DETERMINATION OF THE OPTIMAL TEMPERATURE FOR THE GROWTH OF AN EARLY CUCUMBER CROP IN A GREENHOUSE

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PREFACE

In this paper, the author presents a means of determining the optimal temperature for cultivation of a cucumber crop in a greenhouse. The optimal temperature is derived from a comparison with a standard temperature regime and is selected on the basis of two criteria: (1) expected income from an early crop and (2) heating costs.

The nonlinear problem is solved using the reference point approach as implemented in the DIDASS/N software package.

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1. INTRODUCTION

The main purpose of greenhouses is to provide a beneficial environment for crop growth. In the colder parts of the world, this means that greenhouses must be heated in winter, requiring an energy input which is equivalent to roughly 25% of the total capital costs of protected cultivation. This makes energy a significant cost factor and there has been much research on ways of using fuel more economically. Crop growth and development is closely related to the temperature of the greenhouse air, and traditional research in horticulture focuses on temperature patterns which are in some way "optimal" for production under average conditions, notably the average local weather conditions. These so-called "blueprints" for the greenhouse air temperature are available for a wide variety of crops in various regions. However, at a time of rapidly changing energy costs, the validity of such blueprints is questionable. More recently, research has been reported in which a relation between temperature and yield is used explicitly in an optimization procedure.

The relation between temperature and crop growth is extremely complex, and therefore a simplified relation between the temperature regime and the earliness of the crop is adopted. Earliness (or delay) is the difference between the time when the first fruits grown under some particular conditions can be marketed and the time of marketing of the first fruits grown under a standard or blueprint temperature regime. Because the prices are higher when the first fruits enter the market after the winter, earliness/delay has a significant effect on the economic results. The typical optimization problem in this area would try to weigh the economic gains of an early crop against the extra costs of heating the greenhouse. Note that the objective is not energy conservation as such, but rather the more economical use of fuel.

An example of the above approach is the drawing of thermal screen in a greenhouse when it is still light, in order to conserve energy. The savings are compared with the delay in production (Seginer and Albright, 1980). Another possibility is to make on-line calculations of the desired temperature by weighing the earliness of a cucumber crop against the heating costs (Challa et al., 1980) using an earliness model such as that developed by Challa and Van de Vooren (1980). Here the optimization problem is formulated using a single criterion. Because of the uncertainties associated with the parameters of the models used, however, a more appropriate approach would be based on the theory of multiple-criteria decision making. This paper reports on such a study using the interactive reference point approach (Wierzbicki, 1981) as implemented in the DIDASS/N software package (Grauer and Kaden, 1984).

2. PROBLEM FORMULATION

In general the effect of the temperature of greenhouse air on crop growth and subsequent yield is difficult to assess. The relation between short-term phenomena (processes with time constants up to one day) and long-term processes in particular is plagued with severe methodological difficulties (Udink ten Cate and Challa, 1983). However, with a cucumber crop the problem can be simplified by considering the period from planting until harvesting. The temperature maintained throughout this period affects the earliness of the yield, while the rate of production itself is not affected (Van de Vooren et al., 1978).

A relation can be established between earliness and temperature, with photosynthetically active radiation (light) as an external variable (Challa and Van de Vooren, 1980). Assume that the onset of flowering depends on the stage of development of the plant (expressed in terms of the total number of leaves per plant) and that the time between flowering and harvesting of the first fruits is constant. The rate of development can then be expressed as:

$$\dot{d}(\theta,\phi'';t) = 0.33[1-\exp(5.59-0.4\bar{\theta})(6-\exp(1.704-6.39\cdot 10^{-3}\bar{\phi}''_p))] \qquad (1)$$

where

$\dot{d}(\cdot)$ - rate of development (leaves.day^{-1})

$\bar{\theta}(\cdot)$ - average temperature in the crop canopy over the daylight period (°C)

$\bar{\phi}''_p(\cdot)$ - average photosynthetically active radiation over the daylight period (W.m^{-2}) .

The averages depend on the number of hours of daylight (typically 8 hrs in winter); consequently $\bar{\phi}''_p$ may also be expressed in [J.day^{-1}] . Note that the unit of time is the day. (The night period (16 hrs) is not taken into account in eqn. (1).)

The effect of the optimal temperature θ_o is compared with that of the standard (blueprint) temperature θ_b and leads to a difference in development rate

$$\Delta\dot{d}(t) \triangleq \dot{d}(\theta_o;t) - \dot{d}(\theta_b;t) \ . \qquad (2)$$

Flowering of the (cucumber) crop occurs when d_c leaves are formed. For the standard crop this happens at time t_c , so that $d(\theta_b;t_c) = d_c$. For the optimal crop at development stage $d(\theta_o;t)$ the earliness Δt_c due to the difference in development $\Delta d(t_c) = d(\theta_o;t_c) - d(\theta_b;t_c)$ can be found. Making a linear approximation

$$d(\theta_o;t_c-\Delta t_c) = d(\theta_o;t_c) - \dot{d}(\theta_o;t_c)\,\Delta t_c \qquad (3a)$$

leads to

$$\Delta t_c = \frac{\Delta d(t_c)}{\dot{d}(\theta_o;t_c)} \ . \qquad (3b)$$

The fact that the time between flowering and production is not dependent on the temperature implies that $\Delta t_p = \Delta t_c$. Furthermore, $\Delta d(t_c) = \int_{t=0}^{t_c} \Delta\dot{d}\, dt$. The standard crop and the optimal crop are terminated at the same time. Particularly with an exponentially decaying auction price, the increased earliness of the crop gives rise to the additional profit

$$\Delta p = y(t_p)\, p_f(t_p)\, \Delta t_p \tag{4}$$

where $p_f(\cdot)$ - price of fruits (Dfl. kg^{-1})
$y(\cdot)$ - production rate per unit of ground area ($kg.m^{-2}.day^{-1}$)
t_p - onset of production phase (day)
Δp - additional profit per unit of ground area ($Dfl.m^{-2}$) .

On a daily basis, the effect of the difference in development is

$$\Delta\dot{p}(t) = y(t_p)\, p_f(t_p)\, \frac{\Delta\dot{d}(t)}{\dot{d}(\theta_o;t_c)} \tag{5}$$

where $\Delta\dot{d}(t)$ follows from eqn. (2) . The energy consumption rate and the corresponding costs are estimated using

$$\dot{c}(\theta;t) = KCP_g(\bar{\theta}-\bar{\theta}_a) - Q(\bar{\phi}'') \tag{6}$$

where $\dot{c}(\cdot)$ - cost of energy consumed per unit of ground area per day ($Dfl.m^{-2}.day^{-1}$)
K - heat loss coefficient per unit of ground area ($W.m^{-2}.K^{-1}$)
$\bar{\theta}$ - average air temperature inside the greenhouse during the daylight period (°C)
$\bar{\theta}_a$ - average air temperature outside the greenhouse during the daylight period (°C)
C - conversion factor from Watts to m^3 $gas.day^{-1}$ ($m^3.day^{-1}.W^{-1}$) for a period of 8 hours
P_g - price of gas ($Dfl.m^{-3}$)
$Q(\cdot)$ - effect of external heat sources.

Note that in the night period it is assumed that $\theta_o = \theta_b$. The daily difference in energy costs between the optimal temperature regime and the standard temperature regime is obtained from eqn. (6) as

$$\Delta\dot{c}(t) \,\hat{=}\, \dot{c}(\theta_o;t) - \dot{c}(\theta_b;t) = KCP_g(\bar{\theta}_o - \bar{\theta}_b) \ . \tag{7}$$

The gains expressed in eqn. (5) have to be weighed against the costs given by eqn. (7). Because some of the parameters, especially $y(t_p)$ and $p_f(t_p)$ in eqn. (5), are uncertain, the problem is expressed as a multiple-criteria decision problem based on two objective functions

$$\begin{aligned} &\max \Delta\dot{p}(t) \text{ from eqn. (5)} \\ &\min \Delta\dot{c}(t) \text{ from eqn. (7)} \quad , \end{aligned} \tag{8}$$

where an *expected* average (over the daylight period) of the photosynthetically active radiation $\bar{\phi}''_p$ is used in eqns. (1) and (2). The decision strategy is not to deviate too much from the standard (blueprint) temperature.

3. IMPLEMENTATION

The nonlinear problem described by eqn. (8) was implemented with DIDASS/N (Grauer and Kaden, 1984), using the parameters given in Table 1 (Challa et al., 1980).

The value of the parameter K given in Table 1 is dependent on the average wind velocity over the daylight period. Parameter C is based on a boiler-to-greenhouse efficiency of 72% and a combustion value of 35.7 MJ per normal m^3 of natural gas.

Table 1. Parameter values.

Parameter	Value	Parameter	Value
$y(t_p)$	0.195 kg.m^{-2}.day^{-1}	K	$9.26+0.79\cdot\bar{v}_{wind}$ W.m^{-2}.K^{-1}
$p_f(t_p)$	1.50 Dfl.kg^{-1}	C	0.0011 m^3.day^{-1}.W^{-1}
$\dot{d}(\theta_o;t_c)$	0.7 leaves.day^{-1}	P_g	0.40 Dfl.m^{-3}

The objective functions of eqn. (8) have to be modified in order to comply with DIDASS/N requirements. Therefore, the original problem is reformulated as follows:

$$\max \begin{cases} \Delta\dot{p}(A;t) + 1 = obj1 & \text{(max. earnings due to earliness of crop)} \\ -\Delta\dot{c}(A;t) + 1 = obj2 & \text{(max. heating savings)} \end{cases} \qquad (9)$$

$$15 < \theta_o < 35 \ .$$

The ground area $A = 10\ m^2$ is introduced to scale the objective. The value +1 is added in order to have positive objective functions, as required by DIDASS/N. The bounds on θ_o follow from the horticultural requirements. Using the reference point approach, it is necessary to identify an optimal value for θ_o based on daily expectations of the photosynthetically active radiation and wind velocity. The photosynthetically active radiation $\bar{\Phi}''_p$ was estimated at 25% of the total external radiation (assuming 50% transmission through the greenhouse and 50% photosynthetically active radiation).

Table 2. Values of parameters[a] in typical weather situations.

$\bar{\Phi}''_p$	$\bar{v}_{wind}$	Description
10-20	1	Dark December day
40-60	3	Alternating periods of cloud and sun
80-100	4	Bright February day

[a] The ranges of these parameters are 10-100 for radiation intensity and 1-5 for wind velocity. A standard temperature ($\bar{\theta}_b$) of 20°C was assumed.

Several values of expected radiation are typically considered in making a decision (Table 2). The strategy is not to deviate too much from the standard regime. In the optimization procedure, a situation with $\bar{\theta}_o=\bar{\theta}_b$ corresponds to obj1=1 , obj2=1 .

The differences in income due to use of the optimal regime rather than the standard regime are of the order of 0.01 $Dfl{\cdot}m^{-2}$. For an average commercial holding of 10,000 m^2 , a gain of 0.01 $Dfl.m^{-2}$ represents a total gain of Dfl 100. Table 3 presents some typical results.

Table 3. Typical results with expected $\bar{\Phi}''_p$ in the range 80-100. $\bar{\theta}_b = 20$ and $\bar{v}_{wind} = 1$ were assumed.

	obj1	obj2	$\bar{\theta}_o$	Remarks
$\bar{\Phi}''_p = 100$	1.25	0.88	22.6	Net gain = 0.013 $Dfl \cdot m^{-2}$
$\bar{\Phi}''_p = 80$	1.17	0.92	21.7	Net gain = 0.009 $Dfl \cdot m^{-2}$
Reference point	1.20	0.90		

4. CONCLUSIONS

The optimal cultivation strategy for an early cucumber crop is studied as a multiple-criteria decision problem. The objectives are maximization of extra income due to the earliness of the crop and minimization of extra heating costs relative to a standard or "blueprint" regime. The decision variable is the temperature of the air inside the greenhouse. Parameters considered in the decision include the standard (blueprint) temperature, the expected average photosynthetically active radiation over the daylight period, and the wind velocity. The night period (no radiation) is not taken into account - here the standard temperature is employed in both cases.

The decision is made by comparing the trade-off between the two objectives, with the additional aim of not deviating too much from the standard temperature. This last requirement makes it necessary to use a multiple-criteria formulation. The results demonstrate that the multiple-criteria approach is a feasible way of studying such problems. Since the particular problem considered here is relatively small and uses only a single decision variable, however, a decision based on graphical representation of the objectives could also be envisaged in this case. This would reduce the computational effort considerably.

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