SHELL OPTIMIZATION OF A CLIMATE ADAPTIVE GREENHOUSE USING INVERSE MODELING

Arie Taal[1], Laure Itard[2]
[1] The Hague University of Applied Sciences
[2] Technical University of Delft

ABSTRACT

The sector of greenhouses is responsible for almost 10 per cent of the total gas use in the Netherlands. Thus reducing energy use in this sector is very important.

Up to now greenhouses, like other buildings, are produced with fixed building envelope properties. An innovation would be to have climate responsive shells, in which the envelope characteristics change continuously in time in order to reduce the energy need or even create a greenhouse that delivers energy. This demands advanced materials and control strategies to minimize the need for heating, cooling, ventilation and artificial lighting with a high comfort or a high plant production. In this article the development of simulation models for greenhouses to determine the effects of these control strategies on varying properties are discussed. The achieved energy gains, when the physical attributes of the glass are controlled and optimized on hourly basis, are calculated and analyzed. These simulation models can be used for investigation and the (re)designing of greenhouses, and for the control of the building physics and the HVAC-system. The first results show that an energy saving for heating and cooling of more than 80% is possible.

INTRODUCTION

Clean and energy saving processes for the heating and the cooling of buildings and for the delivery of electrical power to buildings are needed. There are many different ways to achieve this. One of these ways may be to use Climate Adaptive Building Shells (CABS), using materials of which the physical properties can be instantaneously changed and adapted to the outdoor climate and the requirements for the indoor climate (see Bokel et al. 2004 and 2005). An example is the use of smart energy glass, in which the solar transmittance can be adapted (see Loonen et al, 2010). In addition, installations may be integrated in building parts like glass that produces electricity.

In this paper the possible energy savings of a climate adaptive greenhouse envelope based on an inverse control strategy will be handled.

Energy savings in the sector of greenhouses in the Netherlands is important because it is responsible for almost 10 per cent of the total gas use. In 2020 new greenhouses have to be climate neutral, meaning that these greenhouses shouldn’t consume more primary energy during a year than they can generate in a sustainable way. The complete sector has to be climate neutral in 2050. At this moment, recent developments lead to a substantial reduction of energy consumption. The solutions are aimed at better building physics like insulation, high efficiency lighting and high efficiency HVAC-systems. An example is the application of closed greenhouses where no windows van be opened. In these greenhouses the water vapor regulation takes place by mechanical cooling. The mechanical ventilation enables heat recovery as well as thermal energy storage in the ground (e.g. Snijders 2005). However climate neutrality is still far off. The greenhouse envelope is static in its properties. For instance the thermo physical and optical properties of glass are constant over time. Only by using screens and windows that can be opened, the envelope is somehow flexible. It is expected that CABS will lead to higher energy reduction.

INVERSE MODELING

The characteristics of inverse modeling is that this modeling is based on the desired results of the model, for instance energy consumption, costs, plant growth, and given the weather conditions the input parameters of the model are determined. Figure 1 shows the difference between direct and inverse modeling. In a direct simulation, input data are known (e.g. geometry and insulation) and the model calculates the output (e.g. energy consumption or temperature). In inverse modeling, the output is known (e.g. indoor temperatures and energy scenario like zero energy use or energy neutral) and the model calculates the needed input variables to achieve the desired output. In our model the input variables are determined on hourly basis, meaning that the physical parameters of the greenhouse shell are assumed to be adaptable per hour. For the moment it is not possible to change thermal properties like insulation on this time scale, but, if considerable energy savings can be proved, it will be worth working towards such material development in the future.

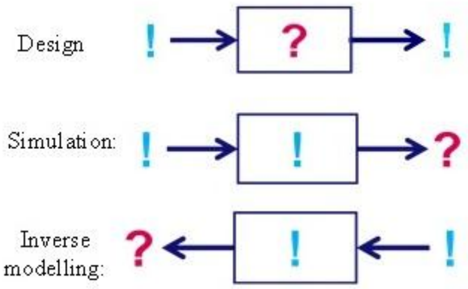

Figure 1 Inverse modeling (from Loonen,2010)

It is generally not possible to make inverse calculations directly by mathematical ways like matrix calculations, because the number of unknown parameters exceeds the number of equations. The optimal input parameters are therefore obtained by using multiple sets of alternatives as input parameters and by searching for the optimal output (see figure 2).

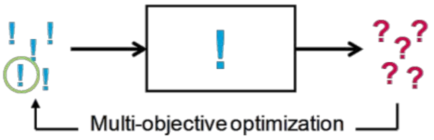

Figure 2 Optimization

In the Dutch project CAGIM (Climate Adaptive Greenhouses: Inverse Modelling) that is supported by Agentschap NL, an agency of the Dutch Ministry of Economic Affairs, Agriculture and Innovation, the possibility of an adaptive greenhouse is investigated. This project started with an investigation of the state of art of greenhouses especially aimed at the energy aspects and the growth parameters of a plant. The inverse simulation model for greenhouses takes into account the influence of solar gain, especially the PAR, and the growth conditions (air temperature, humidity and CO_2-concentration). The PAR, Photosynthetic Active Radiation, is the part of the solar heat that is useful for the growth of the plant. The useful spectral range is 400 - 700 nm.

The present paper describes the first results and the simulation model used for tomato growth: inverse model that is based on good growth conditions for tomatoes. The inverse modeling strategy is based on a model of the greenhouse. The simulations are carried out for a large number of alternative input data and lead to a set of optimized parameters. In this paper, the greenhouse model is presented first, followed by the inverse control strategy. Finally the first results are presented.

THE GREENHOUSE MODEL

One could choose for a detailed physical model which takes into account the variations of material properties and heat transfer coefficients depending on the process variables like temperature and solar radiation angle. Kaspro (see Zwart 1996) is an example of such a software. However, the scope of this paper is not to make very detailed calculations but to test the inverse modeling strategy and to determine whether energy savings are possible by using an adaptive greenhouse shell and in which range the properties should be adaptable. To avoid very long calculation times a simple, but accurate enough simulation model for the greenhouse was developed.

The greenhouse is modeled in Matlab/Simulink (see Simulink, 2013) and consists of 16 nodes, leading to a set of 16 equations.

In figure 3 a scheme of the model is given 2 wall nodes are not shown in the picture).

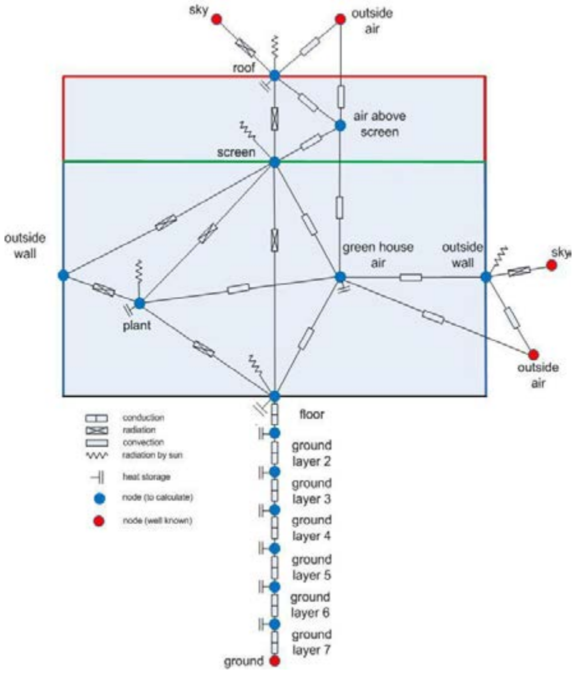

Figure 3 The greenhouse model

The envelope consists of a roof and four outside walls. The floor area is 10000 m2 and the greenhouse has the following dimensions 100x100x6 m. The roof is considered to be flat for solar radiation. The ground is modeled in 7 ground layers with a total depth of 1.5 m, of which the first layer is the floor.

The model's limitations are the following:

- Only horizontal solar radiation on the roof is considered. Because a large greenhouse is considered, the surface area of the walls is small when compared to the surface area of the roof. Therefore the influences of solar radiation on the vertical outside walls can be neglected (see Arentsen 2008). The view factors are calculated based on the ratios between the surfaces.
- The time effects of heat storage in the roof, and in the outside walls are neglected because the

thermal mass of these components can be neglected in comparison with the mass of the ground.

- The heat transfer coefficients in the greenhouse are constant and assumed to be independent of the air temperature and air velocity in the range of temperatures and velocities found in a greenhouse. The absorptance and transmittance of the glass are assumed to be independent of the solar incident angle and are taken equal to the absorptance and transmittance for diffuse radiation.
- The transmittance for long wave radiation for roof, screen and the outside walls are equal to zero. So the reflectance for long wave radiation is r=1-a=1-e, wherein r=reflectance, a=absorptance and e=emissivity
- The absorptance for short wave radiation is assumed constant: a=0.04.

Heat balances for the elements

Each node has a uniform temperature and a heat balance equation is generated per node, resulting in 16 equations with 16 unknown values for the temperatures, which are put in matrix notation and solved in Simulink.

The model determines on hourly basis whether thermal energy is required to maintain an acceptable internal temperature. If this is the case then the needed heat or cold is calculated. Otherwise the heating and cooling energy are set to zero.

The model is validated using the complex and already validated greenhouse model KASPRO (see Zwart. 1996). The correlation coefficient has a value of 0.992. As illustrated by Figure 4, the differences are very small. Therefore, despite its limitations, the developed model is accurate enough to investigate the effects of inverse modeling.

Another validation is the comparison of the annual energy consumption with the actual energy used in real greenhouses. Therefore the yearly energy consumption of the greenhouse is also calculated.
The control strategy is based on the following conditions for the inside air (conditions needed for the growth of tomato (see Swinkels 2011):

-Temperature T: 18<T<28 ^{o}C
-Relative humidity: RH<90 %
-CO_2 concentration >700 ppm

When RH > 90 % latent cooling is applied and when T>28 ^{o}C sensible cooling is applied.
The result of the simulation is 860 MJ heating per m^2 floor. This result corresponds with the actual value in greenhouses and with the result of a simulation with KASPRO (806 MJ/yr.m2). For the sensible cold demand 481 MJ/yr/m^2 is found. And for the latent cold demand 1055 MJ/yr.m^2.

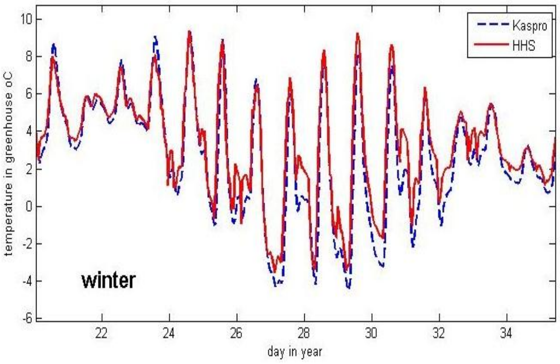

Figure 4 Temperature difference in the winter between our greenhouse model (HHS) and KASPRO

INVERSE CONTROL STRATEGY

To realize good growth conditions for the plants and to minimize the energy consumption at a given time there are several solutions. The glass and the ground properties can be taken into account. In this paper, only the glass properties are considered. the following spectral and thermal properties of the glass are considered:

Spectral properties
- Transmittance
- Absorptance
- Reflectance

Thermal properties
- Thermal conductivity
- Specific heat capacity
- Emissivity

Taking this complete set of properties into account leads to a high simulation time, therefore the number of adaptable properties was reduced in order to limit the simulation time. The specific heat capacity of the glass is not be taken as adaptable parameter because it is expected to have a small effect on the glass temperature in comparison with the effects of spectral properties. Furthermore it seems easier from the technological point of view to realize adaptable spectral properties than adaptable heat capacity. Second, emissivity and heat conductivity will be combined into one factor, the U-value of the glass.

Therefore, the following solutions are considered:

Changing the U-value of the envelope

The U-value of glass can be adapted by changing the heat conductivity and the emission coefficient.
This allows keeping heat indoors when needed, or to get rid of it when cold is needed. Generally in the Dutch climate a good insulation is needed in winter but in the summer it is necessary to remove heat. Because the outdoor temperature in summer is also lower than the indoor temperature in the greenhouse,

reducing the insulation will result in less cooling demand. In the spring and in the autumn the demand for heating or cooling can change every hour. In our simulations, the insulation properties are adaptable per hour.

Changing the transmittance of the envelope

Short wave radiation comes directly from the sun. On the one hand the solar radiation, especially the PAR, is needed for the growth of plants. On the other hand the greenhouse can become overheated, resulting in a need for cooling.

The sum of the transmittance, absorptance and reflectance must be 1 so they are interrelated. We assume that the absorptance always has a constant value and is therefore not adaptable The transmittance (and therefore the reflectance as well) is adaptable per hour.

The optimization is conducted in such a way that the set of optimal parameters is determined for each hour, taking into account the temperatures determined at previous hours (with their own optimal parameters). However, it neglects the fact that the parameters determined this way may be not optimal for future hours. Because a greenhouse is a fast responding system (low thermal mass) this effect is believed to be limited.

For the optimization genetic algorithms can be used. (see Kasinalis 2013). However, this doesn't lead to a simple and fast model. Because we have simplified the optimization problem to the optimization of two main properties, it is possible to use a simple optimization strategy. For several combinations of the U value and transmission coefficients the energy consumption is calculated. The combination with the lowest energy consumption is chosen. When there are more combinations leading to the lowest energy use, the combination with the highest temperature is chosen to avoid too high humidity later on when the air temperature decreases.

In the present simulations, only the heating, and cooling (latent and sensible) demands are considered, meaning that systems for HVAC, lighting, CO_2 supply and (de)humidification are not considered.

RESULTS OF THE INVERSE SIMULATION OF THE GREENHOUSE

In the Simulink model the U-value can be changed between the value of 0 and 5.7 W/m^2K. The first value can only be achieved by an infinitely well insulated greenhouse. The last value is the value of single blank glass. In practice the intermediate values can be obtained by adapting either the heat conductivity and/or the inside and outside emissivity that influence the heat transfer coefficient for radiation.

The solar transmittance can vary between 0 (completely opaque) and the transmittance for diffuse radiation of single blank glass, which is 0.775.

The control strategy calculates for each combination of coefficient-value and the transmittance the energy demand for heating, sensible cold and latent cold. The latest term is needed for dehumidification. The combination which delivers the lowest energy demand is then chosen.

Table 1 shows the results for the optimum for the yearly heat and cold demand when each adaptable parameter is varied between its minimal and maximal value. For the U-value 25 steps were used between the minimum and maximum and for the transmittance 5 steps were used.

Table 1
Result for the annual heat and cold demands

VARIANT	HEAT DEMAND [MJ/YR.M^2 FLOOR]	COLD DEMAND [MJ/YR.M^2 FLOOR]
Without optimization	860	1536
Adaptable U-value	94	1508
Adaptable transmittance	889	440
Adaptable U-value and transmittance	96	245

The hourly behavior of the U-value and transmittance are shown in figures 5 to 8.

Our simplified model shows that by adapting on an hourly basis the U-value of the roof the heat demand can be reduced with more than 89%. So theoretically a large reduction of the energy use for heating is possible. The effect on cooling is very limited. Furthermore we see that by varying only the transmittance the cold demand decreases with 71 %, while the effect on heating is very limited. Adapting both the U-value and the transmittance leads to a heat demand reduction of 89 % and a cold demand reduction of 84 %.

Another advantage of such hourly adaptive shells can be that the adaptable parameters may be chosen in such a way that the heating and cooling demand can have the same value. When energy storage in the ground is used, which is common in the Netherlands, this will enable the realization of a better balance between cooling and heating during a year, which is compulsory in the Dutch regulations.

Figures 5 shows, as an example, how the U-value changes during the year. For every month the mean value is given for day time when the sun is shining, for the night time and for the whole day. In the winter we see that a low U-value is desirable to hold the heat inside the greenhouse. In the summer the greenhouse will be overheated whereby a higher U-value is desirable to remove the heat. This is because, summer outdoor temperatures in the Netherlands are generally low.

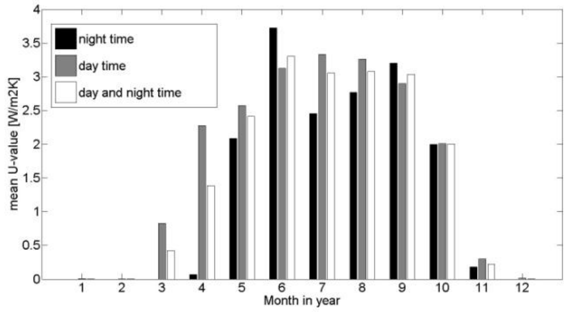

Figure 5: varying U-value (monthly values)

We also see a difference in the desired values during day and night time, especially in March and April. When during night time the outside temperature is low enough to allow for free cooling of the greenhouse a low U-value is desired.

Figure 6 shows for a few typical days in April the changing of the U-values. We see that the value varies between 0 (during night time) and 5.7 at the middle of the day.

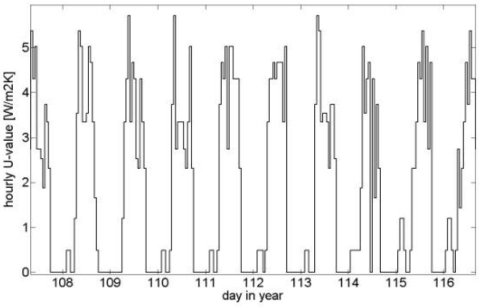

Figure 6: varying U-value of glass (hourly values for days 108 to 116)

Of course a U-value of zero isn't possible in practice. However figure 6 shows that the insulation should be as high as possible during night time in winter days. Currently double glazing isn't even applied in greenhouses. This shows a tremendous potential for improvement.

Figure 7 shows the transmittance. During night time the transmittance has evidently no effect and its value is set to zero.
In the winter we see that the transmittance should be high to heat the greenhouse with solar radiation and should be low in the summer to avoid overheating.

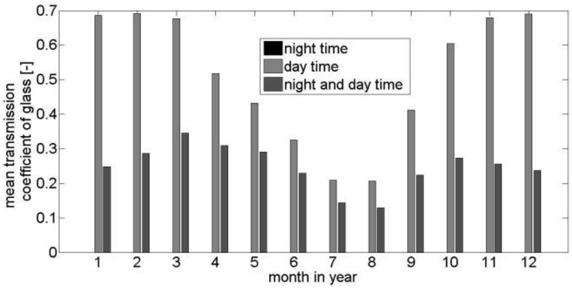

Figure 7: varying transmittance of glass (monthly values)

When we look in detail we see that there are large hourly fluctuations during day time, see figure 8.

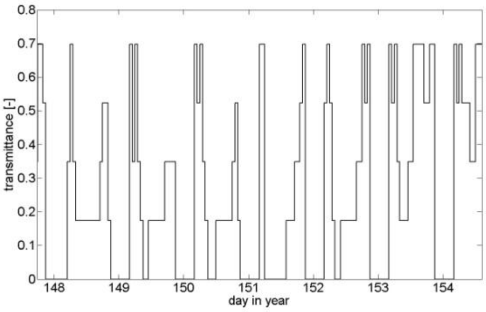

Figure 8: varying transmittance of glass (hourly values for days 148 to 155)

Influence of the number of steps

The number of steps chosen between the minimal and maximal value may influence the results. See Table 2.

Table 2
Results for the annual heat and cold demand depending on the amount of steps

VARIANT	HEAT DEMAND [MJ/YR.M^2 FLOOR]	COLD DEMAND [MJ/YR.M^2 FLOOR]
Adaptable U-value (25 steps) and transmittance (5 steps)	96	245
Adaptable U-value (9 steps) and transmittance (3 steps)	103	254
Adaptable U-value (4 steps) and transmittance (2 steps)	126	253

More steps and therefore more control possibilities between the minimal and maximal values lead to a lower heating demand and a more accurate determination of the minimum. This table shows that the number of steps has very little effect on the cold demand and affects more strongly the heat demand.

However for analysis of the energy reduction by CABS it seems that a small number of steps give a sufficient indication of the possible savings (when we compare with the results of table 1).

CONCLUSIONS AND RECOMMENDATIONS

In this paper a simple model to realize inverse modeling of greenhouses was developed and demonstrated. By adapting the shell properties on hourly basis a high reduction of the energy demand can be expected. This shows that future developments in the field of dynamically adaptable materials and related control strategies would be a promising way of saving energy. Although the results obtained so far are very promising, more realistic calculations, based on U-values that could be achieved in the near feature, are needed. Additionally, the presented model also has limitations, for instance, depending on the type of crop, there may be a limitation on the amount of acceptable solar radiation. The present model only takes into account the optimum at the certain hour, taking into account the temperatures at previous times. It doesn't however predict if the parameters determined this way are optimal for future hours. The results of the simple model will be compared with the one of a more complex model taking this effects into account (see Lee et al. 2012).

Additionally more research is needed on sensitivity of the energy demand on variations of the adaptable parameters. It may be that large variations of certain parameters lead to little energy saving while small variations of others lead to large energy savings.

In the future, the control strategy should be extended with an optimization of the energy used by the HVAC system and the systems for CO_2 supply, lighting and (de)humidification. In addition, the actual plant growth could be taken into account through a photosynthesis model, leading to a multi-objective simulation (see Lee et al. 2012).

When the primary energy is taken into account it is possible that the inverse control strategy supports the use of local generation of solar and wind energy. It is even possible to realize a self-supporting energy system with, for example, the use of electrical driven heat pumps in combination with warm and cold water storage in the ground (e.g. Turgut et al. 2008). But first, more accurate inverse models are needed.

The inverse modeling can be applied to other types of buildings such as homes and office buildings. There is also a considerable potential for energy savings.

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