Toward an Optimal Control Strategy for Sweet Pepper Cultivation – 2. Optimization of the Yield Pattern and Energy Efficiency

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Abstract

Sweet pepper production is characterized by large fluctuations in fruit yield in time. These fluctuations have a detrimental effect on the operational planning of labor at nursery level as well as on the efficiency of the supply chain. At the same time, the dependence of temperate zone greenhouse horticulture on fossil fuel needs to be reduced for long-term viability. Growers are aware of the fact that by modifying the indoor temperature, these fluctuations can be influenced, but the dynamics involved are complex and hard to master. Therefore, in practice the degree of control achieved is limited and sometimes obtained at the cost of a higher energy consumption. In this research, using the framework of optimal control theory and employing a sweet pepper production model, alternative temperature strategies were searched for with the aim of reducing production fluctuations and using a minimum amount of energy. The results obtained in this research indicate that fluctuations in sweet pepper production can be reduced using optimized temperature strategies, either by controlling production in one compartment or by controlling production in opposite phase in two compartments. By doing so, energy savings of 10% can be obtained. In contrast with standard horticultural practice, a striking feature of the optimized temperature trajectories is their considerable variation in time.

INTRODUCTION

Sweet pepper production is characterized by large fluctuations in fruit yield in time. These fluctuations have a detrimental effect on the operational planning of labor at nursery level as well as on the efficiency of the supply chain. At the same time, the dependence of temperate zone greenhouse horticulture on fossil fuel needs to be reduced for long-term viability. Growers are aware of the fact that by modifying the indoor temperature, these fluctuations can be influenced, but the dynamics involved are complex and hard to master. Therefore, in practice the degree of control achieved is limited and sometimes obtained at the cost of a higher energy consumption. The sweet pepper model described in the companion paper of Buwalda et al. (2006), covers some of the phenomena underlying crop growth and production of sweet pepper and describes the fluctuations in the production fairly well. Combined with the KASPRO model (De Zwart, 1996) to calculate energy consumption, this offers the opportunity to search for alternative climate strategies to reduce yield fluctuations with a minimum amount of energy. To pursue this objective, indoor temperature strategies were calculated using the principles of optimal control (Bryson, 1998).

MATERIALS AND METHODS

A Dynamic Model of Sweet Pepper Production

The model of sweet pepper production as presented in the companion paper of Buwalda et al. (2006) is a discrete time model represented by a set of non-linear difference equations of the form:

$$x_{k+1} = f(x_k, u_k, d_k) \tag{1}$$

Here x_k is the state of the system at time instant $t = t_k$, representing the total number of fruits and the development state of each fruit cohort, the carbon mass of each fruit cohort, the carbon mass of the vegetative parts, the development stage of the vegetative parts, the carbon content of the common assimilate pool and the content of the carbon storage buffer. It is worth mentioning that x_k represents the micro-states mentioned by Buwalda et al. (2006). In this research, the sweet pepper production process has one control input u_k, the average daily temperature in the greenhouse. There is one external input, represented by d_k, the solar radiation outside the greenhouse. Given an initial state of the production process x_0, a data sequence of u_k and d_k for $k = 1,\ldots,N$, the evolution of the state variables is fully determined by eqn. (1). In this model the time interval $\Delta t = t_k - t_{k-1}$ equals one day and therefore N is the duration of a cultivation period expressed in days.

A Model Describing the Relation between Average Daily Temperature and Energy Consumption

To be able to determine energy efficient temperature strategies one needs to quantify the energy consumption associated with a certain temperature strategy u_k, $k = 1,\ldots,N$. The indoor temperature depends on the amount of solar radiation, the energy input by the heating system and energy losses through the greenhouse cover and vents. Using practical settings for heating, ventilation, carbon dioxide supply and the use of thermal screens and measured hourly values of outdoor climate data, simulation runs were done with KASPRO to determine a relation between the average daily temperature and energy consumption during a whole production cycle of sweet pepper in 2004 for two growers, hereafter referred to as Grower 1 and Grower 2. By shifting their settings upwards and downwards around the nominal values used, higher and lower average temperatures and associated energy consumptions were simulated. Based on these data, a relation between the average temperature and energy consumption was obtained. This is illustrated in Fig. 1, in which data are shown of the two growers on the 20th of January 2004 and 30th of September 2004, respectively. Fig. 1 demonstrates that different settings will yield different responses. In winter time Grower 2 used more energy than Grower 1, whereas in September Grower 1 used more energy than Grower 2. Grower 2 had a stronger energy conservation attitude and used the thermal screens more often than Grower 1 and did not use a minimum temperature setting for the heating pipes. By doing so, overall Grower 2 used considerably less energy than Grower 1.

Fig. 1 also illustrates that the relationship between average day temperature and energy consumption Q_k, hereafter referred to as energy consumption profile, varies throughout the year. This time variant relation was parameterized on a daily basis by fitting the third order polynomial

$$Q_k = c_{k,1} + c_{k,2}u_k + c_{k,3}u_k^2 + c_{k,4}u_k^3, \quad k = 1,\ldots,N, \tag{2}$$

to the daily KASPRO output of temperature versus energy consumption.

Clearly, the achievable minimum and maximum temperature depend on the greenhouse properties, the available climate conditioning equipment and the outside climate and will vary throughout the year. This is also shown in Fig. 1 indicated by the temperatures at which the curves start (minimum) and end (maximum), respectively. For example, it was not possible to achieve a higher average temperature than approximately 23°C on the 20th of January 2004, with the available equipment. These data were used to constrain the search space for the optimization of the temperature strategies, using the constraint equations:

$$u_{k,\min} \leqslant u_k \leqslant u_{k,\max}\,,\ k = 1,\ldots,N \tag{3}$$

Fig. 2 shows that the KASPRO model was able to reproduce the consumption of natural gas throughout the growing season fairly well.

The Objective Function

In this research, the objective was to reduce fluctuations in fruit yield, in terms of number of harvested fruits, using a minimum amount of energy. This objective was represented by the following expression:

$$J = \alpha \sum_{k=1}^{N}(x_k - \tilde{x}_k)^2 + \beta \sum_{k=1}^{N}(Q_k)^2 \tag{4}$$

The first term on the right-hand side describes a penalty for deviations of the harvested number of fruits from a pre-defined harvesting trajectory represented by $\tilde{x}$, evaluated over the whole growing period. In eqn. (4), x is a sub-set of x of eqn. (1). The second term on the right-hand side penalizes the energy consumption, evaluated over the whole growing period. The parameters α and β resolve the dimensionality problem and provide flexibility in weighting the two goals.

Solution of the Optimal Control Problem

Using the preliminaries given above, the optimization problem was formulated to find the optimal temperature strategy u_k^*, $k = 1,\ldots,N$, that minimizes the performance criterion J of eqn. (4) subject to dynamic model equations in eqn. (1), the relation between temperature and energy consumption of eqn. (2) and the limitations on the temperature represented by eqn. (3). Essentially, this is a parameter optimization problem that can be solved by an iterative numerical search for the best sequence u_k^*, using repeated simulations of the system and evaluation of the performance J. In this research, we used the FFSQP software that employs a Sequential Quadratic Programming (SQP) algorithm to solve the optimization problem (Zhou et al., 1997).

RESULTS AND DISCUSSION

Optimization runs were done for the energy consumption profiles of Grower 1 and Grower 2. Due to the limited printing space, only detailed results of Grower 1 can be shown. Fig. 3 shows weekly averages of the global radiation during the optimization period in 2004. Fig. 4 shows the temperature strategy implemented by Grower 1 in 2004 as well as a simulation of the resulting cumulative sweet pepper production, exhibiting considerable fluctuations. The fuel consumption of this temperature strategy as estimated by KASPRO was 47.7 m^3 natural gas m^{-2}. This scenario will be referred to as REF. Five optimization runs were done. In all runs, temperature optimization started at the time of the first fruit set, 9 weeks after planting. For the initial 9 week period of vegetative growth, the model was not sufficiently validated and therefore, the temperature strategy of the grower was used. The first optimization run (OPT1) showed that exactly the same production profile could be achieved with a natural gas consumption of 44.5 m^3 natural gas m^{-2}. In this run, the harvest trajectory of the REF scenario was used as a reference trajectory during the optimization. This result illustrates the benefits of using advance knowledge of the weather as well as knowledge of the crop production dynamics. A second optimization run (OPT2) was aimed at reducing harvest fluctuations by optimizing the temperature within a single compartment. To achieve this objective, a smooth exponential curve was fitted through the cumulative harvest of the REF scenario and this smooth exponential trajectory was used as a reference trajectory for sweet pepper production in the optimization. The required energy input amounted to 44.2 m^3 natural gas m^{-2}. And as illustrated in Fig. 5, beyond the first few weeks of production fluctuations in production were successfully diminished. But Fig. 5 also shows that this result comes at a price, namely a very dynamic temperature profile compared to standard horticultural practice. Fig. 6 shows results of an alternative approach. In this run (OPT3), the temperature in two virtual compartments of equal size was controlled such that cumulative fruit harvest in both compartments showed a 180 degrees phase shift thus resulting in reduced harvest fluctuations for both compartments combined. In one compartment, the temperature strategy of the REF scenario was used. For the other compartment a reference harvest trajectory was generated with an opposite phase. Fig. 6 shows that, by doing so, fluctuations in the overall sweet pepper production might be reduced. Consumption of natural gas, however, amounted to 47.2 m^3 natural gas m^{-2}. Only a small energy saving was obtained. Being able to control production in opposite phase in two compartments, another scenario was implemented (OPT4) in which oscillations were enhanced, not diminished, in such a way that cumulative sweet pepper production attained equal values as the reference production of scenario REF at eight time instants during the production period indicated by the circles in Fig. 7 in which the results of this optimization are shown. The optimized temperature strategy strongly differs from the reference temperature and interestingly enough, shows a very dynamic behaviour. The figure also shows that the required cumulative production is attained with a reasonable accuracy at the eight time instants. Energy consumption amounted to 37.6 m^3 natural gas m^{-2}, which means a considerable energy saving. Finally, in the last scenario, OPT5, the strong harvest fluctuations resulting from scenario OPT4 were counteracted by calculating a temperature strategy that results in a sweet pepper production with an opposite phase. This approach resembles scenario OPT3. The combined sweet pepper production of two virtual compartments being controlled in this way, shows only small fluctuations, although production in the individual compartments exhibit strong variations, as shown in Fig. 8. Overall energy consumption for the two compartments amounted to 42.7 m^3 natural gas m^{-2}.

The energy consumptions of all individual scenarios are presented in Table 1 for both Grower 1 and Grower 2. These results suggest that also for the energy consumption profile of Grower 2, considerable energy conservation seems possible.

Since the optimization focused on cumulative sweet pepper production in terms of number of fruits, the effect on simulated accumulated dry matter in the fruits was investigated (results not shown). It was found that the average dry weight per fruit differed, however not very much, amongst the different scenarios. Still, this may affect the results when dry matter content of the fruits is explicitly accounted for in the optimization.

Besides the fact that it seems possible to control sweet pepper production using optimized temperature strategies, an intriguing aspect of the results is the fact that the temperature strategies large variations throughout the growing period. The temperature strategies used in horticultural practice might just be too smooth to be able to control the variations in production. The results of this research suggest that the temperature bandwidth should be considerably increased to be able to control the fluctuations in sweet pepper production. This requires further research and, if confirmed, it certainly will require a paradigm shift in horticultural practice.

When application in practice is considered, three issues become important. First of all, model accuracy, secondly, weather prediction and, last but not least, the choice of the performance criterion to be optimized. Early 2006 research on these subjects was initiated in a ‘proof of principle’ experiment in a research greenhouse at PPO, Naaldwijk, The Netherlands.

CONCLUSION

The results obtained in this research indicate that fluctuations in sweet pepper production might be reduced using model based optimized temperature strategies, either by controlling production in one compartment or by controlling production in opposite phase in two compartments. By doing so, energy savings of 10% seem possible. In contrast with standard horticultural practice, a striking feature of the optimized temperature trajectories is their considerable variation in time.

ACKNOWLEDGEMENTS

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Tables

Table 1. Calculated energy consumption expressed in m^3 natural gas m^{-2} used for the various scenarios for Grower 1 and Grower 2.

Scenario	Gas consumption, Grower 1	Gas consumption, Grower 2
REF	47.7 $m^3.m^{-2}$ (100%)	36.4 $m^3.m^{-2}$ (100%)
OPT 1	44.5 $m^3.m^{-2}$ (93%)	32.8 $m^3.m^{-2}$ (90%)
OPT 2	44.2 $m^3.m^{-2}$ (93%)	33.4 $m^3.m^{-2}$ (91%)
OPT 3	47.2 $m^3.m^{-2}$ (99%)	35.4 $m^3.m^{-2}$ (96%)
OPT 4	37.6 $m^3.m^{-2}$ (79%)	25.0 $m^3.m^{-2}$ (68%)
OPT 5	42.7 $m^3.m^{-2}$ (90%)	30.7 $m^3.m^{-2}$ (84%)

Figures

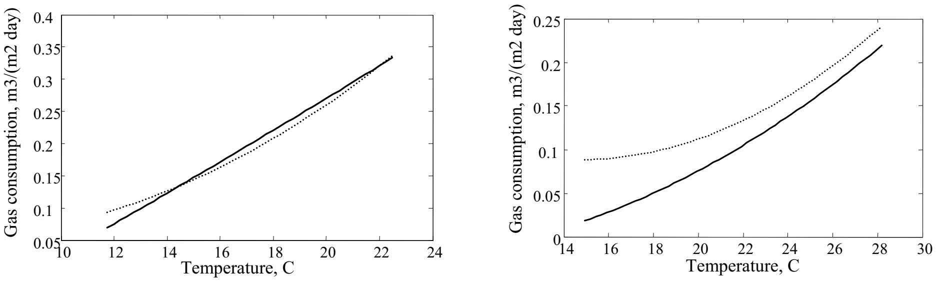

Fig. 1. The relation between the daily average indoor temperature and energy consumption on the 20th of January 2004 (left) and 30th of September 2004 (right) for Grower 1 (dotted line) and Grower 2 (solid line).

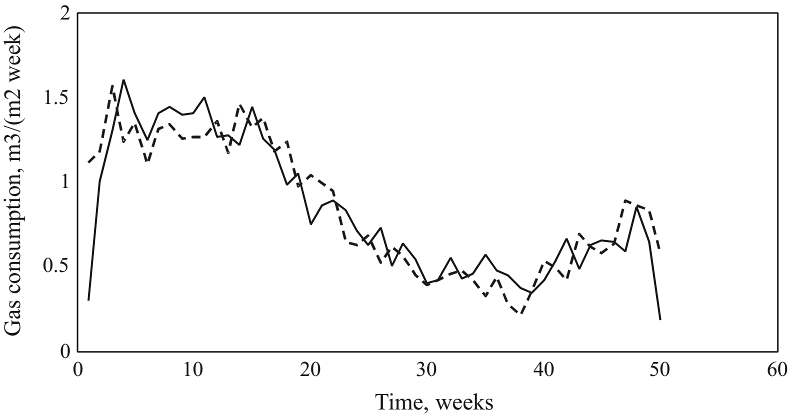

Fig. 2. Measured (solid) and simulated (dashed) consumption of natural gas in the year 2004 for Grower 1.

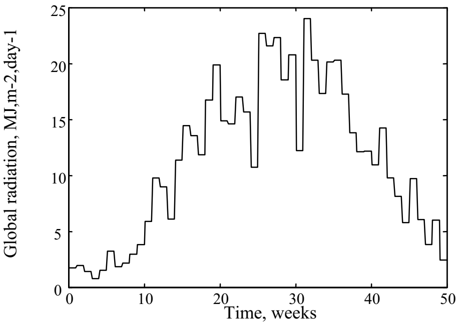

Fig. 3. Global radiation in 2004.

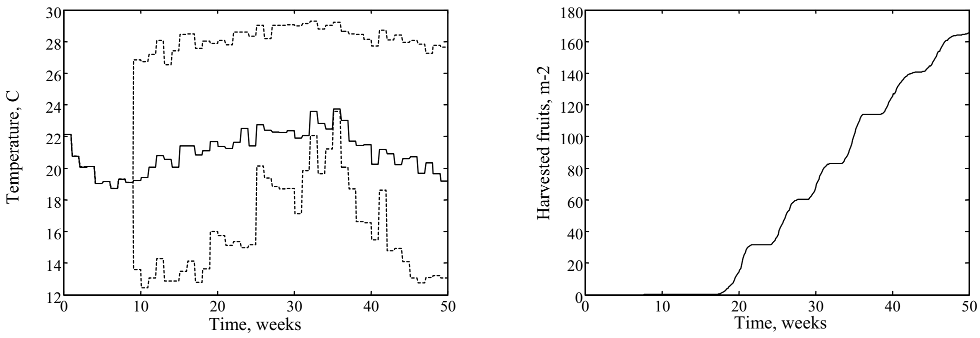

Fig. 4. Left: the practical REF temperature strategy (solid) and minimum and maximum achievable temperature (dashed) throughout the growing period, and right: the resulting cumulative sweet pepper production.

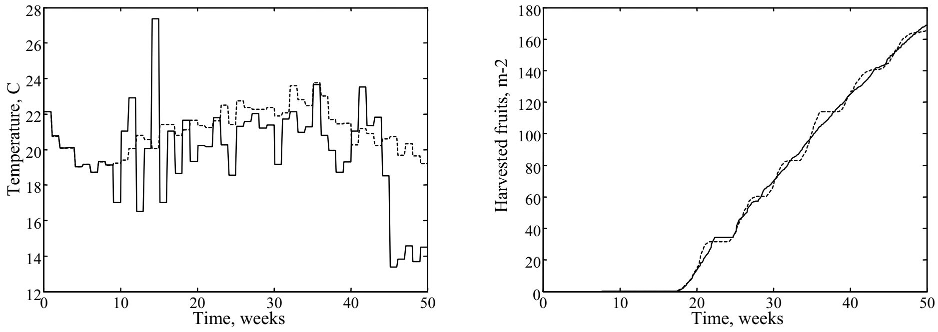

Fig. 5. Left: reference (dashed) and optimized (solid) temperature trajectories, and right: cumulative sweet pepper production for scenarios REF (dashed) and OPT2 (solid), respectively.

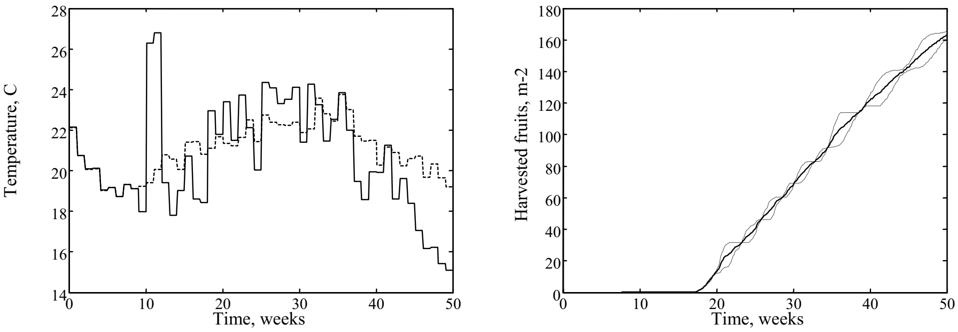

Fig. 6. Left: temperature strategy of scenario REF for virtual compartment one (dashed) and optimized temperature trajectory for scenario OPT3 for virtual compartment two (solid), and right: cumulative sweet pepper production in both compartments (dashed) as well as the total sweet pepper production of the two compartments together (solid).

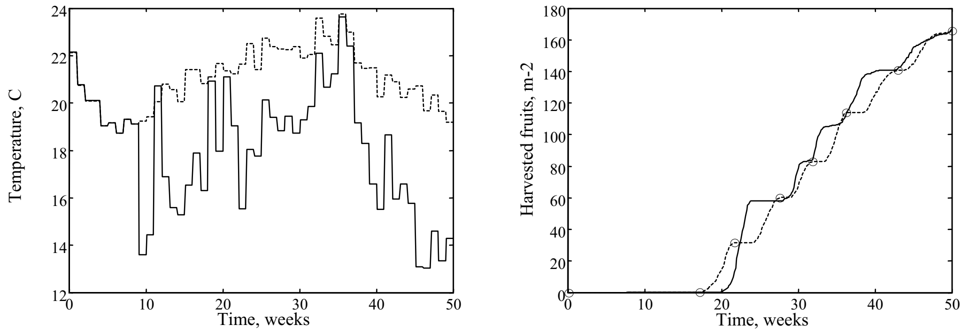

Fig. 7. Left: reference temperature (dashed) of scenario REF and optimized temperature (solid) of scenario OPT4, and right: cumulative sweet pepper production according to scenario REF (dashed) and scenario OPT4 (solid), with 'o' indicating the evaluation points of the OPT4 strategy.

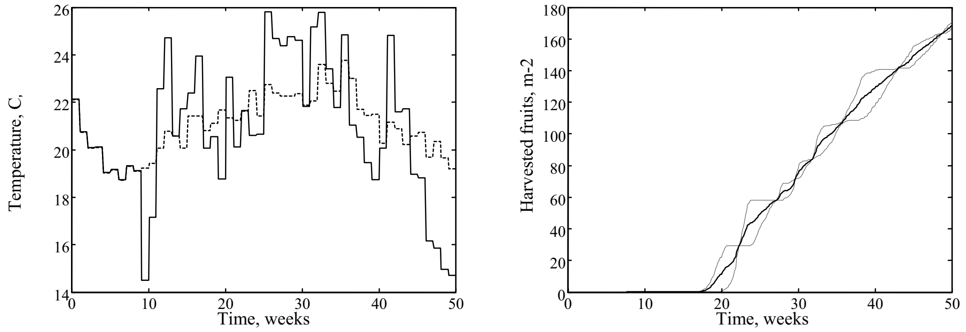

Fig. 8. Left: reference temperature (dashed) and optimized temperature of scenario OPT5 (solid), and right: the resulting cumulative sweet pepper production in two virtual compartments using scenarios OPT4 and OPT5 (dashed) as well as the total sweet pepper production of the two compartments together (solid).