Optimal Greenhouse Design Should Take Into Account Optimal Climate Management

B. Vanthoor[1,2*], C. Stanghellini[1], E. van Henten[1,2] and P. de Visser[1]
[1]Wageningen-UR Greenhouse Horticulture, P.O. Box 16, 6700 AA Wageningen
The Netherlands
[2]Farm Technology Group, Wageningen-UR, P.O. Box 17, 6700 AA Wageningen
The Netherlands
* E-mail corresponding author: bram.vanthoor@wur.nl

Keywords: greenhouse model, optimal design, climate control, crop modelling

Abstract

The objective of this paper is to demonstrate that optimal greenhouse design must account for (and be combined to) optimal climate management. We prove this by showing that different strategies and set-points to control the greenhouse ventilators result in different "optimal sets" of design parameters. We determined these optimal sets for a passive greenhouse in Almería, Spain where tomatoes were grown. The greenhouse design parameters investigated in this research were: 1) the transmission of the cover for photosynthetically active radiation (PAR), 2) the transmission of near infrared (NIR) radiation and 3) the emission coefficient for longwave radiation of the cover. Six optimal sets of design parameters were determined by maximising the marginal revenues (crop yield minus costs of design parameters), under given climate conditions, and for different ventilation control strategies. Each ventilation control strategy had different set-points for the air temperature and carbon dioxide concentration to control the greenhouse ventilators. To solve this optimization problem we used a dynamic crop-greenhouse model and an optimization algorithm. The model described the combined influence of the relevant design parameters, outdoor climate and ventilation control upon economic crop yield, through their effect on indoor climate. The yearly costs of the design parameters were empirically derived from prices, physical properties and lifespan of a number of greenhouse cover materials. Results showed that indeed for different strategies and set-points to control the greenhouse ventilators different "optimal sets" of design parameters and marginal revenues were obtained. For example, the difference between the highest optimal NIR transmission 1.00 and the lowest optimal NIR transmission 0.40 was 60%, while the highest marginal revenues 16.94 €m^{-2} differed 18,7% with the lowest marginal revenues of 13.77 € m^{-2}. Additionally, it was found that the cover design parameters were time dependent. In conclusion, only a combined optimal control and design approach that takes into account the best climate control strategy and the time dependency of the design parameters will ensure optimal design parameters and maximum marginal revenues.

INTRODUCTION

A variety of protected cultivation systems can be found throughout the world. They range from a fully passive "solar greenhouse" with an energy storage wall in China, to the high-tech "closed greenhouses" in Western Europe. Such variety is brought about by local conditions such as climate, economic and social aspects, availability of resources and legislation. All present systems are the result of a "local evolution", since the optimization of a greenhouse design with respect to local climate and economic conditions still remains a challenge for the designer (von Elsner et al., 2000). Besides the design, also the climate management of the greenhouse – and consequently the use of resources – are influenced by the local climate and the economic conditions. Although the greenhouse design and the climate management are strongly related to each other, they are usually treated independently during the design process. Nowadays, greenhouse designers first design a greenhouse based upon strategic choices of the greenhouse grower, whereas the climate control strategy to be used is selected in a later stage. Due to the increasing energy and water prices, the costs of the resources represent an increasing fraction of total production costs. Therefore, minimizing the cost of the climate management should also be a goal of the design process.

The objective of this paper is to demonstrate that optimal greenhouse design must account for (and be combined to) optimal climate management. We prove this by showing that different strategies and set-points to control the greenhouse ventilators result in different "optimal sets" of design parameters.

In this report we work out a case study for a passive greenhouse in Almería, Spain where tomatoes are grown. The Photosynthetically Active Radiation (PAR) transmission, near infrared (NIR) transmission and emission coefficient for long wave radiation (LWR) of the greenhouse cover are optimized. The paper is organized as follows. First, an economic goal function that should be maximized to find the optimal set of design parameters is defined. Subsequently, the costs of the design parameters are related to their physical properties and a model that links the design parameters to the crop yield is described. Thereafter, the ventilation control strategy is worked out. Finally, for 6 different strategies to control the greenhouse ventilators, the optimal sets of design parameters are determined for a winter, summer and yearly period.

MATERIALS AND METHOD

Economic Goal Function

The economic goal function to be maximized by the optimization algorithm was the profit *J,* that is the economic yield *Y,* minus the yearly costs, *Q,* of the cover design parameters:

$$\max_{d} J = Y(u,d) - Q(d) \qquad [€\ m^{-2}] \qquad (1)$$

where *d* are the cover design parameters and *u* is the control input of the system; in this case the ventilation control.

The economic goal function was optimized using the function minimiser, *fmincon*, of Matlab ®. Lower and upper bounds as well as initial guesses of the design parameters, the goal function and greenhouse climate model were inputs of this function.

The Cost of Design Parameters

The costs of the cover design parameters were described by the following relationship:

$$Q(d) = f(d_{PAR}) + q_{NIR} d_{NIR} + q_{\varepsilon LWR} d_{\varepsilon LWR} + q_{\mathrm{Re}m} \qquad [€\ m^{-2}] \qquad (2)$$

with d_{PAR}, the PAR transmission, d_{NIR}, the NIR transmission and $d\varepsilon_{LWR}$, the emission coefficient for LWR. The price trend of the PAR transmission, $f(d_{par})$, was described with a tangent function with the asymptote at the physically impossible transmission of 1. The price coefficients, q_{NIR}, $q_{\varepsilon LWR}$ and q_{REM}, were obtained by fitting the above equation on a number of existing greenhouse cover materials, resulting in q_{NIR}=-2.38, $q_{\varepsilon LWR}$=0.468 and q_{REM}=0.9236, respectively. The remaining costs of the greenhouse cover materials were described by q_{REM}.

In this study we put a lower bound on the NIR transmission, d_{NIR}>0.4, and on the emission coefficient for LWR, $d\varepsilon_{LWR}$ >0.7. Hardly any greenhouse cover materials existed with a NIR transmission lower than 0.4. Also, the price coefficient was unknown in the area below 0.4. Due to dust, condensation and the whitewash, the emission coefficient for LWR could not take values lower than 0.7.

Model to Link Design Parameters to Economic Crop Yield

In order to determine the economic crop yield, the relationships described in Fig. 1 and Fig. 2 were built into a dynamic crop-greenhouse model, represented in a state space format. The states of the model were described by ordinary differential equations. The validation of the model is described elsewhere (Vanthoor et al., 2008). Here only the elements relevant for this paper are described. The economic yield, Y, was described by the following equation:

$$\frac{dY}{dt} = q_{crop}\{t\}\ HI\ \eta_{CO_2\_FW}\left(P - R\right) \qquad [€\ m^{-2}\ s^{-1}] \qquad (3)$$

with q_{crop}, the price of the tomatoes, HI, the harvest index, η_{CO2_FW}, the conversion factor from carbon dioxide to fresh weight of the tomatoes, P, the photosynthesis rate and R, the maintenance respiration of the crop both expressed in kg$\{CO_2\}$ m^{-2} s^{-1}. It is well-known that the price of the tomatoes, q_{crop}, varies with seasons and is time dependent (Cajamar, 2007).

The economical tomato yield was strongly related to the photosynthesis rate because the amount of maintenance respiration was relative small compared to the photosynthesis rate. The photosynthesis rate, P, was described by (Tap, 2000):

$$P = h_T\{T_{Can}\}\, h_{T24}\{T_{Can24}\}\, f\{PAR_{Can}\}\, g\{CO2_{air}\}\, P_{MAX} \qquad [kg\{CO_2\}\ m^{-2}\ s^{-1}] \qquad (4)$$

The potential photosynthesis rate, P_{MAX} was inhibited by non-optimal values for the canopy temperature, T_{Can}, the mean canopy temperature, T_{Can24} , the absorbed PAR by the crop, PAR_{Can}, and the CO_2-concentration, $CO2_{air}$, in the greenhouse. The influence of the absorbed PAR and the CO_2 concentration of the air on photosynthesis rate were both described with a saturation curve.

To describe the photosynthesis inhibition by canopy temperature, h_T, and 24 hour mean canopy temperature, h_{T24}, we applied a trapezoid filter to the photosynthesis (Boote and Scholberg, 2006). Photosynthesis rate was zero below 2°C and above 45°C and maximal between 12°C and 30°C for momentaneous temperatures. A similar filter was applied to 24 hour means, with threshold values of 7°C, 32°C, 18°C and 24°C, respectively.

To implement the photosynthesis inhibition by momentaneous temperature we needed to calculate the canopy temperature, T_{can}:

$$c_{Can}\frac{dT_{can}}{dt} = PAR_{Can} + NIR_{Can} - H_{CanAir} - L_{CanAir} - TIR \qquad [W\ m^{-2}] \qquad (5)$$

with c_{Can}, the heat capacity of the canopy, PAR_{Can}, the absorbed PAR by the canopy, NIR_{Can}, the absorbed NIR radiation by the crop, H_{CanAir}, the sensible heat loss to air, L_{CanAir}, the evaporation of the canopy and TIR, long wave radiation from the canopy to different greenhouse elements. All these heat fluxes depended on outside conditions, the properties of the cover and the management of the ventilators, see Fig. 1 and Fig. 2.

Describing the 24 hour mean canopy temperature in a state space format was complicated because the format assumed that the future states could be predicted by using only the values of the current states and the future inputs. To solve this we calculated the 24 hour mean canopy temperature, T_{can24}, using a 1st order system approach.

The remaining internal variables that influenced the photosynthesis rate and also the goal function were the absorbed PAR by the crop, PAR_{Can}, and the CO_2-concentration of the greenhouse air $CO2_{air}$. These internal variables depend on outside conditions; cover design parameters and the ventilation management, as illustrated by Fig. 1 and Fig. 2. The CO_2-concentration of the air depended on the photosynthesis rate, the maintenance respiration and the CO_2 inflow through the greenhouse ventilators.

Greenhouse Climate Management and Influence on Crop Yield

The important growing factors, CO_2-concentration and canopy temperature, (see Fig. 1, Fig. 2 and equation 4) were influenced by the aperture of the ventilators, u_{vent}. By ventilation heat was released to the outside and CO_2 flowed inside the greenhouse resulting in lower air temperature and a higher CO_2-concentration that favoured crop growth. The strategy to control the ventilators was based upon the set-points of the temperature and CO_2-concentration of the greenhouse air. The ventilators were fully open when the indoor air exceeded a certain maximum temperature set-point, T_{Airmax}. Below this set-point, the ventilators were closed, except in cases when the CO_2-concentration of the air dropped below the CO_2-setpoint, $CO2_{Airmin}$, and the indoor air temperature was higher than the minimum indoor air set-point, T_{Airmin}:

$$u_{Vent} = 1 \quad \begin{cases} T_{Air} > T_{Air\max} \\ CO_{2\,Air} < CO_{2\,Air\min} \wedge T_{Air} > T_{Air\min} \end{cases} \qquad [-] \quad (6)$$

The Optimization Experiment

The cover design parameters of a Spanish 3 span plastic house, of area 630 m^2, with roof (84 m^2) and side ventilation (56 m^2) were optimized for six different control strategies. The optimized cover design parameters were: 1) the PAR transmission, 2) the NIR transmission and 3) the emission coefficient for LWR. We combined three maximum temperature set points (20, 23 and 26°C) with two different minimum CO_2-set-points (200 and 300 ppm) resulting in six different control strategies. Whitewash was applied from August 4th to August 29th and from April 15th to July 15th and it had a PAR and NIR transmission of 0.40. The applied prices of the tomatoes, $q_{crop}(t)$, were averaged weekly values for the last 3 years of the tomato cultivar Long Life G. (Cajamar, 2007).

First the cover design parameters were optimized for a long production cycle that started on August 4th and ended on July 15th of the next year. Thereafter the cover design parameters were optimized for a winter and a summer period to obtain insight into the relative importance and time dependence of the design parameters throughout the year. The winter and summer period ranged from December 19th to December 23rd and from June 19th to 23rd June, respectively.

RESULTS AND DISCUSSION

The impact of the climate control set-points on the optimized cover design parameters for a long production period is shown in Table 1. The optimal NIR transmission changed considerably for different treatments; the PAR transmission did not change a lot and the emission coefficient for LWR was for all treatments higher than 0.98. For the treatments with the higher temperature set-points (26_200 and 26_300), lower NIR transmission values and higher costs of the design parameters were obtained. The difference between treatment 23_300 (d_{NIR}=1.00 and Q = 0.98 € m^{-2}) and treatment 26_200 (d_{NIR}=0.40 and Q = 2.79 € m^{-2}) concerning the NIR transmission and the cost of the design parameters was 60% and 184.7% respectively. The lower NIR transmission at the higher temperature set-points can be explained by the fact that heat problems were the limiting factor for crop growth. These heat problems can be diminished by selecting a low NIR transmission of the cover material resulting in a smaller heat load inside the greenhouse (see Fig. 1 and Fig. 2).

Also the optimal PAR transmission changed for different CO_2-set-points (for temperature set-points of 23°C and 26°C). For the treatments with the CO_2-set-point of 200 ppm lower CO_2-concentration in the greenhouse were obtained which could result that the CO_2-concentration became the limiting factor for crop growth. When CO_2 was limiting, the crop wanted to use the scarce CO_2 as efficient as possible which resulted in a higher PAR transmission for the CO_2-setpoints of 200 ppm.

Further on, the values of the PAR and NIR transmission were coupled for treatments with the same temperature set-point. A trade off between the PAR transmission and NIR transmission existed because a higher PAR transmission was always combined with a lower NIR transmission and vice versa. For all the treatments, high values of the emission coefficient for LWR were obtained which resulted in lower cold stress during the night and consequently in higher economic yield. Also the influence of control strategy on economic revenues was considerable. The highest marginal revenues 16.94 € m^{-2} of treatment 20_300 differed 18,7% with the lowest marginal revenues of 13.77 € m^{-2} of treatment 26_200.

The influence of the climate set-points on the optimized design parameters during winter is shown in Table 2. High values for the PAR transmission (lowest value is 0.956), NIR transmission (all values are 1.00) and emission coefficient for LWR (all values are 1.00) for each treatment were obtained. In winter time, low light levels and low temperatures negatively influenced crop growth and economic tomato yield. Both a higher PAR and NIR transmission favoured a higher canopy temperature (see equation 5) and a higher PAR favoured also the photosynthesis rate (see equation 4).

The treatment 26_200 resulted obviously in a lower CO_2-concentration in the greenhouse and a 16.7 % lower economic yield compared to treatment 26_300. This can be explained by the influence of CO_2-concentration on crop growth (see equation 4). In the treatment 26_200 the CO_2-concentration of 240 ppm inside the greenhouse became the limiting factor for crop growth, which would cause a high PAR transmission to be not cost effective. Therefore it made sense to save on the cover costs, resulting in a poor PAR transmission and 13.8 % lower costs of the cover compared to treatment 26_300. For the emission coefficient upper bound values were obtained for all treatments. A higher emission coefficient for LWR resulted in lower LWR transmission and less heat loss which diminished cold stress of the crop and production losses.

Table 3 (referring to the summer period) shows low values for all the design parameters because then the high temperature is the limiting factor. Although a high PAR transmission had a positive effect on photosynthesis rate, the negative effect of high temperature stress must have been larger. Similarly, the optimized design parameters of the NIR transmission and the emission coefficient for LWR were equal to the lower bounds. A low NIR transmission and a low emission coefficient resulted in lower heat stress and consequently in higher economic yield.

The strong time dependencies of the optimized cover design parameters was proven by comparing the optimization results for the winter and summer period. In the winter poor radiation and low temperature are the factors limiting yield, so that high values of PAR and NIR transmission and emission coefficient for LWR were selected, whereas in the summer low values for the PAR transmission, NIR transmission and emission coefficient of LWR were necessary to lower the high temperature stress of the crop.

CONCLUSION

This work proves that greenhouse design is a multi-factorial problem best approached through optimization algorithms. The results show that different strategies and set-points to control the greenhouse ventilators would result in different “optimal sets” of design parameters. Therefore optimal greenhouse design must account for climate management. We have also shown that the impact of the ventilation control strategy on the economic revenues can be large, and that the best combination of cover design parameter is time dependent. Consequently, a significant improvement of greenhouse design can be attained through an optimal design approach that takes into account the best climate control strategy and the time dependency of the design parameters. Solving such a combined optimal control and design approach is rather difficult. Therefore there is a need for generic tools that are able to solve this problem independently from particular conditions. Developing such a tool is the next objective of our group.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge financial support from Strategic Research Fund of Plant Research International, part of Wageningen University and Research Centre. The climate data were kindly provided by Juan Carlos Lopez Garrido of Estación Experimental de la Fundación Cajamar, Almería, Spain.

Literature Cited

Boote, K.J. and Scholberg, J.M.S. 2006. Developing, parameterizing, and testing of dynamic crop growth models for horticultural crops. Acta Hort. 718:23-34.

Cajamar. 2007. Análisis de la campaña hortofrutícola de Almería 2006/2007. Fundación Cajamar, Almería.
Tap, F. 2000. Economics-based optimal control of greenhouse tomato crop production. PhD Thesis, Agricultural University, Wageningen.
Vanthoor, B., Stanghellini, C., van Henten, E.J. and Gázquez Garrido, J.C. 2008. The Combined Effects of Cover Design Parameters on Tomato Production of a Passive Greenhouse. Acta Hort. (in press).
von Elsner, B., Briassoulis, D., Waaijenberg, D., Mistriotis, A., von Zabeltitz, C., Gratraud, J., Russo, G. and Suay-Cortes, R. 2000. Review of Structural and Functional Characteristics of Greenhouses in European Union Countries, Part II: Typical Designs. Journal of Agricultural Engineering Research 75:111-126.

Tables

Table 1. Optimization results for a long production cycle from August 4th to July 15th. The last 2 columns represent the mean daylight values of the inside air temperature and the CO_2-concentration.

Set-points		Design variables			Yield	Costs	Revenues	T_{air}	CO_2
T_{air}	CO_2	d_PAR	d_NIR	d_LWR	Y (€.m^{-2})	Q (€.m^{-2})	J (€.m^{-2})	(°C)	(ppm)
20	200	0.889	1.00	1.00	18.14	1.32	16.82	23.6	325
20	300	0.900	1.00	1.00	18.38	1.44	16.94	23.5	328
23	200	0.874	0.97	1.00	17.27	1.23	16.04	24.4	310
23	300	0.852	1.00	0.99	17.09	0.98	16.11	24.1	321
26	200	0.893	0.40	1.00	16.56	2.79	13.77	24.6	277
26	300	0.874	0.44	1.00	17.22	2.50	14.72	23.3	312

Table 2. Optimization results for December 19th to December 23rd. The last 2 columns represent the mean daylight values of the inside air temperature and the CO_2-concentration.

Set-points		Design variables			Yield	Costs	Revenues	T_{air}	CO_2
T_{air}	CO_2	d_PAR	d_NIR	d_LWR	Y (€.m^{-2})	Q (€.m^{-2})	J (€.m^{-2})	(°C)	(ppm)
20	200	0.981	1.00	1.00	0.30	0.032	0.2703	20.5	296
20	300	0.984	1.00	1.00	0.31	0.033	0.2722	20.3	307
23	200	0.980	1.00	1.00	0.29	0.032	0.2600	21.8	266
23	300	0.981	1.00	1.00	0.30	0.032	0.2712	20.7	301
26	200	0.956	1.00	1.00	0.25	0.025	0.2245	22.9	240
26	300	0.971	1.00	1.00	0.30	0.029	0.2687	21.0	300

Table 3. Optimization results for June 19th to June 23rd. The last 2 columns represent the mean daylight values of the inside air temperature and the CO_2-concentration.

Set-points		Design variables			Yield	Costs	Revenues	T_{air}	CO_2
T_{air}	CO_2	d_PAR	d_NIR	d_LWR	Y (€.m^{-2})	Q (€.m^{-2})	J (€.m^{-2})	(°C)	(ppm)
20	200	0.438	0.40	0.70	0.104	0.0104	0.0938	25.9	335
20	300	0.438	0.40	0.70	0.104	0.0104	0.0938	25.9	335
23	200	0.430	0.40	0.70	0.100	0.0102	0.0899	26.2	333
23	300	0.430	0.40	0.70	0.100	0.0102	0.0900	26.2	334
26	200	0.423	0.40	0.70	0.087	0.0101	0.0769	26.8	324
26	300	0.428	0.40	0.70	0.088	0.0102	0.0780	26.9	324

Figures

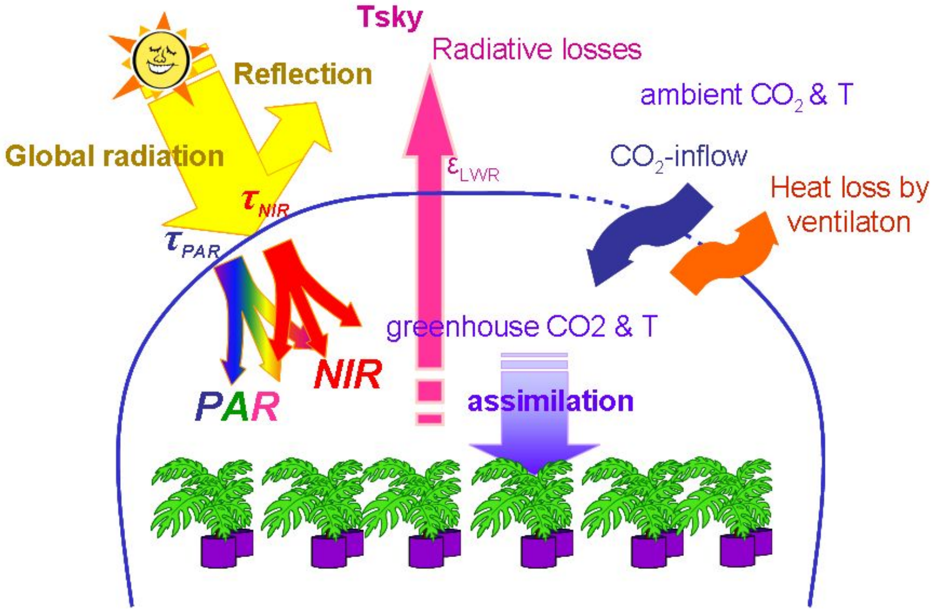

Fig. 1. The influence of outdoor climate conditions (global radiation, air temperature, sky temperature and CO_2-concentration of the air), greenhouse design parameters (PAR transmission, NIR transmission and emission coefficient for LWR) and the control of ventilators on indoor climate (PAR, NIR, temperature and CO_2) and crop yield.

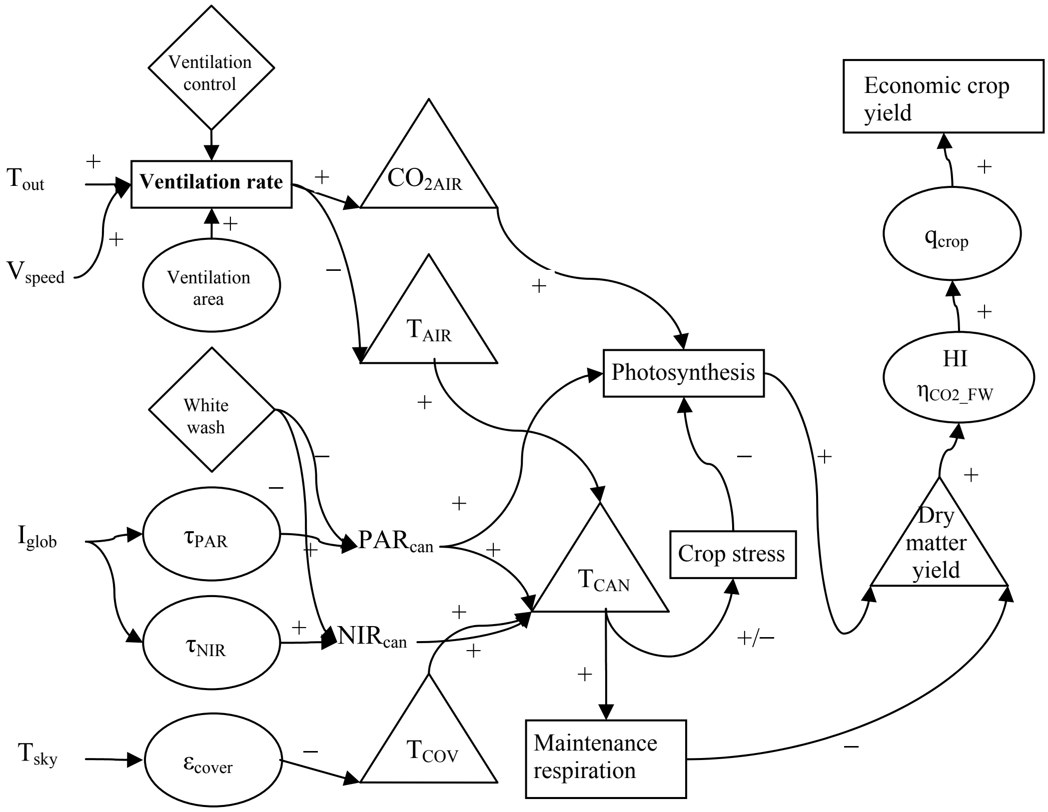

Fig. 2. Relations between outdoor climate (items on the left), the cover design parameters (circles), states of the model (triangles) and the used functions (block). The plus/minus symbols indicate the influence of increasing a measure at the beginning of the arrow upon the measure at the end of the arrow.