Development of simulation algorithms for control scheme optimization in greenhouses

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DEVELOPMENT OF SIMULATION ALGORITHMS FOR CONTROL SCHEME OPTIMIZATION IN GREENHOUSES

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ABSTRACT

This project presents the development of an algorithm predicting ambient greenhouse air conditions to be used for energy efficiency simulation and control schemes optimization. The climatic conditions considered are temperature, relative humidity, CO_2 concentration and solar radiation. The algorithm has two modes of operation, the first simulates the greenhouse while in the second the heating, cooling, humidification or dehumidification, CO_2 injection rates are calculated to maintain certain setpoints.

The algorithm is designed to be used with the TRNSYS 15 simulation software which provides the preprocessing of the weather data, as well as controller models. The model is defined by several components that describe the characteristics of each glazing surface, the plants, the floor, the equipment and the zone itself. Using this approach it is possible to simulate any greenhouse structure, provided that the required information is available.

1. INTRODUCTION

Modern greenhouses feature equipment like humidifiers, CO_2 injection units, heating/cooling systems. Since the introduction of these systems, the need for optimized performance arose. Unfortunately the dynamics of the greenhouse environment depend also on the characteristics of the crops. This makes difficult to assess various control schemes in situ, since the greenhouse would need to be off production for long periods of time – years. Therefore control schemes need to be evaluated in simulations first.

Although there has been significant research in the area of residential and commercial building modelling and analysis, little can be found about greenhouse modelling. Usually the research itself is limited to a specific aspect of the greenhouse environment, namely humidity or CO_2 [1]. The aim of this project is to develop a versatile, yet accurate model for crop-producing greenhouses.

2. MODEL DESCRIPTION

The description of the greenhouse model can be defined by three balances, namely heat, humidity and CO_2. The heat balance inside the greenhouse is influenced by the following parameters [2],[3]:

- Heat flux due to convection between the air and various surfaces (glazing, floor, plants, etc).
- Heat exchange with the outside air due to infiltration and/or ventilation.
- Radiative gains from the sun.
- Heat produced by lights, equipment, people and plants.

The latent heat balance or water balance depends on the following:

- Plant transpiration
- Water exchange with the outside air due to infiltration and/or ventilation
- Water condensation on the glazing and other surfaces
- Moisture added mechanically (dehumidifiers, misting equipment)

Finally the CO_2 balance is a function of the following parameters:

- Respiratory CO_2 production and photosynthetic CO_2 consumption

- CO_2 exchange with the outside environment due to infiltration and/or ventilation
- CO_2 injection.

3. SOLUTION DESCRIPTION

In order to solve the equations describing the heat balance, we can adapt a few simplifying assumptions, so that it will be possible to formulate them as a system of equations in the form of Eq.(1), where the C matrix is constant throughout the simulation, the Y vector contains the unknown variables, and the X vector contains the known variables that change each timestep [4]. The solution to the problem is then given by inverting the C matrix once at the beginning of the simulation, storing the inverse and then calculating the Y vector each timestep by multiplying the stored inverse with the X vector. This approach allows for increased simulation speed.

$$C \cdot Y = X \Leftrightarrow C^{-1} \cdot X = Y \qquad (1)$$

3.1 Radiative gains calculation

Before the solution of the heat balance, it is necessary to calculate the radiative gains to each surface. It can be easily shown that this problem can also be formulated like Eq.(1) and be solved in exactly the same way.

3.2. The latent heat balance

The latent heat balance can be described by a linear differential equation of the form of Eq.(2) which is solvable using the DIFFEQ function of TRNSYS [5].

$$\frac{de_z}{dt} = ae_z + \beta \qquad (2)$$

The *α, β* parameters depend among others on the transpiration rate of the plants and the vapour pressure at saturation of the zone air and the air near the cladding which themselves depend non-linenarly on the temperature. Since the heat balance also depends on the humidity ratio, we can solve the latent heat balance first using the temperatures of the previous timestep or vice versa. We opted for the first alternative.

3.3. The heat balance

Now we can proceed with the solution of the heat balance, using Eq.(3), where *HC* is a constant throughout the simulation matrix, provided that we first make the following simplifying assumptions.

- All surfaces are assumed to be black for long-wave radiation.
- The long-wave radiation exchanges are calculated based on the previous timestep surface temperatures.
- Radiative gains from lights and people are considered negligible.
- The temperature on the inside glazing surface is the same as that of outside surface.
- The zone, floor, plants, and equipment temperature variations are considered to be linear over each simulation timestep.
- The heat flux calculation due to infiltration is based on the zone temperature of the previous timestep.

$$HC \cdot HT = HI \Leftrightarrow HT = HC^{-1} HI$$

where i denotes the surface number, $i = 1$ corresponds to the zone air

HC is a matrix of heat transfer coefficients between surfaces (3)

$HT = T_i$

HI is a matrix of additional heat gains (radiative, etc)

Since the heat balance solution depends on the last estimate of the surfaces' temperatures, the error introduced by inadequate estimates can be significant in rapidly changing environments. Therefore an internal iterative procedure is used until the cumulative error in all surfaces is below a certain limit.

3.4. The CO_2 balance

The solution of this balance is not solvable by the DIFFEQ function since the photosynthetic consumption rate is not linear to the concentration of CO_2. The solution is provided by assuming a linear variation of the CO_2 concentration over each time step.

4. THE TRNSYS MODEL

The goal of this project was not only to produce a theoretical model of the greenhouse environment dynamics but also to provide the means for fast and versatile simulation of greenhouses. To accomplish this second goal the model was implemented as a component in the TRNSYS software package [5], [6].

The TRNSYS simulation environment allows complex models to be formulated by interconnecting smaller models or units. It's advantages come from the large unit library already implemented that features building models, controllers, physical properties calculators, heat exchangers, solar panels, weather generators, etc. Implementing the model as a unit of TRNSYS allows us to use the aforementioned facilities provided by the software itself.

Because of the large number of parameters, inputs and outputs needed to define the greenhouse unit (they may easily exceed 300), the model is divided into several components that each describes a part of the model, following the paradigm of the detailed building zone (type19).

The zone component is obligatory, it defines the main characteristics of the greenhouse and provides the outputs. There are also components for the floor, the equipment and the plants (only one of each allowed). Through repeated use of the glazing component all the glazing surfaces can be described. The user is also obligated to include one geometry component that includes the view factors between the surfaces for radiative transfer calculations and optionally the additional outputs component that provides additional outputs to the standard of the zone component.

4.1. Zone component

The zone component is the main component of the model and provides a description of the general characteristics of the greenhouse air zone. There are two modes for the zone component, temperature level control and energy level control. In the second mode the temperature, humidity and CO_2 are kept constant at a given setpoint and the heating, humidification and CO_2 injection demands are calculated.

4.2. Glazing component

To model the whole glazing of the greenhouse the user makes use of repeated glazing components, each of which is used to model an individual surface. Each component must be assigned a surface number from 1 to the number of glazing surfaces defined in the zone component.

In order to reduce the number of parameters used to describe the model, we used parametric approximations of the transmittance, absorptivity and reflectivity of the surfaces for various angles of incidence. Specifically the following equations were used.

$$\tau(\theta) = 1 - \frac{1}{1 + \tau_{ref} \cos\theta} \tag{4}$$

$$\rho(\theta) = \frac{1}{1 + \rho_{ref} \cos(\theta + 0{,}1)} \tag{5}$$

$$\tau(\theta) = 1 - \frac{1}{1 + \tau_{ref} \cos\theta} \tag{4}$$

$$\alpha(\theta) = 1 - \tau(\theta) - \rho(\theta) \tag{6}$$

These equations were tested against several glazing systems of the window library of the LBNL and were found to have correlation coefficients between 0.9714 and 0.9967. These are parameters that depend on the glazing material used.

4.3. Plants component

There are two ways to model the plants inside the greenhouse. The first method calculates internally the heat, moisture and CO_2 exchange between the plants and zone, while in the second method these are input to the model. The plant component is configured to allow the use of any of the two methods individually for the heat, latent heat and CO_2 gains. Thus we are able to calculate the heat flux internally and use an outside more detailed component for the calculation of the other gains.

4.4. Floor component

There are two ways to model the heat flux through the floor of the greenhouse. The first mode assumes a standard conduction resistance with known surface temperature on the other side, while the second a constant heat flux leaving the zone.

4.5. Equipment component

The equipment component is used to model the effect of the cladding, tanks and other equipment present in the greenhouse by considering them as a lumped system modelled by a single surface.

4.6. Zone geometry component

This component is used to store the view factors between all the surfaces. Since the area of each surface is known, the user needs to specify only the $f_{i,j}$ where i<j and the rest are computed internally.

5. DESCRIBING AND RUNNING THE MODEL IN TRNSYS

For the simulation of a greenhouse the user will need a number of other units. Usually at least a data reader unit will be necessary to read the weather information from a file. This information will be fed to the greenhouse model and also to a radiation processing unit and a fictive sky temperature calculator where needed. The radiation processing unit provides the beam, diffuse and angle of incidence of the solar radiation on each surface. The output data from the greenhouse can be written to a file or the screen using one of the output units provided by TRNSYS.
Also depending on the application a number of other units may be present, like heat exchangers or controllers. An example of such a model is shown in Figure 1.

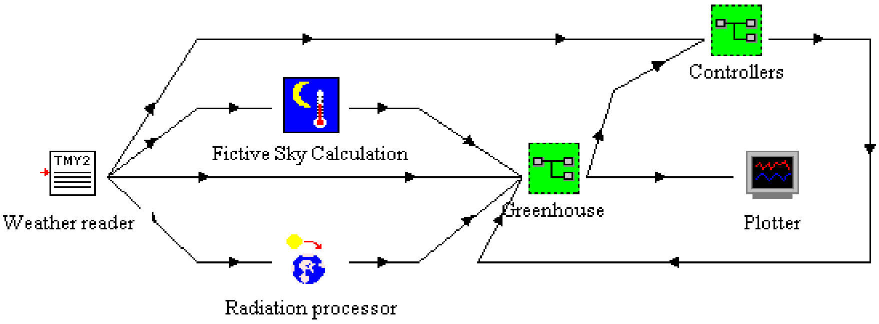

Figure 1. The greenhouse model using TRNSYS software.

6. MODEL TESTING

The model was tested by simulating a real greenhouse operated by the Mediterranean Agricultural Institite of Chania (MAICh) that is situated inside the MAICh complex in Soudha, Chania, Greece (24.15E, 35.53N). The basic characteristics of the greenhouse are summarized in the Table 1.

It should be noted also that the floor does not border with soil, since there is another zone beneath the greenhouse which houses the pumping station, the measuring station and other equipment.

Table 2 that follows summarizes the geometrical characteristics of the glazing surfaces.

Table 1. The characteristics of the greenhouse.

Greenhouse area	: 160 m^2
Greenhouse volume	: 560 m^3
Number of glazing surfaces	: 12
Glazing material	: Glass

Table 2. The geometrical characteristics of the greenhouse's glazing surfaces.

Surfaces	1	2	3	4	5	6	7	8	9	10	11	12
Area (m^2)	38.1	45.5	38.1	45.5	22.3	22.3	22.3	22.3	22.3	22.3	22.3	22.3
Azimuth	-90	0	90	0	-90	90	-90	90	-90	90	-90	90
Slope	90	90	90	90	27	27	27	27	27	27	27	27

The meteorological data available for the region of Souda were not suitable for the simulations, so TMY2 data from Richmond, VA where used instead which is almost on the same latitude and is also not very far from the sea (less than 90km).

For the first series of the model evaluation we are forced to make the following simplifications:

- There are no plants inside the greenhouse.
- The optical characteristics of the glazing and the convection coefficients between the various surfaces are evaluated based on literature.

After the installation of sophisticated measuring equipment it will be possible to accurately validate the entire model.

The results (Figure 2) show the typical rise in greenhouse temperature during the day, that reaches a maximum a couple of hours after midday. During sundown the greenhouse steadily loses heat but maintains a temperature 2-5 degrees higher than ambient during winter and 5-10 degrees during summer.

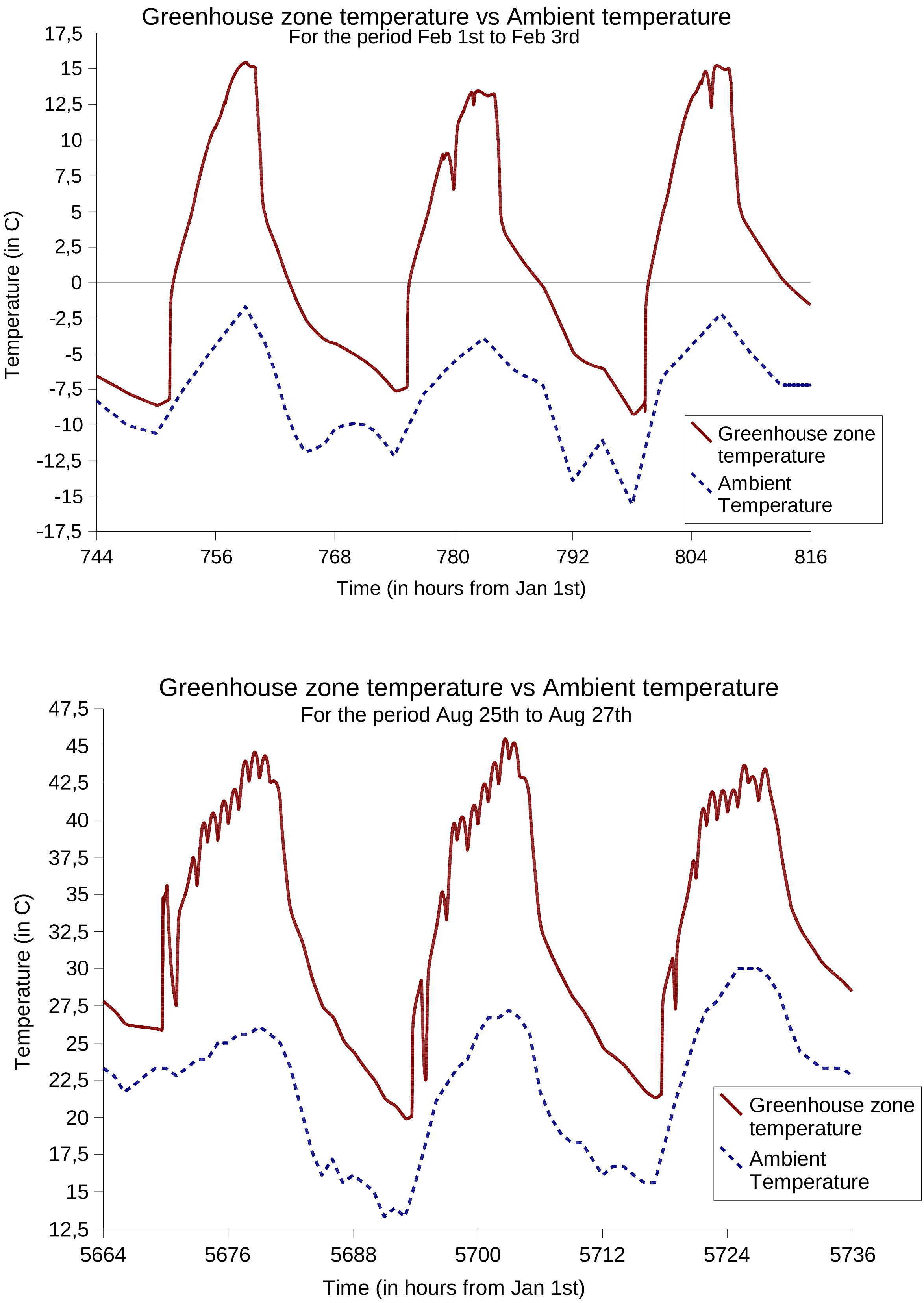

Figure 2. Greenhouse modelled temperature versus ambient temperature**.**

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