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Optimisation of CO_2 and temperature control in greenhouse crops by means of growth models at different abstraction levels I. Control strategies, growth models and input data[1)]

Optimierung der CO_2- und Temperaturführung bei Gewächshauskulturen mit Hilfe von Modellansätzen unterschiedlicher Abstraktionsebenen I. Steuerungsstrategien, Wachstumsmodelle und Inputdaten

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Summary

Efficient greenhouse climate control has to consider the main factors of the complex ecological, technical and economic system. This can be performed only on the base of models. Since all models exhibit specific deficiencies, it was investigated, if the deficiencies of each of the growth models can be reduced by combining a model at high abstraction level (REGRESSION MODEL) with a model at low abstraction level (SUCROS 87).

After a review of literature knowledge of CO_2 and temperature control approaches for greenhouse climatisation, a concept of a combined on-line model has been elaborated. This model consists of the main modules PLANNING, GROWTH PREDICTION, GREENHOUSE CLIMATE and OPTIMISATION.

Input data are classified into the modules holding (crop parameters, potential climate regimes, parameters of greenhouse and site, prices for production factors, opportunity costs of greenhouse area), market (prices of the products) and outside climate. For predicting outside climate (weather) on daily basis, historical data (long term normals of Hannover-Herrenhausen) are implied. For climate data on a hourly basis a procedure was developed based on measured data.

The PLANNING MODULE comprises the PLANNING MODEL, LINEAR PROGRAMMING and empirical data. The module for GROWTH PREDICTION encloses submodels for daily growth and for hourly growth. The data of the PREDICTION MODULE used for OPTIMISATION aiming at maximisation of profit and the outputs of the GREENHOUSE CLIMATE MODULE feed the CONTROLLER of greenhouse climate, resulting in REAL GROWTH. Real growth values are fed back to the PREDICTION MODULE and in weekly intervals to the PLANNING MODULE.

The generation of the input data is reported and their uncertainties are discussed.

Zusammenfassung

Eine effiziente Klimaführung in Gewächshäusern muss die wichtigen Faktoren des komplexen ökologischen, technischen und ökonomischen Systems berücksichtigen. Dies ist nur mit Hilfe von Modellen möglich. Da alle Modelle spezifische Schwächen aufweisen, wurde untersucht, ob sich die Nachteile der jeweiligen Wachstumsmodelle durch die Kombination eines Modells auf hoher Abstraktionsebene (REGRESSIONS-MODELL) mit einem Modell auf niedriger Abstraktionsebene (SUCROS 87) verringern lassen.

Nach einem Überblick über das Literaturwissen zur CO_2- und Temperaturführung in Gewächshäusern wurde ein Konzept für ein kombiniertes Modell entwickelt. Dieses Modell besteht aus den Hauptmodulen PLANUNG, WACHSTUMSPROGNOSE, GEWÄCHSHAUSKLIMA und OPTIMIERUNG.

Die Inputdaten sind zusammengefasst unter den Modulen Betrieb (Pflanzenart, potentielle Klimabereiche, Parameter des Gewächshauses und Standortes, Preise der Produktionsfaktoren, innerbetriebliche Wert der Gewächshausfläche), Markt (Produktpreise) und Außenklima (Wetter). Zur Vorhersage des Außenklimas auf täglicher Basis wurden historische Daten (Normalklima von Hannover-Herrenhausen) verwendet, für die Vorhersage der stündlichen Klimadaten wurde ein Verfahren auf der Basis gemessener Daten entwickelt.

Das PLANUNGSMODUL enthält ein PLANUNGSMODELL, ein Modell für die LINEARE PROGRAMMIERUNG und empirische Daten. Das Modul WACHSTUMSPROGNOSE enthält Submodelle für das tägliche und das stündliche Wachstum. Die Daten des Prognosemodells gehen als Inputgrößen in das OPTIMIERUNGSMODUL mit dem Ziel der Gewinnmaximierung ein und wirken mit dem Output des Gewächshausklimamoduls auf den REGLER des Gewächshausklimas, der zum REALEN WACHSTUM führt. Die Daten des REALEN WACHSTUMS werden zum Wachstumsprognosemodul und in wöchentlichen Intervallen zum Planungsmodell zurückgeführt.

Die Generierung der Inputdaten und ihre Unsicherheiten werden diskutiert.

Introduction

Until the seventies of the last century climate control in greenhouses has been performed empirically, in the last decades supported by more experimentally based blue prints. New potentials were offered by the develop-

ment of modern control techniques and system theoretical approaches, resulting in models for prediction and control of plant growth, for greenhouse climate and for calculating economic aspects (literature see Alscher 1993).

Growth models may be based on the structurization and parameterization of long term reactions of complete plants or organs, that means at high abstraction level. These models allow for estimation of set points for duration of growth periods and/or demand relations and can be used for production planning and long term production control (KRUG and LIEBIG 1979a, 1994). They also may be used for adjustment of set points to longer or shorter periods with a minimum of 24 hours (KRUG and LIEBIG 1995). Constraints of this approach are:

– insufficient data basis, especially insufficient independence of variation of the input factors
– varying environmental rest complexes
– limitations of statistical methods to describe high degree interaction, the injury range, after-effects and feed back relationships
– shortest periods 24 hours
– variability between cultivars and the influence of special raising techniques, not considered in the data basis.

Another category of growth models may be classified as a more mechanistic approach. This aims at describing and parameterising the „basic" processes of growth, that means modelling at lower abstraction level (PENNING DE VRIES 1983; CHARLES-EDWARDS et al. 1986; THORNLEY and JOHNSON 1990; HEUVELINK 1996). Besides a better physiological understanding these models are more flexible and allow for some generalisation. Limitations are e.g.

– gaps in physiological knowledge
– the high degree of interaction inside the system
– the numerous number of parameters, which restrict or even prevent optimisation
– error propagation

These insufficiencies are expected to cause less accuracy in long term prediction compared to describing models at high abstraction level.

To overcome at least some of these disadvantages, models of an intermediate type have been worked out, as for example „SUCROS 87" by SPITTERS et al. (1989), used and simplified for modelling the growth of kohlrabi by MATITSCHKA (1995).

The option of this investigation was to develop a combined model to use the advantages of both approaches and to test, if this can be used as a conception for optimising greenhouse climate control. The basic models should be based on existing approaches and parameters, but had to be supplemented by own experiments for CO_2 and temperature control in greenhouse lettuce production.

Approaches for CO_2 and temperature control

CO_2 concentration

Research has been primarily directed to the development of blue prints to provide guidelines for „optimal" set points of CO_2 concentration over long periods, for instance the whole cultivation period, in order to increase earliness and yield (e.g. NEDERHOFF and SCHAPENDONK 1985; MANN 1986; MORTENSEN 1987).

To apply CO_2 economically ENOCH (1984) compared four methods of enrichment: constant CO_2 concentration, constant CDUE (Carbon Dioxide Uptake Efficiency, which describes the ratio between CO_2 assimilated by the crop and the CO_2 applied to the greenhouse), pulsed CO_2 enrichment (repeated cycles of a period with elevated CO_2 concentration followed by a ventilation period without CO_2 enrichment). The last one was more efficient and led to the highest CDUE under conditions in Israel.

Another strategy is intermittent CO_2 enrichment in unventilated greenhouses (MORTENSEN 1984). This method is considered to prevent long-term adaptation of crops to high CO_2 levels resulting in reduced photosynthesis and growth rates (see BESFORD 1993). Later experiments showed that continuous CO_2 supply is superior to intermittent CO_2 enrichment (MORTENSEN 1986, 1987; NEDERHOFF and VAN UFFELEN 1988).

Changing CO_2 concentrations depending on time of day (CALVERT and SLACK 1976), on opening of ventilation (WILLITS and PEET 1989) and on growth stages (KRUG 1991) are further strategies to economise CO_2 supply.

MANN (1986) quantified the effect of elevated CO_2 concentration on growth of different vegetable species, including lettuce, as a function of radiation and temperature by a descriptive, long-term growth model (PLANNING MODEL – regression type). This allowed for seasonal and climate based timing and estimating long term set points providing maximised gross margins. It also enables to calculate flexible strategies under unfavourable weather conditions, i.e. low light and temperature and high wind speed, when CO_2 loss by air-exchange is large (ALSCHER and KRUG 1988). Stopping CO_2 enrichment at a certain wind velocity or low irradiance saved CO_2. Compared to high constant CO_2 concentrations this strategy resulted in lower CO_2 costs, but depending on the season also in lower growth rates and hence prolonged cultivation periods and according to higher demands of energy and opportunity costs of greenhouse area higher total costs.

In the Netherlands more mechanistic models have been developed, controlling CO_2 supply to optimise crop photosynthesis (CHALLA and SCHAPENDONK 1986; CHALLA and NEDERHOFF 1988; NEDERHOFF 1988, 1994). These models are based on the assumption that for maximal efficiency CO_2 concentration has to be adapted to irradiance and temperature instantaneously. Each quantum of light not used by photosynthesis would be an irreversible dissipation. Therefore, marginal yields minus marginal costs have to be calculated in short intervals of time (dynamic optimisation). SEGINER et al. (1986) described a similar approach for tomato seedlings.

Temperature

As for CO_2 control traditional methods for controlling temperature are empirical set points for – may be seasonal dependent – day/night temperatures, indepen-

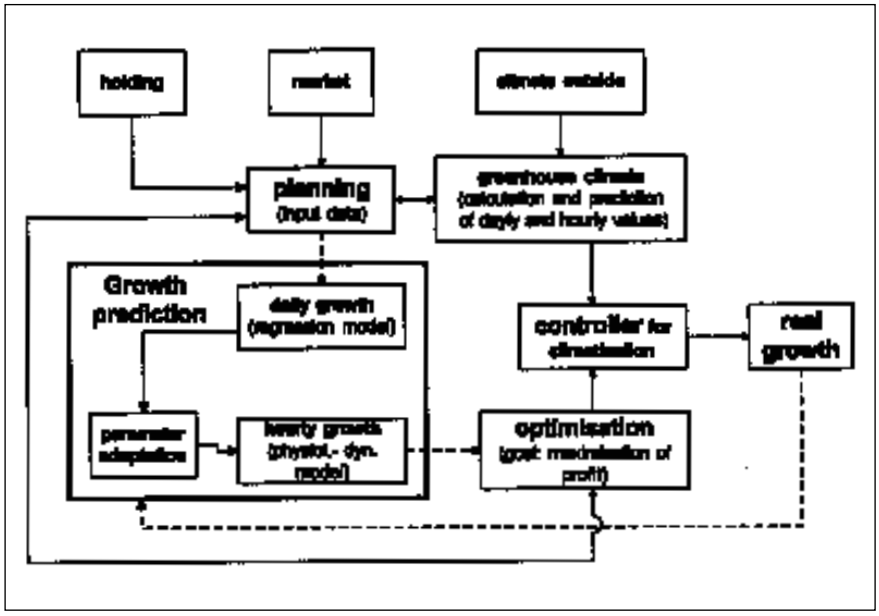


Fig. 1. Structure of the climate control system in greenhouses.
Struktur des Systems Klimaregelung in Gewächshäusern.

dent of site or weather conditions. A more environmental related procedure was worked out by using descriptive regression models as already reported for the CO_2 factor. „Optimised" set points can be estimated on the basis of maximal gross margins (KRUG and LIEBIG 1979a, 1979b, 1981, 1994; LIEBIG 1988) or by numerical optimisation (LENTZ 1987). Temperature set points can be adapted to shorter periods as well (KRUG and LIEBIG 1995).

Using thermal screens, which may effort to modify set points, or wind dependent temperature control may save energy about 5 to 10 % (BAILEY 1985). Day temperature may be adapted to the temperature of the previous day (CHALLA 1976; 1978; GARY 1989). According to WIEBE and LIEBIG (1989) heating energy may be saved by keeping a special temperature sum per period (e.g. a week) for crops, which are sensitive to vernalization, to avoid bolting despite of falling short of critical temperatures.

A model was developed for optimising temperature in greenhouses by SCHMIDT et al. (1982) and HEISSNER et al. (1986) based on a more mechanistic growth model for cucumber (AUGUSTIN and SCHMIDT 1980; HEISSNER et al. 1981). The technique used is called repetitive optimisation (HEISSNER et al. 1986).

SCHAPENDONK et al. (1984) developed a mechanistic model to optimise temperature control with cucumber. They monetarily calculated and evaluated the formation of leaves influenced by radiation and temperature as well as the energy costs dependent on radiation and wind velocity and derived the optimal set point in a cycle of 10 minutes according to potential yield minus marginal costs.

Concept of a combined on-line-model

The general structure of the control system for climate optimisation is presented in figure 1. The operation begins by **planning** the starting conditions. It is based on the PLANNING MODEL (KRUG and LIEBIG 1994) and the LINEAR PROGRAMMING MODEL (see FÖLSTER et al. 1990). Main inputs to be considered are summarised in the subsystems holding (crop parameters, parameters of outside climate, greenhouse and site, prices for production factors, greenhouse area), market (prices of the products) and outside and greenhouse climate.

Growth prediction is realised by estimating daily growth rates using the REGRESSION MODEL of KRUG and LIEBIG (1988), which is rather reliable in predicting longer periods, but due to the descriptive approach limited to a minimum of 24 hours. Simultaneously hourly growth rates are simulated by using the physiological dynamic model SUCROS 87 of SPITTERS et al. (1989). As the growth rates of the SUCROS MODEL proved less realistic than those of the regression model, they were hourly adapted to those of the regression model with meanwhile measured climate data and again adapted at the end of the diurnal cycle (see ALSCHER 1993).

The **set points for climatisation** result from the planning model and the greenhouse climate conditioned by the outside environment, the properties of the greenhouse itself and the predicted optimised values of growth. The resulting **real growth** may deviate from that predicted and has to be considered by feed back information to the growth prediction module. Once a week real growth data are fed back to on-line „optimisation" which may modify the long term (daily) set points for the remaining cultivation period.

Input data

Available data base

Crop parameters are controllable input data of cultivation, e.g. specific plant parameters (see part II), planting date, transplant weight, crop density, weight at harvest, fixed night temperature and set points for ventilation.

Greenhouse climate parameters are physical characteristics of the greenhouse and control system, such as greenhouse area and area of the greenhouse cover, coefficient of energy demand, radiation transmission,

limits such as minimum night temperature, range of set points for temperature and CO_2 concentration and others (see part II).

Outside climate (weather) conditions include global radiation, temperature, CO_2 concentration and wind velocity on daily and hourly basis, respectively. Climate control in daily intervals of time is based on means of climate from 1956 to 1983 for Hannover-Herrenhausen.

Prices for production factors, such as energy and CO_2, are relatively constant and are known at starting cultivation. In the model the price for oil is set to 0,50 DM L^{-1} and the CO_2 price is set to 0,80 DM kg^{-1}. As prices of the products are influenced by a number of external factors, prediction is difficult. For climate optimisation a range of prices for lettuce was generated based on the data collection of FÖLSTER et al. (1990), which are listed in two week intervals and used as a table function. For additional production costs, such as seed, substrate, water, fertilizers, plant protection, packing and sale 2,90 DM per m^2 are assumed.

The **opportunity costs** of the greenhouse area vary during the season and with the duration of cultivation period. Prolonged cultivation periods of the crop under control, e.g. by low ranges of CO_2 and temperatures regimes, lead to losses of profit with the following crop due to later planting time. Based on the data collection of FÖLSTER et al. (1990) the opportunity costs are integrated as a table function by taking into account expected yield and days between estimated harvest date of the crop under control and optimal planting date of the succeeding main crop (here tomato with a February planting) in the respective rotation.

Data prediction for simulation

To simulate the **climate inside the greenhouses** a great number of models have been developed, differing in complexity and option of application (VON ELSNER 1984; TAKAKURA et al. 1985). Taking into account climate control, especially prediction of daily and hourly data, approaches with only a few parameters are required.

Diffuse and direct **radiation** were separated according to SPITTERS et al. (1989). Using measured and calculated radiation data (LIEBIG, unpub.) and the inputs outlined already, the direct irradiances inside the greenhouse are simulated by means of a table function, taking into account site, greenhouse characteristics, alignment of the greenhouse, season and the diffuse fractions by a constant factor of 0,64.

For prediction of hourly outside climate conditions during the diurnal cycle, a forecast model for radiation has been developed, taking into account the course of radiation as a sinus function and actual weather data. The hourly global irradiances are calculated by:

$$R_h = R_{max} * \sin [\quad * DL^{-1} (h - 12 + (DL * 2^{-1}))] \quad (1)$$

$$R_{max} = R_{day} * (2\ DL)^{-1} \quad (2)$$

R_h = irradiance of the actual hour (Wm^{-2}), R_{max} = maximal irradiance (Wm^{-2}), R_{day} = daily sum of irradiance (Whm^{-2}), DL = daylength (h), h = hour

The hourly irradiances were calculated as percentages of the daily sums. The model for hourly prediction of irradiances is demonstrated in figure 2. At the beginning of the day the hourly irradiances are calculated by multiplying the long-term average of the day with the corresponding hourly percentage data. At the end of the hour the calculated data are replaced by the measured data and the daily radiation sum is actualised for calculating the radiation of the following hour. An example for the precision of the estimated values compared to the measured ones is demonstrated in figure 3. As the diurnal course of temperature, CO_2 concentration and wind velocity are influenced by several geographical features and processes, they do not show a strong symmetrical daily course. Therefore, the measured data of the preceding hours were used for prediction.

The 24h daily mean of **temperature** inside the greenhouse is calculated according to VICKERMANN (1969). The hourly temperature is computed by means of the k'-MODEL developed by KANTHAK (1970) and extended by DAMRATH (1980) and later on by RATH (1994, not yet considered here). This model describes thermal processes in greenhouses with one equation. As temperature of the soil and its heat storage is influenced by a great number of factors and the dynamics of this system is difficult to quantify, these factors are not yet integrated.

For optimising CO_2, its concentration inside the greenhouse is assumed to be equal to the set points. For actualisation simulated values are replaced by hourly measured and daily calculated data, respectively.

The **production factor quantities** are simulated in two submodels. The hourly **energy demand** is calculated according to the k'-MODEL of DAMRATH (1980). To calculate the quantity of energy, the energy demand per hour as well as a factor for the energy of the fuel have to be determined and integrated:

$$Oil_{qu} = qHh * f_{br} \quad (3)$$

Oil_{qu} = oil quantity per hour ($Lm^{-2}h^{-1}$), qHhh^{-1} = hourly demand of heating energy ($Whm^{-2}h^{-1}$), f_{br} = coefficient for conversion of fuel (L oil) to energy (LWh^{-1})

For daily optimisation energy demand is determined according to VICKERMANN (1969), for actualisation the same equation is used as for simulation on hourly basis to get comparable data.

For determining **CO_2 demand** the amount of CO_2 for the filling phase, CO_2 consumption of the crop and CO_2 losses to the atmosphere are integrated. CO_2 quantity for filling up to the set point was determined by weight. Simulation of daily consumption of the crop is calculated by the daily growth rate of the crop, a dry weight proportion of 4% and the parameter for the conversion of CO_2 to CH_2O. This is based on the assumption that all dry weight is CH_2O. The hourly consumption of the crop is derived by dividing by daylength. For calculating CO_2 losses to the atmosphere the air exchange rate of the greenhouse was determined by the tracer gas method (BAYTORUN 1986; MANN 1986) and estimated as a function of windspeed by means of the regression method. As respiration of the soil varies depending on the amount of organic substance, its humidity, temperature and irrigation (MANN 1986), the CO_2 rate of the soil is not taken into account.

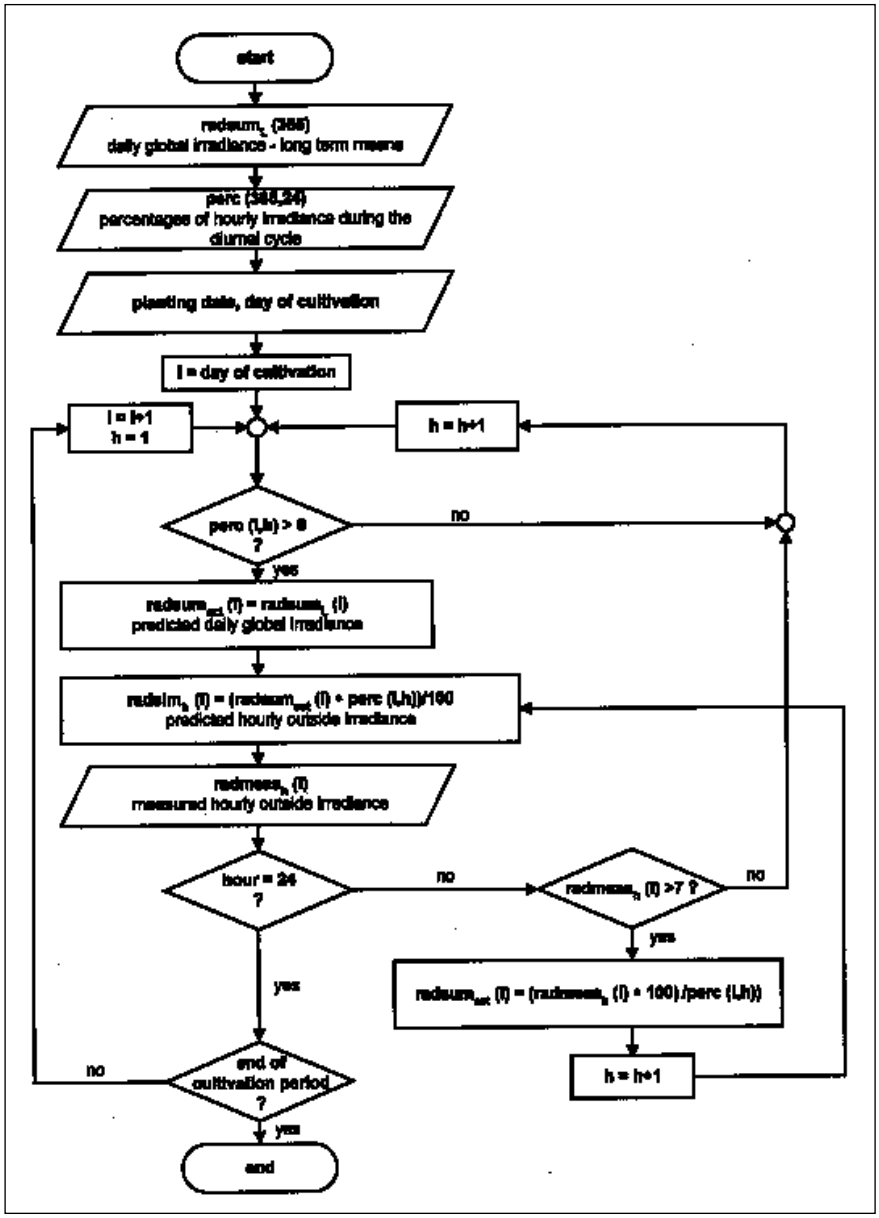


Fig. 2. Flow diagram for hourly prediction of irradiance.
Flußdiagramm für die stündliche Vorhersage der Bestrahlungsstärke.

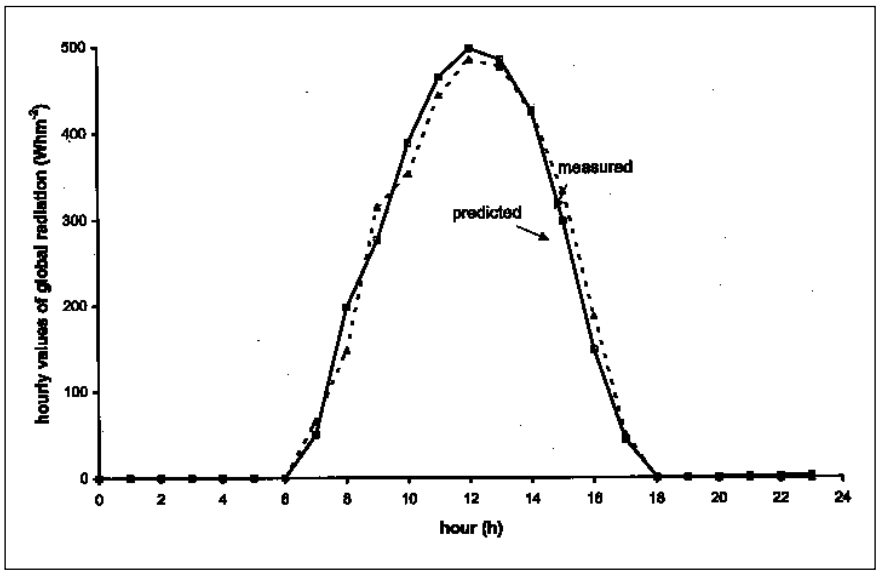


Fig. 3. Predicted and measured values of diurnal global irradiance of March 4.1991.
Prognostizierter und gemessener Tagesgang der Globalstrahlung für den 4.3.1991.

Optimisation

Optimisation by economic criteria is performed by simulation and iteration aiming at maximal gross margins. According to equation (4) gross margin (GM) is defined as monetary output (MO) minus direct costs (DC) minus opportunity costs (OC) for greenhouse area (all in DM m^{-2}):

$$GM = MO - (DC + OC) \quad (4)$$

The monetary output is the quantity of saleable products harvested multiplied by the product prices. The direct costs include the production factor quantities used multiplied by the respective prices, here CO_2 (kg m^{-2} * DM kg^{-1}) and oil (L m^{-2} * DM L^{-1}), plus other direct costs (DM m^{-2}) as seed, substrate, water, fertilisers, plant protection, packing and sale. Costs for seasonal wages, for variable machine costs and costs for leasing are not considered. The opportunity costs of the greenhouse area pay regard to the disadvantage of longer production periods, which mostly result in lower direct costs (see KRUG and Liebig 1988), but reduce the output of the succeeding crops. They are calculated by the difference in days (d) between the estimated harvest date of the crop under control and the optimal planting date of the following crop in the respective rotation multiplied by the costs of the greenhouse area per day (DM m^{-2}).

For estimating optimal temperature and CO_2 concentration, inputs are seven temperature set points in the range of 2/2 to 14/2 °C day/night temperature in combination with 10 CO_2 concentration set points from ambient to 1200 mL L^{-1}. The low night temperature was preferred as large diurnal temperature amplitudes accelerate growth of lettuce (WIEBE and LORENZ 1977). Therefore, only day temperature was optimised. Depending on these temperature-CO_2 regimes and the outside climate conditions growth rates of the lettuce crops as well as factor costs were calculated on a daily and a hourly basis. The harvest date was predicted and the factor costs for the cultivation period, yield and opportunity costs were calculated by means of table functions and gross margin was derived. Optimisation was performed by iteration for maximal daily and hourly gross margins as output. An example of this procedure is given in table 1.

Discussion

With the construction of modern greenhouses, development of efficient computers and the establishment of system theories, also in greenhouse climate control new approaches have been developed. The more comprehensive ones consider climate control as a far reaching system, including numerous elements of different disciplines, which are connected in a complicated network. The relations between these elements contain actions and interactions, which may follow different functions and different response times including long term after-effects, such as development or morphogenesis. Many reactions are not yet understood, many cannot be quantified and there are many technical insufficiencies, as e.g. measuring of the heating energy used.

To overcome some of these deficiencies different models are developed. They differ primarily in the abstraction level, each level and each model causing advantages and disadvantages. Therefore, it was to investigate, if the advantages of models at high and at low abstraction level could be combined to use their preferences and to avoid their deficiencies.

Whatever model or combination of models is used, it has to be kept in mind that modelling involves simpli-

Table 1. Example for daily „optimisation“ of CO_2 and temperature on-line control for lettuce production.
Beispiel für die tägliche „Optimierung“ der CO_2-Konzentration und der Heizungsregelung bei Kopfsalat.

Odds given:				
day of simulation from 1. Oct.	158			
price for CO_2 (DM kg^{-1})	0,80			
price for oil (DM L^{-1})	0,50			
other direct costs (DM m^{-2})	2,90			
yield (plants m^{-2})	16			
alternative:	**I**		**II**	
	CO_2	temp.	CO_2	temp.
set points	380	6/2	600	12/2
estimated harvest date (d)	167,53		167,14	
expected prod. price (DM $plant^{-1}$)	0,61		0,61	
expected monetary output (DM m^{-2})	9,76		9,76	
factor costs per day (DM m^{-2})	0,006	0,015	0,020	0,080
previous factor costs (DM m^{-2})	2,93		2,93	
factor costs for remaining period (DM m^{-2})	0,11		0,10	
value of greenhouse area (DM $m^{-2}d^{-1}$)	0,065		0,065	
DO[1] (d)	25,53		25,14	
opportunity costs (DM m^{-2})	1,66		1,63	
total costs (DM m^{-2})	7,62		7,66	
fresh weight (g)	85,85		88,61	
gross margin (DM m^{-2})	**2,15**		**2,10**	

[1] DO = days between estimated harvest date of lettuce and optimal date of planting of the succeeding crop

fications which cause errors and that models are based on the reliability of the input data. For that reason every approach has to be checked for its weak points and has to be validated.

Validity of input data

To work out the appropriate **crop parameters** was a main presupposition of this investigation and is reported in part II.

Greenhouse parameters are less complex than those of biological systems, but there are still considerable gaps in quantification. Examples are heat storage in the soil and its impact on heating demand, leakage of the cover area causing losses of energy, CO_2 and water vapour.

The **outside climate** can be measured precisely, difficulties, however, arise in modelling and predicting the weather to come. The uncertainties of outside weather and its impact on greenhouse production is shown by WERTHWEIN (1986) and KRUG and LIEBIG (1988). For prediction outside climate conditions in the diurnal circle the following less complex models have been developed:

– long-term climate data derived from singular years (DAMRATH 1980)
– a cubic function for temperature and a trigonometric function for radiation deviated from 24 years for smoothing data (LENTZ 1987)
– averaged daily courses of a month for outside climate (KALB and SCHMIDT 1977)
– reference years (BLÜMEL et al. 1986)

Singular years are statistically accidental events and not representative. Applying of functions for smoothing climate data is not suitable as they do not represent short and long term fluctuations, which are especially important for horticultural production.

The reference year consists of meteorological parameters on hourly base, for instance temperature and radiation. It comprises real events by frequency distributions and generated data based on measurements. The reference year with its averaged values corresponds to the means of climate factors of the region concerned and describes typical courses of outside climate for longer intervals of time (month, season or year). This procedure proved to be most reliable for controlling greenhouse climate on daily basis.

For predicting outside weather on hourly base a special procedure was developed, taking into account measured weather data. As simulated hourly data are replaced by measured data and forecast starts again basing on real data, a more exact prediction is achieved with this approach compared to the methods described in literature (see MATITSCHKA 1995).

Prices of the production factors, e.g. energy, can be considered relatively stable in short term and can be used alternatively. The prices of the products, however, may fluctuate considerably. They are difficult to forecast and may show great variation considering short and long term intervals (VON ALVENSLEBEN 1983; BUCHHOLZ 1985; WERTHWEIN 1986) and are an uncertain factor in optimisation.

The **opportunity costs** can be estimated by linear programming (see FÖLSTER et al. 1990), but include all the uncertainties outlined above. They are, however, an important monetary factor by considering the rotation.

Uncertainties of simulation

For predicting the **climate inside the greenhouses** there are several models available at higher and at lower abstraction level. Models at low abstraction level, simulating a bulk of physical processes, are very instructive, but demand a great number of equations, leading to a considerable risk of errors.

Models for estimating **factor demand** for **heating**, based on hourly weather data, are developed by VICKERMANN (1969) and DAMRATH (1980). The model of DAMRATH is most sophisticated, by neglecting heat storage in the soil, however, a unrealistic high energy demand for heating is modelled. The model of VICKERMANN is most simple. It also neglects heat storage in the soil, but this oversimplification is more or less compensated by using temperature means and reveals data closest to reality. But still considerable uncertainties are involved, especially at low temperature level.

For calculating **CO_2 demand** an approach was developed containing only a few parameters with the purpose of simplification and universal use in practice. As CO_2 delivery of soil depends on several factors and measuring is difficult (TAMM and KRZYSCH 1963) and it is small compared to natural CO_2 exchange and CO_2 enrichment (MANN 1986), it was neglected in this investigation. The CO_2 models of HOUTER et al. (1989) and VERMEULEN (1989) were not yet available. Uncertainties are primarily wind and ventilation dependent CO_2 losses and soil delivery.

For environmental conditions without extremes and more or less constancy the simulation of **growth rates** can be performed rather precisely. Uncertainties are involved mainly in extreme temperatures. Fluctuations seem less problematic concerning radiation (LIEBIG 1988; FINK 1991). Concerning temperature some species react to means (KRUG 1991), but some, such as lettuce, are promoted by diurnal amplitudes (WIEBE and LORENZ 1982). Environmental simulations, such as photoperiodism and vernalization, are not sufficiently quantified and altogether many gaps have to be filled up.

Optimisation

In optimisation the main constraint is polytelism (πολγ τελοσ), concerning physiological criteria, such as development, growth, health, quality and timing as well as economic criteria. Since consideration of all these criteria is out of scope of this investigation, simplifications are required. With respect to growth CHALLA (1990, see also CHALLA and VAN STRATEN 1993) proposes „… is to directly assign an approximated economic value to each unit of photosynthesis“, but restricts „this approach is particularly feasible with generative crops“, but should be worked out in a wider scope.

Concerning economic parameters the primary option should be maximisation of the monetary return of

the rotation, considering boundary conditions, such as hygiene, long term soil fertility and others. For simplification this option may be replaced by the gross margin of the crop or most simply by minimising main factor inputs, such as energy demand.

Other constraints are uncertainties of predictions, such as weather or prices and problems of the algorithms for optimisation. For applying numeric optimising methods the finding of an optimal solution may be difficult because of the topography of the solution surface. This means there are local or weakly marked optima. LENTZ (1987) demonstrated that temperature optimising for given growth stages of vegetables, which depend on different search strategies, lead to different temperature regimes for the stages, because of weakly marked optima. A shortening of the stages and the consequently high expense and time of calculation add to this problem. Furthermore the values of these variables may be beyond the range of validity.

In this investigation the simulation technique was used to maximise the gross margin, including the opportunity costs. The advantages of simulation are the shorter time of calculation (LENTZ 1987), considering empirical knowledge and logic arguments with fixed inputs for climate regimes. Examples are great temperature amplitudes for lettuce and a minimal night temperature of 2 °C. Moreover compared to numeric optimisation these results are easier to understand for the user.

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