77

BARD

FINAL REPORT
PROJECT NO. IS-1995-91

**Optimal Environmental Control for Indeterminate
Greenhouse Crops**

I. Seginer, J.W. Jones, P-O Gutman, C.E. Vallejos

1997

Date: 10 August 1997

BARD Project Number: IS-1995-91RC

Project Title:

Optimal environmental control for indeterminate greenhouse crops

Investigators:

Ido Seginer

James W. Jones

Per-Olof Gutman

C. Eduardo Vallejos

Affiliated Institution:

Technion, Haifa, Israel

University of Florida, Gainesville FL

Technion, Haifa, Israel

University of Florida, Gainesville FL

Project start date: 1 October 1992

Type of Report: **Final**

Signature:

Principal Investigator

Signature:

Authorizing Official, Affiliated Institution

FELIX NAGGAR

MANAGER PROJECTS PROMOTION
and R & D ADMINISTRATION

Technion, Israel Institute of Technology

University of Florida

**Agricultural Engineering Department
Haifa, Israel**

**Agricultural Engineering Department
Horticultural Sciences Department
Gainesville, Florida**

**OPTIMAL ENVIRONMENTAL CONTROL
FOR INDETERMINATE GREENHOUSE CROPS**

Final Report

BARD Research Project No. IS-1995-91RC

presented by

**Ido Seginer, Technion
James W. Jones, UF
Per-Olof Gutman, Technion
C. Eduardo Vallejos, UF**

Haifa, August 1997

OPTIMAL ENVIRONMENTAL CONTROL FOR INDETERMINATE GREENHOUSE CROPS

Ido Seginer, James W. Jones, Per-Olof Gutman, C. Eduardo Vallejos

Table of contents

	page
Abstract	v
Original objectives	vi
Description of cooperation	viii
Evaluation of research achievements	viii
Summary and conclusions	xi
List of publications	xv
Part I Greenhouse models	
1 Neural network models of the greenhouse climate Seginer I., Boulard Th., Bailey B.J. (Journal of Agricultural Engineering Research 59:203-216, 1994)	I-1-1
2 Integrating biological and physical models for greenhouse environmental control Hwang Y.K., Jones J.W. (ASAE Paper 94-4577, 1994, 20 pp.)	I-2-1
Part II Crop models	
3 High temperature tomato experiments Vallejos C.E., Jones J.W., Williams F.M.	II-3-1
4 Model structure for dynamic crop-greenhouse simulations Kenig A., Jones J.W.	II-4-1
5 TOMGRO V3.0: A dynamic model of tomato growth and yield Kenig A., Jones J.W.	II-5-1
Part III Crop model reduction	
6 Developing a simplified crop model Jones J.W., Hwang Y.K., Kenig A.	III-6-1
7 Crop model reduction and simulation in reduced space Seginer I., Ioslovich I. (Acta Horticulturae 406:63-71, 1996)	III-7-1

- 8 Neural networks for dynamical crop growth model reduction and optimization III-8-1
 Ioslovich I., Seginer I.
 (Artificial neural nets and genetic algorithms. Proc. International Conf. in Ales, France. D. W. Pearson, N.C. Steele and R.F. Albrecht (Eds.). Springer. p. 352- 355. 1995)

Part IV Expert decisions

- 9 Mimicking an expert greenhouse grower with a neural-net policy IV-9-1
 Seginer, I., Hwang Y.K., Boulard T., Jones J.W.
 (Trans ASAE 39(1):299-306, 1996)

Part V Local and seasonal optimization

- 10 Sub-optimal CO₂ enrichment of greenhouses V-10-1
 Ioslovich I., Seginer I., Gutman P-O., Borshchevsky M.
 (Journal of Agricultural Engineering Research 60:117-136, 1995)
- 11 Seasonal optimization of the greenhouse environment for a simple two-stage crop growth model V-11-1
 Seginer I., Ioslovich I.
- 12 Approximate seasonal optimization of the greenhouse environment for a multi-state-variable tomato model V-12-1
 Ioslovich I., Seginer I.

Part VI Implementation

- 13 Optimal CO₂ control in a greenhouse modeled with neural networks VI-13-1
 Linker R., Seginer I., Gutman P.O.
- 14 Simultaneous control of temperature and CO₂ concentration in greenhouses VI-14-1
 Linker R., Gutman P.O., Seginer I.

Appendices

- I Steady-state greenhouse environmental model (GHENV): App-I-1
 Documentation of model
 Jones J.W., Hwang Y.K., Kenig A.
- II Documentation of TOMGRO V3.0 App-II-1
 Kenig A., Jones J.W.

Optimal environmental control for indeterminate greenhouse crops

Ido Seginer, James W. Jones, Per-Olof Gutman, C. Eduardo Vallejos

Abstract

Increased world competition, as well as increased concern for the environment, drive all manufacturing systems, including greenhouses, towards high-precision operation. Optimal control is an important tool to achieve this goal, since it finds the best compromise between conflicting demands, such as higher profits and environmental concerns.

The report, which is a collection of papers, each with its own abstract, outlines an approach for optimal, model-based control of the greenhouse environment. A reliable crop model is essential for this approach and a significant proportion of the effort went in this direction, resulting in a radically new version of the tomato model TOMGRO, which can be used as a prototype model for other greenhouse crops.

Truly optimal control of a very complex system requires prohibitively large computer resources. Two routes to model simplification have, therefore, been tried: Model reduction (to fewer state variables) and simplified decision making. Crop model reduction from nearly 70 state variables to about 5, was accomplished by either selecting a subset of the original variables or by forming combinations of them. Model dynamics were then fitted either with mechanistic relationships or with neural networks. To simplify the decision making process, the number of costate variables (control policy parameters) was reduced to one or two. The dry-matter state variable was transformed in such a way that its costate became essentially constant throughout the season.

A quasi-steady-state control algorithm was implemented in an experimental greenhouse. A constant value for the dry-matter costate was able to control simultaneously ventilation and CO₂ enrichment by continuously producing weather-dependent optimal setpoints and then maintaining them closely.

Original objectives

The original objectives are copied here in italics. Brief statements of what has been accomplished is appended to each objective.

The overall objective of this line of work is to produce a generic on-line optimal environmental-control generator for an indeterminate greenhouse crop. Such a software package, when provided with the appropriate crop, engineering and economical parameters, should be able to transfer to the greenhouse controller a set of optimal setpoints, depending on the current state of the system (crop and greenhouse), a weather forecast and the expected price for the produce.

The scope of the present study is limited to crop model improvement, methodology of computations and a demonstration of control logic. If this phase is successful, a proper experimental check of the most promising applications will have to follow. The objectives of the present study are:

- 1 *Develop a clearly-structured generic model for an indeterminate greenhouse crop.*

A newly restructured TOMGRO V3.0 has been prepared, which can serve as a generic prototype for other greenhouse crops.

- 2 *Find medium range effects of high day temperatures and low night temperatures on greenhouse tomato.*

Experiments showed the negative effects of high temperatures.

- 3 *Incorporate into the generic model best available parameter values for tomato, and compare simulation results with available experimental data.*

The new version of TOMGRO has improved coefficients, based on new data from

France and Florida.

- 4 *Simplify model and identify which of its parameters require special experimentation.*

Several model reduction methods showed independently that the state variables of TOMGRO are strongly inter-dependent. It was found that a reduction from 69 to 4-6 state variables preserves most of the information contained in the model. We did not identify the parameters in need for further investigation.

- 5 *Find a computationally economic method to obtain near-optimal temperature and CO₂ control sequences for likely weather and price scenarios. Compare with a limited number of truly optimal solutions.*

We were unable to produce a truly optimal solution, because it requires a prohibitive amount of computing resources. We did, however, develop a shortcut method, which produces good near-optimal setpoints.

- 6 *Produce a neural network (NN) control rule for on-line operation, based on solutions to a range of future price sequences.*

This task was completed even before the project was finally approved (Seginer I., Sher A. 1992. Neural-nets for greenhouse climate control. ASAE Paper No. 92-7013, 18 pp). Here we went further with applying NNs, not only to fitting a model, but by using it successfully in an optimization procedure.

- 7 *Estimate, for a warm-climate, the potential usefulness of optimal dynamic control of CO₂ enrichment, compared to fixed set-point operation.*

We found that even in warm climates, periods can be found in most days when enrichment is effective, provided that enrichment and ventilation setpoints are continuously adjusted and balanced.

- 8 *Demonstrate, through simulation and in a mini-greenhouse, how an NN or an MPC controlled system behaves and responds to imperfect models and imperfect information about the future.*

It turns out that a quasi-steady-state approach, which does not require information about the future, is good enough. An experimental greenhouse was used to demonstrate the implementation of a robust, sub-optimal, model-based control, which uses NNs to build the greenhouse model.

Description of cooperation

The two senior investigators met at least once a year for in-depth consultations regarding the state of the project and plans for the next period. The cooperating scientists on each side had at least two opportunities to meet with the senior investigator of the other group. We found these meetings, which took on the form of small workshops, very stimulating.

In addition to these discussions, the Israeli group, which was mainly responsible for optimization, depended on the US group for the supply of the basic tomato (TOMGRO) and greenhouse (GHENV) models . Queries concerning certain model components and interactions had to be answered regularly. Model modifications imposed by the optimization were conveyed back to the US group, to be included in ensuing versions of the models.

To-date we have two jointly authored papers. We plan to have another one, comparing different model reduction methods which were developed in the two groups. This, however, is beyond the scope of this report.

Evaluation of research achievements

In this section we describe what we consider the main achievements of this study. Generally

speaking, we now have a much improved version of TOMGRO, which can serve as a prototype for other greenhouse crops. We also developed a practical method for nearly-optimal control of the greenhouse climate, which was demonstrated to operate quite well in an experimental greenhouse. The following paragraphs itemize the achievements and indicate the chapters in this report which relate to the various items. The chapters are stand-alone papers, some already published, each with an abstract that can be consulted for further information.

Greenhouse modelling

- 1 We showed the usefulness of neural-networks as greenhouse models that do not require the determination of transfer coefficients. This is important when only standard measurements of the environment and of the control are available, such as in a commercial greenhouse. When the data are collected automatically, as in a computerized greenhouse, continuous adaptation of the greenhouse model is possible. (Chapters 1, 13 and 14).
- 2 An improved TOMGRO-greenhouse joint model, with heat, vapor and CO₂ balances, has been developed. The four-layer greenhouse model, which includes transpiration and assimilation rates, permits condensation on the ceiling. It turns out that the constraints on humidity have a significant effect on the control decisions and that realistic inclusion of all significant humidity fluxes is important. This model was later used in the optimization. (Chapters 2, 12 and Appendix I)

Crop modelling and model reduction

- 3 Additional data on tomato under high heat load were collected. The new data were incorporated into a radically new version of TOMGRO (V3.0). The generic nature of the new architecture can serve as a basis for models of other greenhouse crops. Certain previous mistakes were detected and corrected. A complete listing and

documentation is provided. (Chapters 3, 4, 5 and Appendix II)

- 4 We showed that the 69 state variables of TOMGRO are effectively inter-correlated, so that a few of them, perhaps 4 to 6, properly selected, may be able to represent the crop with sufficient accuracy. The selection of variables was done by intuitive aggregation, as well as by formal reduction techniques (e.g., PCA). A compact model, besides providing a more focused view of the crop's behavior, can reduce considerably the computational effort required for optimization. (Chapters 6, 7 and 8).
- 5 A method for extracting the dynamics of a system from simulated (or measured) data, by means of dynamic neural networks, was demonstrated. This approach is particularly useful when the variables of the reduced model are statistically-derived combinations of the original ones. (Chapters 7 and 8).

Optimization and control

- 6 An analysis of the effect of greenhouse dynamics on the control decisions showed that a quasi-steady-state control approach leads to nearly optimal solutions. From a practical point of view this is superior to an approach which considers the fast dynamics of the greenhouse, since a short-term forecast of the weather is not feasible. (Chapters 10 and 13).
- 7 We showed that an optimal control of the greenhouse environment requires sometimes simultaneous ventilation and CO₂ enrichment. Later, this combined operation was implemented in a controller of an experimental greenhouse. (Chapters 10, 13 and 14).
- 8 Local optimization for a complex crop model was simplified by using a single co-state variable (dry matter) to optimize CO₂ enrichment within a constrained temperature-humidity space. (Chapter 12).
- 9 The dry-matter costate was transformed in a way that resulted in an almost constant

costate throughout the season. This simplifies considerably the evaluation of the costate trajectory while still producing good solutions. (Chapters 11 and 12).

- 10 In addition to the model-based optimization, which was the main line of investigation, an attempt was made to mimic the control decisions of an expert grower. While we were unable to find suitable data sets for a complete example, a methodological approach was outlined, which has the potential of extracting growers' knowledge in an objective way. (Chapter 9).

We believe that now we can offer the greenhouse industry a new concept for greenhouse environmental controllers. Instead of setting a multitude of individual setpoints (e.g., daytime ventilation setpoint), the grower will only have to set a few 'costate' setpoints, such as 'dry-matter' costate, 'development' costate and perhaps a 'risk' costate. This higher level policy will then control, automatically, in response to the changing weather, the trajectories of all traditional setpoints. The 'dry-matter' costate (in \$/kg[d.m.]) will control heating, ventilation and CO₂ enrichment in a manner that will maximize new dry matter, but at a cost that is below the costate value. This costate is probably the most important for vegetable production. The 'development' costate will do the same to the timing of harvest, important mainly to flower growers. The 'risk' costate may take certain chances regarding the infection by botrytis, and so on.

Summary and conclusions

The main idea behind this proposal was that sufficient knowledge is now available to elevate greenhouse controllers to a more general level of control than is now practiced. Today, growers are required to set a multitude of operating points, while the computer's (controller's) main task is to maintain the environment according to these setpoints. The proposed concept is that the grower should only specify a general control policy, leaving the generation of operating points to the controller.

Two approaches have been tried: (1) mimicking an expert grower and (2) model-based optimization. Due to lack of suitable data, the first approach was only outlined, while the bulk of the effort was placed into semi-formal optimization techniques based on a crop-greenhouse model.

Since a good crop model is essential for the latter approach, a considerable effort was made to improve an established tomato crop model, TOMGRO. Experiments were carried out to extend the validity of the model to higher temperatures and the model was completely restructured to serve as a prototype for other greenhouse crops. TOMGRO was also combined with a greenhouse model, as is required for simulated system optimization.

Effective optimization with multi-state-variable crop models, such as TOMGRO, require that the model and/or the decision making procedure be simplified considerably. Both methods were used to arrive at a manageable procedure for seasonal and local optimization. The project culminated with a demonstration, in an experimental greenhouse, of a control algorithm based on the ideas of the project.

Our main conclusion from this exercise is that the proposed approach is feasible, although at the present time knowledge-based constraints must be specified where the crop model lacks intelligence. We feel that, if properly constrained, the control of assimilation rate (CO_2 enrichment and associated control) is ready to be tried in a commercial environment. The following paragraphs itemize the individual conclusions.

- 1 The new structure of TOMGRO V3.0 (comprehensive crop model) and TOMSMP (simple model) is modular, utilizing the methods used in the FSE environment. This facilitates documentation, maintenance, and replacement of components as improvements are made. The models are also structured in a generic way, so that they can be used to simulate single-stem greenhouse vegetable crops, other than tomato, by changing parameters in a data file.
- 2 TOMGRO and similar models can be reduced for environmental control purposes from

a hundred or so state variables to just a few (4 to 6). This can be done either by selecting intuitively a subset of variables, such as total dry weight and total number of nodes (leaves), or by using more formal reduction techniques, such as Principal Component Analysis (PCA) or a Neural Network (NN) with a low-dimensional bottleneck. This reduction is made possible by the strong inter-correlations between the individual variables.

- 3 Once a small number of state variables has been selected, the dynamics of the reduced system can be fitted by either mechanistic or black-box models. Both approaches seem to work quite well. The advantage of an intuitive selection of variables and a mechanistic dynamic model is that this combination satisfied the need for an intuitive grasp of the system. The black-box statistical approach, on the other hand, can produce a better fit to the original model or to experimental data, if available.
- 4 If it is desirable to retain the large original model, a short-cut optimization method, with emphasis on certain basic crop processes, can be the solution. Referring to TOMGRO, a single costate variable, namely the dry-matter costate, seems to produce good results. This may be due to the fact that timing was not critical in our case. If timing is critical, as in flower marketing, and if the developmental module of the model is able to respond to, say, the effect of temperature or photoperiod, a costate associated with the number of nodes (physiological age) may produce better results.
- 5 During the vegetative stage of growth the capture of solar radiation is limited by a small leaf area index. As a result, the dry matter costate is high for the small seedlings, decreasing rapidly as the canopy closes. We showed that by dividing the dry-matter state-variable by the sunlit leaf-area-index, the associated costate becomes essentially constant. This is very convenient for practical application. It is not likely that other variables need to be transformed in order to stabilize their costates except, perhaps, cumulative transpiration, which also depends strongly on leaf area. The costates of other plausible state variables, such as number of nodes, or cumulative degree-hours, are probably constant, at least as long as weather and prices behave

according to expectation.

- 6 It has been shown by analysis, as well as by implementation and environmental (not crop) measurements, that an optimal-control algorithm, based on a quasi-steady-state approach, is practical and useful. Optimal balancing of simultaneous ventilation and CO₂ enrichment was demonstrated to work properly. In the demonstration, an empirical NN model of the experimental greenhouse was combined with a single-state-variable crop model. There is no reason why the same technique could not be applied successfully with TOMGRO replacing the simple model, and using a constant costate of transformed dry matter (item 5). Adapting the technique to a commercial greenhouse should not be difficult.
- 7 These individual conclusions together seem to support the view that the next-generation greenhouse controllers will have just a few 'policy (costate) dials', with labels such as 'dry matter', 'development', 'flower initiation', 'botrytis risk'. The grower will be able to set these dials according to expected market prices, past weather or infection by disease, to indicate the course of action he or she would like to take. All the rest, including the continuous changing of the setpoints, will be left to the computer. This may be later combined with a fault diagnosis module, to take over more of the chores off the growers shoulders.

List of publications

- Hwang Y.K., Jones J.W. 1994. Integrating biological and physical models for greenhouse environmental control. ASAE Paper 94-4577, 20 pp.
- Ioslovich I., Seginer I. 1995. Neural networks for dynamical crop growth model reduction and optimization. *in* Artificial neural nets and genetic algorithms. Proc. International Conf. in Ales, France. D. W. Pearson, N.C. Steele and R.F. Albrecht (Eds.). Springer. p. 352- 355.
- Ioslovich, I., Seginer I. 1996. Normalized costate variable for seasonal optimization of greenhouse tomato production. *Acta Hort.* 417:87-97.
- Ioslovich I., Seginer I., Gutman P-O., Borshchevsky M. 1995. Sub-optimal CO₂ enrichment of greenhouses. *Journal of Agricultural Engineering Research* 60:117-136.
- Jones, J.W., Hwang Y.K., Seginer I. 1995. Simulation of greenhouse crops, environments and control systems. *Acta Hort.* 399:73-84.
- Linker R. 1995. Simultaneous CO₂ enrichment and ventilation of greenhouses. M.Sc. thesis, Agricultural Engineering Department, Technion, Haifa, Israel. 96 pp.
- Linker R., Seginer I., Gutman P.O. 1996. Optimal CO₂ control in a greenhouse modelled with neural networks. *Proceedings ICCTA'96* pp. 550-555.
- Seginer I., Boulard Th., Bailey B.J. 1994. Neural network models of the greenhouse climate. *Journal of Agricultural Engineering Research* 59:203-216.
- Seginer I., Ioslovich I. 1996. Crop model reduction and simulation in reduced space. *Acta Horticulturae* 406:63-71.
- Seginer I., Hwang Y., Boulard T., Jones J. 1996. Mimicking an expert greenhouse grower with a neural-net policy. *Trans ASAE.* 39(1):299-306
- Seginer I., Ioslovich I., Linker R. 1997. Optimal CO₂ enrichment of greenhouses in mild climates. *Acta Horticulturae* 443:129-135.