained in the international market, mainly due to the relatively low production costs and to the capability of supplying products outside season, in addition suffering little competence from developing countries. Currently, this competition is growing, due to the increase of production in developed countries, that supply good quality and service at average cost, and to the import of products coming from new sectors in less developed countries, characterised by low production costs. Only the improvement of the productivity and the quality will allow the maintenance of the yield, being the technology an essential part in this process. A large effort is nowadays being carried out directed to the introduction of technology in each one of the phases of the agricultural commercialisation chain. Obviously, the most important phase is the crop production and so, great efforts are required to improve quality and quantity of horticultural products. Crop growth is mainly influenced by surrounding environmental climatic variables and by the amount of water and fertilizers supplied by irrigation; therefore, the proper handling of these variables will allow the control of crop growth. This is the main reason of why a greenhouse is ideal to cultivate, as it constitutes a closed environment in which climatic and fertirrigation variables can be controlled to allow an optimal growth and development of the crop. Nevertheless, the control of these variables has associate costs related to energy, water and fertilizers. Therefore, the objective from the economic point of view will not be to obtain the maximum production, else to maximize the profit understood as the difference between the incomes from the final production sale and its associate costs.

The climate and the fertirrigation are two independent systems with different control problems. Empirically, the requirements of water and nutrients of different crop species are known and, in fact, the first automated systems were those that control these variables. As the problem of greenhouse crop production is a complex issue, an extended simplification consists of supposing that the plants receive the amount of water and fertilizers that they require at every moment. In this way the problem is reduced to the control of crop growth as a function of climate environmental conditions. This problem involves three systems: the climate variables, the crop and the market. Each one has a different dynamic, so a typical control solution consists in use a multilayer hierarchical architecture, where the control of an objective is split into algorithms or layers, each of which acts at different time intervals in which the dynamic optimisation horizon has been divided [5]. Some authors [6,8,16,17,18] have used this idea describing greenhouse crop production as a hierarchical control system with three levels and different variations. In this scheme, the bottom level (fast time scale – seconds/minutes) corresponds to the control of the greenhouse climate conditions, that is usually implemented by means of classical or optimal feedback-feedforward control, sometimes involving adaptive control algorithms. The middle level is related to control the crop development, where slow time scales (hours/days) are governed by physiological processes. At the top level, production planning and coordination take place (time scale between some days and the total life of the crop).

This paper describes the design and implementation of a hierarchical optimal control system of greenhouse crop growth as a function of inside and outside environmental conditions taking into account economic criteria, in such a way that the difference between the gross profit obtained by the sale of the production and the associate costs is maximized. The system is applied to the special conditions of the Southeast of Spain horticultural sector. The fulfilment of some specific objectives has been required to account for this objective, such as studying and modelling of greenhouse inside climatic variables that affect and characterise crop growth, as well as the design and test of climate control algorithms as is described in [13].

The paper is organised as follows. In section 2, the proposed control hierarchical architecture is shown. Section 3 is devoted to present the management algorithm of this architecture. In section 4, some simulation results are shown in order to study the response of the system in different situations. Finally, section 5 presents some concluding remarks.

2 Hierarchical control architecture

The crop growth is defined by the increase of the biomass or the physical dimensions of the plants [2]. The plants need sugar for growing, produced by the photosynthesis. This process is influenced by the following climate variables: temperature, Photosynthetically Active Radiation (longwave between 0.4 and 0.7 μm) and CO_2 concentration. The humidity affects indirectly, because it causes the closing of the stomas by which the CO_2 assimilation takes place. Jones proposed the description of the crop growth by the total dry weight, the nodes number (leaves and trusts) and the leaf area index (surface of leaves by soil surface) [9,10]. On the other hand, the plants breath and during this process sugar is consumed. Respiration process is strongly influenced by the temperature. Therefore, the crop growth can be managed by controlling these climatic variables using the typical actuators used in these greenhouses: natural ventilation, heating and shade screen. They allow to control of the temperature, radiation and humidity. The CO_2 concentration is only monitored because artificial CO_2 injection is too expensive.

In order to control the crop growth based on economic criteria, a hierarchical control architecture has been proposed as an integral solution. As figure 1 shows, it is constituted by two layers that control the system composed by crop and greenhouse climate, based on the existence of two different time scales. The upper layer (second layer) solves an optimisation problem as a function of the expected production and associate costs or the desired date of harvesting. This optimisation problem maximize an objective function that represents the profit obtained based on the climatic variables that affect the growth of the plants, providing the set points that must follow these climatic variables along the season. The lower layer (first layer) includes the controllers that try to cancel set point tracking errors (these set points are those calculated by the upper layer). By using a receding horizon strategy, when a night-day transition or vice versa occurs, the optimisation problem is again solved by using new real measured data of climatic variables and crop growth, trying to reduce errors coming from plant-model mismatch, deviations in the weather forecast or the produced errors when the climatic variables are not able to reach the climatic set points due to disturbances or limitations in the actuators.

3 Management algorithm of the architecture

The problem of crop growth control based on the greenhouse climatic conditions considering economic criteria has different variants based on the aspects to consider, and the main objective to obtain. Particularly, the approach considered in this paper is based on the following general hypotheses:

- The crop used as reference is the tomato because, with the pepper, are the leading products of the agricultural sector in the Spanish Southeast. Tomato represents the 16,5 % of the hibernated total surface with a value higher than 400 millions euros in the Almería province.
- A single harvesting at the end of the season is considered.
- The crop growth variable to control is the global dry weight of the plant, which can be obtained from simplified models used to simulate the tomato growth as that proposed in [9]. There are different studies demonstrating that at the end of a season, the fraction of total dry weight that corresponds to the tomato fruits is approximately 60%, as it is indicated in [7]. This fact has been corroborated in our own tests. On the other hand, the market prices are referred to the fresh weight. Some authors estimate that approximately the 6% of the fruit weight correspond to dry matter (6.5% [7], 5.5% [11]). Our own experiences have estimated a fraction of 7%, these data used to calculate the prices of the harvested products.
- The optimisation process obtains the optimal setpoint trajectories of the air temperature, that is the main control variable that affects the growth of the crop. The relative humidity is inversely correlated with the temperature. Furthermore, in order to control this variable, it is needed to use the same actuators that for temperature control. An option consists in maintaining the humidity within a certain interval by modifying the setpoint of diurnal temperature based on its value in every control interval. The shade screen is used to diminish the radiation onto the canopy, reason of why the crop growth rate diminishes too. This fact provides a new degree of freedom to control the production, delaying the harvesting date. Nevertheless, it is not considered in the optimisation process because the system often tries to obtain the maximum production. So the shade screen is only used under certain tactical circumstances based on the experience of the producer.
- Two temperature setpoints per day are considered: one for diurnal time and another for nocturnal time, since the experts advices it (the plants do not make the same vital functions at night and at diurnal time). The commutation of the setpoints is made when sun rises or falls.
- The system is well irrigated and fertilized.

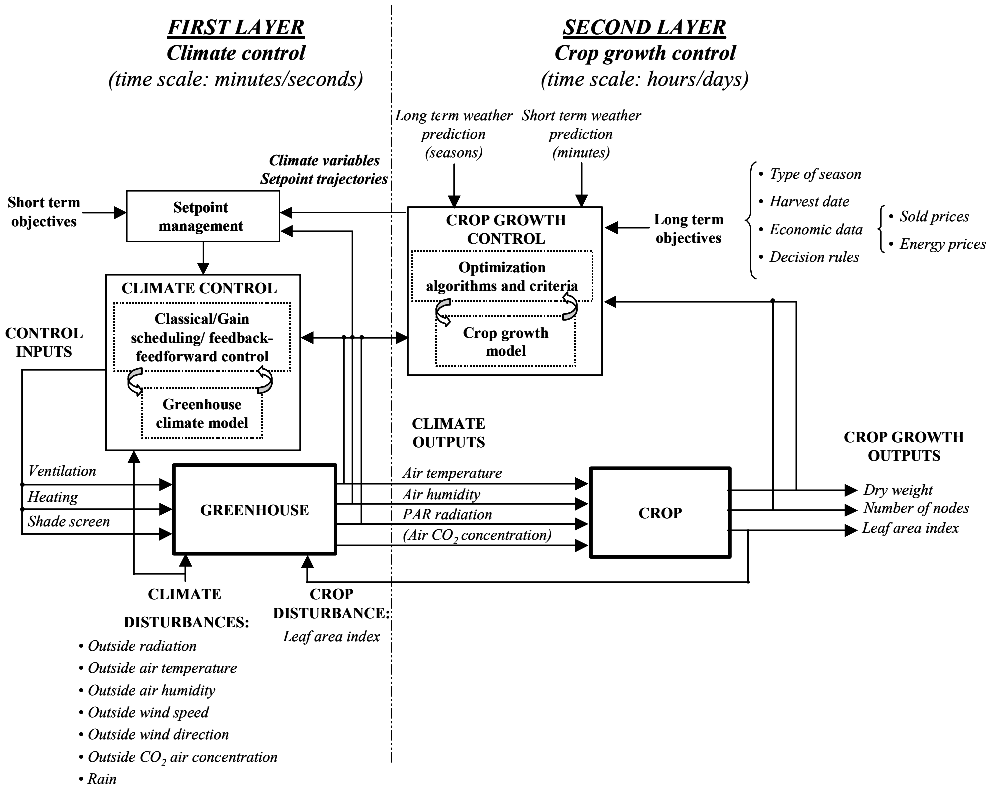


Figure 1. Multilayer hierarchical system proposed to control the crop growth

One important component of this architecture is the coordination between the two layers. After analysing and testing different alternatives, a receding horizon-based algorithm has been selected, whose flow diagram is shown in figure 2. At the beginning, the user must indicate required data to initialise the process of control of the crop growth: Type of season (spring or autumn. It is necessary to determine the climate pattern that is going to be used by the optimiser as long term weather forecast); date of harvesting (based on the experience of previous seasons and possibly market evolution predictions, the date of harvesting is fixed supposing the highest sold prices, for example "*n*" days); initial crop status (dry weight and the number of nodes of the plants when they left the nursery) and the economic data (as the optimisation process is based on economic criteria, it is necessary to indicate the predicted final price of production sale and the evolution of the prices of the electricity and the fuel throughout the season as the production associate costs).

Based on the type of season, the date of harvesting and astronomical data, 2n+1 time intervals (initial horizon) are determined in which it is necessary to calculate the temperature setpoints (the duration of the nocturnal and diurnal time periods is not constant along one year).

Disturbance variables (external weather) have a dominant role and coherent action onto the formation of the greenhouse environment, so a long term weather prediction is required. The *National Institute of Meteorology* (*INM*) is the reference used in Spain for the weather forecast. It estimates the daily climate of each province and provides a three days prediction for each region, offering data of temperature, wind and radiation. Obviously, this information is not sufficient for the weather forecast in an agricultural season whose minimum duration in a short cycle crop is from ninety to one hundred days. Based on the climatic variables, behaviour patterns are repeated every year, and it is possible to use series of historical data as weather forecasts for a certain season. It is also possible to use other kind of patterns for weather forecasts, as those based in clear-day predictions for which prediction models exist [4]. The basic idea is the following:

- Each upper layer control interval, obtain the weather forecast for the next four days from the *INM*.
- Based on this information, assign a value for each variable (minimum and maximum temperature, mean wind speed and direction and type of day as function of the radiation).
- Search the parameterised historical database looking for four day with the previous closest values.
- The long term weather forecast is determined by selecting four days and the consecutive following days until completing the horizon.

Using all these data, an optimisation process is executed to determine the setpoints of temperature in all the time intervals along the prediction horizon. It has to maximize the difference between the incomes coming from the sale of the final production and its associate costs, formulated as the following cost function:

$$J = c_{area,ss} V_{price,cu}(\tau_f) X_{DW}(\tau_f) - \int_0^{\tau_f} V_{\cos,act}(t)\, d\tau \quad (1)$$

where, $c_{area,ss}$ is the greenhouse soil surface, $V_{price,cu}$ is the sold prices of the production at the harvesting date (τ_f), X_{DW} is the dry material, $V_{cos,act}$ are the cost incurred by the actuators (electricity and fuel) and τ is the time.

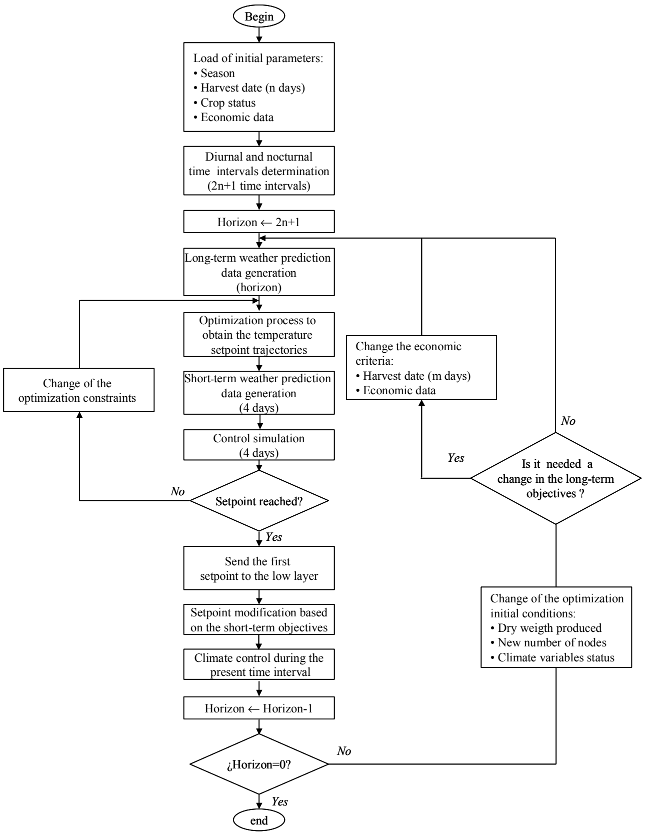


Figure 2. Management algorithm of the proposed architecture

It is necessary to relate these variables with the temperature because this is the output of this optimisation process. The models required for optimisation purposes are shown in [13]. The simplified model *TOMGRO* [10] has been adapted so that the dry weight is represented as a function of the air temperature. In order to consider continuous harvesting, it would be necessary to add the income obtained in each harvesting stage. On the other hand, a simplified air temperature model, $X_{t,a}$, has been developed based on the physical processes involved using the following heat transfer balance equation [14]:

$$c_{ter,a}\frac{dX_{t,a}}{dt} = V_r P_{r,e} + c_h\left(U_{t,h} - X_{t,a}\right) - \left(\phi_v + \phi_c\right)\left(X_{t,a} - P_{t,e}\right) + c_s\left(X_{t,s} - X_{t,a}\right) \quad (2)$$

where $P_{r,e}$ is the solar radiation, $P_{t,e}$ is the outside temperature, $U_{t,h}$ is the temperature of the heating tubes, $X_{t,s}$ is the temperature of the soil, ϕ_v is the heat transfer coefficient due to ventilation (this is related to vents aperture by a highly nonlinear relationship shown in [14]), ϕ_c is the heat transfer coefficient from inside of the greenhouse out, V_r is the solar heating efficiency (where the evapotranspiration process is included), c_h is the a heat transfer coefficient of the heating system and , c_s is the a heat transfer coefficient from soil to inside air. This model relates the inside temperature with control variables. So the associate costs to the actuators can be determined using this model to determine the operating time of the systems. In the upper layer, the optimisation process obtains a single temperature setpoint for each of the intervals along the control horizon, using as forecast the average of the climatic disturbances in each one of those intervals and steady state models. This facilitates the optimisation process, reducing the computational cost. On the other hand, as the long term weather forecasts are vague and induce errors, it has no sense to calculate the temperature setpoint at every control time (one minute). The possible errors are compensated by using a receding horizon control approach. Other approaches include "risks" or safety zones in the prediction within a MPC [3]. This problem is referred to as *constrained nonlinear optimisation*. It has been solved using Sequential Quadratic Programming (SQP) methods since a QP subproblem is solved at each major iteration. The constraints of this process are based on the internal air temperature, that must be between a lower and an upper limit, variable throughout time, with a yearly pattern.

In order to assure that the system is able to reach the calculated setpoints a short term simulation is carried out for the first four days. It is necessary to determine a short term weather forecast based on the data provided by the *National Institute of Meteorology* and the historical data of other seasons. It is a process similar to that used one in the long term weather forecast. In this case, the sample time is one minute. In [11,15] a crop production simulation model is described including a model of the climate variables, a model of a tomato growth and models of controllers. If the simulated temperature does not reach the setpoints, the optimisation process is repeated modifying the constraints (diminishing or increasing the diurnal and nocturnal limits of the allowed temperature) based on the following situations: the diurnal constraints are diminished if the sun does not provide the sufficient energy to reach the setpoint; the nocturnal constraints are increased if the outside temperature is significantly greater than the setpoint; the diurnal constraints are increased and nocturnal constraints are diminished if the actuators (ventilation and heating systems) are saturated. In opposite case, the first calculated setpoint is sent to the low layer at the corresponding nocturnal or diurnal time interval. This step is included to try to guarantee the system reaches the proposed setpoints throughout the season, reducing the deviation between the real production that will be reached at the desired harvesting date and the expected one. As it has been commented previously, the setpoint that is sent to the low is modified based on the short term objectives determined by the producer (based on diseases, plagues, etc.) and the air relative humidity. This process is made every minute and the controllers must calculate the control signal necessary to reach these new setpoints. Some controllers have been tested in simulation and real greenhouses as gain scheduling [13], serial feedforward scheme [14], adaptive control [1] and robust control based in QFT techniques [12] to control the diurnal temperature and cascade control structure with compensation of the external disturbances using feedforward schemes for the nocturnal operation with heating [13]. The obtained results are acceptable for this type of applications.

Before a change day-night or vice versa occurs and until the last interval of the season is reached, the whole process is repeated (receding horizon technique) modifying the initial conditions of the optimisation in two ways:

- The crop growth model is used to determine the dry weight and the number of nodes that have been obtained with the real climate conditions during the control process in the present time interval. This estimation is the feedback that the upper layer needs as initial condition to calculate the new trajectories. The ideal is to have real measurements of the crop state at every moment, but this measurement process is very laborious and expensive. These real measures would reduce the model uncertainty.
- The producer can modify the long term objectives of the optimisation as the harvesting date (based on the tendencies in the sale prices of the products) to advance or to delay that moment (this is a short term policy). In addition, the growth of the culture cannot be modified indefinitely by controlling the climate, this being able to produce variations in the fruits maturation in an interval of seven to ten days. The user also has to introduce the new prices of electricity and fuel when changes are predicted.

This proposed hierarchical control architecture is able to solve the problem of the maximization of the profit in greenhouse crop production, reducing the errors due to the weather forecast using a receding horizon technique.

3 Representative results

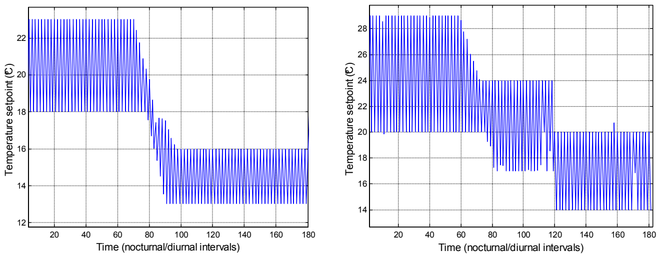
4.1. Initial hypothesis

Several simulation tests have been performed to study the response of the system under different conditions. All of them have the same initial conditions:

- The heating in Southeast Spain is usually necessary in autumn/winter seasons, so all the studies are referred to these months (October/February), although the proposed algorithm is generic and applicable to any season.
- The initial crop state is the same for all the tests with 10.8 leaves, 60 gr/m^2 of total dry material and a density of 3 plants /m^2 of soil surface.
- The length of the crop cycle is ninety days.
- The weather forecast is performed using the data of the 1997/98 season and the data of 1998/99 season is considered as the real disturbance.

4.2. Study of the temperature setpoint trajectory trends

The first tests were carried out to analyse the trends of the temperature setpoint trajectories along the season. Constant energy prices were considered. The results are shown in figure 3, considering both constant and variable limits of the constraints space along the season. The optimal trajectories in each one of the tests present a descendent tendency, maintaining maximum temperatures at the beginning of the season, diminishing them to the minimum allowed at the end. This result is not a common and typical strategy used in tomato crop in this zone where the temperature setpoints are relatively constant and moderate along the season. This behaviour can be explained based on the used model of crop growth. The differential equation that describes the increase of dry weight, X_{DW}, is the following:



a. Constant constraints limits b. Variable constraints limits

Figure 3. Temperature setpoint trajectories

$$\frac{dX_{DW}}{d\tau} = c_{DW,efi}\left(V_{photo} - V_{resp}X_{DW}\right) \tag{3}$$

where V_{photo} is the photosynthesis, V_{resp} is the respiration process and $c_{DW,efi}$ is the conversion efficiency of sugar to plant tissue. The respiration process (which consumes sugar) is modulated by the dry weight, so that when it increases, the respiration term increases consuming sugar. On the other hand, the respiration is function of the temperature as it is shown in figure 4. Therefore, the system diminishes the temperature as the crop increases its dry material, reducing the respiration process. It is necessary to indicate that this strategy also diminishes the dry weight generation by photosynthesis, but at the end of the season the production will be greater. Figure 5 shows the dry weight production obtained with an optimal temperature setpoint trajectory (solid line) and constant temperature setpoint trajectory (dotted line).

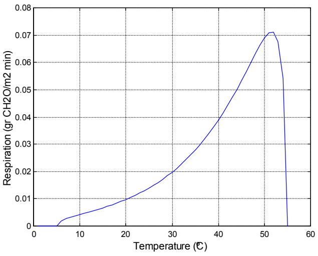


Fig 4. Relationship between temperature and respiration

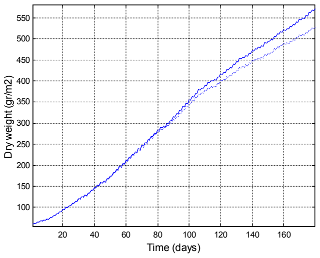


Fig 5. Dry weight production with optimal and typical trajectories

4.3. System response with energy prices changes

In this case, the response of the system to changes in the energy prices is studied. As the fuel of the heating systems is more expensive than the electricity, four cases are considered: the fuel price is constant along the whole season; the fuel price diminishes in the middle of the season; the fuel price increases in the middle of the season and the fuel is free. When the price is cheaper, the system tends to use the heating system more times (table 1). Even so, there is not a significant difference between the final dry weight obtained in each of the simulations (although the difference increases based on the greenhouse soil surface).

	Final dry weight (gr/m^2)	Number of nights with heating
Constant prices	576.87	23
High prices at the beginning	580.76	24
High prices at the end	581.61	24
Free fuel	590.45	26

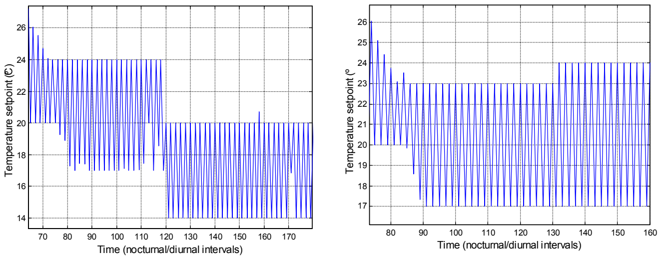
Table 1. Results based on fuel prices

4.4. System response when the setpoint is not reached

There are several situations where the lower layer is not able to reach the temperature setpoint calculated by the high layer: the weather forecast is erroneous; the actuators are saturated; the temperature in diurnal intervals is less than the diurnal setpoint or the temperature in nocturnal intervals is greater than the nocturnal setpoint; the transitions between nocturnal and diurnal intervals are not immediate, etc. For example, if the weather forecast is erroneous., the system is unable to follow the proposed setpoints, so the transition from high to low temperature is delayed. The system tends to maintain high temperatures to produce more dry weight.

4.5. System response when the harvesting date is changed

The following tests are performed to study the response of the system when the user changes the long term objectives, modifying the harvesting date. The system increases the temperature setpoint when the harvesting date is shortened to help the crop growth and diminishes it when this date is delayed to decrease the crop growth rate. Figure 6 shows an example when in the 36th day the harvesting date is shortened ten days (the season is reduced from 90 to 80 days). Figure 6.*a*. shows the typical temperature setpoint trajectories calculated by the optimisation process in the 35th day with a season length of 90 days. When at the next days the harvesting date is changed, the system increases the diurnal and nocturnal temperature setpoints to maximize the profit, obtaining the maximum production.



a. Season length=90 days b. Season length=80 days

Figure 6. response when harvesting date is bring forward

5 Concluding remarks

A hierarchical control architecture for maximizing profit in greenhouse crop production has been explained. The simulation results presented are quite promising because the system behaves properly in different situations. Based on these studies and tests, different conclusions can be stated:

- The control of crop growth in greenhouse is a complex system formed by subsystems with different dynamics, so a hierarchical structure is a good solution, using a high layer to estimate the setpoint trajectories and a low layer to calculate the state of the actuators.
- The use of the receding horizon technique is necessary to diminish the possible errors when the setpoints are not reached and to compensate for model inaccuracies and wrong weather forecasts.
- The long-term and short-term weather forecast is very important. This methodology provides acceptable results.
- The crop status in each optimisation time is feedback using the tomato growth model, so there are errors in the initial conditions of the optimisation process. It would be advisable to use real measurements of the dry weight and the number of nodes once a week. The ideal would be to take on-line measurements in each optimisation time.

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