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Abstract

Efforts to increase the energy use efficiency (EUE) of greenhouses are made in various fields, e.g., crop management and breeding; greenhouse design and technology; and climate control, including optimal control. Quantifying and comparing the influence of the different components of the greenhouse system on EUE is important for improving greenhouse energy efficiency. In this study, we examined an optimally controlled greenhouse lettuce system during a winter cycle in the Netherlands. A model sensitivity analysis of the optimal control problem aimed at minimizing heating was performed to investigate which of the system components had the strongest influence on EUE. The results were compared with a previous study examining energy saving measures in lettuce cultivation. It was found that a reduction in indoor temperature, an increase in roof transmissivity, and to a lesser extent, an increase in insulation, improved the EUE of an optimally controlled greenhouse in a similar way as a conventionally controlled greenhouse. A 10% increase in EUE of the optimally controlled greenhouse was achieved by each of the following: a 0.2°C decrease in minimum indoor temperature; a 7% decrease in heat loss through the cover; a 13% increase in yield factor; and a 13% increase in net photosynthesis. The results suggest that finding ways to decrease the indoor temperature without reducing yield has the highest potential for increasing EUE. In addition, optimal control may be combined with known energy saving measures to achieve a higher EUE than previously found.

Keywords: energy saving, energy use efficiency, greenhouse modeling, crop modeling, optimal control, sensitivity analysis, lettuce

INTRODUCTION

Greenhouses in temperate climates rely on high energy inputs for heating in order to maintain production throughout the year. This energy consumption has great economic and environmental implications, and considerable efforts are being made to improve the energy use efficiency (EUE) of greenhouses.

Greenhouse EUE, defined here as kg of marketable product per megajoule of energy used for heating, may be improved in many ways and involves various fields of research and development (Dieleman and Hemming, 2011) such as structure design and technology (Cuce et al., 2016), plant breeding (Van der Ploeg et al., 2007), and climate control strategies (De Gelder et al., 2012), including optimal control of greenhouse climate management (Van Beveren et al., 2015a, b; Van Ooteghem, 2007).

Quantifying and comparing the roles of the various system components on greenhouse EUE can help direct efforts toward improving those features which have the greatest influence on energy use. In Elings et al. (2005), 11 different energy-saving measures were simulated and compared with regards to their influence on the energy consumption of a tomato greenhouse. It was found that some measures could reduce energy consumption by as much as 25%. A separate approach is the application of optimal control theory to greenhouse cultivation (Van Straten et al., 2010). It has been shown that this may result in a reduction of heating input by 34-47% (Van Beveren et al., 2015b; Van Henten et al., 1997).

In this study, we considered an optimally controlled greenhouse, examined how the various system components influenced EUE, and compared these influences. Following Van

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Henten (2003), we performed a sensitivity analysis of an optimal control problem on a model of a winter lettuce greenhouse in the Netherlands. Whereas Van Henten (2003) focused on the maximization of greenhouse profit, here we focused on minimizing heating.

The results of the analysis were compared with results from Dueck et al. (2004), who quantified and compared energy saving measures as in Elings et al. (2005), but considered, among others, a lettuce crop. By combining these two approaches, we were able to systematically examine which greenhouse system components are most influential on EUE, and see how optimal control affects these influences.

MATERIALS AND METHODS

Crop and greenhouse model

A full description of the model and nominal parameter values used in this study can be found in Chapter 6 of van Straten et al. (2010). The model comprises 4 states, 4 uncontrolled inputs, and 3 controlled inputs. The states are: crop dry weight (W, kg m^{-2}), CO_2 concentration of indoor air ($C_{CO_2,a}$, kg m^{-3}), indoor air temperature (T_a^C, °C), and vapor concentration of indoor air ($C_{H_2O,a}$, kg m^{-3}). The uncontrolled inputs are: CO_2 concentration of outdoor air ($C_{CO_2,o}$, kg m^{-3}), outdoor air temperature (T_o^C, °C), vapor concentration of outdoor air ($C_{H_2O,o}$ kg m^{-3}), and outdoor solar radiation (I_0, W m^{-2}). The controlled inputs are: supply rate of CO_2 (u_{CO_2}, kg m^{-2} s^{-1}), ventilation rate (u_v, m s^{-1}), and energy supplied for heating (u_q, W m^{-2}).

The inputs for the simulations performed in this study were measured in Bleiswijk, The Netherlands (52°02N 4°32E) in 5-min intervals, from January 21, 2014 to March 12, 2014.

The dynamics of the states are described by the following differential equations:

$$\frac{\mathrm{d}W}{\mathrm{d}t} = c_{phot}^{net}\left(c_{\phi_{CO_2}}c_{\alpha\beta}\phi_{CO_2,a\_c} - c_{W,c\_a}W\cdot 2^{\left(0.1T_a^C-2.5\right)}\right)\ (\mathrm{kg\ m^{-2}\ s^{-1}})$$

$$\frac{\mathrm{d}C_{CO_2,a}}{\mathrm{d}t} = \frac{1}{c_{CO_2}^{cap}}\left(-c_{\phi_{CO_2}}\phi_{CO_2,a\_c} + c_{CO_2,c\_a}W\cdot 2^{\left(0.1T_a^C-2.5\right)} + u_{CO_2} - \phi_{CO_2,g\_o}\right)\ (\mathrm{kg\ m^{-3}\ s^{-1}})$$

$$\frac{\mathrm{d}T_a^C}{\mathrm{d}t} = \frac{1}{c_a^{cap}}\left(u_q - q_{g\_o}^{trans,vent} + q_{o\_g}^{rad}\right)\ (\mathrm{°C\ s^{-1}})$$

$$\frac{\mathrm{d}C_{H_2O,a}}{\mathrm{d}t} = \frac{1}{c_{H_2O}^{cap}}\left(c_{\phi_{H_2O}}\phi_{H_2O,c\_a} - \phi_{H_2O,g\_o}\right)\ (\mathrm{kg\ m^{-3}\ s^{-1}}),$$

where

$$\phi_{CO_2,a\_c} = \left(1-e^{-c_{LAI,W}W}\right)\frac{c_{I_0}^{phot}c_{rad}I_0\left(-c_{CO_2,1}^{phot}(T_a^c)^2 + c_{CO_2,2}^{phot}T_a^c - c_{CO_2,3}^{phot}\right)\left(C_{CO_2,a} - c_\Gamma^{phot}\right)}{c_{I_0}^{phot}c_{rad}I_0 + \left(-c_{CO_2,1}^{phot}(T_a^c)^2 + c_{CO_2,2}^{phot}T_a^c - c_{CO_2,3}^{phot}\right)\left(C_{CO_2,a} - c_\Gamma^{phot}\right)}$$

$$(\mathrm{kg\ m^{-2}\ s^{-1}})$$

$$\phi_{CO_2,g\_o} = \left(u_v + c_{leak}\right)\left(C_{CO_2,a} - C_{CO_2,o}\right)\ (\mathrm{kg\ m^{-2}\ s^{-1}})$$

$$q_{g\_o}^{trans,vent} = \left(c_{cap}^{vent}u_v + c_{g\_o}^{trans,vent}\right)\left(T_a^C - T_o^C\right)\ (\mathrm{W\ m^{-2}})$$

$$q_{o\_g}^{rad} = c_{o\_g}^{rad}c_{rad}I_0\ (\mathrm{W\ m^{-2}})$$

$$\phi_{H_2O,c\_a} = \left(1-e^{-c_{LAI,W}W}\right)c_{c\_a}^{evap}\left(\frac{c_{H_2O,1}^{sat}}{c_R(T_a^c+c_\Gamma)}\exp\left(\frac{c_{H_2O,2}^{sat}T_a^c}{T_a^c+c_{H_2O,3}^{sat}}\right) - C_{H_2O,a}\right)\ (\mathrm{kg\ m^{-2}\ s^{-1}})$$

$$\phi_{H_2O,g\_o} = c_{\phi_{H_2O}}(u_v + c_{leak})\left(C_{H_2O,a} - C_{H_2O,o}\right) \text{ (kg m}^{-2}\text{ s}^{-1}).$$

Here, ϕ_{CO_2,a_c} represents gross photosynthesis rate; ϕ_{CO_2,g_o} the loss of CO_2 from ventilation and leakage; $q_{g\_o}^{trans,vent}$ the loss of energy from ventilation and convection; $q_{o\_g}^{rad}$ the energy gain from solar radiation; ϕ_{H_2O,c_a} the canopy transpiration; and ϕ_{H_2O,g_o} the loss of vapor by ventilation. Expressions denoted with a lowercase *c* are parameters (constants).

Optimal control problem

The optimal control problem was defined as follows: for each day of the crop cycle, find a trajectory of the controlled inputs, such that heating is minimized, at least 80% of a reference crop growth is achieved, and indoor climate constraints are respected. In mathematical terms this is formulated as follows: define u(t)=(u_{CO2} (t), u_v (t), u_q (t)) as the control vector. The goal is to find $u(t)$ that minimizes the objective function *J*:

$$\underset{u(t)}{\operatorname{argmin}} J\big(u(t)\big) = \underset{u(t)}{\operatorname{argmin}} \int_{t_n}^{t_{n+1}} u_q(t)\mathrm{d}t$$

while the model states T_a^C, $C_{CO_2,a}$, and $R_{H_2O,a}$ (representing indoor relative humidity) remain within the state bounds $T_a^{min}, T_a^{max}, C_{CO_2,a}^{min}, C_{CO_2,a}^{max}, R_{H_2O,a}^{min}, R_{H_2O,a}^{max}$; and the controlled inputs u_{CO_2}, u_v, and u_q remain within $u_{CO_2}^{min}, u_{CO_2}^{max}, u_v^{min}, u_v^{max}, u_q^{min}, u_q^{max}$. Furthermore, a daily yield constraint, ensuring satisfactory crop growth, was imposed:

$$W(t_{n+1}) - W(t_n) \geq g_n, n = 1,2, \dots, 50,$$

where t_n signifies the beginning of day *n*, W (t_n) is the crop dry weight at the beginning of day *n*, and g_n is the minimal required crop growth on day *n*.

The required daily crop growth g_n was derived by performing a reference simulation, where the objective was to maximize greenhouse profit, as in van Henten (2003). The values for g_n were set as 80% of the daily growth in the reference simulation. In other words, the optimal control problem was defined such that heating is minimized, but no less than 80% of crop growth is achieved, compared to a greenhouse where the goal was to maximize profit.

The solution of the optimal control problem was used to calculate EUE, i.e., the dry weight of the crop at the end of day 50, divided by the total heating input:

$$y = \frac{W(t_{51})}{10^{-6}\int_{t_1}^{t_{51}} u_q(t)\mathrm{d}t} \text{ (kg MJ}^{-1}).$$

The optimal control problems were solved using the PROPT (Rutquist and Edvall, 2010) and TOMLAB (Edvall and Göran, 2009) software packages using MATLAB and Statistics Toolbox Release 2016b (The MathWorks, Inc., Natick, Massachusetts, United States).

Sensitivity analysis

For each of the parameters in this study, the nominal value as described in van Straten et al. (2010), was multiplied by a perturbation factor between 0.2 and 2, while keeping the other parameters fixed. The optimal control trajectory was then calculated and applied to the perturbed system, and the output *y*, representing EUE, was recorded. We denote y_p (x) as the EUE when the parameter *p* was multiplied by *x*.

Two relative sensitivity measures were calculated for each parameter: r_{10}^{gain}, representing the relative change in the parameter that is needed to gain a 10% increase in EUE compared to the nominal simulation, and r_{10}^{loss}, representing the relative change in the parameter that will result in a 10% decrease in EUE. We defined $z_p(x) = \frac{y_p(x)}{y_p(1)}$ as the relative EUE, i.e., the relative change in EUE caused by perturbing p by a factor x. Then,

$$r_{10}^{gain} = 100 \cdot \left(\text{invz}_p(1.1) - 1\right), r_{10}^{loss} = 100 \cdot \left(\text{invz}_p(0.9) - 1\right)$$

where invz_p is the inverse function of $z_p(x)$, e.g., invz_p (1.1) is the x needed such that $z_p(x)$=1.1. The values of invz_p were calculated using a linear interpolation between the simulation results. Figure 1 provides examples for the calculation of these sensitivity measures. Note that low absolute values for these measures signify high sensitivities.

In addition to the unitless relative sensitivity measures r_{10}^{gain} and r_{10}^{loss}, two absolute sensitivity measures were calculated:

$$s_{10}^{gain} = \text{nom}(p) \cdot \frac{r_{10}^{gain}}{100}, s_{10}^{loss} = \text{nom}(p) \cdot \frac{r_{10}^{loss}}{100}$$

where $\text{nom}(p)$ is the nominal value of parameter p. As opposed to the relative sensitivity measures, these absolute sensitivity measures have the same unit as the parameter p, and they represent the absolute change needed in the parameter to gain or lose 10% in EUE.

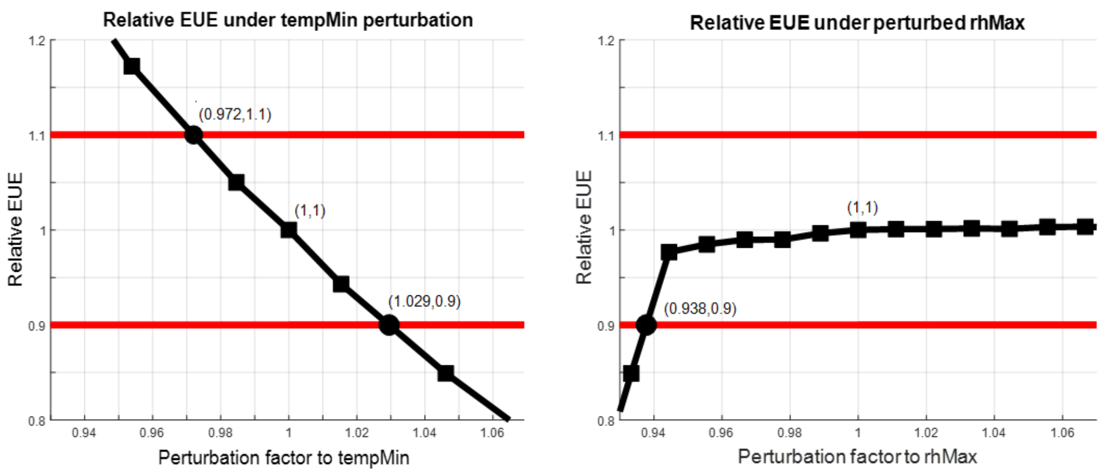

Figure 1. Output for calculation of relative sensitivity measures for parameters T_a^{min} and $R_{H_2O,a}^{max}$. Squares denote simulation results, circles represent interpolated values used to calculate the measures. The curve $z(x)$ (relative EUE) is given in solid black. The figure on the right demonstrates how the absolute values of r_{10}^{gain} and r_{10}^{loss} may be vastly different, and in fact, one (or both) of the measures may not exist.

RESULTS AND DISCUSSION

Comparison with previous study

A comparison between five of the energy saving measures in Dueck et al. (2004) and the results of this study is presented in Table 1. Two differences between the studies should be mentioned: first, Dueck et al. (2004) used fixed set points for temperature and relative humidity, while here we used optimal control with bounds for the indoor climate. The changes in temperatures and relative humidity in Table 1 should be understood accordingly. Second, Dueck et al. (2004) considered a full year whereas we studied a 50-day winter cycle. However, heating is not used during the warmer months of the year, and the effects on heating are only meaningful during winter. Therefore, the two studies may still be compared.

Table 1. Comparison of response to energy-saving measures, in a conventionally controlled (Dueck et al., 2004) and optimally controlled (this study) lettuce greenhouse.

Energy saving measure[a]	Dueck et al. (2004)		This study	
	Change in heating (%)	Change in yield (%)	Change in heating (%)	Change in yield (%)
Decrease temperature by 2°C (T_a^{min})[b]	-39.5	-10	-51	0
Increase insulation by 10% ($c_{g\_o}^{trans,vent}$)	-52.1	-9	-12	0
Increase transmissivity by 10% (c_{rad})	-3.4	+8	-1	+3
Increase relative humidity by 5% ($R_{H_2O,a}^{max}$)[c]	0	0	0	0
Decrease transpiration by 10% ($c_{\phi_{H_2O}}$)	-0.8	0	0	0

[a]In brackets: the parameter perturbed in this study.

[b]Dueck et al. (2004): a change from 7 to 11°C to 5-9°C; this study: from $T_a^{min} = 6.5°C$ to $T_a^{min} = 4.5°C$.

[c]Dueck et al. (2004): a change from 95% to 100%; this study: from $R_{H_2O,a}^{max} = 90\%$ to $R_{H_2O,a}^{max} = 95\%$.

Increasing relative humidity or reducing transpiration had no influence on EUE in both studies. In this study the relative humidity rarely reached the nominal upper bound of 90%: note that evaporation from the soil is neglected in our model, so especially in early crop stages, simulated evapotranspiration is quite low.

Regarding increased transmissivity, the results in Dueck et al. (2004) for yield are in line with Marcelis et al. (2006), who found that a 1% decrease in radiation leads to a 0.8% decrease in growth of a lettuce crop. However, those results were under a constant temperature regime (De Pinheiro Henriques and Marcelis, 2000). In this study, since the objective was only to minimize heating, the added radiation allowed to slightly decrease the daytime temperatures, in a way that the potential for extra growth given by added radiation was used to reach the minimal growth constraint, but was not fully exploited.

Regarding a reduction of temperature, the results for heating in the two studies are close, and the difference may be explained by the fact that this measure has a stronger effect with lower nominal temperatures (Dueck et al., 2004). However, the model used in this study appears to underestimate the adverse influence of low temperatures on yield.

One discrepancy between the studies is the influence of increased insulation. It seems that in Dueck et al. (2004), increased insulation by the use of a double glass reduced both convective heat loss and ventilation, whereas in our case only convection was affected. Nevertheless, it is hard to explain the differences between the studies without a detailed analysis of the simulations performed.

In summary, when comparisons are possible, most of the energy-saving measures from Dueck et al. (2004) can also be applied to an optimally controlled greenhouse, with similar outcomes. This is significant, because it suggests that the energy savings achievable by optimal control may be complemented with other energy saving measures, resulting in an increase of EUE which exceeds the gains of using each method separately.

Sensitivity measures in the current study

Table 2 presents the sensitivity measures for the most influential parameters found in this study, along with the parameters discussed in the previous section. The relative sensitivity measures r_{10}^{gain} and r_{10}^{loss} were used to compare the parameter sensitivities: the table is ordered by the average of their absolute values. When one of the measures did not exist, the value of the existing measure was used for the comparison.

Table 2. Sensitivity of EUE to selected parameters, ordered by the average of the absolute values of the relative sensitivity measures r_{10}^{gain} and r_{10}^{loss}. Note that low absolute values indicate a high sensitivity.

Parameter	Interpretation	Nominal value	Absolute change for 10% EUE increase ($\boldsymbol{s_{10}^{gain}}$)	Absolute change for 10% EUE decrease ($\boldsymbol{s_{10}^{loss}}$)	Relative change for 10% EUE increase ($\boldsymbol{r_{10}^{gain}}$)	Relative change for 10% EUE decrease ($\boldsymbol{r_{10}^{loss}}$)
T_a^{min}	Lower bound on indoor temperature	6.5°C	-0.2°C	0.2°C	-2.8	2.95
$R_{H_2O,a}^{max}$	Upper bound on indoor relative humidity	90%	-	-5.58%	-	-6.22
$c_{g\_o}^{trans,vent}$	Heat transfer through the cover	6.1 W m^{-2} K^{-1}	-0.45 W m^{-2} K^{-1}	0.6 W m^{-2} K^{-1}	-7.42	9.9
$c_{\alpha\beta}$	Yield factor	0.54	0.07	-0.06	12.83	-11.26
c_{phot}^{net}	Perturbation factor on net photosynthesis	1	0.14	-0.12	13.6	-11.66
$c_{\phi_{CO_2}}$	Perturbation factor on gross photosynthesis	1	0.14	-0.11	14.19	-11.26
c_{rad}	Perturbation factor on global radiation	1	0.2	-0.12	20.38	-11.97
$c_{I_0}^{phot}$	Light use efficiency	3.55 10^{-9} kg J^{-1}	0.77 10^{-9} kg J^{-1}	0.49 10^{-9} kg J^{-1}	21.57	-13.77
$C_{CO_2,a}^{max}$	Upper bound on indoor CO_2 concentration	2.75 10^{-3} kg m^{-3}	-	-1.4 10^{-3} kg m^{-3}	-	-50.79
$c_{o\_g}^{rad}$	Heat load coefficient of solar radiation	0.2	-	-0.12	-	-62.2
$c_{\phi_{H_2O}}$	Perturbation factor on crop transpiration	1	-	-	-	-

The results show that the lower bound on temperature T_a^{min}, the heat transfer through the cover $c_{g\_o}^{trans,vent}$ and the radiation in the greenhouse c_{rad} all play an important role in EUE, as described in the previous section. In particular the influence of temperature was significant, with sensitivity measures that were more than twice as influential as the other parameters. The upper bound on relative humidity $R_{H_2O,a}^{max}$ was also found to be important, in the sense that a reduction from 90 to 84.4% resulted in a 10% decrease in EUE. In other words, for a greenhouse with an upper relative humidity bound of 85%, an increase of this bound to 90% would result in 10% higher EUE. Furthermore, parameters relating to photosynthesis ($c_{\alpha\beta}, c_{phot}^{net}, c_{\phi_{CO_2}}, c_{rad}, c_{I_0}^{phot}$), also play a meaningful role, representing 5 of the 9 most influential parameters found in this study.

In summary, the possibility of combining energy saving measures from Elings et al. (2005) with optimal control seems promising, in particular if the temperature bound T_a^{min} could be reduced without major losses in yield. Nevertheless, further research should focus on a more direct comparison of the two approaches, i.e., using the same model and growing conditions. Furthermore, it would be valuable to apply the method proposed here to a year-round tomato or rose cultivation with assimilation lamps, in order to reveal possibilities for energy savings in greenhouses with higher energy demands.

CONCLUSIONS

- For an optimally controlled lettuce greenhouse, the lower bound on temperature, the upper bound on relative humidity, and the insulation of the cover were the most important parameters for EUE.
- This is in line with previous research and shows that energy saving measures such as reducing the indoor temperature or increasing roof insulation may be combined with optimal control to further improve greenhouse EUE.
- Methods to reduce the minimal temperature bound without reducing yield have the highest potential to increase EUE.

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Literature cited

Cuce, E., Harjunowibowo, D., and Cuce, P.M. (2016). Renewable and sustainable energy saving strategies for greenhouse systems: a comprehensive review. Renew. Sustain. Energy Rev. *64*, 34–59 https://doi.org/10.1016/j.rser.2016.05.077.

De Gelder, A., Poot, E.H., Dieleman, J.A., and De Zwart, H.F. (2012). A concept for reduced energy demand of greenhouses: the Next Generation Cultivation in the Netherlands. Acta Hortic. *952*, 539–544 https://doi.org/10.17660/ActaHortic.2012.952.68.

De Pinheiro Henriques, A.R., and Marcelis, L.F.M. (2000). Regulation of growth at steady-state nitrogen nutrition in lettuce (*Lactuca sativa* L.). Interactive Effects of Nitrogen and Irradiance. Ann. Bot. *86*, 1073–1080.

Dieleman, J.A., and Hemming, S. (2011). Energy Saving: from Engineering to Crop Management. Acta Hortic. *893*, 65–73 https://doi.org/10.17660/ActaHortic.2011.893.2.

Dueck, T., Elings, A., Kempkes, F., Knies, P., Garcia, N., Heij, G., Janse, J., Kaarsemaker, R., Korsten, P., Maaswinkel, R., et al. (2004). Energie in Kengetallen : op Zoek naar een Nieuwe Balans.

Edvall, M.M., and Göran, A. (2009). Tomlab Quick Start Guide. 81.

Elings, A., Kempkes, F., Kaarsemaker, R.C., Ruijs, M.N.A., Van de Braak, N.J., and Dueck, T.A. (2005). The energy balance and energy saving measures in greenhouse tomato cultivation. Acta Hortic. *691* (*691*), 67–74 https://doi.org/10.17660/ActaHortic.2005.691.5.

Marcelis, L.F.M., Broekhuijsen, A.G.M., Nijs, E.M.F.M., Raaphorst, M.G.M., and Meinen, E. (2006). Quantification of the growth response to light quantity of greenhouse grown crops. Acta Hortic. *711*, 97–103 https://doi.org/10.17660/ActaHortic.2006.711.9.

Rutquist, P.E., and Edvall, M.M. (2010). PROPT - Matlab Optimal Control Software. 528.

Van Beveren, P.J.M., Bontsema, J., Van Straten, G., and Van Henten, E.J. (2015a). Minimal heating and cooling in a modern rose greenhouse. Appl. Energy *137*, 97–109 https://doi.org/10.1016/j.apenergy.2014.09.083.

Van Beveren, P.J.M., Bontsema, J., Van Straten, G., and Van Henten, E.J. (2015b). Optimal control of greenhouse climate using minimal energy and grower defined bounds. Appl. Energy *159*, 509–519 https://doi.org/10.1016/j.apenergy.2015.09.012.

Van der Ploeg, A., Van der Meer, M., and Heuvelink, E. (2007). Breeding for a more energy efficient greenhouse tomato: past and future perspectives. Euphytica *158* (*1-2*), 129–138 https://doi.org/10.1007/s10681-007-9437-z.

Van Henten, E.J. (2003). Sensitivity analysis of an optimal control problem in greenhouse climate management. Biosyst. Eng. *85* (*3*), 355–364 https://doi.org/10.1016/S1537-5110(03)00068-0.

Van Henten, E.J., Bontsema, J., and Van Straten, G. (1997). Improving the efficiency of greenhouse climate control: an optimal control approach. Neth. J. Agric. Sci. *45*, 109–125.

Van Ooteghem, R. (2007). Optimal Control Design for a Solar Greenhouse (Wageningen University).

Van Straten, G., Van Willigenburg, G., Van Henten, E.J., and Van Ooteghem, R. (2010). Optimal Control of Greenhouse Cultivation (CRC Press).