GREENHOUSE SIMULATION MODELS

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Abstract

A model is a representation of a real system to describe some properties i.e. internal factors of that system (out-puts) as function of some external factors (inputs). It is impossible to describe the relation between all internal factors (if even all internal factors could be defined) and all external factors (if also even all these factors could be defined). Therefore, before building a model, a decision has to be made about both the properties of the system that have to be known for the problem under concern and the relevant external factors. In general, the model will be a mathematical expression and will range, dependent on the application, from relatively simple single input-output models to more complicated multi input-output models. The result can be a black box model, based on curve fitting of experimental data of considered factors. Such models are interesting if only few factors have to be considered and they can be very usefull for comparative studies or for the calculation of changes of a factor instead of the absolute level of it (e.g. in optimization studies). One has to be aware that these models are only valid within the range of the experimental conditions. If one tries to understand and analyse the relation between the internal and external factors then a physical approach can be added. In this approach causal relationships are formulated between the various factors. This visualizes the link between various factors and it is a powerfull tool to analyse the system. Because one has to restrict in the amount of internal and external factors, the physical-mathematical model still is a projection of the real system. Application of this kind of models beyond the range of experimental verification seems reasonable but one has to be conspicious.
In greenhouse engineering both black box and physical models are developed, as will be discussed.

1. Introduction

In science it is common practise to develope models as a description of systems. A greenhouse structure with its equipment and crop is a complicated production system in which various phenomena can be observed. It depends on the background of the observer how phenomena are interpreted and therefore how the system is described.

A horticulturist will focus on the crop and tries to describe how this crop will produce affected by horticultural measures and blue-prints of environmental factors in a given structure. In this approach experience and intuition play an important role and overall effects are described. To understand how the crop produces, the growth-processes in the plant have to be understood and described as function of relevant factors. Therefore plantphysiology has become an important basic science in horticulture.

An engineer considers a greenhouse as a biotechnical reactor in which a crop converts carbondioxide and water, containing fertilizer, into a marketable product, with the aid of light. In the reactor environmental factors have to be realised to allow the crop maximal exploitation of the available light as factor with a major effect on production. The challange in greenhouse engineering is to design the reactor, i.e. the greenhouse, which is best adapted to the operational conditions and to develope methods through which the environment, i.e. crop growth factors, in the greenhouse can be manipulated to get the highest economical yield from the production system. In the design the range of operational conditions have to be known together with the overall production of the crop under various conditions; the problem is mainly of a static nature and the crop is considered as a known factor, of course different for various crops. In the descriptions the emphasis is on the environment in relation to the physical properties of the greenhouse. In optimization the approach can be different. If the optimization has to develope better blue-prints, then the long term performance of the crop is of interest and its description can be static. If one tries to adapt the momentaneous environment to the momentaneous needs of the crop, then the description has to be dynamic.

Both in horticulture and in engineering, descriptions, i.e. models, of relevant aspects of the system play an important role. Models in horticulture are focussed at the description of the production of the crop, in engineering they are pointed at the description of the climate in the greenhouse. In optimization studies they meet each other in models to describe the production of the crop and the operational costs. In this paper the emphasis is on the models in greenhouse engineering; crop growth models are considered as tools available from or to be developed by horticulture and plant physiology.

2. The greenhouse system

A greenhouse is a 3-dimensional structure in which a crop is grown. The structure is aimed at modifying the direct environment of the crop to control crop growth conditions. If a general description could be given it has to include all the factors that define and affect the performance of the greenhouse and the crop in all three dimensions. However, there is not a general greenhouse problem to be solved; problems have to be solved on various aspects of greenhouse operation. In the problem-solving one can focus on the particular aspect and the description of this aspect in a model. Therefore various types of models can be distinguished according to their application in engineering. Before doing so, some general characteristics of a greenhouse with crop, i.e. the greenhouse system, can be given.

Crop growth factors in the greenhouse, referred to as the greenhouse climate, are different from that factors outside due to the separation between internal and external air by the envelope and the short- and longwave radiation characteristics of the envelope. The greenhouse climate is determined by the various processes and mechanisms for the exchange of energy, water vapour and carbondioxide as indicated in fig. 1.a,b,c, for an arbitray place in the greenhouse. The installed systems for heating, ventilation, screening, CO_2 supply and watering allow manipulation of the climate in the factors temperature, water vapour pressure and CO_2 concentration. The requirements of the envelope to insulate the greenhouse interior and to allow the transmission of shortwave radiation are conflicting. Therefore these requirements compromise causing the greenhouse to be a relatively open system directly affected by the outside weather conditions. In general these conditions are highly dynamic, both on a long and short term base. The long term effects are due to daily and seasonal fluctuations, the short term effects are on a minute base and mainly due to sudden fluctuations in shortwave radiation caused by partly cloudiness.

In the greenhouse energy, water vapour and CO_2 are buffered in various parts, having dynamical effects on the greenhouse climate factors. So the greenhouse climate not only differs from the outside weather in the level of the climate factors but also in its dynamic behaviour. While so many buffers cooperate one can expect that the greenhouse system in general behaves like a system with a high order so that the dynamics of the outside weather is transformed as if it passes a complex high order filter. To estimate the effect of the greenhouse system on the various time scales of the outside weather dynamics, the effect of the various buffers in the system can be valued. This indicates which buffers have to be taken into account for calculations of the dynamics on known time scales e.g. on a minute, an hourly or a daily base.

3. Dynamic characteristics

The effect of the dynamic outside weather on the

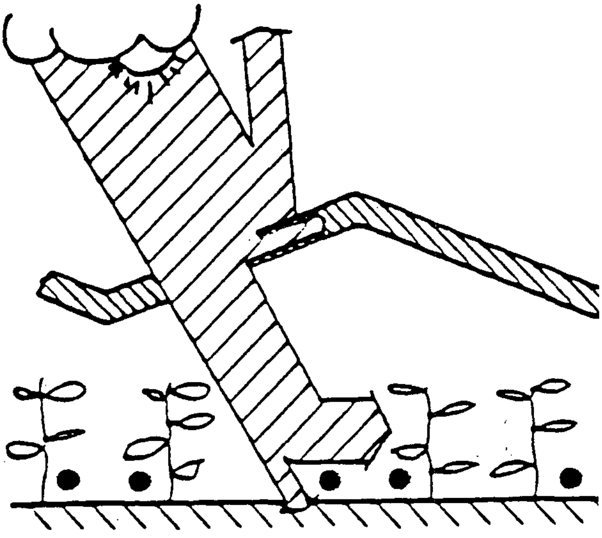

Figure 1.a Energy input by shortwave radiation.

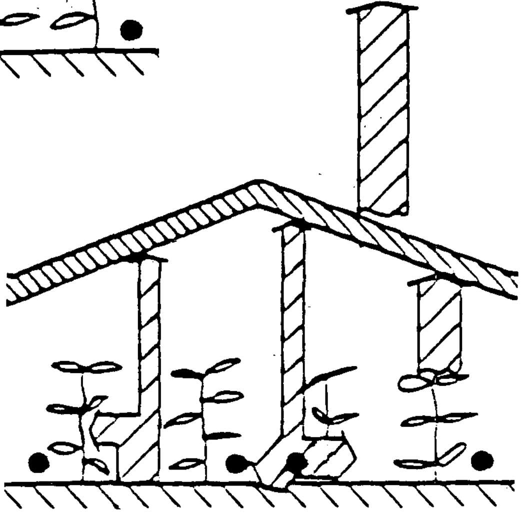

Figure 1.b Energy transfer by thermal radiation.

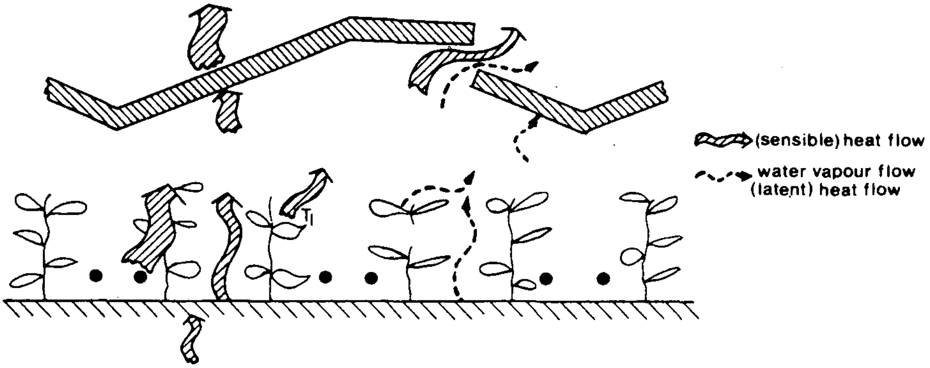

Figure 1.c Energy and mass transfer by ventilation (through openings), convection (to and from the various surfaces) and conduction (in the soil).

large time scale.

Without supposing anything on the spatial distribution within the greenhouse it can be stated that the various energy buffers are parts of the soil, the crop, the greenhouse air, the construction and the equipment. If somewhere such parts are considered per unit area then the order of magnitude of the specific time t_s of these various parts can be determined from the thermal capacity C per unit area of the considered part and the thermal resistance R between this part and the direct environment.

- Greenhouse air: thermal capacity about 3000 $Jm^{-2}K^{-1}$, resistance to the environment about 0.1 $W^{-1}m^2K$; order of magnitude of the specific time RC is 300s., so minute time scale.
- Cover 4 mm glass: thermal capacity about 10000 $Jm^{-2}K^{-1}$, resistance to the environment about 0.04 $W^{-1}m^2K$; order of magnitude of the specific time RC is 400s.,so minute time scale.
- Crop: thermal capacity per unit leaf area about 3000 $Jm^{-2}K^{-1}$, resistance to the environment about 0.05 $W^{-1}m^2K$; order of magnitude of RC is 150s., so minute time scale.
- Soil: thermal capacity for a layer with 1cm thickness about 25000 $Jm^{-2}K^{-1}$, resistance to the environment for such a layer about 0.01 $W^{-1}m^2K$; order of magnitude of RC for a layer of 1cm is 250s. So the surface layer has a minute time scale. For thicker layers both the thermal capacity and the thermal resistance increases with thickness so the time scale elongates to hours for a thickness of about 5 cm and to days for a thickness of about 15 cm.
- Heating pipes: thermal capacity per meter length of a 2" pipe about 8500 $Jm^{-1}K^{-1}$, thermal resistance to the environment about 1.25 $W^{-1}mK$; order of magnitude of RC is 10000s., so time scale of hours, especially of interest if the mixing valve is closed and the pipes cool down.

From the above it can be estimated on beforehand that the response of the greenhouse system on fast variations (on a minute time scale) of the outside weather or of other input signals, like that from the control system, are determined by the greenhouse air, the crop, the cover and the soil surface layer. The response on variations with a time scale of hours is determined by the heating pipes in the cooling mode and the soil with a first layer thickness of about 5 cm. For the effect on variations on a daily base only storage in the soil, with a first layer thickness of about 15 cm, has to be taken into account. Of course fast variations are superposed to the slow varying trend. Therefore also the response on slow varying signals has to be taken into account in a proper way if both the response on fast varying signals and the absolute level have to be determined.

various time scales can be estimated from the dynamic characteristics for energy transfer. The energy transfer in the greenhouse is between the various parts of the green-house. If the greenhouse is considered to be composed from an arbitrary amount of small components, each uniform in temperature, then the dynamic characteristic of each component can be estimated. Such a component can be considered as a simple first order system, consisting of one energy buffer, with thermal capacity C and uniform temperature T, loosing or gaining energy from its environment with temperature T_a, through a thermal resistance R.

The energy balance over the component then can be made up as:

$$C \frac{dT}{dt} = - \frac{1}{R} (T - T_a) \tag{1}$$

with e.g. at t=0, $T = T_i$

The solution of the step-response can easily be found as

$$\frac{T - T_a}{T_i - T_a} = \exp(-t/RC) \tag{2}$$

This response is represented in fig. 2.

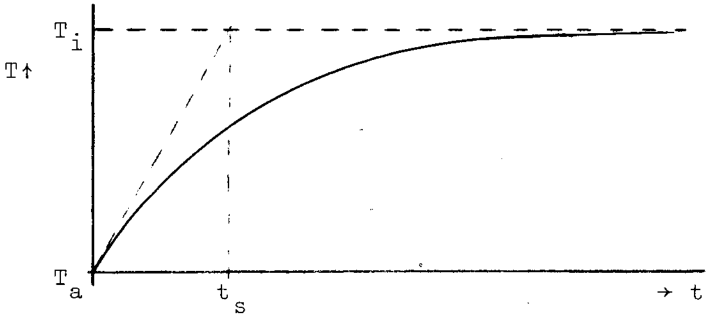

Figure 2 Step response of a first order system.

The combination RC determines the time at which the temperature difference with the environment is 1/e of the initial temperature difference. Therefore RC is called the time constant of this simple first order system and can be referred to as the specific time t_s of the system. The system responds to varying environmental temperatures with a time scale in the same order of magnitude as the specific time. An estimation of the specific times of the various components or subsystems answers the question which parts of the greenhouse determine the response to variations with a small time scale and which parts to a

4. Various approaches in modelling

From the simple analysis of the dynamic characteristics of the greenhouse system various approaches in greenhouse modelling can be commented. These approaches range from single input - single output black box models to complex physical models in which various physical processes are incorporated. The choice for a particular approach is given by the application one has in mind.

4.1. Physical models

As stated before, the greenhouse system is a complex 3-dimensional system in which various coupled energy- and mass-transfer processes determine the dynamic and static behaviour. The representation of all homogeneous components of the system and the accurate description of all exchange processes between these components would be needed to simulate the physical behaviour of the greenhouse in a proper way. This approach is restricted by both the capacity of the available computer systems and by the fact that the descriptions of most exchange processes are empirical and not fundamental.

The exchange processes are characterized in heat- and mass-transfer coefficients. The dependency of these coefficients on the flow field, physical properties of the medium and the geometry is expressed in relations between various dimensionless numbers like Nusselt (Nu), Reynolds (Re), Grasshoff (Gr) and Prandtl (Pr) for convective energy transfer. The relations are constructed using dimension analysis and the unknown coefficients have to be validated by experiments. This implies that the relations have a restricted accuracy and can only be used within the same range of experimental validation at the same conditions as in the experiments. In general transport physics literature, transport equations are reported which are validated under laboratory conditions, so in an environment that can be strictly controlled to allow the variation of one factor at a time. In a greenhouse the experimental conditions differ, so the descriptions of the exchange processes have to be validated under greenhouse conditions.

Also the problem to represent the complex 3-dimensional system is not easy to solve. However in most cases one is interested in the dynamics of a representative spatial average of the greenhouse climate affected by the dynamics of the inputs or in the static 3-dimensional distribution of the climate factors affected by the spatial distribution of the boundary conditions including heating pipes or heating system. Attempts are known (Nara, 1979, Den Hartog, 1988) to represent the spatial distribution in a 2- or 3-dimensional grid of nodal points and to solve the set of energy, mass and momentum balances in the nodal points, the so called Navier-Stokes equations. However, only very simplified greenhouse geometries can be tackled nowadays in this way due to the limited capacity of computers. The new generation of super computers opens new possibilities for these calculations, but this is a very expensive excercise for specialists only.

If the interest is in the overall dynamics, it is common practise to reduce the 3-dimensional greenhouse to a 1-dimensional system (e.g. Van Bavel et al., 1985), in which the soil, crop, greenhouse- air and cover are considered each in one or more homogeneous layers. Between these layers the various exchange processes have to be considered, also representative for the real spatial average situation. In section 4 it was concluded that the energy buffering in the crop, the greenhouse air, the cover and the soil surface layer determines the response of the greenhouse climate on fast varying signals. The simulation of the spatial average greenhouse climate on a small time scale needs the proper representation of these buffers, moreover the transport resistances between the components have to be described in a proper way. Most resistances are not constant but dependent on e.g. the temperature difference, outside factors like wind speed etc., as given by the empirical relations. Therefore the various exchange processes, determining the resistances, have to be described in the greenhouse situation (Bot, 1983, 1988). Calculations on a longer time scale simplify the operational conditions of the simulation model (Jolliet, 1988, a,b). The buffers to be considered for the desired time scale are also given in section 3. Moreover the time scale averages the non- constant behaviour of the resistances and for the long time scale, e.g. on a daily base, the resistances can be considered to be constant at the average operational condition. If the results are integrated over long periods, then the effects of the non-constant factors are also integrated. Considering the factors to be constant for this application, will give accurate final results (Breuer, 1985, Breuer and Van de Braak, 1988).

The application of physical models is in the analysis and design of greenhouses while insight in the underlying processes is an impetus to calculate the performance of the system under various conditions. Another application is in optimization where both crop growth conditions have to be calculated as input for crop growth models and operational costs (Challa et al., 1988). The implementation of the model in optimization algorithms mostly prescribes the representation of the model in vector notation (Bailey and Seginer, 1988, Van Henten, 1988).

4.2. Black box models

If only a few unknown factors of the greenhouse climate are of interest as a function of a few known factors, then it is not really needed to represent the various physical processes. One can define a transfer function between the unknown (output) and the known (input) factors in such a way that the response of the output on variations of the input is represented in a proper way (fig. 3).

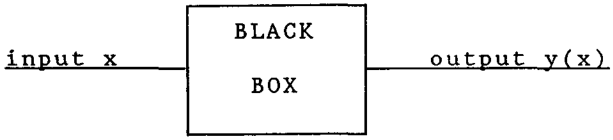

Figure 3 Black box model.

Before correlating output and input parameters, the characteristics of the dynamic behaviour can be estimated from the simple analysis deduced in section 3. The black box is a system containing a high amount of linked buffers. So the response is that of a high order system. If this high order response is compared to a first order response (fig. 4) then the high order behaviour can be simplified to a semi-first order response, characterized by a specific time t_s, activated after a period, called the dead time t_d. The dead time is determined by the order of the system, so will not vary much. The specific time will depend on the various buffers and thermal resistances involved, so will vary under various conditions. So the black box model can be constructed as a semi-first order system with dead time if the specific time is continually adapted by comparison of calculated and measured response. Another observation was made in the simple analysis: the response on variations with small time scale and on long time scale were determined by different buffers. For the small time scale the response was determined by a great amount of buffers with small specfic time and for the long time scale by a small amount of buffers with great specific time. Therefore both the order and involved buffers differ for both time scales, resulting in different dead times t_d and specific times t_s for small and large time scales (Udink ten Cate, 1983).

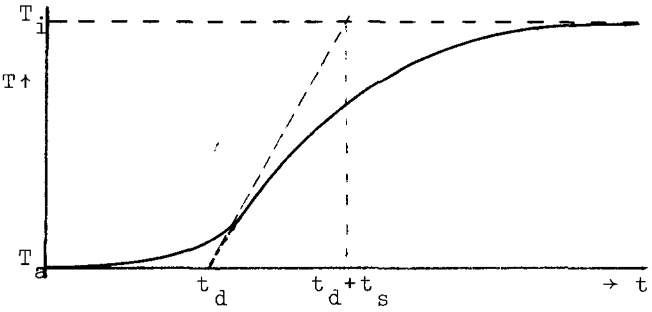

Figure 4 Step response of a high order system.

The application of black box models is in control, where relatively simple methods are needed to characterize the dynamics of a system. The emphasis of the calculations is on the changes of the observed factors and not on the absolute level.

4.3. Combination of physical and black box models

The techniques described in sections 4.1 and 4.2 can be combined if in control a systems description is needed with more than one input and output parameter. In principle between each input and output parameter a relation has to be defined. To validate these relations is cumbersome. In this case a physical analysis in general terms can lead to the choise of the relevant input-output relations. These relations can be set up in the same way as the transfer function described in section 4.2. From the comparison of a physical model and the set of transfer functions it can be concluded which physical parameters affect the various transfer functions (Udink ten Cate and Van de Vooren, 1983).

5. Conclusions

Greenhouse models are projections of some aspects of greenhouse operation. Within their limitations of restricted accuracyand validity they are powerfull tools in analysis, design, control and optimization. There is no general, ideal greenhouse model, but the various applications need their specific approach. A simple analysis can answer the question how simple or complicated the model has to be to give the desired performance.

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