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GREENHOUSE OPERATION FOR BEST AERIAL ENVIRONMENT

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Chapter 0: ABSTRACT

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0-1. INTRODUCTION

Optimal decisions concerning the operation of commercial greenhouses are of various kinds and relate to several time scales (seasonal, daily, hourly). There is a decision to be made concerning the best night time temperature, and a decision concerning the best CO₂ level. Decisions have to be made concerning conflicting effects of different pieces of equipment (e.g. CO₂ generator and ventilating fan). Decisions must also be made in response to changing market prices.

The present study suggests a method of optimization which may be useful in many of these decision-making situations. The method is based on certain assumptions concerning the system, the major one being that the crop may be represented by just one state variable. The model of the system consists of sub-models for the crop, the greenhouse and the economics of the operation.

The eventual implementation of the method is envisioned in the following manner: A main-frame computer will produce, for any given set of crop, greenhouse and economic parameters, an operating table, which takes the instantaneous environmental parameters as inputs and provides the operation levels of the air-conditioning equipment as an output. A micro-processor at the greenhouse could then be used to monitor the environment, consult the tables and make the optimal operational decisions.

0-2. METHODOLOGY

A methodology is described for obtaining optimal operating rules for the equipment influencing the climatic conditions inside a greenhouse. The optimization is based on an economic criterion which takes into account the expected income from the crops versus the cost of operating and maintaining the greenhouse.

The optimal control function is characterized and the analytic conditions for optimality are derived. A numerical scheme for obtaining the desired control is described and a sensitivity analysis is then carried out. This analysis enables derivation of simple operating rules for a real greenhouse.

0-3. SIMULATION OF CO₂ ENRICHMENT

A model describing tomato seedlings in a commercial greenhouse is presented in detail. The model includes the following functions: (1) A "growth function", which relates the growth of the seedlings to the inside environmental conditions. (2) A "greenhouse function", which relates the inside conditions to the outside conditions and to the fluxes from the air-conditioning equipment. (3) An "equipment function", which relates the fluxes to the level of operation of the equipment, and (4) A "cost function", which evaluates the cost of operation.

The model is used to obtain the optimal Lagrange multiplier for growing seedlings during the month of February in Israel. Three greenhouses, which differ from each other only in their CO₂ enrichment capabilities, are examined. The greenhouse with CO₂ supplied from bottles turns out to be superior to the greenhouse with CO₂ supplied by burning gas. The latter system is economically superior to the system without enrichment.

Some of the operation tables, which provide for each set of outside conditions a recommended operation level, are presented graphically for the three greenhouses. The results seem reasonable, but cannot at present be checked for accuracy.

0-4. THERMAL CALIBRATION OF UNVENTILATED GREENHOUSES

A method for in-situ thermal calibration of unventilated greenhouses is proposed. The model, whose coefficients are to be evaluated is

$$H + \alpha S_0 - C(dT_m/dt) - [U(T_1 - T_0) + R] = 0$$

where the four terms represent: (1) The heat from the heater. (2) The heat

generated by solar radiation (S_0). (3) The rate of heat storage in the system, with dT_m/dt representing the rate of change of the thermal-mass temperature. (4) The loss by convection, infiltration and radiation through the cover, due to the temperature difference $T_i - T_o$ between the inside and outside.

The parameters to be evaluated are U - the overall heat transfer coefficient, α - the heating efficiency of the solar radiation, C - the heat capacity of the greenhouse, and R - a correction factor for radiative transfer. Latent heat transfer is not considered explicitly, but does affect the value of U .

Experimental results for small greenhouses at Technion and at Cornell, indicate that the values of the coefficients, in particular U and α , are consistent enough to be useful. The effect of heat capacity on the predictability of inside temperatures and system time constants cannot be ignored.

A comparison between a dry and a wet greenhouse (both empty of plants) showed that the transfer coefficient U for the wet greenhouse was higher by 28% than for the dry greenhouse. This is attributed to the latent heat contribution through an evaporation-condensation cycle and through infiltration.

0-5. TOMATO RESPONSE TO ENVIRONMENTAL CONDITIONS

The literature was searched for simple formulas, which relate net-photosynthesis to solar radiation, CO_2 concentration and temperature. An expression for a single leaf, which can be integrated along the height of the canopy, was also found. Some values of the various parameters, for the vegetative growth stage of tomato, were found. The final expression can be used in the general optimization procedure.

0-6. OPTIMAL NIGHT TEMPERATURES FOR GREENHOUSE TOMATO SEEDLINGS

A method is described, which can be used to estimate the most economical night-time greenhouse temperature for a particular crop. The method requires growth data, engineering data and economic data to produce a solution. Most critical are the growth data.

An example is presented to illustrate the method: Growth-chamber data for tomato seedlings are used to obtain the sensitivity of that crop to deviation from the physiologically optimal night temperature. The available data seem to indicate that a 12 K deviation from that optimum results in a yield decrease of 20%. The recommended night temperature in the example is about half-way between the physiological optimum and the outside temperature.

0-7. GREENHOUSE CONTROL

Two approaches to environmental control are considered: (1) Control of fluxes. (2) Control of inside conditions. The former is more naturally geared to the method of optimization developed in this study. The latter is well established in practice. As long as just one environmental parameter (say, temperature) is to be controlled, the latter method is preferable.

A PI control of temperature, which considers the energy balance of the greenhouse, is developed for the experimental greenhouse at Technion. Examples of the performance of that PI algorithm are presented to show its suitability to the task.

0-8. AN ATTEMPT AT OPTIMAL OPERATION

An attempt was made to apply the method of optimization to tomato seedlings in two experimental greenhouses. Both greenhouses were identically controlled during day-time by a micro-computer, utilizing operation tables which were prepared in advance, based on the best available model of the system. The only difference between the greenhouses was that in one the night temperature was allowed to drop to 8°C ("cold" treatment), and in the other the minimum temperature was 12°C ("warm" treatment).

The seedlings in the "warm" treatment required only 33 days to reach a marketable size, while the plants in the "cold" treatment required 2 more days. The economical analysis showed that the time gained was economically equivalent to the cost of extra heating required to maintain the higher temperature. The results cannot be statistically analyzed, but served to test the feasibility of the proposed optimization and control method.

0-9. STRATEGIES FOR CONTROLLING GREENHOUSE THERMAL SCREENS

Four thermal screens operating strategies were experimentally compared. The objective was to find an operating strategy which maximizes the difference between plant growth and heating costs. The test crop was lettuce (*Lactuca Sativa* L. c.v. Grand Rapids). No significant differences in plant growth due to thermal screen operation were observed. Screen operating strategies based on light level required significantly less heat energy (about 3.3% of the potential savings due the screen) than time clock operation. Adjusting the light level for screen operation as a function of the outside temperature resulted in a heat energy requirement which was not significantly different from operation at a set light level.

0-10. CONCLUSION

The main achievements of the project seem to be the following: (1) The optimization method was developed from an intuitive concept to a rigorous method. (2) It was demonstrated that the whole process, from model to actual control, is technically possible. (3) Useful data on crop response and greenhouse properties were collected. (4) The applicability of the method to determining night temperatures, to CO₂ enrichment and to thermal screen operation was demonstrated.

Chapter 1: INTRODUCTION

Ido Seginer and Louis D. Albright

1-1. PROBLEM

The production of greenhouse crops, compared with open-field crops, requires high energy consumption per unit yield (Stanhill, 1980). In recent years much effort was devoted to replacing conventional energy by alternative energy, such as solar energy (e.g. Van Bavel & Damagnez, 1978; Takakura & Yamakawa, 1981; Jaffrin & Cadier, 1982), and to reducing the energy loss through increased insulation of the greenhouse (e.g. Bailey, 1977; Meijer, 1981; Okada, 1981; Short & Shah, 1981). In addition to these design oriented activities, it is also important to improve the decision making process related to operating a given greenhouse, in order to minimize the waste of resources.

A typical dilemma of a grower today is whether reducing the greenhouse night temperature is economically justified. Obviously, there is some trade-off between the resulting reduction in energy consumption and the resulting loss of yield. The decision of selecting the most economical operating temperature must be based on information from three sources: (1) Crop response to temperature, namely biological information; (2) Heat loss to maintain the required temperature, namely engineering information, and (3) Cost of fuel, namely economic information. Of these three, the first item is by far the most complex and least understood. An attempt to find the optimal temperature for greenhouse cucumbers was reported by Challa and Van de Vooren (1980).

A more complex situation arises when it is required to maintain two (or more) environmental variables at pre-set levels. A typical problem is the maintenance of required levels of temperature and humidity simultaneously. This can be done by a heater and a cooler operating against each other (the crop supplying vapor). For research purposes, where the cost of operation is of no consequence, this can be achieved by operating a heater against an air-conditioner (Jones et al., 1983). When, however, this idea is applied to commercial greenhouses (Heijna, 1979), the cost of operating a heater and a

fan simultaneously may become prohibitive. The strict adherence to pre-assigned multiple set-points must, therefore, be abandoned. It becomes clear that the set-points must be variable with time, depending on the outside conditions, with the biological, engineering and economic characteristics of the production system as parameters.

Sometimes the problem is not directly related to energy. Consider, for example, a day-time situation where the dilemma is whether to ventilate the greenhouse, to prevent over-heating, or to keep it closed, to enable CO₂ enrichment. Even if the costs of CO₂ and of ventilation were insignificant, there still remains the problem of trade-off between their effects on the crop.

Finally, consider a less obvious operation problem, which becomes significant only for complex systems: Suppose that it is required to maintain simultaneously pre-determined levels of n environmental variables. If the number of pieces of equipment available is $m > n$, then in general there is more than one way to obtain the required environmental conditions. A trivial example is the maintenance of a required temperature with a heater and a fan. Unlike this example, where the operation of the heater and fan is mutually exclusive, the solution when more elements are involved, may not be simple.

The sample of decision problems just mentioned illustrates the variety encountered. It would be useful to have a single optimization scheme which could solve, in real time and as a function of the variable outside conditions, for the optimal set-points in all these cases.

1-2. APPROACH

The main objective of the study was to develop a scheme to optimize the operation of a conventional greenhouse. This involves 4 phases:

- (1) Develop the optimization method and algorithms.
- (2) Build the hardware (greenhouse, measurement system and control system) necessary to demonstrate the operation of the proposed method.

(3) Obtain the relevant physical (engineering) characteristics of the greenhouse and the biological characteristics of the crop.

(4) Run the system to demonstrate the process of application.

Optimization method. Several major assumptions had to be made to arrive at a relatively simple scheme that would lead, at least in principle, to optimal decisions.

The major assumption relates to the crop: it was assumed that the state of the crop could be usefully represented by a single state variable (e.g. dry weight). This is a strong assumption, which has at least two major implications:

(1) The harvest point is defined by just one variable. If the other important variables are not well correlated with that variable, an acceptable produce may not be obtained. For example, if sugar content as well as size are important, and if they are not well correlated with each other, harvest time cannot be based on size alone.

(2) The crop has no memory, except through the integrated value of the (single) selected state variable. Memory of historical events can be introduced by adding state variables which are capable (collectively at least), of distinguishing between different past histories. Another way to introduce past history is by increasing the number of environmental variables. For instance, the temperature during the first week of growth may be considered as one environmental variable, while the temperature during the second week is considered as a different variable (compare with Chapter 6, where day temperature is treated as one variable, while night temperature as another). Both ways are generally difficult to implement.

Another assumption, less critical than the former, relates to the greenhouse. It was assumed that the greenhouse possess no heat capacity. It, too, has no "memory" of past events and reacts to the environment and operating conditions in a quasi-steady-state manner.

Since an attempt was made to develop an optimization method which will consider all major elements of the system (crop, greenhouse, economy), the detail within each of these elements was necessarily limited. The growth function chosen was an explicit function of the instantaneous environmental conditions; the greenhouse model was one dimensional without heat capacity; and the economical approach was elementary.

The way in which the optimization was meant to be implemented is as follows: A main-frame computer is to be used to produce a set of recommended inside conditions. For every given set of biological, engineering and economical parameters, a different set of recommended inside conditions must be calculated. For each set of outside environmental conditions a set of recommended inside conditions is to be calculated.

Once the table, which relates inside to outside conditions, is available, it can be used in real-time by a micro-computer to control the greenhouse. The micro-computer must first sense and determine the outside environmental conditions, then search in the table provided by the main-frame computer for the recommended inside conditions, and finally control the equipment available in the greenhouse to produce the desirable inside conditions.

Hardware. Two pairs of small greenhouses was all that could be afforded. The scaling up of the results to commercial size greenhouses should not pose any real problems, since the decision making process does not vary with size. To change from one greenhouse to the next, it is only necessary to change the relevant engineering parameters.

The equipment used to control the experimental greenhouses was in certain respects different from the equipment in commercial greenhouses. For instance, the heating system at Technion had 5 possible operation levels, compared to a single on-off operation of commercial heaters. The measurement system was far more elaborate than the system available to ordinary control systems. The assumption was made that between the present research and an eventual application there will be one more stage: a pilot-plant stage.

Most of the equipment was bought off the shelf. Only in a few cases, where equipment was not available, or its cost prohibitive, did it seem justified to

build hardware within the project. General purpose equipment (such as personal computers) was used whenever possible, to increase flexibility. Eventually, the expensive data logger and microcomputer are expected to be replaced by special purpose micro-processors.

Physical and biological characteristics. Some of these characteristics had to be obtained within the project: The greenhouses were partially calibrated in-situ and the crop response to temperature was obtained experimentally in growth chambers.

The selection of a suitable crop for the final experiments (Chapters 8 and 9) was not easy. The crop had to be sensitive to temperature in order to be of interest. It had also to be a vegetative crop which could be represented by a relatively simple model. The decision, finally, was to work with tomato seedlings at Technion and with lettuce seedlings at Cornell.

Demonstration. It was clear at the outset that it was hopeless to demonstrate properly (statistically), that the operation by the optimization algorithm is actually superior to other reasonable operation schemes. The differences in performance near the optimum are of the order of a few percent, and with biological systems under only semi-controlled conditions, a prohibitive number of replications is necessary to test anything properly. With the state of the art of modelling the crop, no reliable practical answers could be hoped for.

At Technion, the purpose of making comparisons between two treatments (in the two greenhouses within each pair), was only to demonstrate how the proper economic comparisons should be made. At Cornell, only comparisons between heating requirements produced statistically significant results.

1-3. OVERVIEW OF REPORT

The report consists of 10 chapters of which the first and last are the INTRODUCTION and SUMMARY AND CONCLUSIONS. The other chapters discuss specific activities of the project and are the main body of the report.

Chapters 2 and 3 describe the optimization scheme and its component models. Chapter 2 is a mathematical treatment of the optimization method. In Chapter

3 available data are used in a computer simulation to illustrate how the method is meant to be applied.

Chapters 4, 5 and 6 supply some experimentally derived parameters of the sub-systems involved. Chapter 4 describes how a greenhouse can be thermally calibrated in-situ to provide values of some of the engineering parameters required. Chapter 5 is a review of literature attempting to formulate the photosynthetic response of tomato plants to their environment. Chapter 6 reports on a growth chamber experiment to determine the response of tomato seedlings to day and night temperatures. In the latter chapter an attempt is also made to apply the optimization scheme to the simple problem of deciding on the economically best night-time temperature.

Chapter 7 described some of the problems related to the actual control of the greenhouse environment. The control system receives the output of the optimization scheme and is required to implement its recommendations.

Chapters 8 and 9 describe two independent experiments intended to demonstrate that the approach of the project can produce a working system. Chapter 8 described how tomato seedlings were grown under two treatments of automatic environmental control. Only temperature control was applied, but the complete process as envisioned originally was executed. Optimal control instructions were produced by the main-frame computer, these were utilized in real time by the greenhouse micro-computer, and a crop was grown and monitored. Chapter 9 described an application of the optimization approach to a thermal curtain operation. Here, too, comparisons between pairs of treatments were made.

Chapters 2, 3, 4, 6, 8 and 9 were written basically as individual papers. Chapter 2 is already in print, Chapter 6 has been accepted for publication, and Chapter 4 has been submitted for publication. As a result of this there is less inter-reference between the chapters than perhaps desirable in a report. In the final chapter, SUMMARY AND CONCLUSIONS, an attempt is made to bring the various elements into a common focus.

Each one of the chapters can be read independently of the others (except for necessary referencing). Each chapter has its own lists of symbols and references (symbols may differ slightly between chapters). Tables and figures appear at the end of each chapter.

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Chapter 2: METHODOLOGY

S. Gal, A. Angel and Ido Seginer

2-1. INTRODUCTION

The control of the aerial environment in greenhouses is often limited to air temperature. While this is the most critical parameter, other parameters, such as CO₂ concentration, relative humidity and light, are also important, and an ideal system should have these parameters also under control. Attempts have been made to control simultaneously air temperature and humidity, as well as to vary the temperature set-points as a function of solar radiation (e.g. Bokhorst et al., 1972; Hand & Soffe, 1971). These improvements have reached the application stage, as is evident from lists of commercially available equipment (e.g. Gieling & van Meurs, 1977), but are not yet standard worldwide. The introduction of digital micro-devices into commercial greenhouses enables further sophistication of the control algorithms, but it seems that not enough is known about the economically justified level of automation, mainly because not enough is known of plant response to variable environmental conditions.

The purpose of this study is to synthesize available knowledge (engineering, crop and economic) into a useful method of optimizing greenhouse operation. Testing the sensitivity of the greenhouse system to various parameters should help determine the potential gain from further sophistication of control algorithms.

In contrast with other approaches to automatic operation of greenhouses, the present approach seeks an economic optimum. An optimizing algorithm is executed at short intervals of time (several times an hour), weighing contradicting demands (such as ventilating and heating) by their economic value.

The system to be considered is shown in Figure 2-1. Known in advance are the greenhouse structure, the air-conditioning equipment and the crop, while the weather conditions vary continuously. (The term "air-conditioning" is used

here in the general sense.) The unit prices of the various commodities (e.g. fuel) are input parameters. The optimum is obtained by maximizing the objective function "INCOME minus COST-OF-OPERATION". The estimation of the effect on INCOME of alternative operation modes seems to be the most difficult task, because present knowledge of plant response is limited, and short term feedback from the plant is difficult to measure and interpret.

To start a systematic analysis of the problem, a model of the system is required. To simplify the real system, two major assumptions are made:

- (1) The state of the crop is defined by just one parameter (e.g. leaf area);
- (2) The greenhouse has no heat capacity.

Both assumptions are made by necessity, but can be justified under certain circumstances. The first assumption may be considered acceptable for the vegetative growth stage, and the second - for a greenhouse where the soil surface is insulated from the air (by well-developed canopy, benches, etc.).

Based on these assumptions, two general relationships can be formulated:

Growth function:

$$\frac{dS}{dt} = G(S, I, t) \quad (2-1)$$

Greenhouse function:

$$I = I(O, M) \quad (2-2)$$

where S is the state of the crop (scalar), t is time, O is a vector of outside conditions, I is a vector of inside conditions and M is a vector of states of the air-conditioning equipment.

The objective of the environmental control is to select the level of operation M such that the objective function is maximized. If the price that can be

obtained for the product is constant with time, the problem may reduce to weighing the rate of growth (dS/dt) against the cost of maintaining a certain inside environment. If the price is expected to change with time (for instance, before a holiday), there may be an additional incentive to increase or reduce the rate of growth.

A detailed description of the growth and greenhouse functions is presented in Chapter 3. Right now only a few comments will be made:

- (1) To enable the integration of the growth function by separation of variables, it is necessary to change it to

$$\frac{dS}{dt} = (S)g(I,t) \quad (2-3)$$

The dependence on t of $g(I,t)$ follows from the fact that the response of the crop to the environmental conditions is different for different stages of its life cycle. During each such stage, however, it shall usually be assumed that g depends on I but not explicitly on t , i.e., for a specific stage $g = g(I)$.

A few empirical forms of $g(I)$ are available, or can be composed of available data (e.g. Enoch and Sacks, 1988). They are based on just one process, photosynthesis, and therefore apply directly to day-time only. To introduce the night-time dominant activity of translocation and growth (even in a sketchy manner), a second state variable - temporary storage of photosynthates - must be introduced. This is outside the scope of the present study.

- (2) The greenhouse function is basically a set of non-linear conservation equations. They are energy balances of the various greenhouse elements and mass balances of the inside air. The number of equations depends on the level of detail that is attempted. In the present study, the minimum number that still preserves the essential behavior is used: 3 energy balances of greenhouse elements plus 1 on the inside air, and 2 mass balances (H_2O and CO_2) of the inside air, for a total of 6.

Based on the general concepts and relationships outlined above, a mathematical model is developed and solved in the following sections. The final product is a method of calculating (off-line) an operation table to be used by a micro-computer in the greenhouse. During the actual control operation, with the outside conditions as input to the micro-computer, the table will be searched for the optimum operation level of the air-conditioning equipment. This level will be maintained until the outside conditions change enough to justify a change of operation level.

2-2. COMPONENTS OF THE MATHEMATICAL MODEL

At this stage of the work a method was devised for computing the optimal control of a greenhouse for standard atmospheric conditions, which are assumed known in advance. In Section 2-6 an approach is suggested which can be used in case of deviations from the assumed conditions. The vector of the atmospheric conditions at time t will be denoted by $O(t)$ or simply by O , where $O = (O_1, \dots, O_K)$ (e.g., temperature, solar radiation, long wave radiation, humidity and wind velocity). The state of the controlling equipment at time t will be denoted by $M(t)$ or simply by $M = (m_1, \dots, m_N)$ where m_i is the "level" of operation of the i -th controlling equipment. (This equipment can constitute heater, fan, wet pad, HID lamps, CO_2 generator, etc.) The atmospheric conditions O and the control M induce climatic conditions inside the greenhouse which will be denoted by I . Obviously, I is a function of O and M . This function depends on the physical properties of the greenhouse which are assumed as known. In the proposed model I is a six component vector (temperatures of leaves, air and cover, light, humidity and CO_2 concentration) which can be determined as a solution of six balance equations

$$B_i(O, M, I) = 0 \quad i=1, \dots, 6. \quad (2-4)$$

It is assumed that the state of the crop at time t can be described by a scalar $S = S(t)$. At the beginning of the relevant stage $S = S_0$ while at the end of that stage $S = \bar{S}$, where S_0 and $\bar{S}$ are known constants. The assumed rate of growth is given by equation (2-3), i.e.,

$$\frac{dS}{dt} = \alpha(S) \cdot g(I, t)$$

where α and g are known functions (actually these functions can only be estimated from growing experiments). Since $I = I(0, M)$, it can be written that $g(I, t) = g(0, M, t)$. Let $\bar{t}$ be the time at the end of the relevant stage (referred to as the "termination time"); then it follows from (3) that

$$\int_0^{\bar{t}} g(0, M, t) dt = \int_{S_0}^{\bar{S}} \frac{dS}{\alpha(S)} \equiv \gamma$$

where γ is a constant determined by the RHS of the above expression.

The termination time $\bar{t}$ has important economical implications because the greenhouse space is used in the time interval $(0, \bar{t})$ and this use, obviously, has a cost due to the investment and the maintenance expenses. In addition, $\bar{t}$ usually influences the revenue obtained from the crop. This influence can sometimes be very significant, as can happen, for example, if flowers are planned to be marketed shortly before Christmas. The above mentioned parts of the cost function will be called the "termination cost" and will be denoted by $C(\bar{t})$. The cost of operation per one unit of time is denoted by $L(M)$.

Now the problem is to find the optimal control. The problem can be mathematically formulated as follows:

Find a control function $M = M(t)$ which minimizes the total cost $\delta(M)$ defined by

$$\delta(M) = \int_0^{\bar{t}} L(M) dt + C(\bar{t}) \quad (2-5)$$

subject to

$$\int_0^{\bar{t}} G(0, M, t) dt = \gamma \quad (2-6)$$

In addition, for all $0 \leq t \leq \bar{t}$ the control M has to satisfy a "maximal" capacity constraint

$$0 \leq m_i \leq \bar{m}_i \quad i = 1, \dots, N \quad (2-7)$$

and

$$I(0, M) \text{ has to be a feasible growing climate.} \quad (2-8)$$

A control $M(t)$ which satisfies (2-7) and (2-8) for all t will be called a "feasible control".

2-3. SOLUTION OF THE OPTIMIZATION PROBLEM

At first sight it seems that in order to solve the optimization problem described in the previous section, one has to search through the whole space of control functions. We now show that it is sufficient to search in a narrow subfamily which is characterized by a Lagrange multiplier λ , $0 \leq \lambda < \infty$. Let $M_\lambda(t)$ be the control which solves for all $t \geq 0$

$$\min_M [L(M) - \lambda G(0, M, t)] \quad , \quad M \text{ feasible} \quad (2-9)$$

and determine the termination time t_λ by the following equality

$$\int_0^{t_\lambda} G(0, M_\lambda, t) dt = \gamma \quad (2-10)$$

The following results will be useful in finding the optimal control:

Proposition 1. $M_\lambda(t)$ is optimal among all the controls which terminate at time t_λ .

Proof: For any $t \geq 0$, all feasible M satisfy $L(M_\lambda) - \lambda G(0, M_\lambda, t) \leq L(M) - \lambda G(0, M, t)$.

Integrating the above inequality it follows that

$$\int_0^{t_\lambda} L(M_\lambda) dt - \lambda \int_0^{t_\lambda} G(0, M_\lambda, t) dt \leq \int_0^{t_\lambda} L(M) dt - \lambda \int_0^{t_\lambda} G(0, M, t) dt. \quad (2-11)$$

if M has termination time t_λ then

$$\int_0^{t_\lambda} G(0, M, t) dt = \gamma$$

and thus (2-10) and (2-11) imply that

$$\int_0^{t_\lambda} L(M_\lambda) dt \leq \int_0^{t_\lambda} L(M) dt.$$

Since the terminal cost for M_λ and M is the same it follows that $\delta(M_\lambda) \leq \delta(M)$.

Q.E.D.

Proposition 2: If $\lambda > \mu$ then $t_\lambda \leq t_\mu$.

Proof: For all $t \geq 0$

$$L(M_\lambda) - \lambda G(0, M_\lambda, t) \leq L(M_\mu) - \lambda G(0, M_\mu, t)$$

and

$$L(M_\mu) - \mu G(0, M_\mu, t) \leq L(M_\lambda) - \mu G(0, M_\lambda, t).$$

It follows from the above inequalities that

$$\begin{aligned} L(M_\lambda) - \lambda G(0, M_\lambda, t) &\leq L(M_\mu) - \mu G(0, M_\mu, t) - (\lambda - \mu) G(0, M_\mu, t) \\ &\leq L(M_\lambda) - \mu G(0, M_\lambda, t) - (\lambda - \mu) G(0, M_\mu, t). \end{aligned}$$

Thus,

$$(\lambda - \mu)G(0, M_\mu, t) \leq (\lambda - \mu)G(0, M_\lambda, t).$$

Since $\lambda > \mu$ it follows that for all t

$$G(0, M_\mu, t) \leq G(0, M_\lambda, t) \text{ which implies that the termination times satisfy } t_\mu \geq t_\lambda.$$

Q.E.D.

It will later be shown that propositions 1 and 2 imply that the optimal control belongs to the family $\{M_\lambda, 0 \leq \lambda < \infty\}$. This fact makes it possible to derive an efficient algorithm for optimization. However, the significance of the Lagrange multiplier λ should be pointed out first. In order to simplify the exposition it will be assumed here that we are dealing with a specific stage of the crop's life cycle so that the growth rate G depends on O and M but not on t itself, so that $G = G(O, M)$. To this end let the function $\tilde{L}(O, x)$ be defined as follows:

$$\tilde{L}(O, x) = \min\{L(M) : G(O, M) = x, M \text{ feasible}\}. \quad (2-12)$$

$\tilde{L}$ is the minimal cost which has to be paid in order to obtain a growth rate x under the atmospheric conditions O . The control which corresponds to this minimal cost will be denoted by $\tilde{M}(O, x)$. Obviously, (2-9) is equivalent to

$$\min_x [\tilde{L}(O, x) - \lambda x]. \quad (2-13)$$

If x is the solution of (2-13), then the control M which solves (2-9) is denoted by $\tilde{M}(O, x_\lambda)$.

In order to get better insight into the solution of (2-13), define $\bar{L}(O, x)$ as the convex envelope of $\tilde{L}(O, x)$ (Figure 2-2). It is easy to see that (2-13) is equal to

$$\min_x [\bar{L}(0, x) - \lambda x]. \quad (2-14)$$

Problem (2-14) can be solved by finding x_λ which satisfies $\frac{d}{dx} \bar{L}(0, x_\lambda) = \lambda$.

(If the derivative of $\bar{L}$ is not continuous then the exact condition is

$$\frac{d}{dx} \bar{L}(0, x_\lambda - \epsilon) < \lambda \text{ and } \frac{d}{dx} \bar{L}(0, x_\lambda + \epsilon) > \lambda.)$$

Thus λ represents the marginal cost worth paying for an additional unit of growth rate. Since $\bar{L}$ is a convex function it follows that the desired growth rate x_λ which corresponds to λ is monotonic nondecreasing in λ .

From the above discussion it follows that the control M_λ corresponds to a fixed marginal cost per growth during all the growing period. Thus, the following observations can be made:

- (1) The control M_∞ (i.e., $\lambda = \infty$) maximizes the growth rate irrespective of operation cost during all the growing period. Thus the termination time of M_∞ , t_∞ , is the minimal termination time which can ever be achieved.
- (2) The control M_0 (i.e., $\lambda = 0$) minimizes the operation cost irrespective of the growth rate during all the growing period. This implies that in all reasonable problems the optimal termination time cannot exceed t_0 . Thus, the relevant interval of termination times needed to be considered is $t_\infty \leq \bar{t} \leq t_0$.
- (3) Usually if $\lambda > \mu$ then $t_\lambda < t_\mu$. The case $t_\lambda = t_\mu$ is possible only if the derivative of $\bar{L}$ is discontinuous at x_λ .
- (4) The following question should now be considered:
Let $t_\infty < \bar{t} < t_0$. Can a control M_μ which terminates at $\bar{t}$ be found?
In order to answer this question first consider the possibility of discontinuity of t_λ as a function of λ , i.e., the existence of a positive number β with

$$t_{\beta-} = \lim_{\lambda \uparrow \beta} t_{\lambda} > \lim_{\lambda \downarrow \beta} t_{\lambda} = t_{\beta+}$$

This situation can occur only if for a certain time interval:

$$x_{\beta-} = \lim_{\lambda \uparrow \beta} x_{\lambda} > \lim_{\lambda \downarrow \beta} x_{\lambda} = x_{\beta+}. \quad \text{Such a situation is depicted in Figure 2-3. In}$$

this case, problem (2-13) with $\lambda = \beta$ has a whole segment of optimal solutions:

$$x_{\theta} = (1-\theta)x_{\beta-} + \theta x_{\beta+}, \quad 0 \leq \theta \leq 1. \quad (2-15)$$

The growth rate x_{θ} can actually be achieved by using, for a small time interval Δt , the control $M_{\beta-}$ during period $(1-\theta)\Delta t$ and the control $M_{\beta+}$ during period $\theta\Delta t$. Such a control will be denoted by $M_{\beta,\theta}$. It is obvious that the termination times of the controls $M_{\beta,\theta}$, $0 \leq \theta \leq 1$, covers the whole interval $[t_{\beta-}, t_{\beta+}]$. Using an argument similar to the one used in proposition 1, it can easily be shown that $M_{\beta,\theta}$ is optimal among all the controls which have the same termination time. Obviously, if $\tilde{L}$ is convex for all t then t_{λ} is continuous in λ and the above mentioned problem does not arise.

From the above discussion it follows that for any $t_{\infty} \leq t \leq t_0$ one can find a control $M_{\bar{\lambda}}$ (or $M_{\bar{\lambda},\theta}$ if necessary) which terminates at $\bar{t}$ and dominates all the other controls which terminate at $\bar{t}$. Thus, only the family M_{λ} , $0 \leq \lambda \leq \infty$, can be considered. (For those λ 's with discontinuity in t_{λ} , $M_{\lambda,\theta}$ will also have to be considered as candidates for the optimal control.)

Denote

$$\Psi(t) = \int_0^{\bar{t}} L(M_{\bar{\lambda}}) dt$$

Then it follows from the above discussion that the presented optimization problem is equivalent to minimizing

$$[\Psi(\bar{t}) + C(\bar{t})]$$

Let t^* be the t which minimizes (2-16). The corresponding λ will be denoted by λ^* and the optimal control is then M_{λ^*} . (For simplicity of exposition, it will be assumed that t_λ is continuous at λ^* so that a control of the type $M_{\lambda^*,\theta}$ does not have to be used. However, the necessity of using such a control should not cause any special problems.)

The significance of the parameter λ^* is as follows: at any time instant t , it is worthwhile to pay an amount not exceeding λ^* to increase the growth by one unit. A criterion for finding the optimal λ^* is now presented:

Proposition 3: Assume that C is a differentiable function. For any $0 < \lambda < \infty$, if

$$\lambda < \frac{L(N_\lambda(t_\lambda)) + C'(t_\lambda)}{G(0(t_\lambda), M_\lambda(t_\lambda))} \quad (2-16A)$$

then the total cost can be reduced by increasing λ , while if the reverse inequality holds then the total cost can be reduced by decreasing λ .

Proof: Assume that (2-16A) holds. If $M_{\lambda+\Delta\lambda}$ is used ($\Delta\lambda$ being small), then for any $0 \leq t < t_\lambda$ the growth rate, denoted by $s_\lambda(t)$, is increased by $\Delta x_\lambda(t)$. Denote $\Delta t_\lambda = t_{\lambda+\Delta\lambda} - t_\lambda$ then

$$G(0(t_\lambda), M_\lambda(t_\lambda)) \cdot \Delta t_\lambda \cong \int_0^{t_\lambda} \Delta x_\lambda(t) dt \quad (2-17)$$

Since λ is the marginal cost per unit growth for the control M_λ it follows that for all t

$$L(M_{\lambda+\Delta\lambda}(t)) \cong L(M_\lambda(t)) + \lambda \Delta x_\lambda(t)$$

Using (2-17) we obtain

$$\int_0^{t_\lambda} L(M_{\lambda+\Delta\lambda}(t)) dt \cong \int_0^{t_\lambda} L(M_\lambda(t)) dt + \lambda G(0(t_\lambda), M_\lambda(t_\lambda)) \Delta t_\lambda \quad (2-18)$$

Thus,

$$\int_0^{t_\lambda + \Delta\lambda} L(M_{\lambda + \Delta\lambda}(t)) dt + C(t_\lambda + \Delta\lambda) \cong \int_0^{t_\lambda} L(M_\lambda(t)) dt + C(t_\lambda) \\ + \Delta t_\lambda [L(M_\lambda(t_\lambda)) + C'(t_\lambda) - \lambda G(0(t_\lambda), M_\lambda(t_\lambda))]$$

(where the notation $\cong$ means within an error proportional to $\Delta^2 t_\lambda$).

It now follows from (2-16) that using $M_{\lambda + \Delta\lambda}$ reduces the total cost. The second part of the proposition is proved similarly.

It follows from proposition 3 that if λ satisfies

$$\lambda = \frac{L(M_\lambda(t_\lambda)) + C'(t_\lambda)}{G(0(t_\lambda), M_\lambda(t_\lambda))} \quad (2-19)$$

then M_λ is a (local) minimum of the cost function (2-5). Our numerical procedure is designed so as to find a λ which satisfies (2-19) (within a given tolerance).

2-4. NUMERICAL PROCEDURE OF CALCULATING THE OPTIMAL SOLUTION AND ITS IMPLEMENTATION

From the discussion in Section 2-3 it follows that the optimal control can be obtained by finding the optimal Lagrange parameter λ^* . An iterative procedure for finding λ^* and M_{λ^*} is now described. For this procedure a starting point must be used and can be provided by the (standard) control $M^{(0)}$ which is currently used by the greenhouse growers. Using equation (2-19), it is reasonable to take the initial Lagrange parameter $\lambda^{(0)}$ as

$$\lambda^{(0)} = \frac{L(M^{(0)}(t^{(0)})) + C'(t^{(0)})}{G(0(t^{(0)}), M^{(0)}(t^{(0)}))}$$

Then, the iterative procedure is described by the flowchart in Figure 2-4.

In principle, it is possible to take the optimal control $M_{\lambda^*}(t)$ and directly obtain a sequence of instructions for operating the equipment as a function of the time t . A better way, however, is to use the following approach: given λ^* , it follows from the previous discussion that during any specific stage of the life cycle of a crop the optimal control at any time instant t depends on the atmospheric conditions $O(t)$ but not on t itself. Thus, it is possible to build a table of operating instructions as a function of $O(t)$. The major advantage of using such an approach is that the optimal instructions become much less sensitive to the assumed standard atmospheric conditions. For example, it easily follows from the discussion in the previous chapter that if the assumed atmospheric conditions are changed by a permutation of the same conditions at the beginning of the growing period, then the optimal $M(t)$ would have to be permuted in the same manner, but the recommended table of instructions would not have to be changed at all.

An efficient way of building such a table of instructions, which could also be used in the program described in Figure 2-4, is to use the fact that small deviations in $O(t)$ do not much influence the optimal control. Thus, the set of atmospheric conditions $\{O(i\Delta t), i=0,1,\dots\}$ can be divided into clusters of "similar" atmospheric conditions. A "representative point" for each cluster can then be chosen and the optimal instructions for this point can be used for the whole cluster. The method of building those clusters and choosing the representative conditions depends on the sensitivity of the optimal control to deviations in the atmospheric conditions and is described in the next chapter.

2-5. SENSITIVITY ANALYSIS AND ITS APPLICATIONS

The method of optimization described in Chapter 3 is based on the following principle: At each time instant t a feasible "level" of operation M^* is found which minimizes $f(O,M)$ where

$$f(O,M) = L(M) - \lambda^*G(O,M) \quad (2-20)$$

λ^* being the optimal Lagrange parameter and G the growth rate. Since λ^* measures the benefit per one unit of growth rate it follows that f can be

considered as the "total cost" at time t . The minimal cost $f^*(0)$ can be defined as

$$f^*(0) = \min_M f(0, M) = f(0, M^*). \quad (2-21)$$

(During any specific stage of the life cycle of the crop f^* depends on $0(t)$ but not explicitly on t itself.)

The following important problem is now considered: assume that the atmospheric conditions were changed by an amount $\Delta 0$; this will usually change the optimal operation M^* . If, however, $\Delta 0$ is small enough then it is reasonable to assume that M^* can still be used without being greatly affected; actually in this case it is preferable to leave M^* as it is. The problem which naturally poses itself is: how small should $\Delta 0$ be in order for M^* to be "near optimal"? (Solving this problem will provide the possibility of using M^* not only for the point 0 but also for a whole region of atmospheric conditions, making the recommended control much easier to use. This point will be discussed later.) Obviously, solving the above problem involves estimating the "penalty", P , of using M^* for $0 + \Delta 0$, defined as follows

$$P(\Delta 0) = f(0 + \Delta 0, M^*) - f^*(0 + \Delta 0) \quad (\geq 0) \quad (2-22)$$

(see 2-20) and (2-21)).

It will now be shown that, usually, if $\Delta 0$ is small then P is a quadratic form in $\Delta 0$, i.e.,

$$P(\Delta 0) \cong \Delta 0 U \Delta 0^T \quad (2-23)$$

where U is a symmetric matrix which can be calculated using the following method:

Let the optimal control for $0 + \Delta 0$ be denoted as $M^* + \Delta M$, i.e.,

$$f(0 + \Delta 0, M^* + \Delta M) = f^*(0 + \Delta 0). \quad (2-24)$$

Then (see (2-22))

$$P = f(0 + \Delta 0, M^*) - f(0 + \Delta 0, M^* + \Delta M),$$

where $M^* = (m_1^*, \dots, m_i^*, \dots)$.

Denote

$$f_i(0, M) = \frac{\partial}{\partial m_i} f(0, M) \quad (2-25)$$

Since m_i has to satisfy $0 \leq m_i \leq \bar{m}_i$, two types of m_i must be specified. If m_i^* is on the boundary, i.e., $m_i^* = 0$ or $m_i^* = \bar{m}_i$, then it may be assumed that for slight changes of 0, m_i will still be on the boundary. Thus, the corresponding component of ΔM equals zero so that those components of M in the sensitivity calculations can be disregarded. Thus the case is confined to the following:

$$0 < m_i < \bar{m}_i \quad i=1, \dots, n. \quad (2-26)$$

In this case, a necessary condition for the optimality of M^* to 0 and of $M^* + \Delta M$ to $0 + \Delta 0$ is (see (2-25))

$$f_i(0, M^*) = 0 \quad i=1, \dots, n \quad (2-27)$$

and

$$f_i(0 + \Delta 0, M^* + \Delta M) = 0 \quad i=1, \dots, n \quad (2-28)$$

By subtracting (2-27) from (2-28) the following is obtained

$$\sum_{k=1}^k \frac{\partial}{\partial 0_k} f_i(0, M^*) \Delta 0_k + \sum_{j=1}^n \frac{\partial}{\partial m_j} f_i(0, M^*) \Delta m_j \cong 0. \quad i=1, \dots, n. \quad (2-29)$$

Denote

$$A(0, M^*) = (a_{ij}) = \left(\frac{\partial}{\partial m_j} f_1(0, M^*) \right) = \left(\frac{\partial^2}{\partial m_i \partial m_j} f(0, M^*) \right), \quad \begin{matrix} i=1, \dots, n; \\ j=1, \dots, n \end{matrix} \quad (2-30)$$

and

$$B(0, M^*) = (b_{ik}) = \left(\frac{\partial}{\partial o_k} f_1(0, M^*) \right) = \left(\frac{\partial^2}{\partial m_i \partial o_k} f(0, M^*) \right), \quad \begin{matrix} i=1, \dots, n; \\ k=1, \dots, K. \end{matrix} \quad (2-31)$$

Then, (2-29) can be written as

$$B \Delta O^T + A \Delta M^T \cong 0. \quad (2-32)$$

Since M^* is a minimum point of f it follows that A is positive semi-definite. It may reasonably be assumed (unless a pathologic behavior is expected, which is not the case here), that A is positive definite so that A^{-1} exists. Thus,

$$\Delta M^T \cong -A^{-1} B \Delta O^T \quad (2-33)$$

(where $\cong$ means "within an error of order of magnitude less than ΔO ").

Now P (see (2-22) and (2-24) is estimated by

$$P(\Delta O) = f(0 + \Delta O, M^*) - f(0 + \Delta O, M^* + \Delta M)$$

$$\cong - \sum_{i=1}^n f_1(0 + \Delta O, M^*) \Delta m_i - \frac{1}{2} \Delta M A(0 + \Delta O, M^*) \Delta M^T$$

(see (2-30))

$$\cong - \sum_{i=1}^n f_1(0, M^*) \Delta m_i - \Delta M B \Delta O^T - \frac{1}{2} \Delta M A \Delta M^T$$

(using (2-24) and (2-33))

$$\begin{aligned} &\cong \Delta 0 \ B^T \ (A^{-1})^T \ B \ \Delta 0^T - \frac{1}{2} \ \Delta 0 \ B^T \ (A^{-1})^T \ A A^{-1} \ B \ \Delta 0^T \\ &= \frac{1}{2} \ \Delta 0 \ B^T \ (A^{-1})^T \ B \ \Delta 0^T \end{aligned}$$

(where $\cong$ means "within an error of order of magnitude less than $\Delta^2 0$ ").

Thus, the penalty for using M^* for $0 + \Delta 0$ is (approximately) a quadratic form of $\Delta 0$ with a matrix

$$U = \frac{1}{2} \ B^T \ (A^{-1})^T B \quad (2-34)$$

where A and B are defined by (2-30) and (2-31). An explicit derivation of A and B is presented in the appendix.

Formulas (2-23) and (2-34) enable one to estimate the effect of using the control M^* (which is optimal for 0) for a whole region around 0). A reasonable approach is to set a predetermined tolerance, ϵ , (say 2% of the objective function) and to use the control M^* for any $0' (= 0 + \Delta 0)$ if

$$P(\Delta 0) \leq \epsilon \quad (\text{see 2-22}) \quad (2-35)$$

Condition (2-35) enables one to consider a given set of atmospheric conditions

$$T_0 = \{0_1, \dots, 0_N\} \quad (2-36)$$

as vertices of a graph with the following property: two vertices of this graph, 0_i and 0_j , are connected if and only if condition (2-35) holds with $\Delta 0 = 0_i - 0_j$. The problem which obviously is of interest here is to find a set with a small number of "representative conditions", $T_{0\epsilon}$, that will cover the whole graph in the following sense: for any $0 \in T_0$ there exists an $0' \in T_{0\epsilon}$ such that 0 is connected to $0'$. The problem of covering a graph

has received some attention in the literature, and there exist some reasonable algorithms for solving it, which are sufficient for the present purposes (see Chvatal, 1979).¹

The set of representative conditions TO_ϵ can be used both in the optimization and in the real operation, as follows: at the beginning of each iteration of the optimization program (see Fig. 2-4), the optimal control M^* is calculated for all $O_1 \in TO_\epsilon$. Then, during the optimization program, for each $O(t)$, $f(O, M)$ is not minimized, but instead the following procedure is used: first try the optimal solution already obtained for the time instant $t - \Delta t$, using (2-23) to estimate the penalty. If this penalty is less than the tolerance, then the same control is used for the present time interval; otherwise, another element O_r is sought in the set TO_ϵ which can "represent" $O(t)$. (Such an element exists by the construction of TO_ϵ). The optimal operation for O_r , M_r^* , is then used for the time interval $(t, t + \Delta t)$.

After completing the optimization program, its output, i.e., the optimal operating rules, can be arranged as a table which identifies each region of the atmospheric condition with specific operating rules recommended for that region. (These rules are the optimal rules for the representative conditions of that region.) This table can be stored in a microprocessor which will be able to use a small program of the type described above in order to determine the operating rule which should be applied at each instant t .

2-6. DEVIATION FROM THE ASSUMED STANDARD ATMOSPHERIC CONDITIONS

In the case that the atmospheric conditions are close to the assumed standard conditions the method of solution described in Chapters 3, 4 and 5 solves the whole problem. In real life, however, there will be deviations from the

¹In general, the set TO_ϵ will depend on the Lagrange parameter λ . Usually, however, the sensitivity will increase as λ increases. Thus a set $\overline{TO}_\epsilon$ calculated for $\lambda = \overline{\lambda}$ will also cover all the relevant atmospheric conditions for any $\lambda < \overline{\lambda}$. Thus, if the set $\overline{TO}_\epsilon$ has a small number of elements (which seems to be the case here) then $\overline{TO}_\epsilon$ can be used for all $\lambda < \overline{\lambda}$ without containing many redundant elements.

assumed conditions so that the above described solution may deviate significantly from the optimum. In order to overcome this difficulty the following approach is suggested: at first, several numerical computations of the optimal solution for some atmospheric profiles $O'(t)$ which deviate from the standard $O(t)$, should be made in order to obtain the sensitivity of the solution to such deviations. The output of these calculations should give the user an idea about the significance of several types of deviations from the standard conditions.

The suggested procedure is to start operating the greenhouse using the rule M_{λ^*} , where λ^* is the optimal Lagrange parameter for some standard $O(t)$. At several time instances t_i , $i=1, \dots, J$, the user should check the actual history of atmospheric conditions $O'(t)$ $0 \leq t < t_i$ versus the assumed standard conditions $O(t)$ (with respect to its influence on the optimal control) has occurred, then the whole problem should be resolved (as described in sections 2-3 and 2-4) using t_i as a starting point; otherwise using rule M_{λ^*} should be continued.

2-7. REFERENCES

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2-8. APPENDIX: CALCULATION OF THE SENSITIVITY MATRIX

The sensitivity matrix U given by (2-34) is determined by the two matrices A and B where

$$A = \left(\frac{\partial^2}{\partial m_1 \partial m_2} \right) f(0, M^*) \quad (2-A1)$$

$$B = \left(\frac{\partial^2}{\partial m_1 \partial \theta_k} \right) f(0, M^*) \quad (2-A2)$$

$$f(0, M^*) = L(M^*) - \lambda G(0, M^*) = L(M^*) - \lambda g(I) \quad (2-A3)$$

g being a known function and the operating cost $L(M^*)$ is assumed for convenience to be linear in M^* . The climatic conditions inside the greenhouse $I = I(0, M^*)$ are determined by a set of balance equations (2-4).

$$B_j(0, M^*, I) = 0 \quad j=1, \dots, J. \quad (2-A4)$$

Since L is a linear function it follows that A and B can be obtained by calculating $-\lambda \frac{\partial^2 g(I)}{\partial m_1 \partial m_2}$ and $-\lambda \frac{\partial^2 g(I)}{\partial m_1 \partial \theta_k}$ subject to (2-A4). This can be done as follows:

$$\frac{\partial g}{\partial m_1} = \sum_{j=1}^J \frac{\partial g}{\partial I_j} \frac{\partial I_j}{\partial m_1}$$

²In the calculation in this report, the case is not considered in which one, or some, of the climatic conditions inside the greenhouse lies on the boundary of its feasibility region (e.g., minimum temperature). In such a case, the boundary condition usually determines the control in a unique fashion so that there is no sense in carrying out a sensitivity analysis.

Thus,

$$\frac{\partial^2 g}{\partial m_1 \partial m_l} = \sum_j \sum_r \frac{\partial^2 g}{\partial I_j \partial I_r} \frac{\partial I_j}{\partial m_1} \frac{\partial I_r}{\partial m_l} + \sum_j \frac{\partial g}{\partial I_j} \frac{\partial^2 I_j}{\partial m_1 \partial m_l} \quad (2-A5)$$

and

$$\frac{\partial^2 g}{\partial m_1 \partial O_k} = \sum_j \sum_r \frac{\partial^2 g}{\partial I_j \partial I_r} \frac{\partial I_j}{\partial m_1} \frac{\partial I_r}{\partial O_k} + \sum_j \frac{\partial g}{\partial I_j} \frac{\partial^2 I_j}{\partial m_1 \partial O_k} \quad (2-A6)$$

The expressions $\frac{\partial I_j}{\partial m_1}$, $\frac{\partial I_r}{\partial O_k}$, $\frac{\partial^2 I_j}{\partial m_1 \partial m_l}$, and $\frac{\partial^2 I_j}{\partial m_1 \partial O_k}$, can be calculated as follows.

From (2-A4) four sets of equations are obtained:

(1) For any $i=1, \dots, n$, the set of linear equations

$$\frac{\partial C_j}{\partial m_1} + \sum_{l=1}^J \frac{\partial C_j}{\partial I_l} \frac{\partial I_l}{\partial m_1} = 0 \quad j=1, \dots, J \quad (2-A7)$$

enables us to calculate $\frac{\partial I_l}{\partial m_1} \quad l=1, \dots, J.$

(2) For any $k=1, \dots, K$, the set of linear equations

$$\frac{\partial C_j}{\partial O_k} + \sum_{l=1}^J \frac{\partial C_j}{\partial I_l} \frac{\partial I_l}{\partial O_k} = 0 \quad j=1, \dots, J \quad (2-A8)$$

enables one to calculate $\frac{\partial I_l}{\partial O_k} \quad l=1, \dots, J.$

(3) For any i and k

$$\begin{aligned} \frac{\partial^2 C_j}{\partial m_i \partial m_k} + \sum_{r=1}^J \sum_{\ell=1}^J \frac{\partial^2 C_j}{\partial I_r \partial I_\ell} \frac{\partial I_r}{\partial m_i} \frac{\partial I_\ell}{\partial m_k} + \sum_{\ell=1}^J \frac{\partial^2 C_j}{\partial m_i \partial I_\ell} \frac{\partial I_\ell}{\partial m_k} \\ + \sum_{\ell=1}^J \frac{\partial^2 C_j}{\partial m_k \partial I_\ell} \frac{\partial I_\ell}{\partial m_i} + \sum_{\ell=1}^J \frac{\partial C_j}{\partial I_\ell} \frac{\partial^2 I_\ell}{\partial m_i \partial m_k} = 0 \quad j=1, \dots, J. \end{aligned} \quad (2-A9)$$

Using the solution obtained from (2-A7) the second derivatives $\frac{\partial^2 I_\ell}{\partial m_i \partial m_k}$ $\ell=1, \dots, J$, can be calculated as the solution to the linear equation (2-A9).

(4) For any i and k

$$\begin{aligned} \frac{\partial^2 C_j}{\partial m_i \partial O_k} + \sum_{r=1}^J \sum_{\ell=1}^J \frac{\partial^2 C_j}{\partial I_r \partial I_\ell} \frac{\partial I_r}{\partial m_i} \frac{\partial I_\ell}{\partial O_k} + \sum_{\ell=1}^J \frac{\partial^2 C_j}{\partial m_i \partial I_\ell} \frac{\partial I_\ell}{\partial O_k} \\ + \sum_{\ell=1}^J \frac{\partial^2 C_j}{\partial O_k \partial I_\ell} \frac{\partial I_\ell}{\partial m_i} + \sum_{\ell=1}^J \frac{\partial C_j}{\partial I_\ell} \frac{\partial^2 I_\ell}{\partial m_i \partial O_k} = 0 \quad j=1, \dots, J. \end{aligned} \quad (2-A10)$$

Using the solution obtained from (2-A2) and (2-A8), the second derivatives $\frac{\partial^2 I_\ell}{\partial m_i \partial O_k}$ $\ell=1, \dots, J$, can be calculated as a solution of the linear equations (2-A10).

After completing the above four stages the desired expressions (2-A5) and (2-A6) can be calculated.

2-9. LIST OF SYMBOLS

Main Symbols

B - balance functions
 C - termination cost
 G - growth function
 g - growth due to inside conditions
 I - inside environmental conditions
 L - cost of operation
 M - operational parameters
 m - components of M
 O - outside conditions
 P - greenhouse parameters
 S - state of crop
 t - time

 α - function of state of crop
 γ - a constant
 λ - Lagrange multiplier
 δ - total cost

Subscripts

o - initial value

Superscripts

- - terminal value

Figure 2-1. Schematic representation of the greenhouse system.

Figure 2-2. The cost-of-growth function.

Figure 2-3. A discontinuity of the optimal growth rate.

Figure 2-4. A description of the method for obtaining the optimal control.

Chapter 3: SIMULATION

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3-1. INTRODUCTION

In Chapter 2, a method of optimizing greenhouse operation was laid out. In the present chapter a few examples are presented to illustrate how the Lagrange multiplier on which the method hinges is determined, and what are the resulting recommended operation levels of the various pieces of air-conditioning equipment under various meteorological conditions.

The problem posed in Chapter 2 was to minimize the following overall objective function (Equation 2-5):

$$Z(\underline{M}) = B(t') + \int_0^{t'} K(\underline{M})dt \quad (3-1)$$

subject to producing a certain size of crop. Here Z is the objective function of $\$/m^2$, B is the termination cost, which is a function of the termination time t' , K is the cost of operation of the equipment, in $\$/m^2s$, and t is time. $\underline{M}$ is a vector of the levels at which the air conditioning equipment (heater, CO_2 generator etc.) are operated. The policy of operation, $\underline{M}(t)$ should be such that $Z(\underline{M})$ be minimized.

It has further been shown that a coefficient v (a Lagrange multiplier) may be found which, when used to minimize the instantaneous objective function

$$z(\underline{M}) = K(\underline{M}) - vG(\underline{I}[\underline{O}, \underline{F}(\underline{M})]), \quad (3-2)$$

will yield the solution to (3-1). Here $G(I)$ is the growth rate of the crop under the set of inside conditions $\underline{I}$. $\underline{I}$ itself is a function of the outside conditions $\underline{O}$, the thermal properties of the greenhouse and the various fluxes, $\underline{F}$, generated by the equipment when operated at the level $\underline{M}$.

The method by which the appropriate Lagrange multiplier ν is obtained is also briefly described in Chapter 2. An initial guess of ν is used in a simulation of the growth of the crop up to the termination time, t' , determined by

$$\int_0^{t'} G(I) dt = \gamma \quad (3-3)$$

where γ is the amount of CO_2 fixed by a unit leaf area during the growing period. When the integration of Equation (3-3) reaches the value γ , the crop is ready for sale.

When the termination time is reached, the expression

$$\nu - [K(\underline{M}') + (dB/dt)'] / G(\underline{I}') \quad (3-4)$$

is tested for sign. If it is negative, ν is increased, and vice versa. Then the simulation is repeated until the expression (3-4) becomes close enough to zero. The value of ν for which (3-4) becomes zero is the optimal value of the Lagrange multiplier, which minimizes the overall objective function Z (Equation (3-1)). It should be emphasized that the optimal value of ν may vary from month to month.

Once the optimal value of ν is available, then for any given set of outside conditions $\underline{O}$, there is an optimal way of operating the air conditioning equipment, such that the instantaneous objective function z (Equation (3-2)) is minimized. Note that in general, a certain flux vector $\underline{F}$ may be produced by different vectors $\underline{M}$.

To minimize $z(\underline{M})$ it is required to know $G(\underline{I})$, $I(\underline{O}, \underline{F})$, $\underline{F}(\underline{M})$ and $K(\underline{M})$, as well as the following constraints:

- (1) Maximum values of the elements of $\underline{M}$, such as: Q_v , fan discharge per unit floor area; H_h , heat flux of hot air heater; and C_g , the flux of CO_2 from CO_2 generator.
- (2) Permissible range of the elements of $\underline{I}$, such as of T_a , the inside air temperature and of q_a , the inside specific humidity.

In the next section the various models used to construct the functions $G(I)$, $I(O,F)$, $F(M)$ and $K(M)$, are written out in detail. Note that the greenhouse function $I(O,F)$, while far from the complexity of some greenhouse models, is still rather complex relative to the other functions. The crop, which is certainly the most complex element of the system, is represented by a rather simple model $G(I)$, mainly due to ignorance. Considering this imbalance, it is suggested that in the future the greenhouse model could be further simplified, perhaps along the lines of Chapter 4.

3-2. DETAILS OF MODELS

Growth function, $G=G(I)$.

The growth function used here is essentially the function developed for the tomato crop in Chapter 5. It is of the general form

$$G = G(P_a, X_a, T_1) = f_1(P_a, X_a)f_2(T_1) + f_3(T_1) \quad (3-5)$$

where P_a is the flux of PAR (photosynthetically active radiation), X_a is the CO_2 concentration and T_1 is the leaf temperature, all inside the greenhouse. The first term on the RHS of Equation (3-5) represents the gross photosynthesis, and the second term represents the respiration. Only the seedling state of growth is considered, and it is assumed that the leaf area index is less than about 1. This seemed to justify using the growth function for a single leaf (Equations (5-28), (5-29), (5-30)):

$$G = \left[\frac{X_a - 200E-6}{250 + 90E6 X_a/P_a} \right] [1 - 0.004(T_1 - 20)^2] - 60E-9 \times 2^{(T_1 - 20)/10} \quad (3-6)$$

The range of permissible environmental conditions for the crop was set to

$$8^\circ C < T_a < 45^\circ C \quad 0.6 < R_a < 0.9 \quad (3-7)$$

The minimum temperature permissible is somewhat lower than the optimal value found in Chapter 6. The other constraining values are taken from the horticultural practice.

Greenhouse function, $I=I(0,F)$.

The greenhouse is considered to consist of 5 isothermal elements (layers): Crop canopy, inside air, inner cover, outer cover and outside air. These, as well as some of their properties and the various fluxes, are shown in Figure 3-1. The greenhouse is assumed to have an insulating floor and no heat capacity.

The greenhouse function consists of 6 simultaneous steady state conservation equations, as follows:

(1) Energy balance of canopy:

$$(P_{a1} - P_{1b}) + (N_{a1} - N_{1b}) + (L_{a1} - L_{1b}) - H_{1a} - \lambda E_{1a} = 0 \quad (3-8)$$

(2) Sensible heat balance of inside air:

$$H_{1a} + H_e - H_{ab} - H_i = 0 \quad (3-9)$$

(3) Water vapor balance of inside air:

$$E_{1a} + E_e - E_{ab} - E_i = 0 \quad (3-10)$$

(4) CO₂ balance of inside air:

$$C_e - C_{a1} - C_i = 0 \quad (3-11)$$

(5) Energy balance of inner cover:

$$(P_{tb} - P_{bt} + P_{1b} - P_{ba}) + (N_{tb} - N_{bt} + N_{1b} - N_{ba}) + (L_{tb} - L_{bt} + L_{1b} - L_{ba}) + (H_{ab} - H_{bt}) + \lambda E_{ab} = 0 \quad (3-12)$$

(6) Energy balance of outer cover:

$$(P_{ot} - P_{to} + P_{bt} - P_{tb}) + (N_{ot} - N_{to} + N_{bt} - N_{tb}) + (L_{ot} - L_{to} + L_{bt} - L_{tb}) + (H_{bt} - H_{to}) = 0 \quad (3-13)$$

The partitioning of the solar spectrum into its PAR and NIR components, namely into P and N, was made to enable easier treatment of artificial lighting.

The following should be noted:

- (1) Condensation is only permitted on the inner side of the inner cover.
- (2) To simulate a greenhouse with a single cover, the outer cover is eliminated by setting $r_{bt}=0$, $\tau_{st}=\tau_{lt}=1$.
- (3) The artificial radiation flux (from lamps) is downwards only.

Each of the fluxes used in the six conservative equations must now be written in terms of the outside conditions and the variables of the system. There is no need for initial conditions, since the system is assumed to be in a quasi-steady-state. The detailed expressions for the various fluxes can be found in the Appendix.

Equipment function, $F=F(M)$.

In the computer program, 5 different pieces of equipment are included: Hot air heater, ventilation fan, CO₂ generator, wet pad, and HID lamp. Only the first three were used in the examples presented later. Each of these pieces of equipment affects one or more of the six fluxes of which $\underline{F}$ is composed, namely P_e , N_e , L_e , H_e , E_e and C_e . A matrix relates the equipment to the fluxes:

<u>Flux</u>	<u>Symbol</u>	<u>Heater</u>	<u>Fan</u>	<u>CO₂ Generator</u>	<u>Wet Pad</u>	<u>HID Lamp</u>
PAR	$P_e =$					P_r
NIR	$N_e =$					N_r
FIR	$L_e =$					L_r
heat	$H_e =$	$H_h +$	$H_v +$	$H_g +$	$H_p +$	H_r
vapor	$E_e =$		$E_v +$	$E_g +$	E_p	
CO ₂	$C_e =$		$C_v +$	$C_g +$	C_p	

The way this matrix should be interpreted can be explained by an example. The water vapor flux entering the inside air, E_e (Figure 3-1) is the result of fluxes from three different sources - fan, CO₂ generator (when burning gas) and wet pad system.

Let us now consider only the first three pieces of equipment. The vector of operation levels becomes

$$\underline{M} = (H_h, Q_v, C_g) \quad (3-14)$$

Let us further assume that the heater is a pure convective heater, and consider two alternative sources of CO₂: bottled gas and burner. Bottled gas is assumed to produce neither heat nor water vapor, while burning gas to generate CO₂ produces both.

The various fluxes resulting of such operation can be found in the appendix.

Cost functions, $K=K(M)$ and $B=B(t)$.

The total production cost is assumed to consist of three components:

- (1) Costs which are constant, independent of length of growth period or operation of equipment (e.g. cost of seeds). These costs do not enter the optimization process.
- (2) Costs which are proportional to the time the greenhouse has been used (e.g. cost of rent, water and any operation which is not included explicitly in the optimization). These costs, which are called here fixed costs, are included in B, the termination cost, and are denoted by K_f .
- (3) Costs which are proportional to the fluxes generated by the equipment. K is the sum of these costs.

In addition to the fixed costs, the termination cost B includes also possible effects due to change of market prices for the produce, or penalty for delayed delivery. This component is not included in the examples. In other words:

it is assumed in the examples that the market price for the produce is constant with time.

The cost of operating the equipment, K , is assumed to be proportional to the fluxes generated by the equipment. For the equipment used in the examples it is

$$K_h = hH_h \quad (3-15)$$

$$K_v = vQ_v \quad (3-16)$$

$$K_g = gC_g \quad (3-17)$$

$$K = K_h + K_v + K_g \quad (3-18)$$

3-3. OPTIMAL LAGRANGE MULTIPLIER

Section 3-2 and the appendix completely describe the model, which was subsequently programmed in FORTRAN and incorporated into two main programs:

- (1) A program which searches for the optimal Lagrange multiplier for the system described by the model under a given time series of outside conditions.
- (2) A program which produces for a given Lagrange multiplier (presumably the optimal), the recommended operation set M for any given set of outside conditions I .

The particular values of the various parameters were chosen to represent a typical Israeli greenhouse, namely a 1000 m^2 area, 4 m high, single polyethylene covered structure. The crop was tomato seedlings with small leaf area index (about 1). The outside conditions, used for the determination of the optimal Lagrange multiplier, were representative of February at Bet Dagan, Israel. The data, provided by the Israel Meteorological Service, were taken once every 3 hours during the years 1972 to 1974. February data of consecutive years were added to each other to produce a time series of over 100 February days. This synthetic time series was used in the various simulations of the system. The growth (of the tomato seedlings) was continued until $\gamma = 0.8 \text{ kg/m}^2$ was reached.

Three different systems were simulated:

- (1) A greenhouse without CO₂ generation.
- (2) A greenhouse with bottled CO₂ ("cold" CO₂).
- (3) A greenhouse with CO₂ generated by burning ("hot" CO₂).

The range of Lagrange multipliers covered by the search for its optimal value was from close to zero to 18 \$m²/kgm². The results, in terms of the overall objective function (total costs), the fixed costs and the operation costs are shown in Figure 3-2.

The night time optimization with the present model is trivial: Since the plant has no memory, the night time temperature only affects the night time respiration, which is minimized by keeping the lowest permissible temperature. The day-time trade-off between expenses and increased production is more realistically represented by the model, and most of the variation in Figure 3-2 is due to day-time effects.

The figure shows three triplets of curves. The lowest triplet shows the operating expenses required to reach $\gamma = 0.8 \text{ kg/m}^2$ under the three systems considered.

The system with no CO₂ enrichment shows an almost constant value of the operating expenses. These are mainly caused by the heating required to maintain the minimum air temperature (8°C). The only piece of equipment operating during the day is the fan, which has a limited capacity and is rather inexpensive to operate. As a result, the operating expenses are hardly affected by the choice of the value of the Lagrange multiplier.

The next curve in the lower triplet is related to enrichment with "hot" CO₂. It shows that the additional expenses (for CO₂) increase roughly linearly with the Lagrange multiplier. That the cost of operation increases with the Lagrange multiplier is to be expected, since by Proposition 2 of Chapter 2, as the Lagrange multiplier increases, the termination time decreases. To achieve this reduction in time, costly environmental conditions must be provided.

The third curve in the lowest triplet is for "cold" CO₂. The cost of CO₂ from both sources was assumed to be the same. In cold climates "hot" CO₂ has an advantage over "cold" CO₂, while the reverse is true in warm climates. Under the climatic conditions of the present simulation the "hot" CO₂ adds much heat, which limits its usefulness. For any given Lagrange multiplier, about 60% more "cold" CO₂ is applied than "hot" CO₂, probably for a good reason.

The middle triplet of curves shows the fixed costs as a function of the Lagrange multiplier. The fixed costs are (by definition) proportional to the time required for growth, and can be viewed in terms of the time scale on the right of the figure. Since the termination time must decrease with increasing Lagrange multiplier, these curves decrease monotonically. The results suggest that while without CO₂ enrichment the minimum time required is about 40 days, the time can be reduced to less than half that much by applying CO₂ generously. According to Equation (3-6) G increases asymptotically with X_a , and as a result the growth time decreases asymptotically with X_a (and also with v).

The sum of the operating costs and fixed costs produces the total costs, namely the objective function Z (Equation 3-1). The values of Z , for the three cases studied, are shown by the upper triplet of Figure 3-2. Each one of the three curves has a minimum, within the range of v covered. The three minima are rather shallow, so that their exact location is not critical. The values selected from the graph are:

- (1) No CO₂ enrichment : $v = 2$
- (2) "Hot" CO₂ enrichment : $v = 7$
- (3) "Cold" CO₂ enrichment : $v = 5$

It should be stressed that the operating expenses are not necessarily monotonically increasing with v . There may be local bumps in the curves, but they do not dominate their general shape.

3-4. RECOMMENDED OPERATION.

Once the optimal Lagrange multiplier is known (for the particular case of interest), it is possible to determine, for any set of outside conditions, Q ,

the best operating levels $\underline{M}$. If $\underline{M}$ is calculated for a representative set of outside conditions, a table can be constructed, which can then be used by a micro-processor whose task is to actually control the greenhouse environment. The table is basically a 6-input, 3-output table, where the six inputs are the elements of $\underline{O}$ and the three outputs are the elements of $\underline{M}$.

From previous experience (e.g. Seginer, 1981), it is evident that the outside solar radiation, S_o , and the outside temperature, T_o , are the two most dominant outside variables. The other factors: the long-wave sky radiation, L_o , the relative humidity, R_o , the wind speed V_o and the CO_2 concentration X_o , are either well correlated with S_o and T_o , or vary within a relatively narrow range. It was therefore decided to reduce the input variables to 2 (S_o and T_o) and represent the other variables by their mean value for any given S_o and T_o .

The range of outside conditions, for which the table must be prepared, should be the range relevant to the time of year for which the optimal Lagrange multiplier was obtained. It is not clear at this point, how the optimal Lagrange multiplier changes with the seasons. The shallow minima of Figure 3-2 suggest that the exact value of the Lagrange multiplier is not critical. Since the present study deals mainly with methodology, the range of meteorological conditions for which the tables were constructed is significantly larger than that relevant to the month of February. In fact, meteorological data of 3 full years at Bet Dagan were used to obtain the representative set of outside conditions.

Figure 3-3 shows the range of day-time data for the whole year, represented by 4 K by 100 W/m^2 cells in the S_o - T_o plane. The range of February data, represented by a strip of width $\pm 3 \text{ K}$, is superimposed on the same figure. The solid curve at the center of the strip, may be viewed as the course of a typical bright February day, starting at about 12°C in the morning, and reaching $S_o = 800 \text{ W/m}^2$ and 21°C at noon. The strip around the solid line contains over 75% of the day-time February data.

The behavior of the 4 outside variables L_o , R_o , V_o , and X_o , within the annual range of S_o and T_o , is generally as follows: X_o is roughly constant at $500\text{E}-6 \text{ kg/kg}$ (330 vpm). The long-wave radiation L_o tends to

increase towards higher values of S_o and T_o . The range of values is from about 200 W/m^2 to about 350 W/m^2 . The wind speed V_o increases mainly with solar radiation. The range of the mean cell-values is from about 1 m/s to about 5 m/s . Finally, the mean cell-value of the outside relative humidity is shown in Figure 3-4, as a function of the main variable S_o and T_o . It is evident from the figure that above about $T_o=30^\circ\text{C}$, the relative humidity decreases rapidly to much below the permissible minimal humidity in the greenhouse, namely $R_o=0.6$. This is peculiar to Israeli conditions (Hamsin), and turns out to be an important factor in determining the recommended operation levels.

Tables of recommended operation levels were calculated for the three systems for which the optimal Lagrange coefficients were obtained in Section 3-3. For each set (2 inputs) of outside conditions, the following was calculated: (1) The operation levels H_h , Q_v and C_g . (2) The expected resulting inside conditions, such as P_{a1} , T_a , R_a and X_a . (3) Other physical quantities, such as T_b and C_{a1} , and (4) Various costs, such as K_h , K_v , K_g and K_f .

Figure 3-5 shows the recommended ventilation level, Q_v , for the system without CO_2 enrichment. Generally speaking, below $T_o=28^\circ\text{C}$ the ventilation level is controlled by the heating load, which is a linear combination of T_o and S_o (the so-called sol-air temperature). The ventilation rate increases roughly linearly with T_o and S_o . Above 29°C , the relative humidity, which is not permitted to increase above 0.6 inside the greenhouse, becomes the controlling factor. This constraint restricts the ventilation rate and causes an increased temperature, which in that region is much beyond the optimal temperature ($T_1=20^\circ\text{C}$, Equation 3-6). No heating is necessary during the day-time.

The expected resulting inside temperature, T_a , is shown in Figure 3-6. It is very similar to Figure 1a of Seginer (1981), especially in that it exhibits distinct patterns in the ventilated and unventilated regions. A simplified analysis, which shows why results of that general form are to be expected, can be found in Seginer (1981).

The resulting net photosynthesis is shown in terms of C_{a1} in Figure 3-7. It turns out (results not presented) that the CO_2 concentration almost never falls below $440E-6$ kg/kg (290 vpm) and therefore is not the major factor affecting the distribution of Figure 3-7. The figure shows that at low heat loads the factor controlling the net photosynthesis is the solar radiation, while at high heat loads the temperature inside the greenhouse becomes the controlling factor.

Consider now the system with "cold" (bottled) CO_2 enrichment. Figure 3-8 shows the recommended ventilation rate. The start of ventilation has moved to a much higher heat load level than without enrichment, and, except at very high heat loads, the ventilation rate is much smaller than before.

Figure 3-9 shows the expected resulting inside temperature. The features typical to the unventilated situation cover now a larger region, qualitatively similar to Figure 1b of Seginer (1981), where a "heat loving" crop was simulated. Typically the inside temperature within the February region is now about 5 K higher than without enrichment.

The rate of CO_2 enrichment is shown in Figure 3-10. It exhibits a maximum at a high solar radiation level and a low outside temperature, and a minimum at a high ventilation rate. The resulting net photosynthesis, which is shown in Figure 3-11, shows a strong dependence on the CO_2 enrichment level. The maximum net photosynthesis with enrichment is about 3 times higher than without enrichment. The difference between corresponding values of Figures 3-10 and 3-11 is the rate of CO_2 lost by ventilation (or infiltration) from the greenhouse. On the average, for the range covered by February data, 0.85 of the CO_2 supplied is not taken up by the plants.

The CO_2 concentration which is expected to exist in the greenhouse enriched with "cold" CO_2 is shown in Figure 3-12. The range of values for February operation is about 1200 to 2800 kg/kg (800 to 1800 vpm), somewhat higher than is common in commercial greenhouses.

The system with "hot" CO_2 exhibits results which are in many respects intermediate between the two other systems. The heat that accompanies the CO_2 enrichment in this system adds to the heat load and therefore, compared to

enrichment with "cold" CO₂, increases the recommended ventilation rate, reduces the CO₂ enrichment rate, and increases the inside temperature. The resulting CO₂ concentrations, shown in Figure 3-13, are generally smaller than those of Figure 3-12 ("cold" CO₂). The whole pattern of Figure 3-13 seems to be shifted towards smaller heat loads, compared to Figure 3-12. The resulting net photosynthesis is shown in Figure 3-14.

3-5. SUMMARY AND CONCLUSION

Optimal Lagrange coefficients were determined for tomato seedlings grown under Israeli conditions during February in 3 different commercial greenhouses. The greenhouses differed only with respect to their CO₂ generating equipment. The "cold" CO₂ system was found to be superior to the "hot" CO₂ system, and the latter was found to be superior to no CO₂ enrichment.

Several points should be emphasized before concluding this chapter:

(1) The main weakness of the model by which the results were generated is due to the limitations of the crop sub-model. In particular, since the night time conditions only affect the night time respiration, a minimum night temperature had to be imposed as a constraint. Otherwise no heating would be justified at night. Nevertheless, the daytime behavior seems reasonable and after refinement may serve as a guide to CO₂ enrichment.

(2) The model predicts a very significant improvement in production due to CO₂ enrichment, even in greenhouses without special cooling or energy absorbing devices. Figure 3-2 suggests a reduction of the growing time from about 40 days without CO₂ enrichment, to about 20 days with "cold" CO₂ enrichment. That, of course, does not mean reduction of the production costs to half their original level. The same Figure (3-2) shows that the total production costs decreased by only about 25% (from about 3.80 \$/m² without enrichment to about 2.85 \$/m² with "cold" CO₂). The cost of CO₂ is a significant factor, which affects the economic rate of enrichment and the net income from the whole operation.

(3) The model shows that ventilation and CO₂ enrichment are not necessarily mutually exclusive. For the month of February Figures 3-8 and 3-10 show that

both ventilation and CO₂ enrichment increases with solar radiation. The results actually suggest that enrichment could continue all day long, while ventilation at about 1/8 of full capacity is sufficient to maintain the inside air temperature below 30°C.

(4) The accuracy of the predictions, needless to say, is not very high. The results, however, are not ridiculous and probably represent correct trends. The production figures with CO₂ seem higher than encountered in practice, but are not impossible under the best of conditions. It should be remembered that the time required for a tomato seedling in a commercial nursery to reach its marketable size varies between 50 days in mid-winter to 30 days in mid-summer (Chapter 6). This is almost a two-fold increase in the rate of growth. It should also be remembered that the outside conditions encountered during February (low outside temperatures), are favorable to CO₂ enrichment, as may be seen in Figure 3-10.

In conclusion it may be said that despite important shortcomings of the model, the suggested method of optimization yields reasonable results for the effect of CO₂ enrichment. With future improvements and calibration of the model, a useful tool for optimizing the day-time greenhouse environment may become available.

3-6. REFERENCES

Seginer I. 1981. Economic greenhouse temperatures. *Acta Hort.* 115:439-452.

3-7. APPENDIX: DETAILED EXPRESSIONS FOR THE VARIOUS FLUXES.

Radiation fluxes.

It is assumed that the spectra properties of the greenhouse are constant with time (namely independent of solar angle and atmospheric turbidity).

The solar radiation is partitioned into PAR (P) and NIR (N) according to

$$P = \alpha S \quad ; \quad N = (1-\alpha)S \quad (3-A1)$$

The value of α in the simulations was 0.5.

The solution for the PAR and NIR fluxes is independent of the rest of the solution for the greenhouse environment, since none of the other variables (specifically temperatures) affects these fluxes. It is assumed that the spectral properties of the components of the greenhouse are the same for both parts of the solar spectrum. The relationships between the various solar radiation fluxes are given below in terms of S only, to save space. The actual algorithm contains two such sets of equations, one for P and one for N.

$$S_{tb} = \tau_{St} S_{ot} + \rho_{St} S_{bt} \quad (3-A2)$$

$$S_{ba} = \tau_{Sb} S_{tb} + \rho_{Sb} S_{lb} \quad (3-A3)$$

$$S_{al} = S_{ba} + S_e \quad (3-A4)$$

$$S_{lb} = \rho_{Sl} S_{al} \quad (3-A5)$$

$$S_{bt} = \tau_{Sb} S_{lb} + \rho_{Sb} S_{tb} \quad (3-A6)$$

$$S_{to} = \tau_{St} S_{bt} + \rho_{St} S_{bt} \quad (3-A7)$$

Required input: S_{ot} , S_e .

Values of parameters used in the simulations: $P_{sl}=0.1$, $P_{sb}=0.1$, $P_{st}=0$, $\tau_{sb}=0.8$, $\tau_{st}=1$.

The FIR (Far Infra-Red), or Long-wave, radiation fluxes cannot be solved separately like the solar radiation fluxes. The following equations for these

fluxes must be solved simultaneously with the conservation Equations (3-7) to (3-12). The FIR fluxes are treated one-dimensionally. This is suitable for large greenhouses.

$$L_{tb} = \tau_{Lt} L_{ot} + \rho_{Lt} L_{bt} + \epsilon_{Lt} \sigma T_t^4 \quad (3-A8)$$

$$L_{ba} = \tau_{Lb} L_{tb} + \rho_{Lb} L_{lb} + \epsilon_{Lb} \sigma T_b^4 \quad (3-A9)$$

$$L_{a1} = L_{ba} - L_e \quad (3-A10)$$

$$L_{lb} = \rho_{L1} L_{a1} + \epsilon_{LR} \sigma T_4 \quad (3-A11)$$

$$L_{bt} = \tau_{Lb} L_{lb} + \rho_{Lb} L_{tb} + \epsilon_{Lb} \sigma T_b^4 \quad (3-A12)$$

$$L_{to} = \tau_{Lt} L_{bt} + \rho_{Lt} L_{ot} + \epsilon_{Lt} \sigma T_t^4 \quad (3-A13)$$

for completeness:

$$\rho_L + \tau_L + \epsilon_L = 1 \quad (3-A14)$$

Required input: L_{ot} , L_e .

Values of parameters used in the simulation: $\rho_{L1}=0$, $\rho_{Lt}=0$, $\rho_{Lb}=0.1$, $\tau_{Lt}=1.0$, $\tau_{Lb}=0$.

Convective fluxes.

Sensible heat (except by infiltration)

$$H_{to} = \rho c (T_t - T_o) / r_{to} \quad (3-A15)$$

$$H_{bt} = \rho c (T_b - T_t) / r_{bt} \quad (3-A16)$$

$$H_{ab} = \rho c (T_a - T_b) / r_{ab} \quad (3-A17)$$

$$H_{la} = \rho c (T_1 - T_a) / r_{la} \quad (3-A18)$$

Water vapor (except by infiltration)

$$E_{ab} = \rho (q_a - \hat{q}_b) / r_{ab} \quad \text{when } q_a > \hat{q}_b \quad (3-A19)$$

$$E_{ab} = 0 \quad \text{otherwise (dry cover)} \quad (3-A20)$$

$$E_{la} = \rho (\hat{q}_1 - q_a) / (r_{la} + r_s) \quad \text{when } \hat{q}_1 > q_a \text{ and leaves dry} \quad (3-A21)$$

$$E_{la} = \rho (\hat{q}_1 - q_a) / r_{la} \quad \text{otherwise} \quad (3-A22)$$

The values of the various resistances as used in the simulation are:

$$r_{to} = \rho c / [(2.6 + 4.0 V_o) m] \quad (3-A23)$$

$$r_{bt} = 0 \quad (3-A24)$$

$$r_{ab} = \rho c / (2.6 m) \quad (3-25)$$

$$r_{la} = \rho c / [20(\Lambda + 1)] \quad (3-A26)$$

$$r_s = 20000 / [(P_{a1} + 10)\Lambda] \quad (3-A27)$$

$$\Lambda = 1 \quad m = 1.6 \quad (3-A28)$$

Infiltration

$$H_i = \rho c Q_i (T_a - T_o) \quad (3-A29)$$

$$E_i = \rho Q_i (q_a - q_o) \quad (3-A30)$$

$$C_i = \rho Q_i (X_a - X_o) \quad (3-A31)$$

$$Q_i = (0.5E-3 + 0.3E-3 V_o) m \quad (3-A32)$$

Equipment

$$H_v = \rho c Q_v (T_o - T_a) \quad (3-A33)$$

$$E_v = \rho Q_v (q_o - q_a) \quad (3-A34)$$

$$C_v = \rho Q_v (X_o - X_a) \quad (3-A35)$$

for bottled CO₂

$$H_g = E_g = 0 \quad (3-A36)$$

for CO₂ generated by burning gas

$$H_g = 0.190E8 C_g \quad (3-A37)$$

$$E_g = 0.8182 C_g \quad (3-A38)$$

constraints

$$\text{Maximum ventilation rate: } Q_v = 0.08 \text{ m}^3/\text{m}^2\text{s.} \quad (3-A39)$$

Costs

h	$= 9.8E-9 \text{ \$}/J$	(3-A40)
v	$= 2.0E-6 \text{ \$}/m^3$	(3-A41)
g	$= 0.2 \text{ \$}/kg$	(3-A42)
K_f	$= 0.9E-6 \text{ \$}/m^2s$	(3-A43)

3.8 LIST OF SYMBOLS

Main symbols

a	- heating efficiency of solar radiation	-
B	- termination cost	$\text{\$/m}^2$
C	- CO_2 flux	kg/m^2s
c	- thermal capacity of air at constant pressure	J/kgK
E	- water vapor flux	kg/m^2s
F	- fluxes due to operation of equipment	*
f	- a function	*
G	- growth function	$kg[CO_2]/m^2[leaf]s$
g	- cost of CO_2	$\text{\$/kg}[CO_2]$
H	- sensible heat flux	W/m^2
h	- cost of energy for heating	$\text{\$/J}$
I	- inside climatic conditions	*
K	- cost of operating the air-conditioning equipment	$\text{\$/m}^2s$
L	- far infra-red (FIR, long-wave) radiation flux	W/m^2
M	- discharges of air conditioning equipment	*
m	- cover/floor area ratio	-
N	- near infra-red (NIR, part of solar) radiation flux	W/m^2
O	- outside climatic conditions	*
P	- photosynthetically active radiation (PAR) flux	W/m^2
Q	- air flow rate through greenhouse	m^3/m^2s
q	- specific humidity	$kg[H_2O]/kg[air]$
R	- relative humidity	-
r	- convective resistance	s/m
S	- solar radiation flux ($S=P+N$)	W/m^2

T - temperature	K
t - time	s
U - overall transfer coefficient	W/m^2K
V - wind speed	m/s
v - cost of energy for ventilation	$\$/m^3$
X - CO ₂ concentration	kg[CO ₂]/kg[air]
Z - overall objective function	$\$/m^2$
z - objective function for given instant	$\$/m^2[floor]s$
α - ratio of PAR to solar radiation	-
γ - CO ₂ fixed by unit leaf area during growing period	kg[CO ₂]/m ²
ϵ - emissivity	-
Λ - leaf area index (leaf/floor ratio)	-
λ - latent heat of vaporization of water	J/kg
ν - Lagrange multiplier	$\$/m^2[leaf]/kgm^2[floor]$
ρ - reflectivity (when with subscripts S or L)	-
ρ - air density (when without subscript)	kg/m ³
σ - Stefan-Boltzmann's constant	W/m^2k^4
τ - transmissivity	-

- notes: (1) fluxes are calculated per unit floor area, unless indicated otherwise.
- (2) - indicates dimensionless quantities.
- (3) _ indicates a vector.
- (4) * indicates that dimensions are different for the different items (elements) represented by the symbol (vector).

Subscripts

- a - inside air
- b - lower (inside) cover of greenhouse
- s - crop canopy (including floor)
- e - due to operation of equipment
- f - fixed (costs)
- i - infiltration
- L - long-wave
- l - leaf, canopy

o - outside (above) greenhouse
p - wet pad
r - HID lamps
S - short-wave (solar)
t - upper (outside) cover of greenhouse

Superscripts

^ - at saturation
' - at termination time

Note: Double subscripts on fluxes should be interpreted as follows:

from first subscript to second subscript

Figure 3-1. Schematic representation of the greenhouse model, defining the various fluxes. Arrows indicate positive direction of fluxes. Circles indicate sources of fluxes due to operation of air-conditioning equipment.

Figure 3-2. Operating costs, fixed costs and total costs to produce a total growth of $\gamma = 0.8 \text{ kg/m}^2$ for a range of Lagrange multipliers. Results for three systems are shown: (1) Without CO₂ enrichment. (2) With "hot" CO₂ enrichment. (3) With "cold" (bottled) CO₂ enrichment. Arrows indicate the location of the optimal Lagrange multipliers.

Figure 3-3. Ranges of annual and February day-time meteorological conditions at Bet-Dagen, Israel. Frequency of occurrence, on an annual basis (out of a total 3230 day-time observations) is indicated by size of circles. The strip covers 75% of all day-time February data.

Figure 3-4. Mean value of outside relative humidity as a function of outside solar radiation, S_o , and temperature T_o .

Figure 3-5. Recommended ventilation rate, Q_v , as a function of outside solar radiation and temperature for the system without CO₂ enrichment. Ventilation rate is in m³/m²[floor]s.

Figure 3-6. Expected inside temperature, T_a , as a result of the recommended ventilation rate for the system without CO_2 enrichment. Temperature is in $^{\circ}C$.

Figure 3-7. Expected net-photosynthesis rate, C_{al} , for the system without CO_2 enrichment. Net-photosynthesis is in $\text{kg}[\text{CO}_2]/\text{m}^2[\text{floor}]_s$.

Figure 3-8. Recommended ventilation rate, Q_v , for the system with "cold" CO_2 enrichment.
 Q_v is in $\text{m}^3/\text{m}^2[\text{floor}]\text{s}$.

Figure 3-9. Expected inside temperature, T_a , for the system with "cold" CO_2 enrichment. T_a is in $^{\circ}\text{C}$.

Figure 3-10. Rate of CO₂ enrichment, C_g , in the system with "cold" CO₂. C_g is in $\text{kg}[\text{CO}_2]/\text{m}^2[\text{floor}]\text{s}$.

Figure 3-11. Expected net-photosynthesis rate, C_{al} , for the system with "cold" CO_2 enrichment. C_{al} is in $kg[CO_2]/m^2[floor]s$.

Figure 3-12. Expected CO_2 concentration, X_a , for the system with "cold" CO_2 enrichment. X_a is in $kg[CO_2]/kg[air]$.

Figure 3-13. Expected CO_2 concentration, X_a for the system with "hot" CO_2 enrichment. X_a is in $kg[CO_2]/kg[air]$.

Figure 3-14. Expected net-photosynthesis rate, C_{al} , for the system with "hot" CO_2 enrichment. C_{al} is in $kg[CO_2]/m^2[hour]$.

Chapter 4: IN-SITU THERMAL CALIBRATION OF UNVENTILATED GREENHOUSES

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4-1. INTRODUCTION

It can be desirable to determine the thermal characteristics of existing greenhouses on the basis of measurements made in-situ. As digital control of greenhouse environment becomes more widely adopted, and control becomes more sophisticated, it would be preferable to base control on continuously updated estimates of thermal parameters as the seasons and crop characteristics change. Examples of in-situ determinations are studies by Bailey and Cotton (1980) and Garzoli and Blackwell (1981).

The greenhouse thermal parameters estimated most frequently are: the overall heat transfer coefficient, U ; and the transmissivity of the greenhouse cover to solar radiation, τ . Each is defined in terms of the measurements employed for its evaluation, as follows:

$$U = H / (T_i - T_o) \quad (4-1)$$

$$\tau = S_d / S_o \quad (4-2)$$

where symbols are defined in the list of symbols.

Neither U nor τ is constant. The value of U for a single-glazed greenhouse is significantly affected by wind, as indicated by Bailey (1975):

$$U_c = 5.0 + 0.5 V \quad (4-3)$$

The value of τ is known to vary with solar azimuth and altitude, and with the quality of light, whether beam or diffuse (e.g., Kozai and Kimura, 1977).

Another, less common, parameter was used by Bailey (1977) to express the portion of solar radiation falling on a greenhouse which is effective in heating the greenhouse. It may be defined by the following steady-state energy balance:

$$H + \alpha S_0 = U (T_i - T_o) \quad (4-4)$$

where α is the solar heating efficiency. There is a computational indication (Seginer, 1981) that α decreases with increasing inside temperature (perhaps at a rate of 0.01/K), as is expected of solar collector efficiency (e.g., Kreith and Kreider, 1971, p. 221). It is also expected that α is proportional to τ , which is itself not constant. Duncan, et al. (1981) suggest

$$\alpha = \tau \eta \quad (4-5)$$

where η is the absorptivity of the greenhouse floor to solar radiation. Bailey (1977) did not include in α all the solar energy absorbed in the greenhouse. By subtracting the energy transformed into latent heat (and also due to other differences) he arrived at a considerably lower value (0.32) than did Duncan, et al. (1981) (0.65).

The direct way to evaluate parameters of this kind is to extract them from experimental data collected specifically for that purpose. As will be shown later, there may be a large discrepancy between the value of a parameter calculated through its "intuitive" (definitional) meaning, and the "effective" value of that parameter extracted from experiments according to a specific model.

The problems of non-constant parameters, and the discrepancies between intuitive and effective values of the parameters, stem from our attempts to describe complex phenomena by simple models. However, because simple and therefore approximate models have many uses, it is important to devise the best approximation and then be aware of the limits of usefulness of any given model.

In recent years, detailed models have been widely published in scientific greenhouse literature (Takakura, et al., 1971; Soribe and Curry, 1973; Kimball, 1973; Froehlich, et al., 1979; Chandra, et al., 1981; Duncan, et al., 1981; Kimball, 1981). Despite being very different from each other, most were reported to perform satisfactorily when tested against measured temperatures. Inside air, leaf, and greenhouse cover temperatures were predicted to within 1 to 3°C. A review of the literature indicates that not only do models of

different forms provide similar prediction accuracy, but also that models may not be too sensitive to the magnitudes of certain of their parameters. This is sometimes surprising, but perhaps it is a hint that the reverse route; namely, experimental extraction of some model parameters, may not be a trivial task.

Usually parameters such as U , τ and α are extracted from data collected during only part of the diurnal cycle. The value of U is found from nighttime data (Equation 4-1) while τ and α (Equations 4-2 and 4-4) are estimated using daytime data. To estimate α requires previous knowledge of U .

In this study, an attempt was made to develop a greenhouse thermal calibration method which extracts several parameters simultaneously from all the available data. The method, based on linear regression analysis, is similar to the methods used by Seginer and Albright (1981) and Pryor and Winn (1982) for similar problems. A four parameter greenhouse thermal model is proposed, and the four parameters are estimated simultaneously using linear regression. A fifth parameter, important in describing the effect of the thermal mass, is also obtained. Usefulness of the model is discussed.

4-2. ANALYSIS

Greenhouse Energy Balance

A simple, time-dependent, thermal model of a greenhouse (shown in Figure 4-1) is used, similar to the energy balance used by Udink ten Cate (1983). The model is quite simple, but time-dependency of the thermal response is considered through a thermal mass effect. The thermal mass is treated in the simplest way -- as a lumped parameter rather than a distributed one.

An energy balance, considering the air inside the greenhouse as the control volume, yields the following:

$$H + h (T_m - T_i) - U(T_i - T_o) = 0 \quad (4-6)$$

The thermal mass is a separate component of the greenhouse thermal system. It absorbs solar energy, exchanges energy with the greenhouse air by convection, and can store and release heat. It is comprised to a large extent of the

greenhouse floor, but also includes all other elements in the greenhouse except the air. An energy balance considering the mass as the control volume is as follows:

$$\alpha S_o - h (T_m - T_i) - C \frac{dT_m}{dt} - R = 0 \quad (4-7)$$

The overall greenhouse energy balance is the sum of Equations 4-6 and 4-7.

$$H + \alpha S_o - U(T_i - T_o) - C \frac{dT_m}{dt} - R = 0 \quad (4-8)$$

The term R may be interpreted as an additional radiation heat loss factor. It is included to be consistent with the observation that in a steady-state situation at night with no heating, greenhouses have been observed to cool below the outside air temperature by as much as 5 K in a dry greenhouse under a clear sky. The cause is thought to be radiation to the sky. In such a case

$$T_i - T_o = R/U \quad (4-9)$$

Sinusoidal Forcing Functions

If the heat storage term were not present in Equation (4-8), a plot of $T_i - T_o$ against S_o , when the heater is off, would result in a straight line. Points obtained during the morning hours would overlap points obtained during the afternoon. The presence of the storage term creates loops on the $T_i - T_o$ vs S_o plane, such that morning values of $T_i - T_o$ are smaller than the corresponding afternoon values (Figure 4-6).

To explore the effect of the heat capacity of the thermal mass on the width of the hysteresis loop just described, Equations 4-6 and 4-7 were subjected to sinusoidal forcing functions (similar to Seginer and Levav, 1971; Kowalczewski, 1962; Koppe and Stoffers, 1967). For simplicity it was assumed that $R = 0$.

Two sinusoidal forcing functions are assumed

$$S_o = A + B \sin (\omega t) \quad (4-10)$$

and

$$T_o = D + E \sin (\omega t - g_o) \quad (4-11)$$

The outside temperature lags behind the outside solar radiation by g_o . Equation 10 is the least realistic assumption in the model, since the daily cycle of the solar radiation, being a truncated sinusoidal wave, requires more than one harmonic for even an approximate description.

The solution for the inside and floor temperatures is of the form

$$T_i = F + G \sin (\omega t - g_i) \quad (4-12)$$

and

$$T_m = I + J \sin (\omega t - g_m) \quad (4-13)$$

The width of the loop, W , is given by

$$W = (T_i - T_o)_{\omega t = \pi} - (T_i - T_o)_{\omega t = 0} = 2(G \sin g_i - E \sin g_o) \quad (4-14)$$

As the heat capacity of the floor, C , increases, the amplitude G decreases, while the phase shift g , increases. As a result, W reaches a maximum for an intermediate value of C . (Solutions for G and g_i , as well as for T_i and T_m are in Appendix 4-A.) An example showing the variation of W with C , for a set of input values not too different from those observed in the present study, is shown in Figure 4-7.

Frequency Response Analysis

To further explore the possible importance of the thermal mass, Equations 4-6 and 4-7 are manipulated to yield

$$(T_m - T_e) + \theta \, dT_m/dt = 0 \quad (4-15)$$

where

$$T_e \equiv (T_o + H/U) + \frac{h + U}{hU} (\alpha S_o - R) \quad (4-16)$$

$$\theta \equiv C(h + U)/hU \quad (4-17)$$

T_e is a forcing function with temperature units. It approaches the conventional sol-air temperature as R and H approach zero, and h approaches infinity. θ is the time constant of the first order system described by Equation 4-15.

The standard frequency response solution of Equation 4-15 is

$$\frac{|T_m|}{|T_e|} e^{i\phi} = \frac{1}{1 + i\omega\theta} \quad (4-18)$$

where $|T_m|$ and $|T_e|$ are the amplitudes of the temperature of the thermal mass and of the forcing temperature, respectively, when expressed as circular functions. The right hand side of Equation 4-18 is the transfer function of the thermal system.

When the amplitude ratio is graphed as a Bode diagram (Figure 4-2), the breakpoint of the low frequency and high frequency asymptotes is at $\omega\theta = 1$. Along the low-frequency asymptote, away from the breakpoint, the thermal mass temperature follows the forcing temperature very closely, indicating that thermal capacity effects are insignificant. In this region one cannot expect to be able to determine the value of C by in-situ measurements. Along the high-frequency asymptote, away from the breakpoint, the thermal mass temperature responds very little to the forcing temperature. In this region the thermal mass effect is significant, but the thermal mass temperature signal-to-noise ratio is so small, that an accurate determination of C is unlikely.

Let us now estimate the location of the daily weather cycle on the Bode diagram of a typical greenhouse.

If the floor is the major thermal mass in the greenhouse, one would expect that $hU/(h + U)$ would be of the order of $5 \text{ W/m}^2\text{K}$. Next it can be shown that the net amount of heat stored in a homogeneous soil during one (daily) cycle is

$$Q = 2T_A \sqrt{k_s \rho_s C_s / \omega} \quad (4-19)$$

where ρ_s , C_s , and k_s , are the density, specific heat and thermal conductivity, respectively, of the soil, and T_A is the temperature amplitude at the soil surface. Dividing through by $2T_A$, an estimate of C may be obtained. Based on typical values of moist-soil parameters, (Hillel, 1982) $C = Q/2T_A$ is found to be about 100 to 250 kJ/m² K. The expected time constant of the greenhouse is therefore, by Equation 4-17, about 6 to 14 hours. Forcing such a system with a daily cycle would correspond to a normalized frequency between about 1.5 and 3.6. These points are near the breakpoint on the Bode diagram. The expected amplitude ratio under these circumstances is between 0.6 and 0.3.

The estimated location on the Bode diagram suggests: (1) thermal mass effects may be important and should be considered, and (2) a value to represent C may be obtainable from in-situ measurements.

4-3. EXPERIMENTAL PROCEDURE

Facilities

Data to estimate parameters of the simple greenhouse thermal model were obtained at Technion, in Israel, and at Cornell University in the United States. At each research station, data were obtained in greenhouses representative of the type of commercial greenhouses used in that region. In Figure 4-3 is a sketch of the small greenhouse used for the experiments at Technion. Its semi-circular cross-section is typical of "high tunnels" in which winter vegetables are grown in Israel. Its limited length resulted in a high cover-to-floor ratio ($m = 2.48$). The floor was insulated by 0.1 m of polystyrene foam, and a single layer of 0.2 mm (8 mil) polyethylene covered the greenhouse. There were no openings except for the door, and the structure was kept as tight as possible during the experiments. No direct measurements of air infiltration rates were made during the experiments, but later measurements indicated air exchange rates between 0.5/h at night to 2/h at mid-day. The very high mid-day greenhouse temperatures exaggerated the natural ventilation effect.

The measuring instruments consisted of:

- (1) 6 aspirated, locally fabricated psychrometers, 4 inside the greenhouse and 2 outside.
- (2) 3 fine thermocouples taped to the cover from the inside, and 2 taped to the floor.
- (3) 2 pyranometers (solarimeters) and 2 pyradiometers (net radiometers with adapters) facing upwards, one pair inside and one outside.
- (4) Wind speed measured 3 m above the ground at a location approximately 100 m away from the greenhouse.
- (5) Wind direction measured atop a nearby building.

In Figure 4-4 is shown a sketch of the greenhouse used for the experiments at Cornell University. It was a free-standing, aluminum-framed, structure covered with air-inflated double polyethylene (0.15 mm, or 6 mil), and was a module of a standard, gutter-connected commercial greenhouse range. Sidewalls were 2.4 m high, with the ridge oriented east-west. The north wall and the entire perimeter up to a height of 0.6 m were insulated with 50 mm of polystyrene foam boards.

The measuring instruments consisted of:

- (1) An aspirated, locally fabricated, psychrometer.
- (2) Two fine thermocouples taped to the inside of the inner cover, and 6 buried just below the floor surface.
- (3) One pyranometer inside, facing upward.
- (4) Six shielded thermocouples to measure inside air temperature, and one to measure outside air temperature.

Air exchange was not measured, but being a double-polyethylene structure, it was quite low. The structure had previously been pressure tested with a

blower door. With a negative pressure of 57 Pa, $0.40 \text{ m}^3/\text{s}$ (4.5/h) of air infiltration was measured. At a positive pressure of 60 Pa, $0.36 \text{ m}^3/\text{s}$ (4.1/h) of air exfiltrated from the structure. These data, however, were not correlated with natural air exchange rates.

Transmissivity of the greenhouse structure had been measured previously as approximately 0.56 overall. However, analysis for thermal calibration was based on the solar radiation sensed by the pyranometer, which was inside the greenhouse.

Procedures

The main body of the experiment at Technion consisted of four runs, numbered 104 to 107, which lasted for two days each. Numbers 104 and 107 were with a dry floor. For the other two, a film of polyethylene was laid on the floor, lifted at the edges and taped to the inside walls, and used as a basin for water. There was no vegetation in the greenhouse during the experiments, for no greenhouse crop would survive the extreme temperatures which developed. The experiments were conducted during summer 1981 and the greenhouse air temperature reached almost 60°C at noon in the dry greenhouse.

The greenhouse was not ventilated because extreme variations were deemed necessary to enable a rigorous check on the greenhouse model. To provide as wide a range of conditions as possible, two electric convective heaters, each of approximately 2 kW, were installed and operated during one of the two nights of each experimental run. The heaters, with attached perforated sleeves, were in contact with the floor for run 104, but were suspended above the floor for the rest of the runs.

Dust, which accumulated on the cover during the summer, was thoroughly washed away between runs 105 and 106. As a result, one dry run and one wet run were carried out with a dirty cover and one of each with a clean cover.

Data at Cornell University was collected over a period of several weeks in late winter. All data were recorded on a continuing basis in connection with other greenhouse research. The thermal calibration data were taken from the larger data base for days and times when

- (1) The thermal screen in the greenhouse was not operated at night, and
- (2) The greenhouse was not vented.

A crop of chrysanthemums was grown in the pots on benches (benching ratio of approximately 0.6) and cared for using standard greenhouse practices. Standard greenhouse temperature blueprints were observed. Heat was provided by a forced-air, electric heater.

4-4. RESULTS AND DISCUSSION

Radiative Properties

One consideration of great importance in a greenhouse thermal model is the presence of water condensing on the greenhouse cover. Condensate scatters incoming solar radiation, and acts as an absorber and radiator of long-wave thermal energy. In Figure 4-5 are shown two examples of solar and long-wave radiation fluxes outside and inside the Technion greenhouse.

There was little qualitative difference between the outside conditions of the two runs. During the dry run the cover was practically dry throughout, while during the wet run the inside of the cover was wet with heavy drops at all times.

Interestingly, the transmissivity to solar radiation was hardly affected by the condensate. The mean transmissivity was 0.82 during the dry run and 0.81 during the wet run. It was fairly constant during the day, with slightly lower values during early morning and late afternoon. The observed values are high relative to common results from commercial greenhouses ($\tau = 0.65$), where structural elements absorb and reflect about 15% of the incoming radiation (Edwards & Lake, 1965). The solar absorptivity, η , of the floor was measured separately and found to be 0.80.

To evaluate the apparent emissivity of the cover to long-wave radiation, the following formula was used

$$\epsilon_c = (L_d - L_o) / (\sigma T_c^4 - L_o) \quad (4-20)$$

Equation 4-20 was developed on the assumption that the reflectivity of the cover to long-wave radiation was negligible.

It was observed that the emissivity was very different between runs. During the dry run the result was $\epsilon_c = 0.55$, based on Equation 4-20, and during the wet run ϵ_c was 1.1. Obviously the true emissivity cannot be greater than 1, but even considering the somewhat inaccurate measurements of long-wave radiation and cover temperature, the difference between the dry and wet cover is large. The wet cover was (at least at night) practically opaque to long-wave radiation, while the dry cover had only about half the emissivity of a black body. This casts some doubt on the claim that polyethylene films significantly increase the energy loss by radiation compared to glass. If the greenhouse is tight and the cover is condensate covered, the difference between glass and polyethylene may not be very large.

Temperature Difference vs. Solar Insolation Relationships

In Figure 4-6 is shown the variation of $T_i - T_o$ with solar radiation for the same experiments at Technion. Well-defined (counterclockwise) loops are evident, indicating a significant heat capacity of the system. The heat capacity effect of the water layer in the wet greenhouse was to be expected, but surprisingly, the width of the dry run loop, in terms of $T_i - T_o$, was similar to that of the wet run loop. This means a quasi-steady state model of the greenhouse (neglecting heat capacity), could not predict properly the thermal behavior of either greenhouse configuration. The two loops differ mainly in the slope of their major axes. The slope of the loop for the dry greenhouse is much steeper as a result of the much larger temperature amplitude inside the greenhouse. It should be noted that both loops exhibit a slight upwards convex curvature. This may be the result of decreasing solar heating efficiency with increasing $T_i - T_o$ (Kreith and Kreider, 1978). Comparison of Figure 4-6 with Figure 4-7 suggests perhaps the wet and dry greenhouses were on opposite slopes of the W versus C curve. Real greenhouses may well be represented by intermediate C values, so that if not ventilated, may exhibit a wide loop.

If greenhouses are ventilated, the greater constancy of temperature may make passive thermal storage effects less noticeable. Some evidence for this was seen in data taken in the Cornell greenhouse. Data from a wide range of

weather conditions (winter and summer) were compiled, and are graphed in Figure 4-8. The data which are plotted are whether or not the vents were open with that combination of temperature difference and insolation. If there is no thermal mass effect, the regions of "vent" and "no vent" should be well delineated. If there is a significant thermal mass effect, there should be a substantial overlap of the two conditions. The boundary lines drawn on the two figures are the theoretical lines based on a steady-state analysis (Equation 4-4):

$$T_i - T_o = \frac{\alpha}{mU_c} S_o \quad (4-21)$$

For conditions of increasing insolation, there are many points where the greenhouse was not vented, although the steady-state analysis predicted it should be. This can be attributed to the effect of the thermal mass as it warmed and acted as an energy sink. When solar energy was decreasing, there were fewer instances of not venting when venting might be expected.

Of interest in Figure 4-8 is the way the greenhouse vents were essentially never open when steady-state analysis predicted them to be closed. This may indicate the release of stored energy from the thermal mass (a convective process) was significantly slower than the rate of loading into storage (a radiative process).

Linear Regression Analysis

The major effort of this work was to extract the coefficients of Equation 4-8 by means of linear regression. Data from both the Technion and the Cornell greenhouses were analyzed, although independently because of the differences between the greenhouses.

Data from four Technion experimental runs (a total of 8 days) were analyzed separately for each run. Results of the linear regression (with H as the dependent variable) are in Table 4-1.

Data from nine days in the Cornell experiment were analyzed. Those results are in Table 4-2, with the data first analyzed day-by-day, and then as a combined data set. Because the solar data at Cornell were taken inside the

greenhouse, α was not estimated directly. The coefficient of S_d , as determined by regression, was multiplied by the time-averaged transmissivity of the greenhouse ($\tau = 0.56$, as measured separately) to yield the values of α presented in Table 4-2.

Comparing the results in Tables 4-1 and 4-2 shows there was reasonable agreement among the estimates based on the Technion data, but not among the Cornell data. The difference is proposed to result from the conditions under which the two sets of data were obtained. In the Technion experiments, where there were no plants in the greenhouse each run contained a very wide spread of the independent variables of temperature and solar insolation. In addition, the heater was operated for part of the time to reduce the correlation between the temperature difference and the solar insolation. In the Cornell experiments, many days showed little variation of temperature, and some of the days were very cloudy, with snow. When the Cornell data were considered as a single set, the ranges of insolation and temperature differences were greatly expanded, with data spread fairly uniformly over the range of each independent variable.

The success of the regression model in explaining the variation of the observed data may be expressed by the residual variation about the regression surface. Table 4-1 shows the standard deviation and the residual variation to be 1 to 2 K. This compares favorably with results of others, especially in terms of the ratio of the standard deviation to the temperature amplitude.

Transfer Coefficient, U

The mean transfer coefficient (U) of the wet runs at Technion (Table 4-1) was 28% higher than that of the dry runs. This increase is probably due to two mechanisms related to evaporation in the wet greenhouse: 1. enhanced energy exchange between the floor and the cover by means of an evaporation-condensation cycle, and 2. leakage of water vapor (i.e. latent heat) from the greenhouse due to infiltration. These processes are qualitatively the same as those discussed theoretically by Seginer (1981), except that here the values of U are averages over the whole day and therefore should not be compared directly with night estimates. The increase in U due to evaporation, as obtained in the present study, lies between the bounds set by theoretical predictions: 12% for a hermetically sealed greenhouse and 60% for a

critically ventilated greenhouse. An order of magnitude calculation shows the observed difference of 28% may be explained by assuming an infiltration rate of 1 air change per hour, well within the above mentioned range (0.5/h to 2/h).

The values of U in Table 4-1 are per unit floor area. To find values of U_c , the heat transfer per unit cover area, U must be divided by the cover-to-floor area ratio, m . Since $m = 2.48$, the mean results for the dry and wet greenhouses become $U_c = 4.8$ and $6.1 \text{ W/m}^2\text{K}$, respectively. The result for the wet greenhouse compares favorably with Bailey's (1975) results for a single-layer cover, considering the mean wind speed of 2 m/s. It should be remembered, however, that Bailey's numbers refer to nighttime only.

The values of U in Table 4-2 are also per unit floor area. The cover-to-floor area ratio, m , was 2.2, and the north wall of the greenhouse was insulated with 50 mm of polystyrene. When these adjustments are made, the U_c value is $4.2 \text{ W/m}^2\text{K}$. The accepted standard value of the heat loss coefficient for a double plastic greenhouse is $4.0 \text{ W/m}^2\text{K}$ (e.g., ASAE, 1983), which does not include infiltration heat loss. The agreement is an indication the linear regression procedure yields accurate results if the data set is adequate.

The Cornell data were divided into night and day values, and separate regressions were obtained from the two data subsets. The day value of U was $7.3 \text{ W/m}^2\text{K}$, and the night value was 8.6 . The difference was statistically significant at the 95 percent level. The difference did not seem correlated to wind or precipitation. A possible explanation can evolve by considering daytime absorption of solar energy in the cover. As a rough approximation, each layer of polyethylene absorbs ten percent of the solar insolation. This absorption is a heat source within the cover, a source which acts to retard heat loss from the greenhouse air to the inside surface of the cover. Because the conductance was estimated based on air temperature difference, and the cover temperature was not considered, the regression procedure interpreted the effect as a reduced value of conductance.

Solar Heating Efficiency α

The values of α determined in the Technion greenhouses all were within the range of 0.40 to 0.45. There was little difference between the dry and wet

runs, which is another indication that condensation on the greenhouse cover had little effect on the cover's transmissivity. When $\alpha = 0.41$ from regression is compared with $\tau\eta = 0.80 \times 0.8 = 0.64$ (Equation 4-5), a discrepancy of about 50% becomes apparent. The mean value of α determined at Cornell is 0.34, somewhat lower than the value at Technion. This may be ascribed to the higher transmissivity of the Technion greenhouse cover.

The present approach to α is more similar to that of Duncan, et al. (1981) than to that of Bailey (1977). The heaters and the sun are considered as alternative sources of energy. That energy may be eventually partitioned between sensible and latent heat, but this does not affect the equivalence of energy, from the two sources as far as air heating is concerned.

Radiation Correction, R

It is clear from Table 4-1 that the value of R is higher for the dry runs than for the wet runs. This is another indication the long-wave thermal transmissivity of a plastic greenhouse cover is very different when dry than when covered with condensate. In a wet (or functioning commercial) greenhouse the radiative loss term is likely to be small, and for some purposes may be neglected. The data in Table 4-2 confirm the relative unimportance of R. Although there is a large discrepancy in the daily values, the combined average is equivalent to the outside air temperature being approximately 1 degree colder ($10 \text{ W/m}^2 \div 8 \text{ W/m}^2\text{K}$).

Thermal Capacitance, C

The last parameter is C, the effective thermal capacitance of the thermal mass. Intuitively, in the Technion experiments, it should equal the heat capacitance of the water layer plus some contribution from the structure. The heat capacitance of the water is

$$C_w = \rho_w c_w \delta \quad (4-22)$$

In Figure 4-9 the values of C (from regression) were plotted against the values of c_w (Equation 4-22), showing good correlation. The slope of the

line, however, is only 0.33, indicating the water was less effective in heating the greenhouse air than expected.

Time Constant, θ

The estimates of C , h and U can now be combined according to Equation 4-17 to yield estimates of θ . The results are shown in tables 4-1 and 4-2. The time constant of the dry Technion greenhouse is about 40 minutes; the time constant of the wet greenhouse is somewhere between 4 and 5 hours. The time constant of the Cornell greenhouse is also about 4 hours. The latter values are probably representative of commercial greenhouses.

If θ is about 4 to 5 hours, then $\omega\theta$ based on the daily cycle is about 1.0 to 1.3, just to the right of the breakpoint on the Bode diagram (Figure 4-2).

4-5. SUMMARY AND CONCLUSIONS

A method to characterize the main thermal properties of a greenhouse in-situ has been presented. The method, based on simple energy balances and linear regression, was applied to a small experimental greenhouse at Technion, and to a slightly larger greenhouse at Cornell. Four parameters, U , α , C and R were used to characterize the greenhouse, each representing a certain property of the structure: convective loss, solar heating, heat capacitance, and a long-wave radiation correction. A fifth parameter, h , characterizes thermal coupling between thermal mass in a greenhouse and the greenhouse air.

The most important conclusions that may be drawn from the thermal calibration study are:

- (1) An unventilated greenhouse can be characterized sufficiently well by 4 thermal parameters, U , α , C , R . R may be disregarded in commercial greenhouses without incurring a serious loss of accuracy. The parameters can be estimated from a test period of a few days with continuous measurements of T_o , T_i , T_f , S and H .
- (2) Regression analysis can be used to obtain simultaneous estimates of greenhouse thermal parameters in-situ. However, it is essential to have

a wide range of the independent variables with little or no correlation among them if regression is to provide meaningful results.

- (3) Analysis of the simple model using frequency-analysis techniques shows, for the 24-hour diurnal cycle, thermal mass effects can be significant in a commercial greenhouse. The significance is greater when night insulation is used to reduce night heating needs to roughly the order of magnitude of the passive thermal effect.
- (4) The method used in this report is not standardized, and such standardization is essential before comparisons among greenhouses can be made on its basis. In particular, it is important to standardize determination of the thermal mass temperature.

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4-7. APPENDIX 4-A

Solution for sinusoidal temperatures T_i and T_m .

To obtain values of the constants F , I , G , J , g_1 and g_m , Equation 4-13 is differentiated, and together with Equations 4-10 to 4-13 is introduced into Equations 4-6 and 4-7 ($R = 0$). The constant portions of the resulting equations yield:

$$F = D + (H + \alpha A)/U \quad (4-A1)$$

$$I = F + \alpha A/h \quad (4-A2)$$

The sinusoidal portions are evaluated for $t = 0$ and $t = \pi/2$ and, after manipulation, yield the following expressions:

$$N_m = \frac{(h + U)(\alpha B - C\omega E \sin g_0) + hUE \cos g_0}{((h + U)C\omega)^2/hU + hU} \quad (4-A3)$$

$$M_m = E \sin g_0 + (h + U) C\omega N_m/hU \quad (4-A4)$$

$$M_1 = M_m - C\omega N_m/h \quad (4-A5)$$

$$N_1 = N_m + (C\omega M_m - \alpha B)/h \quad (4-A6)$$

Finally

$$G = (M_1^2 + N_1^2)^{1/2} \quad (4-A7)$$

$$J = (M_m^2 + N_m^2)^{1/2} \quad (4-A8)$$

$$g_1 = \arcsin (M_1/G) \quad (4-A9)$$

$$g_m = \arcsin (M_m/J) \quad (4-A10)$$

4-8. LIST OF SYMBOLS

<u>Primary Symbols</u>	<u>SI Units</u>
C heat capacity	$\text{J/m}^2\text{K}$
c specific heat	J/kgK
H heat flux from heater	W/m^2
h transfer coefficient between floor and air	$\text{W/m}^2\text{K}$
i $\sqrt{-1}$	-
k thermal conductivity	W/mK
L long-wave radiation flux	W/m^2
m cover to floor area ratio	-
Q stored heat	J/m^2
R additional heat loss term	W/m^2
S solar radiation flux	W/m^2
T temperature	K
t time	s
U transfer coefficient between inside and outside air	$\text{W/m}^2\text{K}$
V wind speed	m/s
W width of temperature vs solar radiation loop	K
α solar heating efficiency	-
δ depth of water	m
ϵ emissivity to long-wave radiation	-
η absorptivity of floor to solar radiation	-
θ time constant	s
ρ density	kg/m^3
σ Stefan-Boltzman constant	$\text{W/m}^2\text{K}^4$
τ transmissivity of cover to solar radiation	-
ω angular velocity	rad/s
ϕ phase angle	rad

Various constant coefficients, empirical and computational
A,B,D,E,F,G,I,J,M,N,g

Subscripts

A amplitude
c of cover
d downwards inside greenhouse
e equivalent
i inside greenhouse
m of thermal mass
o outside greenhouse; when related to radiation implies downwards
s of soil
w of water

Table 4-1. Results of regression analysis, Technion experiments.

Run	State	s.d. ^a K	U, ^b W/m ² K	α^c	R, W/m ²	C, kJ/m ² K	δ , mm	h, W/m ² K	θ , min
104	Dry, Dusty	1.2	11.6	0.41	34.8	14.0	0	14.0	37
107	Dry, Clean	2.2	12.1	0.45	13.3	14.6	0	13.1	39
105	Wet, Dusty	1.7	14.9	0.40	3.0	94.5	62	13.4	223
106	Wet, Clean	1.2	15.5	0.40	-18.6	137.2	82	13.8	313

a: Based on solar radiation outside the greenhouse.

b: Based on floor area.

Table 4-2. Results of regression analysis, Cornell experiments.

Day	U, W/m ² K	α	R, W/m ²	C, kJ/m ² K	h, W/m ² K	θ , min
89	7.5	0.26	13	28		
90	2.4	0.10	1.9	22		
91	0.46	0.06	15	20		
92	11.1	0.37	-17	26		
93	8.4	0.42	21	102		
94	10.4	0.48	-16	47		
95	14.1	0.47	-107	36		
96	13.1	0.54	-109	51		
97	5.2	0.35	78	24		
Combined	8.0	0.34	10	42	4.0	262

Figure 4-1. Simplified greenhouse thermal model.

Figure 4-2. Amplitude-ratio Bode plot for time-dependent response of thermal mass.

Figure 4-3. Sketch of experimental greenhouse used for thermal calibration studies at Technion.

Figure 4-4. Sketch of experimental greenhouse used for thermal calibration studies at Cornell University.

Figure 4-5. Solar and long-wave radiative fluxes outside and inside the greenhouse during two runs at Technion; (a) wet run number 106, and (b) dry run number 107.

(a)

(b)

Figure 4-6. Radiation: temperature difference loops for two runs at Technion; (a) wet run number 106, and (b) dry run number 107.

Figure 4-7. Predicted effect of heat capacity on width of radiation: temperature difference loops.

Figure 4-8. Radiation: temperature difference combinations and their effect on venting in the greenhouse at Cornell University; (a) when solar radiation was increasing, and (b) when solar radiation was decreasing.

Figure 4-9. The effective heat capacity of the greenhouse at Technion compared with the actual heat capacity of the water.

Chapter 5: TOMATO RESPONSE TO ENVIRONMENTAL CONDITIONS

A literature review

Ido Seginer

5-1. INTRODUCTION

In recent years several computer programs have been developed which attempt to simulate the growth of plants as affected by environmental conditions. Most loosely related to the present study of growth in a greenhouse are perhaps the program "Tomatosimulator" (Hoogenboom, 1980), and a program on greenhouse production by Kohl (1978). Both programs utilize daily time steps and claim to make reasonable predictions along the growing period.

Unfortunately, the requirements of the optimization model of Chapters 1 and 2 are such that the simulation programs of the kind just mentioned cannot be incorporated into it. Since the optimization program includes several building blocks (crop, structure, economy), only simple models of these building blocks can be handled. Furthermore, at present only single-state crops are permitted, so that intermediate storages (e.g. of photosynthates) cannot be accommodated. The present optimization scheme requires a simple production function of the form $G(\underline{I})$, where G is the rate of growth and $\underline{I}$ is a vector of environmental conditions. The purpose of this literature review is to search for a production function of the form $G(J, X, T)$, where J is the photosynthetically active radiation (PAR) flux, X is the CO_2 concentration and T is the temperature of the environment in which the crop is immersed.

The emphasis in the optimization scheme is on the day-time. The inside conditions are continuously adjusted to the varying outside conditions, in an attempt to optimize the production. The shortest thermal time-constant of a greenhouse is about 15-30 min, and it is felt that operational decisions during the day must be made as frequently as once every 10 minutes or less. The night-time conditions, on the other hand, are normally less variable, and can perhaps be treated on a much longer time scale. An approach which results in a mean night-time temperature is presented in Chapter 6.

The main chain of events leading to plant growth starts with photosynthesis, which provides the raw material to all other processes. Photosynthesis takes place only during day-time, and optimizing that process during the day seems to be a reasonable first step towards overall optimization. Since photosynthesis is mainly affected by light, CO_2 and temperature, all these must be controlled during the day. At night the only important factor is temperature, which affects translocation and other processes leading to growth.

The above brief review of considerations leads to a search for a simple net-photosynthesis model of a plant canopy, which is independent of the past history of the crop, is of the form $G(I)$, and describes processes with time constants of the order of minutes.

5-2. NET PHOTOSYNTHESIS OF SINGLE LEAVES

GENERAL

It is customary to write the photosynthates balance as follows

$$G_L = P - R_p - R_D \quad (5-1)$$

where P is gross photosynthetic rate, R_p is photo- (or light-) respiration rate, R_D is dark-respiration rate, and G_L is net photosynthesis of a single leaf.

Thornley (1976, Chapter 4) has examined a number of forms for the components of Equation (5-1), and it seems that there are two popular formulas to describe P

$$P = \alpha J_L P_m / (\alpha J_L + P_m) \quad (5-2)$$

and

$$P = P_m [1 - \exp(-\alpha J_L / P_m)] \quad (5-3)$$

where J_L is the light (or PAR) flux impinging on the surface of the leaf, P_m is the value of P at light saturation (maximum value), and α is the photosynthetic efficiency at low light levels.

Equation (5-2) was used, among others, by Monteith (1965a,b) and Acock et al. (1978), while equation (5-3) was preferred by Peat (1970) and de Wit (1978). Goudriaan (1979) suggested to view these two 2-parameter formulas as particular cases of a whole family of curves, each derived from its predecessor by a transformation of the independent variable, J_L .

Equations (5-2) and (5-3) assume constant CO_2 concentration and temperature. The effect of CO_2 concentration may be introduced in various ways. Chartier (1970) presented a detailed model with 4 resistances in series (boundary-layer, stomata, mesophyll and carboxylation), to the flux of CO_2 . Here a simpler model, following de Wit (1978), is considered. First, light saturated net photosynthesis is defined

$$G_m = P_m - R_T \quad (5-4)$$

where R_T is total respiration. Then G_m is expressed in terms of a CO_2 concentration difference

$$G_m = \tau(X - X_c) \quad (5-5)$$

where X is the CO_2 concentration in the environment, X_c is the compensation CO_2 concentration, and τ is the combined conductance to CO_2 (inverse of sum of resistances).

From equations (5-2), (5-4) and (5-5) one obtains

$$P = \frac{\alpha J_L [\tau(X - X_c) + R_T]}{\alpha J_L + \tau(X - X_c) + R_T} \quad (5-6)$$

Many investigators (e.g. Acock et al., 1978; Monteith, 1965) simplified this equation by eliminating $R_T - \tau X_c$ from the numerator and denominator. Their expression for the net photosynthesis is

$$P = (\alpha J_L \tau X) / (\alpha J_L + \tau X) \quad (5-7)$$

Acock et al. (1976) retained an extra constant, β , in the numerator, namely

$$P = \alpha J_L (\tau X - \beta) / (\alpha J_L + \tau X) \quad (5-8)$$

Equation (5-8) serves as the basis of the tomato model developed here.

RESPIRATION

Photo-respiration, R_p , is sometimes modelled as proportional to the gross photosynthesis, P (e.g. Curry, 1971; Enoch and Sacks, 1978). Here it will be assumed that the coefficients α , τ and β are evaluated on the assumption that P stands for $P-R$. Equation (5-1) therefore becomes

$$G_L = P - R_D \quad (5-9)$$

Dark-respiration is often expressed as an exponential function of temperature

$$R_D = R_{Dr} Q^{(T-T_r)/10} \quad (5-10)$$

where T is leaf temperature, T_r is a reference temperature, R_{Dr} is the value of R_D at T_r , and Q is a constant. In many cases the value of Q is about 2, which is equivalent to saying that respiration rate doubles each time the temperature is increased by 10 K.

There seems to be enough evidence to show that dark respiration is a function not only of temperature, but also of previous photosynthesis. Enoch and Sacks (1978) suggested the following formula for R_D :

$$R_D = (g + h \ln J_p) Q^{(T-T_r)/10} \quad (5-11)$$

where J_p denotes the flux of PAR in the hour preceding the evaluation of R_D , and g and h are constants. Ludwig et al. (1975) presented data which relate total night-time respiration to total net photosynthesis of the previous day. Quantitatively, the ratio between night respiration and net photosynthesis was found to be about 1/10. On a continuous basis their R_D results may perhaps be approximated by

$$R_D = be^{-t/\theta} + c \quad (5-12)$$

where t is time, θ is a time constant (of the order of 4 hours), and b and c are constants. The last equation is perhaps an indication that the dark respiration is linearly related to the reserve of photosynthates in the plant.

De Wit (1978, p. 41) proposed to adopt 12 hours as the appropriate characteristic time and to set R_D equal to 1/9 of the CO_2 assimilation rate averaged over the previous 12 hours.

OPTIMAL TEMPERATURE

High temperature has already been shown to have some adverse effect by increasing respiration (Equation (5-10)). Low temperature also has an adverse effect by limiting photosynthesis (e.g. Mastalerz, 1977, p. 100), as well as other processes.

When experimental results of net photosynthesis or growth are related to temperature (of the environment or of the leaves), a clear maximum usually can be observed (e.g. Went, 1945; Went 1957; Mooney and Harrison, 1969; Soribe, 1972; Horie, 1977; Andersen, 1979). Went (1957, p. 103) and Friend and Helson (1976) have shown that maximum production is obtained at a certain combination of day and night temperatures. The optimal combination differs among plants, and the best day-time temperature may be up to 10 K higher than the best night temperature. The main difference between species, varieties, and even age, is

with regard to the temperature at which the maximum is observed. Greenhouse tomatoes seem to have a lower optimal temperature than do field varieties. The optimal temperature seems also to decrease with age, even within the vegetative stage (Went, 1945). Typically, a deviation of 6-8 K from the maximum results in a loss of production of 20%.

The incorporation of the effect of temperature into the growth model can take several forms. De Wit (1978, p. 37) proposed to multiply Equation (5-3) by an empirical function of temperature. This would mean that the optimal temperature (during the day) is independent of light (J), or CO₂ level (X). This limiting feature is not present in Enoch and Sack's (1978) model, since there both P and R_p are functions of T. It turns out that in their model the optimal temperature increases with the light intensity, a behavior which seems realistic. In the present study De Wit's approach will be adopted for lack of sufficiently detailed data.

5-3. INTEGRATION ALONG HEIGHT OF CANOPY

Once an expression for $G_L(I)$ of a single leaf is established, and I is known as a function of the depth into the canopy, G_L can be integrated to yield

$$G_C = \int_0^L G_L(I(L)) dL \quad (5-13)$$

where L is the specific leaf area, accumulated from the top of the canopy downwards, and G_C is per unit soil area. Of the three main components of I , X and T may be assumed to be rather constant with L . On the other hand J is a decreasing function of L , roughly of the form

$$J(L) = J_0 \exp(-kL) \quad (5-14)$$

where J_0 is the value of J at the top of the canopy. Both J and J_0 are measured on a horizontal surface and should be converted to flux impinging on the surface of the leaves J_L . To do this two simplified approaches have been tried. One, treating the canopy as a continuum, leads to (Saeki, 1963)

$$J_L = \frac{k}{1-m} J(L) = \frac{k}{1-m} J_0 \exp(-kL) \quad (5-15)$$

where m is the transmissivity of leaves to light.

The other approach is to trace light rays and calculate at each depth in the canopy the fraction receiving radiation after interception by one leaf, two leaves, etc. This provides not just an average light level, as in Equation (5-15), but also the light intensity distribution at each level. Monteith (1965b) developed a binomial distribution which yielded a mean light level of

$$J = [n + (1-n)m]^L J_0 \quad (5-16)$$

where n is the fraction of light passing through one unit of leaf layer without interception. From Equations (5-14) and (5-16) one finds that

$$n + (1-n)m = \exp(-k) \quad (5-17)$$

Acock et al. (1969) elaborated on Monteith's model, but when it came to application (Acock et al., 1976), they came back to Saeki's model (Equation (5-15)). To model tomato plants, they made the assumption of Equation (5-9) and integrated Equation (5-8) over the height of the canopy to yield

$$G_C = \int_0^L G_L dL = \frac{\tau X - \beta}{k} \ln \left\{ \frac{\alpha k J + (1-m) \tau X}{\alpha k J_0 \exp(-kL) + (1-m) \tau X} \right\} - L R_D \quad (5-18)$$

In a further paper by Acock et al. (1978) also assumed a dependence of τ and R_D on the light intensity recently experienced by the leaves.

Curry (1971), modelling lettuce, adopted Monteith's approach, but used only the mean light level.

5-4. TOMATO LEAVES

The model of gross photosynthesis for which some tomato data are available is that of Equation (5-8). When introduced into Equation (5-9) and after some rearrangement, one obtains

$$G_L = \frac{X - \beta/\tau}{1/\tau + X/\alpha J_L} - R_D \quad (5-19)$$

Table 5-1 shows a few values of the various parameters of Equation (5-19). All day-time measurements on tomatoes were made of 20°C, and most of them at CO₂ concentrations close to ambient. The light levels during the experiment were typical of England. The values in the table are normally for the highest light level of the experiment.

The values of α seem to be most consistent, with an average value close to 10E-9 kg/J for tomato. The values for the other C₃ plants suggest a somewhat higher value. On the basis of these data, the value finally selected was

$$\alpha = 11E-9 \text{ kg/J} \quad (5-20)$$

The next parameter is R_D , or rather R_{D_r} , since the available data are for $T=T_r=20^\circ\text{C}$. Figure 5-1 is a plot of R_{D_r} against J_L and it shows no clear relationship between the two variables. One possible approach is to select the average of all R_{D_r} values. This average is approximately

$$R_{D_r} = 60E-9 \text{ kg/m s} \quad (5-21)$$

Another approach is to try to relate R_{D_r} to light. The curve in the figure is one way of doing it.

The conductance to CO₂ flux, τ , is given much attention to Acock et al. (1978). According to their analysis, the conductance increases with light intensity, asymptotically approaching a value of about 5E-3 kg/m²s. Stanhill et al. (1973) obtained, for a crop of roses on a January day in Israel, a

value of $\tau \approx 5\text{E-}3 \text{ kg/m}^2\text{s}$, almost constant for 7 mid-day hours. For the simulation of tomato plants under mediterranean climate, the average value selected was

$$\tau = 4\text{E-}3 \text{ kg/m}^2\text{s} \quad (5-22)$$

With respect to the last parameter to be evaluated, β , two approaches are possible. The first is to refer to the only study that seemed to have determined it experimentally. The second is to use an estimate of X_c . The results of Acock et al. (1976), whose model includes β , suggest the following value for β/τ

$$\beta/\tau = 250\text{E-}6 \text{ kg/kg} \quad (5-23)$$

On the other hand, from Equation (5-19) for saturation light level

$$\beta/\tau = X_c - R_D/\tau \quad (5-24)$$

From de Wit (1978, p. 44) an estimate of X_c is

$$X = 80\text{E-}6 \text{ kg/kg} \quad (5-25)$$

Using the values from equations (5-21), (5-22) and (5-25) in Equation (5-24), one obtains the estimate

$$\beta/\tau = 65\text{E-}6 \text{ kg/kg} \quad (5-26)$$

which is different from the estimate of Equation (5-23) by a factor of 4. Some of this difference may be due to the treatment of R_p . Since the present model follows the form of Equation (5-9) rather than Equation (5-10), the larger value of β/τ should be preferred. The value finally selected was

$$\beta/\tau = 200\text{E-}6 \text{ kg/kg} \quad (5-27)$$

Inserting the values of the various parameters into Equation (5-19) the result is

$$G_L = \frac{X - 200E-6}{250 + 90E6 X/J_L} - 60E-9 \quad (5-28)$$

This crude model does, optimistically, describe, to a useful accuracy, the net photosynthesis of a single tomato leaf at 20°C.

The temperature effect will now be introduced as a correction factor to P. On the basis of the literature review it may be concluded that a reasonable value of the optimal day-time temperature for greenhouse tomatoes is about 20°C, and that the production reduces to 80% as the temperature deviates by 7 K from the maximum.

Equation (5-19) may now be modified to read

$$G_L = \frac{X - \beta/\tau}{1/\tau + X/\alpha J_L} F - R_{Dr} Q^{(T-t_r)/10} \quad (5-29)$$

where F is a temperature correction factor

$$F = 1 - 0.004 (T - T_r)^2 \quad (5-30)$$

and $T_r = 20^\circ\text{C}$.

It should be noted that it has not been explicitly stated whether T is air or leaf temperature. In practice the leaf temperature of transpiring plants is not very far from the air temperature, and the error, as a result of replacing one of these temperatures by the other, is not the largest in the present model. In principle, however, the relevant temperature is the leaf and not the air temperature.

5-5. INTEGRATION AND EXAMPLE

Finally, Equation (5-29) is to be integrated along the height of the canopy. It is assumed that only J_L changes along the canopy, so that Equation (5-18) still holds. The final result is

$$G_C = \int_0^L G_L dL = \frac{\tau X - \beta}{k} \ln \left\{ \frac{\alpha k J_0 + (1-m) \tau X}{\alpha k J_0 \exp(-kL) + (1-m) \tau X} \right\} F - LR_{Dr} Q^{(T-T_r)/10} \quad (5-31)$$

Based on Acock et al. (1976) and other sources, the estimates of k and m are

$$k = 0.6 \text{ m}^2/\text{m}^2 \quad (5-32)$$

$$m = 0.1 \quad (5-33)$$

A summary of the values of the various parameters and factors to be used in Equation (5-31) is as follows:

Q	$= 2.0$	(Equation (5-10))
α	$= 11\text{E-}9 \text{ kg}[\text{CO}_2]/\text{J}$	(Equation (5-20))
R_{Dr}	$= 60\text{E-}9 \text{ kg}[\text{CO}_2]/\text{m}^2[\text{leaf}]\text{s}$	(Equation (5-21))
τ	$= 4\text{E-}3 \text{ kg}[\text{air}]/\text{m}^2[\text{leaf}]\text{s}$	(Equation (5-22))
β	$= 0.8\text{E-}6 \text{ kg}[\text{CO}_2]/\text{m}^2[\text{leaf}]\text{s}$	(Equation (5-22) and (5-27))
F	$= 1 - 0.004(T - 20)$	(Equation (5-30))
k	$= 0.6 \text{ m}^2[\text{soil}]/\text{m}^2[\text{leaf}]$	(Equation (5-32))
m	$= 0.1$	(Equation (5-33))
T_r	$= 20^\circ\text{C}$	

It should be re-emphasized that the present literature review was done to provide a reasonable growth function for the optimization method of Chapters 1 and 2. Due to the requirements of the optimization method, the function $G(J, X, T)$ can only utilize current values of the environmental conditions. This affects mainly the dark respiration term, which is not a large term during the day time. The very wide scatter of the available estimates of the various parameters suggests that the quantitative accuracy of Equation (5-31) is doubtful. Fortunately, the optimization method only requires relative values of G , which increases the probability of producing reasonable optima.

Inserting the values of the various parameters into Equation (5-19) the result is

$$G_L = \frac{X - 200E-6}{250 + 90E6 X/J_L} - 60E-9 \quad (5-28)$$

This crude model does, optimistically, describe, to a useful accuracy, the net photosynthesis of a single tomato leaf at 20°C.

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Equation (5-19) may now be modified to read

$$G_L = \frac{X - \beta/\tau}{1/\tau + X/\alpha J_L} F - R_{Dr} Q^{(T-t_r)/10} \quad (5-29)$$

where F is a temperature correction factor

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Finally, Equation (5-29) is to be integrated along the height of the canopy. It is assumed that only J_L changes along the canopy, so that Equation (5-18) still holds. The final result is

$$G_C = \int_0^L G_L dL = \frac{\tau_X - \beta}{k} \ln \left\{ \frac{\alpha k J_0 + (1-m) \tau_X}{\alpha k J_0 \exp(-kL) + (1-m) \tau_X} \right\} F - LR_{Dr} Q^{(T-T_r)/10} \quad (5-31)$$

Based on Acock et al. (1976) and other sources, the estimates of k and m are

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τ	$= 4\text{E-}3 \text{ kg}[\text{air}]/\text{m}^2[\text{leaf}]\text{s}$	(Equation (5-22))
β	$= 0.8\text{E-}6 \text{ kg}[\text{CO}_2]/\text{m}^2[\text{leaf}]\text{s}$	(Equation (5-22) and (5-27))
F	$= 1 - 0.004(T-20)$	(Equation (5-30))
k	$= 0.6 \text{ m}^2[\text{soil}]/\text{m}^2[\text{leaf}]$	(Equation (5-32))
m	$= 0.1$	(Equation (5-33))
T_r	$= 20^\circ\text{C}$	

It should be re-emphasized that the present literature review was done to provide a reasonable growth function for the optimization method of Chapters 1 and 2. Due to the requirements of the optimization method, the function $G(J, X, T)$ can only utilize current values of the environmental conditions. This affects mainly the dark respiration term, which is not a large term during the day time. The very wide scatter of the available estimates of the various parameters suggests that the quantitative accuracy of Equation (5-31) is doubtful. Fortunately, the optimization method only requires relative values of G , which increases the probability of producing reasonable optima.

The function of G is defined in the optimization scheme per unit leaf area, so that Equation (5-31) should be divided by the leaf area index L to produce an average value for the canopy

$$\bar{G}_L = \frac{\tau X - \beta}{kL} \ln \left\{ \frac{\alpha k J_0 + (1-m) \tau X}{\alpha k J_0 \exp(-kL) + (1-m) \tau X} \right\} F - R_{Dr} Q^{(T-T_r)/10} \quad (5-34)$$

In the course of developing the growth function, data of net photosynthesis and cumulative growth as a function of temperature have been used. In Chapter 6 it will be shown that whenever the growth rate deviates from exponential, the function G is not exactly proportional to the cumulative growth.

Let us now consider an example which illustrates how to combine the response to light and CO_2 , as derived from the literature review, with the response to temperature presented in Chapter 6. Figure 6-6 shows G for tomato seedlings as a function of day and night temperature. That figure suggests that the crop response to day-time temperature may depend on the average night temperature the crop experienced. Let us consider as an example an average night temperature of $12^\circ C$. This suggests an optimal day temperature of $25^\circ C$ (and not $20^\circ C$ as suggested by the literature review). Since dark respiration increases with temperature, the maximum of the gross photosynthesis (P) is at a somewhat higher temperature than the maximum of the net photosynthesis (G). In our example it will be approximately at $26^\circ C$. The sensitivity of the crop to day-time temperature when the night temperature is $12^\circ C$, shows a 20% loss at a deviation of 6 K from the optimum.

The temperature factor F can now be estimated. Its value should be 1.0 at $20^\circ C$, should be maximal at $26^\circ C$ and should be 80% of the maximum at $20^\circ C$ and $32^\circ C$. The parabola satisfying approximately these requirements is

$$F = 1.25 - 0.007(T-26)^2 \quad (5-35)$$

Strictly speaking, if $G(T)$ is symmetrical about its maximum, $P(T)$ should not be symmetrical, since the respiration term is not. The accuracy of the $G(T)$ data of Figure 6-6, however, is such that no further refinement is justified.

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5-7. LIST OF SYMBOLS

Main symbols

SI units

a - a constant	$\text{kg}[\text{CO}_2]/\text{m}^2[\text{leaf}]\text{s}$
b - a constant	$\text{kg}[\text{CO}_2]/\text{m}^2[\text{leaf}]\text{s}$
c - a constant	$\text{kg}[\text{CO}_2]/\text{m}^2[\text{leaf}]\text{s}$
F - temperature correction factor	-
G - growth rate in terms of CO equivalence of dry matter	$\text{kg}[\text{CO}_2]/\text{m}^2[\text{leaf}]\text{s}$
g - a constant	$\text{kg}[\text{CO}_2]/\text{m}^2[\text{leaf}]\text{s}$
h - a constant	*
I - vector of inside environmental conditions	*
J - light (or PAR) flux	W/m^2
k - light extinction coefficient	$\text{m}^2[\text{soil}]/\text{m}^2[\text{leaf}]$
L - specific leaf area	$\text{m}^2[\text{leaf}]/\text{m}^2[\text{soil}]$
m - transmissivity of leaves to light	-
n - fraction of light passing layer without interception	-
P - gross photosynthesis rate	$\text{kg}[\text{CO}_2]/\text{m}^2[\text{leaf}]\text{s}$
Q - respiration ratio	-
R - respiration rate	$\text{kg}[\text{CO}_2]/\text{m}^2[\text{leaf}]\text{s}$
T - temperature	K
t - time	s
X - CO ₂ concentration	$\text{kg}[\text{CO}_2]/\text{kg}[\text{air}]$
α - photosynthetic efficiency	$\text{kg}[\text{CO}_2]/\text{J}$
β - a constant	$\text{kg}[\text{CO}]/\text{m}[\text{leaf}]\text{s}$
θ - time constant	s
ρ - air density	$\text{kg}[\text{air}]/\text{m}^3$
τ - combined CO ₂ conductance	$\text{kg}[\text{air}]/\text{m}^2[\text{leaf}]\text{s}$

notes: (1) - indicates a dimensionless entity

(2) * indicates that units vary according to the specific item under consideration

Subscripts

C - canopy

c - compensation point

D - dark-
L - leaf
m - at light saturation
o - at top of canopy
P - photo-, light-
p - previous
T - total
r - reference

Superscripts

- - spatial mean

Table 5-1: Some values of leaf photosynthesis parameters.

<u>First author</u>	<u>year</u>	<u>plant</u>	α	R_D	τ	β/τ	G_m	J_o
			E-9 kg/J	E-9 kg/m ² s	E-3 m/s	E-6 kg/kg	E-9 kg/m ² s	W/m ²
Peat	1970	tomato	10	50			540	150
Charles-Edwards	1975	tomato	8.3	80			890	400
Ludwig	1975	tomato		70				250
Acock	1976	tomato	8.6	18		250		60
Acock	1978	tomato	11	37	2.5			200
Chartier	1977	sugar beet	11.5					
De Wit	1978	C	13.9

Figure 5-1. Respiration of tomato leaves as a function of incident light.

Chapter 6: OPTIMAL NIGHT TEMPERATURES FOR GREENHOUSE TOMATO SEEDLINGS

Ido Seginer and Michael Raviv

6-1. INTRODUCTION

The traditional approach to the determination of the best night temperature for greenhouse plants has been to adhere, as much as possible, to the temperature at which the physiological optimum (highest yield) is achieved. As the cost of fuel became a significant expenditure item, the economic operation had to be shifted towards lower night temperatures. The optimal temperature levels is then determined by the condition

$$dV/dT = C(dE/dT) \quad (6-1)$$

where V is the market value of the crop in $\$/m^2$ [soil], E is the energy supplied by the heater in J/m^2 [soil], T is the air temperature in the greenhouse in K , and C is the cost of energy (fuel) in $\$/J$.

Equation (6-1) should be satisfied on a seasonal basis, which means that one has to make operational decisions during the growing season, while the market value becomes known only at the end of the season. The problem is how to make these decisions rationally from the economic point of view.

If the quality of the produce is assumed to be invariant with treatment, then its market value is the result of two factors: the quantity of the marketed produce, and the price attainable for the particular produce at the particular time. To simplify the analysis let us assume that the crop is harvested not at a predetermined time, but rather at a predetermined stage of growth (e.g. at 5 leaves or at 200 g per plant). This seems compatible with agricultural practice for many crops. The problem can then be formulated in terms of the effect that the harvest time has on the net income from the crop.

An attempt to utilize this approach to find the optimal night temperature for early cucumbers, was made by Challa and van de Vooren (1980), and Challa et al. (1980). The stage of growth for which time comparisons were made was the

start of flowering, which determines the start of fruit production a month later. The value of advancing this critical stage of development by an increment of time, was determined by the value of cucumbers that could be harvested during an equal increment of time once the harvest could begin. Since flowering starts after a certain number of leaves have developed, the value of an additional leaf could be calculated and compared with the cost of the heating required to produce that additional leaf.

The procedure of Challa and van de Vooren (1980) may be expressed by a modification of Equation (6-1):

$$(dV/dt_F)(dt_F/dt_L)(dt_L/dT) = C(dE/dT) \quad (6-2)$$

where t_F is the time of initiation of flowering, and t_L is the time increment between the emergence of successive leaves.

A similar approach to the problem was suggested by Seginer (1980) and developed in Chapter 2. It is briefly reviewed in the following paragraphs:

Let us assume that the state of a crop is represented by a scalar (e.g. number of leaves or dry weight or sugar concentration). The total growth period may be divided into several stages, for each of which a different property may be taken to represent the state, s .

Within each stage it is assumed that the growth function is

$$ds/dt = \xi(I, s) \quad (6-3)$$

where I is a vector of the environmental conditions inside the greenhouse and t is time. It is further assumed that for sufficiently short stages (perhaps up to a month), the function ξ may be replaced by

$$\xi(I, s) = G(I)g(s) \quad (6-4)$$

If the beginning and end of a stage of growth are identified by the subscripts b and e respectively, integration of Equation (6-3) yields

$$\int_{s_b}^{s_e} (1/g(s)) ds \equiv \gamma = \int_{t_b}^{t_e} G(I(t)) dt \quad (6-5)$$

where γ is a constant equal to the integral on the left and independent of $G(I)$. A change in I , the greenhouse inside conditions, results in a change of G , the rate of growth, which in turn affects t_e , the time at which the end of the stage is reached. If $G(I^*)$ denotes the rate of growth under standard conditions, then a deviation from these conditions at time t for an increment of time dt , leads to an incremental change in t_e

$$dt_e = [(G(I^*(t)) - G(I(t))) / (G(I(t_e)))] dt \quad (6-6)$$

The cost of delaying the end of a stage by dt_e is the sum of two components: 1) The cost of maintaining the crop in the greenhouse for dt_e (rent, labor, heating etc.), and 2) The loss of revenue due to change in the market price of the produce (or a fine imposed due to change in delivery time). Combining the two costs into one coefficient c_e (\$/m²s), the increment of cost due to delay in t_e becomes

$$c_e(dt_e/dt) = - c_e \Delta G / G(I(t_e)) \quad (6-7)$$

where $\Delta G \equiv G(I(t)) - G(I^*(t))$. The optimal inside conditions are obtained when the change in cost of operation equals the change in benefit at the end of the growing stage

$$\Delta c(t) = (c_e / G(I(t_e))) \Delta G(t) \quad (6-8)$$

where Δc is the increment of cost of operation (at a certain point in time) in \$/m²s. Differentiating on both sides with respect to I , one obtains, for a given set of outside conditions $O(t)$:

$$(dc/dI) = (c_e / G(t_e)) (dG/dI) \equiv \lambda (dG/dI) \quad (6-9)$$

This is the condition which is satisfied at the optimal level of I . (A more rigorous definition of λ as a Lagrange multiplier may be found in Chapter 2.

In simple cases c is linear and G is convex upwards when plotted against I . Figure 6-1 illustrates such a case schematically for a two-element vector I .

The rest of this chapter shows how the method just described can be applied to a simple vegetative crop. The empirical relationships to be used are the simplest which still retain the essential elements of the problem. When more accurate data (especially growth rate data) become available, further refinement of the model may be justified.

6-2. TOMATO SEEDLINGS

Let us consider now a specific and relatively simple crop: Tomato seedlings. They are grown year-round in greenhouse nurseries and marketed at about the same stage of development, independent of season. Figure 6-2 shows that the length of growing period in a commercial nursery (from emergence to marketing) varies, depending mainly on the availability of solar radiation. During the 4 to 7 weeks that the seedlings are kept in the nursery, the growth is vegetative and therefore relatively simple to model. Nevertheless, Went (1957, p. 231) showed that even in this simple case, the response to environmental temperature is not constant with time. In fact the physiologically optimal night temperature decreases as much as 4 K during the first month of life of tomato plants. Some of this variation in the growth function can be accommodated by $g(s)$ of Equation (6-4), but Equation (6-4) is still only a crude approximation to the real processes.

It will be assumed that the state, s , of the tomato plant is well represented by the dry matter of its shoot, w . Thus the units of the various variables of Equation (6-5) become:

w - dry matter content of shoot	$\text{kg/m}^2[\text{soil}]$
G - net dry matter production rate contributing to growth of shoot	$\text{kg/m}^2[\text{leaf}]\text{s}$
g - leaf area index of canopy (plus other correction factors)	$\text{m}[\text{leaf}]/\text{m}[\text{soil}]$
Y - net amount of dry matter produced by a unit area of leaves and consequently stored in the shoot during the growth stage under consideration	$\text{kg/m}^2[\text{leaf}]$

Shortly after emergence the leaf area index of the seedlings is small, so that practically no leaves are shaded by others. As a result, the rate of growth is roughly proportional to the leaf area, resulting in an exponential growth. As the plants grow and leaves shade each other, the rate of growth approaches a constant, independent of leaf area. The dependence of the rate of growth on the leaf area is represented by $g(s)$. When growth data cover a limited period of time, they may be fitted by an equation of the form

$$g = \eta w^n \quad (6-10)$$

where the exponent n is between 0 (constant growth rate) and 1 (exponential growth).

Let us consider now a period of time of the order of one month, during which all environmental variables are stationary with daily period. With daily time steps in mind, one may replace Equations (6-3) and (6-4) by

$$dw/dt = Gw^n \quad (6-11)$$

where, from here on, G is the daily growth rate in kg/m^2 [leaf] day. Integration over a period of time, starting at the beginning of a growth stage, yields

$$w^{1-n} - w_b^{1-n} = (1-n)Gn(t-t_b) \quad (6-12)$$

Equation (6-12) may be solved for G to yield

$$G = A(w^{1-n} - w_b^{1-n})/(t-t_b) \quad (6-13)$$

where A is a constant equal to $1/n(1-n)$. Experimental data may be fitted to Equation (6-12) by successive approximations of n . For the proper value of n , w^{1-n} should be linearly related to t . Data of Hammer et al. (1978) yield for n a value of 0.85 (nearly exponential). A similar value is obtained for the data of Ormrod et al. (1980).

It should be emphasized that when G is plotted as a function of the environmental conditions (e.g. Figure 6-1), the curvature of the resulting surface is smaller than that for an equivalent surface for w (except for the case $n=0$). Therefore the loss of production, due to deviation from the physiologically optimal conditions, is less than what seems to be suggested by a response surface for w . Normally, experimental results are given in terms of w , and attention should be paid to this point.

6-3. OPTIMAL TEMPERATURES

Let us consider now a growth function G resulting from the following type of experiment: Tomato seedlings are grown in light conditions representative of a certain month, under various combinations of day-time temperature, T_d , and night-time temperature, T_n . Typical results (in terms of w) of such thermoperiod experiments may be found in Went (1957, p. 103) and Friend and Helson (1976).

Once $G(T_d, T_n)$ is available, the optimal combination of T_d and T_n is obtained by applying Equation (6-9) in the following form:

$$\partial c / \partial T_d = (c_e / G) (\partial G / \partial T_d) \quad (6-14)$$

$$\partial c / \partial T_n = (c_e / G) (\partial G / \partial T_n) \quad (6-15)$$

where c denotes the cost of operation under a given set of temperatures, in $\$/m^2[\text{soil}]\text{day}$, and

$$c_e = c - w_e (dP/dt)_e \quad (6-16)$$

where w_e is the dry matter yield at the end of the stage of growth, and $(dP/dt)_e$, assumed to be constant, is the rate of change of the price attainable for the yield at that time. The cost of maintaining the greenhouse, c ($\$/m^2[\text{soil}]\text{day}$), is the sum of a constant, c_f (for rent, ventilation, fines, labor etc.), and the cost of heating c_h

$$c = c_f + c_h \quad (6-17)$$

A simple formula to express night time heating costs is

$$c_h = CmUt_n(T_n - T_o) \quad (6-18)$$

where m is the ratio of greenhouse cover to soil area in m^2 [cover]/ m^2 [soil], U is the overall heat transfer coefficient of the cover in W/m^2 [cover]K, T_n is the night temperature inside the greenhouse in K, T_o is a representative (mean) outside night temperature in K, and t_n is the length of night per 24 hour day in s/day. In a later section U will no longer be assumed to be constant, but for the time being the simplest possible formulation is considered.

To further simplify the problem of obtaining the optimal temperatures, let us assume that the cost of day-time operation (in Israel it is mainly ventilation), is negligible relative to the cost of night-time heating, or that it is constant, independent of T_d . This removes the need to solve Equation (6-14). To solve Equation (6-15) analytically, a simple form of the production function $G(T_n)$ must be assumed. A convenient and reasonable form for $G(T_d, T_n)$ is a parabolic ellipsoid

$$G = a_1 T_n^2 + a_2 T_d^2 + a_3 T_n T_d + a_5 T_d + a_6 \quad (6-19)$$

where the a 's are constant coefficients.

Since the absolute value of G is of no consequence to the solution of Equation (6-15), a relative function

$$\hat{G} \equiv G/G_x \quad (6-20)$$

may be defined, whose maximum value is 1. Any cross-section through the point of maximum (T_{dx}, T_{nx}) and perpendicular to the $T_d; T_n$ plane, is a parabola, whose projection on the $T_n; \hat{G}$ plane is

$$\hat{G} = 1 - b(T_n - T_{nx})^2 \quad (6-21)$$

where b is a constant, representing the curvature of the parabola. The constant b is uniquely related to the distance δ along the T_n axis, from T_{nx} to the point where the value of G is a certain fraction of the maximum (Figure 6-6). Let us set this fraction arbitrarily to 0.8 and obtain

$$b = 0.2/\delta^2 \quad (6-22)$$

Crops which are more sensitive to deviation from the physiological optimum are characterized by smaller values of δ .

Substituting in Equation (6-15) from Equations (6-16), (6-17), (6-18) and (6-21), and differentiating, one obtains

$$(K+T_n-T_o)[2b(T_n-T_{nx})]/[b(T_n-T_{nx})^2-1] = 1 \quad (6-23)$$

where

$$K \equiv (c_f - w_e(dP/dt)_e) / (CmUt_n) \quad (6-24)$$

Note that under conditions of constant price P , K may be interpreted as the temperature difference (between inside and outside), that could be maintained if all the fixed costs were devoted to heating. The relevant solution of Equation (6-23) for (T_n-T_{nx}) is

$$T_n-T_{nx} = (T_o-T_{nx}-K) + \sqrt{(T_o-T_{nx}-K)^2 - 1/b} \quad (6-25)$$

During heating $T_{nx}+K > T_o$, so that the condition for a real solution of Equation (6-23) is

$$T_o < K + T_{nx} - 1/\sqrt{b} \quad (6-26)$$

The limiting value of T according to Equation (6-26) is not necessarily the temperature at which the heating is actually turned on. Only when the solution of Equation (6-23), namely Equation (6-25), is such that

$$T_n > T_o \quad (6-27)$$

is it justified to turn on the heating.

Introducing Equation (6-27) into Equation (6-25) yields the range of outside temperatures for which the heater should be turned on:

$$T_o < K + T_{nx} - \sqrt{K^2 + 1/b} \quad (6-28)$$

The limiting value of T_o decreases, according to Equation (6-28), with K (namely, with the ratio of fixed costs to heating costs), and increases with T_{nx} (namely, with the physiologically optimal temperature) and with b (the curvature of the response function).

Equation (6-25) is plotted in Figure 6-3 (solid curves) as $T_n - T_{nx}$ against $T_o - T_{nx} - K$ (left and bottom scales), with δ as a parameter.

The diagonal $T_n - T_{nx} = T_o - T_{nx} - K$ is the lower-right border of the region where a solution of Equation (6-24) is possible. Scales for T_o and T_n (top and right of Figure 6-3) can be added if T_{nx} and K are known for a particular case (in the example $T_{nx} = 23C$ and $K=15K$). The diagonal $T_n = T_o$ is then the lower-right border of the region where heating is justified. The recommended inside temperature is clearly higher for the more sensitive crops, approaching T_{nx} , the physiological optimum, as δ decreases. The results also show that where the outside temperature is lower, the recommended inside temperature is higher, perhaps contrary to intuition. The latter result can be explained by the following example (Figure 6-4):

Consider two pairs of identical greenhouses, one pair at a "warm" location (perhaps on a coastal plain), and another pair at a "cool" location (perhaps on a nearby mountain). The solar radiation at the two locations is identical. One greenhouse of each pair, A, is operated at a certain night temperature, and the other one, B, is operated at a higher temperature. Under these assumptions there will be two termination times for the stage of growth under consideration: t_{eA} and t_{eB} respectively. Since outside and inside conditions are stationary, the costs of maintaining the greenhouse are

constant with time, and since the cost of heating is proportional to $(T_n - T_o)$, according to Equation (6-18), the difference in daily expenses between greenhouses A and B, $(c_{eB} - c_{eA})$, is the same for both locations.

The costs of operation from beginning to end of the growing stage are represented in Figure 6-4 by the 4 rectangles whose one corner is at 0 and whose opposite corner is at either A or B. The difference in area within each pair is obtained by comparing the shaded rectangles. At the warm location greenhouse A (cool treatment) is more profitable than greenhouse B (warm treatment), while in the cool location the opposite is true. From the construction of Figure 6-4 it is apparent that the higher is c_e , the more likely is a higher temperature justified. Since a cooler climate is associated with a higher c_e , it follows that cooler climates (with similar solar radiation) justify higher inside (night) temperatures. Temperatures should also be higher where the fixed costs, $(c_e - c_h)$, are higher.

It should be clear from the foregoing discussion, that if U is not constant with T_n , the simple relationships of Figure 6-4 do not hold. In practice the value of U , as defined by Equation (6-18), depends on $T_n - T_o$, as well as on wind speed, cloud cover and greenhouse characteristics. In a dry and radiatively transparent greenhouse, the overall transfer coefficient U appears to decrease with increasing $T_n - T_o$ (Minagawa and Tachibana, 1982), while in a wet and leaky greenhouse, where infiltration is significant, U increases with $T_n - T_o$. To illustrate the sensitivity of the solution to assumptions about U , the relationship for natural convection was selected, with U increasing as $1/4$ power of $T_n - T_o$. A new solution was numerically calculated, based on the following relationships:

$$c_h = C_m U \beta t_n (T_n - T_o)^\beta \quad (6-29)$$

where, in our example, $\beta = 1.25$, $U\beta$ is a constant, and

$$([K_\beta + (T_n - T_o)^\beta][2b(T_n - T_{nx})]) / ([\beta(T_n - T_o)^{\beta-1}][b(T_n - T_{nx})^2 - 1]) = 1 \quad (6-30)$$

Equation (6-29) replaces Equation (6-18), and Equation (6-30), to be solved for $T_n - T_{nx}$, replaces Equation (6-23). The relationship between K_β and K is as follows:

$$K_\beta/K = U/U_\beta = (T_n - T_o)^{\beta-1} \quad (6-31)$$

where $T_n - T_o$ is selected to be representative temperature rise for the situation under consideration. Selecting $T_n - T_o = 10K$, yields $K_\beta/K = 1.78$.

Since Equation (6-30) cannot be normalized in the same way as Equation (6-23), a comparison of the results for $\beta = 1.25$ with those for $\beta = 1$ (constant U) can only be made in terms of the axes T_n and T_o . Selecting $K = 15K$ and $T_{nx} = 23C$ as before, the dashed curves of Figure 6-3 are obtained. Again, the line $T_n = T_o$ is the right lower border of the heating region, but the shape of the new optimal curves in the neighborhood of that border is different than for $\beta = 1$: As the outside temperature decreases, the optimal inside temperature also decreases, but at a slower rate, until $T_n - T_o$ reaches a minimum of about 4 K. Beyond this point T_n increases in a manner similar to the case $\beta = 1$.

The exact shape of the curves is only critical if deviation from the optimum involves a significant penalty. To test the sensitivity to deviation, the total expense required to complete the growing stage was calculated as a function of T_o and T_n in the following manner: The total expense is

$$Z = c_e t_e \quad (6-32)$$

The termination time t_e can be deduced from Equation (6-5), setting $t_b = 0$, to be

$$t_e = \gamma/G \quad (6-33)$$

Multiplying Z by $G/(\hat{G}\gamma C_m U_\beta t_n)$, which is independent of T_n , a convenient expense function is obtained:

$$\zeta = (K_\beta + (T_n - T_o)^\beta) / (1 - b(T_n - T_{nx})^2) \quad (6-34)$$

Numerical results for our example show that a deviation of 5K from the optimum results in about 6% increase of the costs.

6-4. GROWTH CHAMBER EXPERIMENT

To illustrate the method outlined in the foregoing sections, a growth chamber experiment was carried out with greenhouse tomato (cv. Fl04) seedlings. Seeds were sown, one per cell (3.8 cm square), in "Speedling" trays, filled with a 1:1 mixture by volume of peat moss and Vermiculite No. 2. The trays were placed for 4 days in a constant temperature of 24°C before being transferred to 3 to 5 growth chambers, where step function temperature and light levels could be maintained. A 16h light period (24-t_n) of 115 $\mu\text{E}/\text{m}^2 \text{ s}$ intensity, produced by a 1:1 combination of Gro-lux and Coolwhite fluorescent lamps, was common to all treatments. Various combinations of light and dark temperatures were applied to the treatments, with the combination 24C/24C (T_d/T_n) repeated in all runs. Altogether there were 36 observations in 10 runs, all indicated on Figure 6-6. It is evident that the treatments were concentrated towards the high light-temperatures and low dark-temperatures region, where the economic optimum was expected to be found. The seedlings were irrigated every other day, in excess, with nutrient solution based on 100 ppm N, 44 ppm P, 83 ppm K and 6 micronutrients.

Most seedlings were grown for 30 days and then harvested to obtain their dry weight. In four cases samples were harvested at one or two week intervals, their dry weights to be analyzed according to Equation (6-12). The analysis yielded the following values: $n=0.7$, $w_b=4\text{mg}$ and $t_b=12\text{d}$. The normalized results are shown in Figure 6-5.

The dry weights of the 30-day harvests were used to determine G/A from Equation (6-13). These, in turn, were used to obtain the best fit parameters for the model

$$(G/A)_{ij} = h_1(a_1T_n^2 + a_2T_d^2 + a_3T_nT_d + a_4T_n + a_5T_d + a_6) \quad (6-35)$$

which is based on Equation (6-19). In Equation (6-35) the index i represents the experimental run (about one every month), and j represents a particular temperature combination within the run. The difference between the measured and predicted values of (G/A) is a measure of the goodness of fit.

Figure 6-6 shows contours of $\hat{G}=G/G_x$ together with some other information. The ellipses are elongated (more than to be expected from results of Went (1957) and Friend and Helson (1976)) in the direction of constant mean daily temperature. This may suggest that the crop is reasonably tolerant to deviations from the physiological optimum (here about 22C). Supporting evidence to the importance of maintaining just the mean temperature may be found in Langhans et al. (1981).

The line which satisfies $\partial G/\partial T_d=0$, the best choice under the assumption which eliminated Equation (6-14), is the line along which the economical optimum is located. The value of δ for this line is about 12.3K.

The goodness of fit is illustrated in Figure 6-7, and the parameter h , which may be interpreted to indicate growing experience, is shown in Figure 6-8. Both figures show considerable scatter, but the general form of the growth function is probably correct.

Suppose that the results of the growth chamber experiment are to be applied to a real situation where $K=15K$. Figure 6-3, which is based on $K=15K$ and $T_{nx}=23C$ is applicable to this case. For $\delta = 12K$ and outside (night time) temperature around $T_o=0C$, a reasonable choice for the inside temperature is $T_n=10C$ (midway between the curves for the two heating models). Thus the thermostat setting for the month for which the growth chamber light regime was selected, should be 10C. Since the typical outside night temperature is lower than the inside temperature, the heater will be on most of the time and the inside temperature will be maintained almost continuously at 10C. With this information one may enter Figure 6-6 and reach the conclusion that the optimal day-time temperature under these conditions should be slightly above 25C. If we assume that the data are of fair accuracy, then, as the outside temperature decreases, the night-time inside temperature should be increased and the day-time temperature decreased.

6-5. DISCUSSION AND CONCLUSIONS

Obviously this paper does not present much more than a crude methodology with an example. More accurate data, and perhaps a more sophisticated model, are required before a practical method could emerge. Most critical, and most

expensive to obtain, are the growth rate data. Equations (6-14) and (6-15) show that the first derivative of G (as well as of c) enters the calculation. Empirical derivatives are expensive to obtain, and the rapid replacement of crop varieties may prohibit extensive growth-chamber studies. Nevertheless, if agriculture aims at an ever increasing control over the production process, and as long as there is no direct feedback from the plants (the so-called "speaking plant" concept; Udink ten Cate et al., 1978), improved modeling should be attempted to aid rational decisions.

Several specific notes can be made at the present time:

- (1) Accurate gradients of G are only required in the neighborhood of the economical optimum. Under normal conditions this optimum shifts relatively slowly with changing varieties and economic conditions. Therefore, once the neighborhood of the optimum is located, an efficient experimental procedure could be devised to continuously adjust the recommendations to the growers (at least for the more common crops). After all, the present greenhouse practice cannot be unrealistically far from the optimum.
- (2) It is not clear at this time how the temperature response (such as Figure 6-6) is affected by the light regime. The fact that the long axis of our ellipses is parallel to the lines of equal daily mean seems to support the view that the total cumulative temperature (degree-hours per day) is the most significant temperature parameter. Whether this is true or not is of great practical importance, and has not been resolved yet. If it is sufficient to maintain a certain average daily temperature (excluding, of course, extreme temperatures), the expected direction of the long axis of the ellipses should vary with day length. As the day becomes longer, the long axis should become more parallel to the night temperature axis.
- (3) Care should be taken when artificially lit growth-chamber data are used to obtain growth functions for greenhouse crops. Even if the light quality is correct; and even if a step function operation provides useful results for the constantly varying greenhouse environment; still, care should be taken in interpreting the temperature results: The well insulated growth chamber protects the leaves from radiative cooling, and therefore the leaf-to-air temperature difference is small. On the other hand, in a commercial

greenhouse the leaves are radiatively cooled against a cold roof and a cold sky (the latter under semi-transparent covers). If the growth function is based on air temperature, rather than on leaf temperature, care must be taken in the process of adapting the growth-chamber results to the greenhouse situation.

(4) Figure 6-3 shows that the recommended inside temperature is rather sensitive to the assumption about U. This may indicate that some more work should be done concerning the relative importance of the various heat transfer mechanisms under field conditions.

6-6. REFERENCES

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6-7. LIST OF SYMBOLS

<u>Main symbols</u>	<u>SI Units</u>
A - a constant. Equation (6-13)	*
a_j - constant coefficients. Equation (6-19)	*
b - a constant. Equation (6-21)	1/K
C - cost of heating energy	\$/J
c - cost of operation	\$/m ² [soil]s
E - energy supplied by heater	J/m ² [soil]
G - internal conditions factor of δ . Equation (6-4)	kg/m ² [leaf]s
G - relative value of G	-
g - crop-state factor of ξ . Equation (6-4)	m ² [leaf]/m ² [soil]
h - growing experience parameter	*
I - vector of inside conditions	*
K - defined in Equation (6-24) and (6-31)	*
n - an empirical exponent. Equation (6-10)	-
O - vector of outside conditions	*
P - market price of crop	\$/m ² [soil]
s - state of crop	*
T - air temperature	K
t - time	s
t_F - time of flowering initiation	s
t_L - time increment between emergence of successive leaves	s
V - market value of crop	\$/m ² [soil]
w - dry mass of shoot	kg/m ² [soil]
Z - total expense to complete a stage of growth	\$/m ² [soil]
β - power of $T_n - T_o$. Equation (6-29)	-
γ - growth per unit area of leaves during stage	kg/m ² [leaf]
δ - distance from the physiological optimum to where G is 80% of the maximum	K
ζ - expense function. Equation (6-34)	*
η - a constant defined in Equation (6-10)	*
λ - a constant defined in Equation (6-9)	\$/m ² [leaf]/kg m ² [soil]
ξ - growth rate as function of I and s. Equation (6-3)	kg/m ² [soil]s

note: (1) * indicates that units vary according to the specific item under consideration.

(2) - indicates dimensionless entities.

Subscripts

A - of greenhouse A
av - daily mean
B - of greenhouse B
b - beginning of stage of growth
d - day time; inside
e - end of stage of growth
f - independent of heating level
h - heating
i - index of experimental run
j - index of temperature combination
n - night time; inside
o - outside greenhouse
x - maximum
 β - for that power
 δ - for that fraction
* - standard conditions

Figure 6-1. Growth rate and cost of operation as a function of two environmental parameters.

Figure 6-2. Length of time from emergence to marketing of tomato seedlings in a commercial nursery in Israel.

Figure 6-3. Recommended inside temperature (T_n) as a function of the outside temperature (T_o), plant response parameters (T_{nx} , δ) and an expense parameter (K). The solid lines are for a heat loss function with $\beta = 1.0$, and the dashed lines are for $\beta = 1.25$.

Figure 6-4. The cost of operation of a greenhouse to produce a crop in two locations and two heating levels. Schematic.

Figure 6-5. Normalized cumulative dry weight of tomato seedlings grown in growth chambers, as a function of time.

Figure 6-6. Normalized growth rate, G , as a function of day (light) temperature and night (dark) temperature, for tomato seedlings.

Figure 6-7. Normalized growth rate as a function of normalized distance (in terms of temperature) from the physiological optimum.

Figure 6-8. The experience parameter, h , as a function of run number, i .

Chapter 7: GREENHOUSE CONTROL

Ido Seginer and Louis D. Albright

7-1. INTRODUCTION

The environmental control systems of greenhouses, traditionally based on analog equipment, have shifted in recent years towards the use of digital hardware. The Netherlands was the country which pioneered digital computers in commercial greenhouses (Gieling, 1980), and is now followed by others. In research there are investigators who are interested in developing special purpose greenhouse computers, and others who are interested in developing control algorithms which could be adapted for use with any available micro-computer.

In the present project the hardware of the control system was the means rather than the end. Therefore, the decision was made to utilize standard commercial equipment as far as possible. To facilitate flexibility in programming, general purpose micro-computers (HP 85 at Cornell and Apple II+ at Technion) were used to drive the systems. Data were collected by data loggers (HP 6940B multi-programmer at Cornell and Acurex Autodata 20 at Technion). The control signals to the greenhouses were transferred by means of a commercial unit (the HP 6940B at Cornell) and a specially made unit (at Technion, Figure 7-1). Both systems operated satisfactorily. There were occasional problems with the Technion unit, usually not associated with the commercial components of the system.

This chapter of the report deals neither with the description of the systems (except Figure 7-1), nor with the particular operation in any of the experiments. Information on the latter is provided in the appropriate sections of Chapters 4, 8 and 9. The present chapter deals briefly with some of the more general aspects of the control algorithms.

Generally speaking, 3 approaches to control have been attempted:

(1) The usual thermostatic control with a preset sequence of set-points. This method of control essentially simulates the operation of an analog control system, including the differentials between heating and venting etc. This approach was used for temperature control at Cornell. It will not be discussed any further in this chapter.

(2) A kind of adaptive control, where the set point varies as a function of outside conditions, rather than as a function of time. This approach was used at Cornell for operation of the thermal screen (Chapter 9), and at Technion for temperature control of the final experiment (Chapter 8). The development of a PI control algorithm for temperature control in the final experiment is described in Section 7-3.

(3) A control aimed at providing fluxes (of heat, CO_2 etc.) rather than at maintaining certain concentrations (of CO_2 , water vapor etc.) or potentials (e.g. temperature). This approach is a natural outcome of the optimization method, and will be dealt with in Section 7-2. This method of control has been worked out and programmed, but has not been applied in any of the experiments, because in the final experiments simultaneous operation of several pieces of equipment was unnecessary.

The final section of the present chapter deals, in an elementary way, with the possibility of adjusting a control algorithm to the variation which may occur in the parameters of the system over time.

7-2. FLUX CONTROL

In Chapters 2 and 3 it is shown that for each set of outside conditions and level of operation of the air-conditioning equipment, there is only one possible solution for the inside conditions. In other words, each element of $\underline{I}$ (the inside conditions), is a single-valued function of $\underline{O}$ (the outside conditions) and of $\underline{M}$ (the level of operation of the air-conditioning equipment). The opposite is not generally true: There are many ways of operating the air-conditioning equipment, which will produce the same inside conditions. For instance: more heating and more ventilation, simultaneously,

may cancel each other's effect on temperature. Therefore, whenever several pieces of equipment are required to operate simultaneously, some optimization is required in order to determine the least expensive combination of operating levels.

The optimization is performed on a main-frame computer. The computer produces, for any required set of outside conditions, $\underline{Q}$, the economically best operation level of all the equipment, $\underline{M}_r$, as well as the inside conditions, $\underline{I}_r$, to be expected as a result of this operation. Since the main-frame computer cannot be tied to the greenhouse, it is programmed to produce a table to be used by the micro-computer in charge of controlling the greenhouse. The table consists of a limited number of sub-tables, n_r , one for each of n_r sets $\underline{Q}_j$, which are representatives of the range of meteorological conditions under consideration. An observed set of outside conditions $\underline{Q}_o$ may be said to be "close" to a representative set $\underline{Q}_j$, if by operating at the level $\underline{M}_j$ (which is recommended for the representative set), while the outside conditions are $\underline{Q}_o \neq \underline{Q}_j$, the economic loss (compared to operating at the optimal values for $\underline{Q}_o$), is less than a certain value. The "distance" between points is a measure of the loss.

In the actual control operation, the micro-computer receives signals from the sensors in the outside environment; it then searches in the table for that representative set, $\underline{Q}_s$, which is closest to the observed set of outside conditions $\underline{Q}_o$. The operation level recommended for that representative set is then applied to the greenhouse. This process, which the micro-computer must perform in real time, requires little time and memory space, since it was found that about 20 representative sets may be sufficient to cover the whole range of meteorological conditions at a certain location.

Mathematically, the distance, D_j , between an observed set of outside conditions $\underline{Q}_o$, and the j th representative set, $\underline{Q}_j$, is given by

$$D_j = (\underline{Q}_j - \underline{Q}_o)^T \underline{S}_j (\underline{Q}_j - \underline{Q}_o) \quad (7-1)$$

where $\underline{S}_j$ is the sensitivity matrix of the j th set (Chapter 2), and T denotes a transpose. The inside conditions, which are expected to result from operating at the recommended level $\underline{M}_s$ for the closest representative set (while the actual outside conditions are $\underline{O}_o$), is given by

$$\underline{I}_r = \underline{I}_s + (\underline{O}_o - \underline{O}_s) \underline{V}_s \quad (7-2)$$

where $\underline{I}_r$ and $\underline{I}_s$ are the recommended inside conditions when the outside conditions are $\underline{O}_o$ and $\underline{O}_s$, respectively, and $\underline{V}_s$ is an extrapolation matrix for the closest representative set.

Let us denote the number of elements of the outside environment (temperature, radiation etc.) by n_o , the number of inside elements by n_I , the number of pieces of equipment by n_M , and the number of representative sets by n_R . The size of the various vectors and matrices for each set is thus: $\underline{O}_j$, n_o ; $\underline{I}_j$, n_I ; $\underline{M}_j$, n_M ; $\underline{S}_j$, $n_o \times n_o$; $\underline{V}_j$, $n_o \times n_I$. A generous estimation of these numbers is: $n_o = 5$; $n_I = 5$; $n_M = 5$; $n_R = 20$. Thus the total space required for the table is $20 \times 65 = 1300$ numbers. The number of multiplications required to perform the calculation of Equation (7-1) is also only $(n_R)(n_I)(n_o)(1+n_o) = 12,000$.

A sub-program to calculate Equations (7-1) and (7-2) was used in several preliminary runs, but was not used in any of the experiments since it was never required that several pieces of equipment be operated simultaneously. If, in some future time, it will become necessary to control a more complex situation, by using a table such as the one just described, any micro-computer should be able to accommodate it with ease. As the crop, season or prices change significantly, it is only necessary to replace the existing table by a new one.

7-3. PI TEMPERATURE CONTROL

Once the temperature set-point for a thermostatic control system is determined, it is necessary to maintain the required temperature with minimum

deviation (and minimum energy waste). This is true whether the temperature set-point is given as a function of time, or as a function of outside conditions. Experience shows that in our case a PI (Proportional-Integral) control algorithm is required to prevent systematic deviation of the temperature from its set-point.

The PI control equation appropriate for the inside temperature under heating is:

$$H = W(T_R - T_i) + R \int (T_R - T_i) dt + M \quad (7-3)$$

where H is the heat flux of the heater, T_R is the required (set-point) temperature, T_i is the actual inside temperature, t is time and W and R are constant multipliers. In conventional PI control, M is a constant, but under variable outside conditions, the control could be improved by making M a function of these conditions.

To select a reasonable value for M , let us consider first the P (Proportional) control equation

$$H = W(T_R - T_i) + M \quad (7-4)$$

The process which is to be controlled may be approximated by the following energy balance of the greenhouse:

$$H + aS_0 = mU(T_i - T_0) + \rho cQ(B+1)(T_i - T_0)/B \quad (7-5)$$

where S_0 is the solar radiation flux outside the greenhouse, T_0 is the outside air temperature, a is the heating efficiency of the solar radiation, m is the cover-to-floor surface ratio, U is the transfer coefficient for energy across the cover (including convection-conduction, radiation and infiltration), ρ is the air density, c is the specific heat of air at constant pressure, Q is the ventilation discharge per unit area, and B is the Bowen (sensible to latent heat) ratio. Under normal operating conditions heating and ventilation are not applied simultaneously. Therefore there are two specific situations:

$$\text{Heating} \quad H + aS_o = mU(T_i - T_o) \quad (7-6)$$

$$\text{Ventilation} \quad aS_o = [mU + \rho cQ(B+1)/B] (T_i - T_o) \quad (7-7)$$

Let us consider these two situations separately:

HEATING

Consider Equation (7-4). If M is perfectly selected, the $T_{rH}=T_i$, and Equation (7-4) degenerates to $H=M_H$, where the subscript H indicates heating. Substitution in Equation (7-6) results in the desirable value for M_H as a function of the outside conditions:

$$M_H = mU(T_{rH} - T_o) - aS_o \quad (7-8)$$

If M_H is selected in this manner, the P control equation (Equation (7-4)) becomes

$$H = W_H(T_{rH} - T_i) + mU(T_{rH} - T_o) - aS_o \quad (7-9)$$

In reality the correct values of a and U are not constant with time and are not accurately known. As a result Equation (7-9), if used, would still result in a systematic deviation $T_{rH}-T_i \neq 0$.

Suppose that a and U are the true present values of the heating efficiency and the transfer coefficient. Our present estimates of these parameters, however, are a' and U' , so that our present P control equation is

$$H = W_H(T_{rH} - T_i) + mU'(T_{rH} - T_o) - a'S_o \quad (7-10)$$

Equating the last equation with the process equation (7-6), yields an estimate for the systematic deviation of the P control

$$T_{rH} - T_i = [m(U-U') (T_i - T_o) - (a-a')S_o] / [W_H + mU'] \quad (7-11)$$

The deviation increases as $U-U'$ and $a-a'$ increase, and decreases as W_H is increased. A large value of W_H , however, may cause instability. To overcome the difficulty of a systematic deviation, the integral term of Equation (7-3) is introduced.

Let us assume now that a PI control is used. The control equation with our best guesses of a and U becomes

$$H = W_H(T_{RH} - T_i) + R_H I + mU'(T_{RH} - T_o) - a'S_o \quad (7-12)$$

where $I = \int (T_R - T_i) dt$. If a steady state is reached, which in this case also means $T_{RH} = T_i$, Equation (7-12) becomes

$$H = R_H I + mU'(T_{RH} - T_o) - a'S_o \quad (7-13)$$

which, when equated with the process equation (7-6), results in an estimate of the value of $R_H I$ under steady-state conditions

$$R_H I = m(U-U')(T_{RH} - T_o) - (a-a')S_o \quad (7-14)$$

Steady-state, and thus a constant value of $R_H I$, can approximately be reached at night, when the conditions change very slowly. At night

$$R_H I = m(U-U')(T_{RH} - T_o) \quad (7-15)$$

This relationship makes it possible to correct the value of U as follows

$$U'' = U' + R_H I / [m(T_{RH} - T_o)] \quad (7-16)$$

where U'' is the new estimate of U . This method of correction is not reliable when $T_{RH} - T_o$ is small.

The values of W_H and R_H should be determined by experience. In the control algorithm for the mini-greenhouses, the value of W_H was set to $4 \text{ W/m}^2\text{K}$, which is roughly the value of U (on cover area basis). The value of R_H was set to $20 \times 10^{-3} \text{ W/m}^2\text{sK}$.

VENTILATION

The ventilation situation is treated in the same way as the heating situation. First the process equation is determined from Equation (7-7)

$$Q = G [aS_O / (T_{rV} - T_O) - mU] \quad (7-17)$$

where $G=B/\rho c(B+1)$, and the subscript V indicates ventilation. The P control equation is

$$Q = W_V(T_{rV} - T_i) + R_V I + M_V \quad (7-18)$$

The proper value of M_V is

$$M_V = G [aS_O / (T_{rV} - T_O) - mU] \quad (7-19)$$

but due to inaccuracies in a and U , the actual control equation becomes

$$Q = W_V(T_{rV} - T_i) + R_V I + G [a'S_O / (T_{rV} - T_O) - mU'] \quad (7-20)$$

Under steady-state conditions (perhaps around noon on a clear day)

$$R_V I = G [(a-a')S_O / (T_{rV} - T_O) - m(U-U')] \quad (7-21)$$

If it is assumed that U has already been corrected (through night-time observations), the estimate of a can now be improved

$$a'' = a' + R_V I (T_{rV} - T_O) / G S_O \quad (7-22)$$

The usefulness of Equation (7-22) is doubtful, since day-time conditions may not be steady enough for a reliable asymptotic value of I to develop.

In the application of these results to the actual control of the mini-greenhouses, the value of W_V was set to $0.01 \text{ m}^3/\text{m}^2\text{sK}$ and the value of R_V to $20 \times 10^{-6} \text{ m}^3/\text{m}^2\text{s}^2\text{K}$.

SWITCHING BETWEEN HEATING AND VENTILATION

It is clear from the previous discussion that before taking any control action, it must be decided whether heating or ventilation is required at any point in time. To make this decision let us start with a situation where neither heating nor ventilation is applied ($H=0$, $Q=0$). This is satisfactory as long as

$$aS_o - mU(T_{rH} - T_o) > 0 > aS_o - mU(T_{rV} - T_o) \quad (7-23)$$

If the above condition is not met, heating or ventilation must be applied.

Consider first the night situation, where the following holds:

$$\text{if } mU(T_{rH} - T_o) > 0 \quad \text{then apply heat} \quad (7-24)$$

The value of U is not accurately known, but an estimate can be obtained from Equation (7-15). When it is inserted into Equation (7-24), one obtains the following condition for heating at night

$$mU'(T_{rH} - T_o) + R_{HI} > 0 \quad (7-25)$$

During the day the following conditions hold

$$\text{if } mU(T_{rH} - T_o) - aS_o > 0 \quad \text{then heat} \quad (7-26)$$

$$\text{if } mU(T_{rV} - T_o) - aS_o < 0 \quad \text{then ventilate} \quad (7-27)$$

Inserting from Equation (7-14) into (7-26) and from (7-21) into (7-27), one obtains

$$\text{if } mU'(T_{rH} - T_o) - a'S_o + R_{HI} > 0 \quad \text{then heat} \quad (7-28)$$

$$\text{if } mU'(T_{rV} - T_o) - a'S_o + (T_{rV} - T_o)R_{VI}/G < 0 \quad \text{then ventilate} \quad (7-29)$$

Conditions (7-25), (7-28) and (7-29) must be incorporated in the control program. Provisions must also be made for situations where for some unexpected reason both conditions (7-28) and (7-29) are met simultaneously.

The above development nicely fits systems with continuous power output (like hot water systems and roof windows). The experiments in this study were carried out with a heating system which had 4 distinct non-zero operation levels (50, 100, 150 and 200 W/m^2) and a ventilation system with 3 distinct non-zero levels (0.0245 , 0.0490 , $0.0735 \text{ m}^3/\text{m}^2\text{s}$).

The practical solution was as follows: The required temperature was calculated and the actual temperatures were measured once every 2 min. The conditions of the previous section (namely (7-25), (7-28) or (7-29)), were applied and then the control equations (7-12) or (7-20) were used to determine the required rate of heating or ventilation. At this point the closest available stage of operation was applied for the following 2 min., until a new decision was taken.

Another point of practical importance is the switching between ventilation and heating. Frequent switching may occur whenever $T_{RH}=T_{RV}$ and the outside conditions are such that $aS_o - mU(T_r - T_o) \approx 0$. To prevent the energy loss due to frequent switching, a delay was incorporated into the control program, such that switching from heating to ventilation, and vice versa, could not occur more frequently than once every predetermined time interval (e.g. 20 min). A similar approach was used for the operation of the thermal screen (Chapter 9).

SAMPLE RESULTS

The control program of the experiment described in Chapter 8 was written on the basis of the approach of this section (7-3). The experiment ran for about two months without any failure in logic. Two examples of how the control program actually performed will serve to illustrate the ideas mentioned.

The first example shows the short term (once every 2 min.) behavior. Figure 7-2 shows what happened during a 160 min. period on a day with scattered

clouds. For about 50 min. during that period the sky was overcast. The solar radiation peaked significantly at least 6 times (at a frequency of about once every 10 min.). These were the periods when the observed inside temperature deviated significantly from the required temperature T_{RV} . A typical maximum deviation was about 2 K for a period of about 4 min. The two greenhouses responded similarly to the control and, overall, the results are satisfactory considering the fact that the ventilation could not be adjusted continuously.

To illustrate this last point, consider the process equation during ventilation (Equation(7-17)). The derivative of Q with respect to T is

$$dQ/dT_{RV} = -GaS_0/(T_{RV} - T_0)^2 \quad (7-30)$$

Under the conditions of the example the value of the derivative is of the order of $dQ/dT_{RV} = -0.01 \text{ m}^3/\text{m}^2\text{sK}$. This means that one ventilation stage, which is equivalent to $0.0245 \text{ m}^3/\text{m}^2\text{sK}$, may produce, under these conditions, a temperature change of over 2 K. Therefore it seems that under fluctuating conditions a deviation of 2 K for a few minutes is not excessive.

The second example, Figure 7-3, covers a period of 40h, including two days and one night. The values are 20 min. averages of the following variables:

Figure 7-3A - The minimum permissible temperatures in the two mini-greenhouses; the recommended inside day-time temperature (the same for both greenhouses); and the actual inside temperature in each of the greenhouses. Figure 7-3B - the value of the integral I in the two greenhouses. Figure 7-3C - the relative rate (as a fraction of full rate, 200 W/m for the heaters and $0.0735 \text{ m}^3/\text{m}^2\text{s}$ for the fans), at which the fans and heaters were operated in greenhouse 2.

The total time may be divided into day-time, during which the recommended temperature was expected to be followed, and night-time, during which the fans were not operated at all and the heaters were turned on only when the need arose. Figure 7-3A shows that normally the deviation from the required temperature during the day was less than 1 K. An exception can be found towards the end of the second day. At night greenhouse 1 was permitted to

cool down to 8°C and required no heating. Greenhouse 2 was kept within ± 0.5 K from the 12°C required temperature for most of the time.

Figure 7-3B shows that the value of the integral I may increase indefinitely if the actual temperature is not forced to follow the recommended temperature. At night the recommended temperature in greenhouse 1 served actually only as a minimum temperature. To prevent the integral from reaching extreme values under such conditions, it was restricted to 3600 Ks.

Another restriction on the integration of I had to be placed whenever the fans or heaters reached their maximum capacity, but could not maintain the required temperature. In such cases the integration was stopped for as long as this condition lasted. An example is the time around noon of the second day. As can be seen in Figure 7-3C, while the fans operated at full capacity, the integral did not change.

There are two periods of time, shown on Figure 7-3B, when the value of I seems to be steady enough to enable estimation of the errors in U and in a. The first period is about noon of the first day, when the value of I is about -1500 Ks. The second is at night for greenhouse 2, the value of I for that greenhouse being about +1900 Ks. When correction of U and a according to Equations (7-16) and (7-22) is attempted, the corrections (e.g. $U''-U'$), are almost as large as the original values (e.g. U'). These large corrections may be locally applicable, but if introduced into the algorithm may result in instability. Perhaps just a fractional correction (say 20% of the calculated one) should be applied. Over a few days time a better average value of U (and perhaps even of a) may be obtained by this method.

The main reason why an absurdly large correction for U was obtained in the present example is that $T_{RH} - T_0$ during the night under consideration was small.

CONCLUSION

The application of a modified PI control algorithm to a mini-greenhouse, with air conditioning equipment possessing a quick response time and a small number of stages, seems to be successful.

The deviations from the required temperature were usually small ($\pm 0.5K$), except when the power requirement exceeded the rated power.

The additive term M in the control equation could be estimated by means of a simple model of the process. The values of the coefficients W and R had to be obtained by trial and error, but were not critical.

Under conditions of high heat requirement at night, the value of the integral I may be used in a learning process through which the value of the transfer coefficient U could be improved with time.

7-4. SELF LEARNING OPTIMAL CONTROL

In Section 7-3 it was shown how the integral I could be used to test whether the underlying energy balance is sufficiently accurate to be useful. It has also been suggested that a systematic deviation could be corrected with time. Those results are applicable whenever the set-point of a thermostatic control is predetermined and fixed. When optimal control (in the sense of Chapters 2 and 3 and Section 7-2) is considered, a learning algorithm should be able to re-optimize each time an error in the models is detected.

To illustrate this point suppose that the transfer coefficient U was originally underestimated. During operation it soon becomes apparent that more heat is required to maintain a certain temperature than was originally calculated. If the newly estimated U value is introduced into the optimization scheme, it is likely that a somewhat lower set-point for heating will emerge. The general model (Chapters 2 and 3) requires a re-optimization by a main-frame computer. Simpler models, however, may perhaps be re-optimized on-line by the greenhouse micro-computer. A suggestion, based on the model of Chapter 6, will now be briefly described.

The recommended temperature set-point T_n (Equation (6-25)) is given by

$$T_n = T_o - K + \sqrt{(T_o - T_{nx} - K)^2 - 1/b} \quad (7-31)$$

where $K = J/U$ (7-32)

T_o is the outside night temperature, T_{nx} is the physiologically optimal night temperature, b represents the temperature sensitivity of the crop, and J is a constant parameter.

The heating requirement used to produce Equation (6-18) is

$$H = mU(T_n - T_o) \quad (7-33)$$

where H is the heating rate per unit floor area and m is the cover to floor surface ratio.

After having operated the greenhouse on the assumption that $U=U'$ for some time (perhaps a few days), an new estimate of U'' can be determined from measured values of H and $T_1 - T_o$

$$U'' = \int H dt / [m \int (T_1 - T_o) dt] \quad (7-34)$$

A correction to the original value could then be carefully made by setting the new U value to $U' + f(U'' - U')$, where f is a fraction (perhaps 0.2). The new value of U could then be introduced into Equation (7-31) via Equation (7-32), to produce a new set point T_n .

The procedure just outlined is simple enough to be implemented by a micro-computer, if a continuous record of T_1 , T_o and H is available.

7-5. REFERENCE

Gieling Th. H. 1980. Commercial greenhouse computer systems: Inventarisation of implemented research, carried out by commercial firms. Acta Hort. 106:59-66.

7-6. LIST OF SYMBOLS

Main Symbols

a - heating efficiency of solar radiation -
 B - Bowen ratio -

b - crop sensitivity to temperature	$1/K^2$
c - specific heat of air at constant pressure	J/kgK
D - distance between 2 sets of outside conditions	$\$/m^2[\text{floor}]s$
f - coefficient of proportional correction	-
G - $B/\rho c(B+1)$	$m^3 K/J$
H - heat flux from heater	$W/m^2[\text{floor}]$
I - integral of $T_{RH} - T_0$ with time	Ks
$\underline{I}$ - vector of inside environmental conditions	*
J - KU	$W/m^2[\text{cover}]$
K - thermo-economical parameter	K
M - constant term in control equation	*
$\underline{M}$ - vector of level of operation of air-conditioning equipment	*
m - cover to floor area ratio	-
n - number of elements	-
$\underline{O}$ - vector of outside environmental conditions	*
Q - ventilation discharge per unit area	$m^3/m^2[\text{floor}]s$
R - coefficient of integral-control term	*
S - solar radiation flux	$W/m^2[\text{floor}]$
$\underline{S}$ - sensitivity matrix	*
t - time	s
U - overall heat transfer coefficient through cover	$W/m^2[\text{cover}]K$
$\underline{V}$ - extrapolation matrix	*
W - coefficient of proportional-control term	*
ρ - density of air	kg/m^3

Notes: - indicates a dimensionless entity

* indicates that units vary according to the
specific item under consideration

Subscripts

H - during heating
I - of inside conditions
i - inside greenhouse
j - jth set
M - of air-conditioning equipment

n - inside at night
O - of outside conditions
o - outside
r - recommended set-point for inside conditions
R - of representative sets
s - of closest representative set
V - during ventilation
x - for maximum production

Superscripts

T - transpose of a matrix
' - first approximation
" - second approximation

BLOCK DIAGRAM

Figure 7-1A. Schematic of Technion control system. General block diagram.

Figure 7-lB. Schematic of Technion control system. Peripheral card for Apple.

Figure 7-1C. Schematic of Technion control system. Junction box on greenhouse.

Figure 7-lD. Schematic of Technion control system. Controller for greenhouse.

Figure 7-1E. Schematic of Technion control system. Electric wiring diagram.

Figure 7-2. Results of PI temperature control.

Figure 7-3A. Required and actual air temperatures.

Figure 7-3B. Variation of I with time.

Figure 7-3C. Heating and ventilation levels in Greenhouse 2.

Chapter 8: AN ATTEMPT AT OPTIMAL OPERATION

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8-1. INTRODUCTION

In previous chapters the various components of an optimization method for greenhouse operation have been developed. In Chapter 2 the methodology was laid out; In Chapter 3 the day-time optimization process was simulated; In Chapter 5 the response of the tomato plant to day-time conditions was explored; In Chapter 6 the optimal night temperature for tomato seedlings was determined. Finally, in Chapter 7 the system by which the actual control was achieved was described. Once these components were available, a demonstration of the operation of the complete system became feasible.

In the present chapter an experiment is described, which purpose was to 'go through the motions' of the whole optimization process, starting with the preparation of control tables for the micro-computer, then developing a control program, operating simultaneously two mini-greenhouses under two different control programs, growing tomato seedlings for a period of about two months and finally analyzing the economic outcomes of the two treatments.

The basic difference between the two treatments was in the minimal night temperatures permitted, namely 8°C and 12°C. The better treatment would be that which would yield a given size of seedlings for the smaller total (fixed and running) costs. Obviously just two treatments without replications cannot give real result, especially not close to the optimum. The purpose of the exercise was, accordingly, to check whether technically the whole system works and to demonstrate how the various calculations are to be made.

On top of the limitation on accuracy due to the limited size of the experiment, two other problems were present: (1) The growth models available (based on Chapters 5 and 6) were rather crude, and (2) Tomato seedlings are not very sensitive to low night temperatures (for instance compared to roses). As a result the two treatments were not very different from one another. On top of

this the climatic conditions during the experiment were such that the full difference of 4 K between the treatments could not be achieved.

With these limitations in mind the experiment will now be described with emphasis on the growth response and the economic significance of the results.

8-2. PROCEDURE

Environmental Control

The main-frame IBM/370 computer was used to produce the control tables that the greenhouse micro-computer requires. These tables were based on a growth function for tomato seedlings, on the thermal properties of a commercial greenhouse and on the cost of energy in Israel. The day-time growth function was based on the results of Chapter 5 and the selection of the night temperatures was based on the analysis of Chapter 6.

The experimental greenhouses were only equipped with hot-air heaters and fans, which never have to operate simultaneously in the Israeli climate. As a result, there was no need for flux control (Section (7-2)), and a relatively simple thermostatic control (Section (7-3)) was sufficient. The required air temperature was set in the following manner: The recommended inside temperature from the operation tables (as prepared by the main-frame computer), was plotted against the most important outside conditions: Solar radiation (S_0) and air temperature (T_0). By means of a curve fitting technique the recommended temperature (T_r), was expressed as a function of S_0 and T_0 :

$$T_r = T_0 + 1.56 \ln \{ (S_0 - 75) / [0.625(T_0 - 8)^2] \} \quad (8-1)$$

To this relationship two constraints were added:

$$\text{whenever } S_0 < 100 \text{ W/m}^2 \quad \text{then } T_r = T_0 \quad (8-2)$$

$$\text{at all times} \quad T_0 < 20^\circ\text{C} \quad (8-3)$$

Once every 2 minutes the outside conditions, S_o and T_o , were measured and used in Equation (8-1) to yield a value of T_r . The values of S_o , T_o and T_r were then used in Equation (7-8) or (7-19) to yield a new value of M (Chapter 7). Finally, the measured value of the actual inside temperature (T_i) was used together with T_r and M in the PI control equation (such as (7-3)), to produce a value for the heat flux H or the fan discharge Q . Examples of how the actual inside temperature followed the recommended temperature are shown in Figures 7-1 and 7-2A. Figure 7-2A shows how the two greenhouses had practically the same temperature during the day, while at night the minimum temperature was 8°C for one of them (henceforth 'cool' greenhouse) and 12°C for the other ('warm') greenhouse.

Crop

Tomato seedlings (cv F-104) were grown in single polyethylene covered mini-greenhouses (Chapter 4), from sowing on 28 February 1983, to final harvest two months later. The seedlings were grown in Speedling trays with density of 125 cells per 1 m². The volume of each cell was 270 cm³, and the growth medium was a 1:1 mixture of sphagnum peat and coarse (No. 4) perlite. A slow-release fertilizer (Osmocote, N:P:K=14:6.1:11.6) was added to the growth medium at a dose of 2.5 g/l. Plants were irrigated daily by mini-jets in excess, to prevent salinity buildup.

The greenhouses were kept at a constant air temperature of 26°C during the first 10 days after sowing, to facilitate germination. After germination, half of the trays were exchanged between the two greenhouses, to make sure the treatments started with statistically the same material in each greenhouse.

Plant samples were taken every few days, beginning on the 13th day from sowing. In each sampling 40 plants, 1 per tray, were harvested. The harvested shoots were individually weighed, their leaf area determined by means of a leaf area meter (Hayashi Denko, Japan), and oven dried at 65°C for 48 h. The dried shoots were weighed as a combined sample to determine the dry matter content.

8-3. RESULTS AND DISCUSSION

Growth

Table 1 shows cumulative results of fresh weight, dry weight, leaf area and temperature exposure (in degree-hours above 8°C). The results of the temperature exposure show that the difference between the treatments was far from what it could have been under colder outside conditions. The difference of 460 Kh between the temperature exposures of the two treatments is equivalent to only about 0.8 K on the average during the night (rather than 4 K).

Figure 8-1 shows the cumulative dry weight for the 2 treatments, normalized with respect to the dry weight on the 13th day. The figure shows that the growth was almost exponential up to about the 45th day (from sowing), at which time the leaf area ratio was approximately 0.7. At that time the warm treatment had an advantage of about 2 days over the cool treatment, this being about 5% of the time from germination to harvest.

Figure 8-2 shows the same dry weight results, but this time as a function of temperature exposure. The figure shows an almost perfect exponential growth up to 7000 Kh, which is achieved around the 50th day. The results of the two treatments fall practically on the same curve, and this, if repeatable, may indicate that the temperature exposure is the limiting factor of the growth process under the conditions of the experiment.

Economic Evaluation

If the data of Figures 8-1 and 8-2 are considered to be correct, the economic evaluation of the results is as follows: Consider the cool treatment to be the standard treatment, and a dry weight of 425 mg/shoot (Table 8-1) to be the standard harvest dry-weight. It follows that the standard harvest time is day 48, and the standard growth period under comparison (beginning on day 13) is 35 days. The warm treatment required only 33 days to achieve the same crop.

The fixed costs per day on a unit floor basis in commercial greenhouses in Israel is about $0.078 \text{ \$/m}^2\text{d}$. The cost of heating in the cool treatment turned out to be negligible compared to the fixed costs (less than 0.1%). The cost of heating in the warm treatment, if applied in a commercial greenhouse, is calculated as follows:

The total exposure difference during the 35 days between day 13 and day 48 was 380 Kh. Averaging over that period, one obtains a mean exposure per day of $E=39000 \text{ Ks/d}$. The cost of heating is then calculated in the following manner:

$$C_h = cmUE = 9.8E-9 \times 1.6 \times 7 \times 39000 = 4.3E-3 \text{ \$/m}^2\text{d}$$

The total cost of operation for 35 days of the cool treatment is thus

$$C_c = 35 \times 0.078 = 2.73 \text{ \$/m}^2$$

while the total cost of operation for 33 days of the warm treatment is

$$C_w = 33 \times (0.78 + 0.0043) = 2.72 \text{ \$/m}^2$$

This result shows that both treatments are economically equivalent, as long as the price of the produce is constant with time. If the price of the seedlings decreases with time along the season, or if a penalty is to be paid for delay in delivery, it is advisable to adopt the warm treatment. On the other hand, if the price of seedlings increases with time, it is advisable to cut the heating and let the seedlings grow more slowly.

8-4. LIST OF SYMBOLS

<u>Main Symbols</u>	SI Units
C cost of operation	*
c cost of energy	\$/J
E temperature exposure difference	Ks/d
M constant term in control equation	*
m cover to floor area ratio	m^2/m^2
S solar radiation flux	W/m^2
T temperature	K
U heat transfer coefficient across cover	W/m^2K

Note: * indicates that units vary according to the specific item under consideration.

Subscripts

c	cool treatment
h	heating
i	inside (actual)
o	outside
r	recommended
w	warm treatment

Table 8-1: Cumulative growth and temperature exposure for two groups of tomato seedlings.

Day from Sowing	Sampling Date	Min. Night Temp. = 8°C				Min. Night Temp. = 12°C			
		Fresh Weight mg	Dry Weight mg	Leaf Area cm ²	Temp. Exp. Kh	Fresh Weight mg	Dry Weight mg	Leaf Area cm ²	Temp. Exp. Kh
13	13 MAR	22	3.9	-	0	21	3.8	-	0
20	20 MAR	68	7.9	1.2	950	65	7.6	1.1	1150
27	27 MAR	236	17.9	5.5	2070	222	18.6	4.7	2400
34	3 APR	615	50.2	15.0	3730	769	66.3	19.2	4050
39	8 APR	1482	139.6	38.0	4810	1529	152.4	39.5	5140
45	14 APR	2315	285.4	54.0	5910	2900	393.9	68.2	6280
48	17 APR	2898	425.2	67.1	6580	3040	476.4	68.0	6960
55	24 APR	4300	788.6	79.4	7920	4850	897.1	89.5	8380
59	28 APR	5554	888.1	-	8940	6217	1012.4	-	9400

Values in table are cumulative per plant up to indicated date. Temperature exposure accumulates from end of germination stage and above 8°C.

Figure 8-1. Seedlings' dry weight (relative to their weight when the treatments were applied), as a function of time, for the two treatments.

Figure 8-2. Seedlings' dry weight as a function of temperature exposure (the integral of temperature above 8°C with time).

Chapter 9: STRATEGIES FOR CONTROLLING GREENHOUSE THERMAL SCREENS

L. S. Marsh, L. D. Albright and R. W. Langhans

9-1. INTRODUCTION

Thermal screens can significantly reduce heat energy consumption in greenhouses (White et al., 1980). This energy savings is a result of increased insulation when the thermal screen is closed and is accompanied by a reduction in light illuminance. Economically, the best time to open or close a thermal screen is when the potential gain from heat conservation when closed equals the potential gain from photosynthesis when open.

Seginer and Albright (1980) indicate that the savings due to a thermal screen can be increased by approximately 6% when the screen is operated on a radiation level basis rather than a time clock basis. They conclude that if a mechanized screen already exists, "its performance can be significantly (not dramatically) improved by adding a radiation control system, which cost is probably the same as the cost of a timer." Their statement is based on a calculational study.

The research reported in this paper was initiated to determine experimentally the relative economic merits of four thermal screen control strategies.

9-2. MATERIALS, METHODS AND EXPERIMENTS

Two identical double polyethylene-covered greenhouses (7.3 x 14.6 m) with Cornell's multilayer thermal screen (Farrell, 1980) were used for this experiment. Four screen operating strategies were compared:

- 1) Time clock operation
- 2) Opening when the light level reached 30 W/m^2 under the greenhouse covering, and closing when it fell below 30 W/m^2 in the afternoon
- 3) The light level for opening and closing was a linear function of the outside temperature, requiring 30 W/m^2 under the covering at 0°C outside temperature and 0 W/m^2 at 15°C outside temperature. The curtain remained open if outside temperature exceeded 15°C .

- 4) The light level for opening and closing was a linear function of the outside temperature, requiring 50 W/m^2 under the cover at 0°C outside temperature and 0 W/m^2 at 15°C outside temperature. The curtain remained open if the outside temperature was above 15°C .

The screen operating times for the time clock treatment were 8:00 A.M. and 5:00 P.M. November through February, 7:30 A.M. and 5:30 P.M. in March and 6:30 A.M. and 6:30 P.M. in April. These times were chosen to operate the screen within 30 minutes of sunrise and sunset. Constraints were added to the light level treatments to insure that the screen operated only once daily on partly cloudy days. These constraints were:

- 1) Once the screen opened it was not allowed to close earlier than three hours before sunset.
- 2) Once the screen closed it was prevented from opening until the next day.

Testing four operating strategies in two greenhouses necessitated a randomized incomplete block experimental design, time of year being the blocking factor. Each thermal screen operating strategy appeared in each greenhouse, paired with every other strategy. This resulted in twelve incomplete block tests. The tests began in November 1982 and ended in April 1983.

A Hewlett-Packard 85 computer and 6904B multiprogrammer controlled operation of the greenhouse thermal screens, the environmental control equipment (vents, fans and heaters), and served as a data acquisition system. Environmental parameters (air temperature, soil temperature, and light level) were monitored every 30 seconds and 15 minute averages of these values were recorded. Also the length of time that each piece of equipment operated in the 15 minute period was recorded. The heaters were electric, allowing conversion from minutes of operation to energy consumed.

The test crop was lettuce (*L a c t u c a S a t i v a* L. c. v. Grand Rapids). The seeds for the test crops were separated on an air stream to obtain uniform seed weight. Cornell peat-lite growth media was placed in 10 cm pots. The pots were filled to level. Six seeds were placed in each pot.

The plants were all grown for fourteen days in a glass house, with fluorescent tubes 50 cm above the pots added to supplement the low winter light. The air temperature was 20°C, 15°C night (8:00 A.M. day, 5:00 P.M. night). Each pot received 50 ml of one half strength Hoagland solution every four hours.

The lettuce plants for the first eight test sequences were transferred to their respective treatments at fourteen days from seed. Five plants were sampled at this time; the leaf area was determined with a Licor model 3100 area meter. The area meter was calibrated before use with a disc of known area. The accuracy was $\pm 1\%$. The samples were dried in a 70°C forced-air oven for 48 hours and weighed on an analytical balance with a .1 mg sensitivity.

Problems with the test equipment delayed the experimental sequence. Concern that the last trials would occur after the heating season ended forced a change in the experiment. The plants for the last four trials were held in the glass greenhouse under light for three weeks and were exposed to the thermal screen treatments for only one week.

Twenty plants were placed in each of the two test greenhouses. Day and night temperatures were keyed to screen operation, i.e., a 20°C day temperature was maintained when the screen was open and a 15°C night average was achieved when the screen was closed. It required several hours for the temperature in the greenhouse to decay from the day set point to the desired night set point. The computer calculated a running average of the night temperature; when the average reached 15°C the temperature was brought up to 15°C and maintained until the screen opened. The minimum allowable temperature during the "night average" phase was 10°C; however, since the temperature decay was not linear, the temperature when the 15°C average was achieved was generally about 12°C.

The plants were exposed to the treatments for fourteen or seven days; they were 28 days from seed at the final harvest. Watering continued at 50 ml of one-half strength Hoagland every four hours. The data collected during the tests included:

- 1) Total solar radiation received (measured with an Epply Solarimeter on a horizontal plane under the double polyethylene).

- 2) Temperature in each greenhouse (measured with shielded, aspirated thermocouples).
- 3) The time each thermal screen opened and closed.
- 4) The heat used by each greenhouse.
- 5) The leaf area and dry weight of the lettuce at 21 and 28 days from seed.

The lettuce leaf area and dry weight data were taken on a randomly selected five plant sample from each treatment. The average dry weight and leaf area of the five plant sample was used as the experimental unit. The plant data and heating data were analyzed separately.

9-3. RESULTS OF THE PLANT DATA

The amount of solar radiation received varied greatly from one test period to the next. Since the test crops were started under glass with supplemental light, this resulted in large differences in the initial sizes of the various test crops. Plants with a larger initial leaf area would result in larger final dry weights regardless of the effect of the thermal screen operation. Also the test periods which received the most light would be expected to produce the largest final dry weights independent of screen operation. The leaf area at 21 days from seed and the total solar radiation received during the test were used as covariates in the analysis of the growth data to remove these effects. the leaf area at 21 days accounted for 88.9% of the total variability. Total solar radiation received accounted for an additional 2.5% of the total variability. Both were significant predictors of the final dry weight ($\alpha = 0.01$).

The goal of this experiment was to determine whether screen control based on light level is economically superior to time clock control and whether light-temperature modulated control is superior to operating the screen at a fixed light level. Three treatment contrasts were considered to answer these questions:

- 1) Time clock operation vs. the average of the three light level operating criteria.

- 2) Operating at 30 W/m^2 vs. 30 W/m^2 at 0°C outside temperature.
- 3) Operating at 30 W/m^2 vs. the average of the two light-temperature modulated schemes.

There were no significant differences in plant growth ($\alpha = 0.50$) due to the different screen operating treatments. The data are presented in figure 9-1.

9-4. RESULTS OF THE HEAT DATA

The difference in the temperatures inside and outside the greenhouse, as well as the solar radiation received in the greenhouse, have a major influence on heating requirements. These factors varied over the test sequence, creating different heating demands which were independent of thermal screen control. Heating degree hours and total solar radiation received during the test period were used as covariates in the analysis of the heat data to remove these effects. Heating degree hours accounted for 83% of the total variability in the data and solar radiation accounted for an additional 2.8%.

The same contrasts as used on the plant data were tested. The time clock treatment used significantly more heat ($\alpha = 0.07$) than did the average of the light level control strategies. There was no significant difference ($\alpha = 0.5$) between the 30 W/m^2 treatment and the average of the two light-temperature modulated treatments. Likewise, there was no significant difference between the 30 W/m^2 and the 30 W/m^2 at 0°C outside temperature (light-temperature modulated) schemes. No single light level treatment used consistently less heat than any other light level treatment. The differences in the heat requirement with time clock control versus the heat requirement with light level control averaged 1044 MJ/m^2 week. The 90% confidence interval on this difference is 41 to 2047 MJ/m^2 week.

The effect of light-modulated thermal screen control on heat energy consumption is due to the extra time that the increased insulation is in place. The time clock treatment was set to open within 30 minutes after sunrise and to close within 30 minutes before sunset. The average length of time between sunrise and screen opening, and sunset and screen closing for each of the light level control strategies is presented in table 9-1. Based on this data it isn't surprising that the average heat energy requirement with light or

light-temperature modulated control is significantly smaller than the corresponding heat energy requirement with time clock control. Likewise, the lack of significant differences between the light and light-temperature modulated control heat requirements isn't surprising.

The results of this experiment support the analysis of Seginer and Albright (1980). Thermal screen control based on light level can have a small but significant economic advantage over time clock control. Also the use of the more complicated light-temperature modulated control strategy is not justified over a simple light level controller. The average heat savings of light level control over time clock control was $1044 \text{ MJ/m}^2 \text{ week}$. The average heat requirement was $21,100 \text{ MJ/m}^2 \text{ week}$. The thermal screen had been previously shown to reduce overall heating requirements approximately 60% (Farrell, 1980) when time clock control was used. Assuming this 60% reduction, the average saving was $31,700 \text{ MJ/m}^2 \text{ week}$. Light level control showed an average additional savings over the time clock control of 3.3% of the potential savings of the thermal screen.

9-5. DISCUSSION

The main effect on plant growth of screen operation is to change the amount of solar radiation received. During the time clock treatments the screen was open on the average when 98.5% (standard deviation = 0.71%) of the total light was received. The 30 W/m^2 treatment resulted in the screen being open while 97.2% (standard deviation = 1.3%) of the total radiation was received. When the 30 W/m^2 at 0°C and 50 W/m^2 at 0°C treatments were used, the screen was open for 97.9% (standard deviation = 1.2%) and 95.2% (standard deviation = 4.02%) of the total radiation received, respectively. It is not surprising with the small difference in solar radiation received due to treatments that no significant differences in plant growth were observed.

The plants were harvested at 28 days from seed and had an average dry weight of 0.28 g. Harvest weights varied from 0.08 g in winter to 0.85 g in the spring (figure 9-1). the magnitude of the experimental error term required a 0.14 g difference in dry weights to conclude at the 95% confidence level that the plants came from different populations. The lack of significance for treatment effect is possibly due in part to the small amount of growth

achieved during the test periods as a result of the low winter solar radiation received in Ithaca, NY.

These results apply only to the weather conditions received during the tests. However, during the six month period a wide range of conditions were experienced. Also the lettuce was handled as individual plants, results for a canopy could differ. The light, plant growth, and heat data is summarized in table 9-2.

9.6 REFERENCES

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Seginer, I. and Albright, L. 1980. Rational operation of greenhouse thermal-curtains. Transactions of the ASAE, 23(5):1240-1245.

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Table 9-1: Light level controlled thermal screen opening and closing data.

Screen Operating Criteria	Avg. Difference in Sunrise and Opening Time (Standard Deviation)	Avg. Difference in Closing Time and Sunset (Standard Deviation)
30 W/m ²	1.38 hr (0.99 hr)	1.38 hr (0.89 hr)
30 W/m ² at 0°C (light-temp. modulated)	1.41 hr (0.90 hr)	1.23 hr (0.89 hr)
50 W/m ² at 0°C (light-temp. modulated)	1.95 hr (1.34 hr)	1.65 hr (0.97 hr)

Table 9-2: Summary of light, heat and plant growth data.

Test No.	Treatment	Total Light Received in Greenhouse (MJ/m ² -week)	Degree-hours (°C-hr)	Heat Used (MJ/m ² -week)	Final Dry Weight (g)
1	30 W/m ²	25098.6	1220	5707.6	.150
	Time Clock			8564.6	.229
2	30 W/m ²	21997.3	1715	10403.1	.085
	30 W/m ² @0°C			13713.7	.079
3	30 W/m ²	23828.4	2840	26625.8	.084
	50 W/m ² @0°C			24598.0	.085
4	Time Clock	17745.8	3550	46536.7	.140
	30 W/m ² @0°C			33074.8	.075
5	30 W/m ² @0°C	22387.1	2705	32467.8	.122
	30 W/m ²			33279.9	.129
6	Time Clock	47546.0	3990	47625.3	.076
	30 W/m ² @0°C			38635.3	.130
7	Time Clock	37666.7	2780	28259.3	.231
	30 W/m ²			27083.4	.258
8	50 W/m ² @0°C	27388.7	1645	19184.7	.143
	30 W/m ² @0°C			26961.0	.159
9	50 W/m ² @0°C	66525.2	2075	9558.0	.519
	30 W/m ²			11028.9	.584
10	30 W/m ² @0°C	24095.7	1520	13556.5	.466
	Time Clock			17769.8	.504
11	30 W/m ² @0°C	18879.4	1800	12421.5	.389
	50 W/m ² @0°C			10467.2	.398
12	50 W/m ² @0°C	46020.0	960	5175.6	.846
	Time Clock			4047.4	.775

Figure 9-1. The variation of harvest dry weight as a function of test sequence number (effectively, harvest date). Tests 2, 3, 4 are midwinter. Test 12 ended in May.

Chapter 10: CONCLUSION

Ido Seginer and Louis D. Albright

10-1. ACHIEVEMENTS

The main objective of the project was to develop a method of optimizing the environmental control of conventional greenhouses. The original idea was intuitive and required checking and substantiating in several respects. Much of the effort was spent on experimental work, but the main stress was on the development of the methodology, rather than on supplying statistically firm quantitative results. The experimental results were used mainly to illustrate the method. This section points to the achievements, but there are still many unsolved problems, on all levels. Some of these will be mentioned in Section 10-2. In particular, we wish that the material presented in this report will convince horticulturists that the effort required to supply useful growth functions is a worthwhile one.

The main achievements in our opinion are as follows:

- 1) The optimization method, which started as an intuitive idea, was brought by way of mathematical proofs to the level of a rigorous approach. This phase of the study is reported in Chapter 2. The basic weaknesses of the method, due to several strong assumptions made along the way, were not eliminated, of course, by the mathematical proofs. These will be mentioned in the next section.
- 2) It has been demonstrated that the whole process, starting with the model, and continuing all the way to actual control of the experimental greenhouses, is technically possible and does not contain internal contradictions. All the tools necessary for implementation, hardware as well as software, are available or can be easily developed. More specifically, the following steps were carried out: The optimal Lagrange coefficient was determined for several systems (Chapter 3). Operation tables were prepared for specific cases (Chapter 8). A micro-computer based control system was assembled and

programs written (Chapter 7). Actual demonstration experiments were carried out (Chapters 8 and 9).

- 3) Useful data were collected in two areas: The response of tomato seedlings to environmental conditions (Chapters 5 and 6), and the thermal properties of greenhouses (Chapter 4). These data add to the data already available in the literature, but much more work is still required here, especially with respect to the crop response.

In hindsight it seems that the greenhouse model used in the optimization model could be replaced by the much simpler model of Chapter 4, without losing accuracy. The latter model can be calibrated in-situ and (after such calibration) is expected to produce better predictions than the original, more complex model.

- 4) It would seem from the study on optimal night temperature, that this could be one of the first applications of the model. Applying the optimization method to problems where daily (rather than shorter) time steps are considered, removes a basic difficulty. The model as it stands now cannot handle temporary storages (of, say, photosynthates) in the crop. If only daily time steps are considered, one may assume that temporary storage effects are negligible.
- 5) It was demonstrated (Chapter 9) that an analysis similar to that of the present approach, could lead to an improved operation of thermal screens. There are probably more, relatively easy, specific problems that could be located and solved by an optimizing control approach.
- 6) The simulation results for the effect of CO₂ enrichment (chapter 3) suggest that an improvement can be expected even under relatively warm conditions. It seems that CO₂ enrichment and ventilation are not necessarily mutually exclusive. The validity of the prediction made through the simulation could not be tested, but the trends indicated by the results could help in devising an intelligent enrichment strategy.

10-2. PROBLEMS AND DIFFICULTIES

It was clear from the outset that a rigorous experimental test of the proposed optimization method was not possible within the scope of the present project. As a result, an assessment of the usefulness of the method is still not possible. It is felt that any improvement over the present practice of the better growers would be restricted to about 10% saving in the production costs. Such an improvement is very important economically, but not easy to prove experimentally.

The main problem with the method is that reliable and simple growth functions are not available, even for the simplest crops. There are still controversies with regard to the best night temperature, with regard to root zone heating, as well as other topics. Not much progress in optimization can be expected before reliable short term response functions become available. Further improvement through sophistication of the crop model, and thus the overall model, will not produce more reliable predictions before better data become available.

An unexpected problem, to which much more effort was devoted than originally planned, was the in-situ calibration of the greenhouses. The unventilated greenhouses yielded consistent results for some of the parameters under experimental conditions. It is not clear, however, that these parameters can be reliably extracted in commercial installations. Some results of the model (e.g. Section 6-3), are quite sensitive to the behavior of certain coefficients of the system.

Some of the original plan of work was not carried out, mainly due to unexpected difficulties and shift of emphasis. The intended experiment of controlling both temperature and humidity at Technion was reduced to just temperature control. In hindsight a CO₂ enrichment experiment might have been a better choice. Another activity that should be continued is a sensitivity analysis of the optimization model: It is important, for example, to find how much the Lagrange multiplier changes with season, and how sensitive are the results to the various (crop, engineering, economic) parameters of the model.

10.3. LIST OF PUBLICATIONS

Accepted for publication:

Gal S., Angel A., Seginer, I. 1984. Optimal control of greenhouse climate: methodology. Europ. J. Operational Res.

Seginer, I., Raviv, M. 1984. Optimal night temperatures for greenhouse tomato seedlings. Sci. Hort.

Submitted:

Albright, L.D., Seginer, I., Oke, A., Marsh, L. Thermal calibration of unventilated greenhouses. J. Agric. Eng. Res.

In preparation:

Chapter 3.

10-4. BENEFIT TO AGRICULTURE

This research was aimed at improving the efficiency of producing greenhouse crops. The method outlined in the report could be the basis on which optimal environmental control could be developed. The general approach may be useful not only to greenhouse production, but also to other biological processes in controlled environments. Two examples come easily to mind: environmental control of broiler houses and environmental control of harvested fruit storages.

As far as greenhouse production is concerned, the situation seems to be as follows: the screen operation can be implemented right away. The application to optimal night temperature requires more data on plant response, but these data are relatively simple to obtain. The application to CO₂ enrichment is more complicated, but the predicted improvement justifies further efforts.

The main contribution of the project is in the methodology developed. It should bear fruits if the idea is picked up and tried in various situations.

10-5. COOPERATION

The cooperation took on various forms. First there was the exchange of ideas. The same general method was applied to the experimental work at both Technion and Cornell. Then there was exchange of information concerning instrumentation and methods. One paper (Chapter 4) contains data from both institutes. The cooperation within Israel, between Technion, IBM and ARO at Neve-Yaar, yielded Chapters 2, 6 and 8. Cooperation between the departments of Agricultural Engineering and Floriculture at Cornell yielded Chapter 9.

The climatic differences between the two countries contributed to the wide scope of application of the method (the model including a wet pad on the one hand and HID lamps on the other). This is desirable if generalizations are sought.

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