A Numerical Simulator of a Crop-Producing Greenhouse

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Abstract

This report describes a greenhouse simulator. The described simulator is translated from a German description (Pohlheim and Heißner, 1996), and some minor modifications are introduced. The simulator is reimplemented in Java and is based on the original MatLab version. The purpose of the simulator is to explore various techniques for control of non-linear systems. The greenhouse is controlled by four parameters, and the state is modeled by six non-linear differential equations. Translation information is provided to allow the reader to verify the equations and seek additional information in the original description.

Keywords

Greenhouse simulator, non-linear differential equations, control problems, dynamic systems

1 Introduction

This technical report describes a simulator for a crop-producing greenhouse. The simulator is implemented in Java and is, to a large extent, based on the greenhouse simulator described in (Pohlheim and Heißner, 1996). The original description and MatLab code are online at `www.pohlheim.com`. The simulator described here differs on a few minor aspects:

- The description is in English. The original description is in German.
- The naming of state variables follows the control engineering terminology and the terminology presented in (Ursem et al., 2001).
- The greenhouse is made more realistic by including the wind speed in the equations related to air-exchange with the surroundings. The original simulator was, to some degree, modeling a hermetically closed greenhouse.
- The approximation of the non-linear differential equations is protected to prevent unrealistic values in the variables such as realtive humidity above 100%, negative steam pressures, and temperatures below 0 Kelvin.

The interaction between the controller, the greenhouse, and the immediate surroundings of the greenhouse is illustrated in Figure 1. Table 1 provides an overview of the variables associated with the controller (u), the greenhouse state (x), and the environment state (v). The simulator models the profit per m^2 over time. The profit is equal to the income from the production minus the expenses to heating and CO_2 (see Section 2.5).

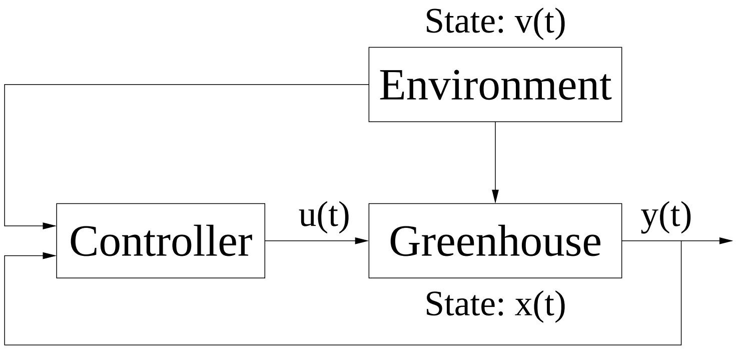

Figure 1: The interaction between the controller, the greenhouse, and the greenhouse environment.

Description	Variable	Unit
Heating	u_{heat}	[W/m^2]
Ventilation	u_{vent}	[m^3/(m$^2 \cdot$ h)]
CO_2 injection	u_{CO2}	[g/(m$^2 \cdot$ h)]
Water injection	u_{water}	[g/(m$^2 \cdot$ h)]
Indoor steam density	x_{steam}	[g/m^3]
Indoor air temperature	x_{atemp}	[°C]
Indoor CO_2 concentration	x_{CO2}	[ppm]
Accumulated biomass	x_{biom}	[g/m^2]
Accumulated profit	x_{profit}	[DKK/m^2]
Condensation on glass	x_{cond}	[g/m^2]
Outdoor sunlight intensity	v_{sun}	[W/m^2]
Outdoor air temperature	v_{atemp}	[°C]
Outdoor ground temperature	v_{gtemp}	[°C]
Relative humidity	v_{RH}	[% r.H.]
Wind speed	v_{wind}	[m/s]
Outdoor CO_2 concentration	v_{CO2}	[ppm]
Price of heating	v_{Pheat}	[DKK/(W·h)]
Price of CO_2	v_{PCO2}	[DKK/kg]
Price of crop (tomatoes)	v_{Ptom}	[DKK/kg]

Table 1: The control, system, and environment variables.

2 State equations

The greenhouse state (x) is modeled by six non-linear differential equations describing the change over time. The solution to the equations can be approximated by a fourth-order Runge-Kutta formula. The control variables are measured in hours, which is converted to seconds in the equations because the differential equations have to be approximated using a rather short step size to avoid instability. Preliminary tests showed that a step size of one minute is appropriate. The following sections describe each of the equations in detail. Real weather data is used to model the environment (v). Weather data can usually be obtained from your national meteorologic institute at a reasonable price.

2.1 Indoor steam density x_{steam}

The indoor steam density is influenced by four factors:

1. Transpiration of the plants (TRANS).
2. Water injection (WATERINJ).
3. Exchange with environment through ventilation (ENVEXC).
4. Condensation and evaporation on the greenhouse hull (CONDEVAP).

The change in the indoor steam density [g/(m$^3\cdot$s)] is modeled by the following equation. Please refer to Appendix A for definition of constants, auxiliary variables, and functions.

$$\dot{x}_{steam} = \frac{1}{\text{GH}\cdot 3600}\cdot(\text{TRANS} + \text{WATERINJ} - \text{ENVEXC} - \text{CONDEVAP}) \quad (1)$$

The auxiliary variables TRANS, WATERINJ, ENVEXC, and CONDEVAP are calculated as follows.

$$\begin{aligned}
\text{TRANS} &= 100\cdot \text{LEAFSIZE}[\text{MONTH}]\cdot \text{PM2}\cdot \text{LEAFTRANS}[\text{MONTH}]\cdot \text{TRGROW} && (2)\\
\text{TRGROW} &= (1 - b_0\cdot(x_{CO2} - 600))\cdot\frac{\text{TRCUR}}{\text{TRSTD}} && (3)\\
\text{TRCUR} &= (b_1 + b_2\cdot x_{sun} + b_3\cdot(x_{sun})^2 + b_4\cdot f_{RH}(x_{steam}, x_{atempA}))\cdot && (4)\\
&\quad f_{SD}(x_{steam}, x_{atempA})\\
\text{TRSTD} &= (b_1 + b_2\cdot 300 + b_3\cdot 300^2 + b_4\cdot 60)\cdot 10 && (5)
\end{aligned}$$

$$\text{WATERINJ} = \text{CW}\cdot u_{water}\cdot(f_{SSP}(x_{atempA}) - f_{SP}(x_{steam}, x_{atempA})) \quad (6)$$

$$\text{ENVEXC} = (u_{vent} + \text{VM0} + \text{VM1}\cdot v_{wind})\cdot(x_{steam} - v_{steam}) \quad (7)$$

$$\text{CONDEVAP} = \begin{cases}\text{COND} & \text{if COND} > 0 \quad \text{(Condensation)}\\ \text{COND} & \text{if COND} < 0 \text{ and } x_{cond} > 0 \quad \text{(Evaporation)}\\ 0 & \text{if COND} < 0 \text{ and } x_{cond} = 0 \quad (x_{cond} = 0 \implies \text{no evap.})\end{cases} \quad (8)$$

$$\text{COND} = \text{TRPO}\cdot\text{GR}\cdot\frac{f_{SP}(x_{steam}, x_{atempA}) - f_{SSP}(x_{htempA})}{0.5\cdot\text{RWS}\cdot(x_{atempA} + x_{htempA})} \quad (9)$$

$$\text{TRPO} = \frac{1.33\cdot 3600\cdot|x_{atemp} - x_{htemp}|^{0.33}}{\text{DA}\cdot\text{HCA}} \quad (10)$$

$$x_{htemp} = \begin{cases}-2.71 + 0.00811\cdot v_{sun} + 0.795\cdot x_{atemp} + 0.289\cdot v_{atemp} & \text{if } 5 \le \text{MONTH} \le 9\\ \frac{1}{3}x_{atemp} + \frac{2}{3}\cdot v_{atemp} & \text{Otherwise}\end{cases} \quad (11)$$

where $b_0 = 5.4\cdot 10^{-4}$, $b_1 = -2.219\cdot 10^{-4}$, $b_2 = 5.213\cdot 10^{-6}$, $b_3 = -6.623\cdot 10^{-9}$, and $b_4 = 8.5\cdot 10^{-6}$. The transpiration of the plants (TRANS) is influenced by the leaf size (LEAFSIZE[·]), the number of plants per m^2 (PM2), the transpiration of the leaves (LEAFTRANS[·]), and the current growth conditions (TRGROW). The growth conditions are modeled as the ratio between the transpiration at the current state (TRCUR) and the transpiration under standard conditions (TRSTD), which is at 25°C, x_{sun} = 300 W/m^2, x_{CO2}=600 ppm, and $f_{SD}(\cdot)$=10 hPa. The actual transpiration of the plants is influenced by the CO_2-level, the sunlight intensity, and the relative humidity. The steam density is also influenced by the water injected

(WATERINJ) by the controller (u_{water}), which, of course, increases the steam density, but is limited by the saturation steam pressure ($f_{SSP}(\cdot)$) and the actual steam pressure ($f_{SP}(\cdot)$). Furthermore, the steam density is affected by the exchange with the environment (ENVEXC), which is determined by the controlled ventilation (u_{vent}), the minimal air exchange (VM0), and the wind speed (v_{wind}). Finally, condensation and evaporation (CONDEVAP) on the greenhouse hull (the glass) influence the steam density. The amount of water on the hull is represented by the state variable x_{cond}, which is limited between 0 and 25 g/m^2 (CHM in Table 3). The *change* in water is modeled by one variable (CONDEVAP), which is negative when evaporation occurs and positive when condensation occurs. The calculation of the greenhouse hull temperature (x_{htemp}) depends on the month of the simulation. The sunlight intensity (v_{sun}) influences the hull temperature during the summer period (May-September).

Important note: The simulator must ensure that $f_{SP}(x_{steam}, x_{atempA}) \leq f_{SSP}(x_{atempA})$. Otherwise, the greenhouse might reach an infeasible state (infinite temperature, negative pressures, temperatures below 0 K, humidity above 100%, etc.). This can easily be prevented by introducing two variables, SSP and SP, in the calculation of the derivatives, assigning the function values, and checking whether SP$\leq$ SSP. If SP>SSP then set SP equal to SSP, i.e., SP is limited by SSP.

2.2 Indoor air temperature x_{atemp}

The indoor temperature is influenced by the following components:

1. Heat capacity of the air and the plants (HCAP).
2. Heating through the heating system (u_{heat}).
3. Heating from the sun (HSUN).
4. Heat exchange with the environment through ventilation (HEXVENT).
5. Heat exchange through the ground (HEXGROUND).
6. Heat exchange through the greenhouse hull (HEXHULL).
7. Heat change due to condensation on the greenhouse hull (HCONDEVAP).
8. Heat change due to change in indoor humidity (HHUM).

The change in the indoor temperature is modeled as follows.

$$\dot{x}_{atemp} = \frac{1}{\text{HCAP}} \cdot (u_{heat} + \text{HSUN} - \text{HEXVENT} - \text{HEXGROUND} - \text{HEXHULL} - \text{HCONDEVAP} - \text{HHUM}) \tag{12}$$

where

$$\text{HCAP} = \text{LEAFSIZE[MONTH]} \cdot \text{LSW} \cdot \text{HCW} + \text{GH} \cdot \text{HCA} \cdot \text{DA} + \text{GH} \cdot \text{HCS} \cdot x_{steam} \tag{13}$$

$$\text{HSUN} = \text{TS} \cdot x_{sun} \tag{14}$$

$$\text{HEXVENT} = \frac{1}{3600}(u_{vent} + \text{VM0} + \text{VM1} \cdot v_{wind}) \cdot (x_{energy} - v_{energy}) \tag{15}$$

$$x_{energy} = \text{HCA} \cdot \text{DA} \cdot x_{atemp} + x_{steam} \cdot (\text{EEW0} + \text{HCS} \cdot x_{atemp}) \tag{16}$$

$$v_{energy} = \text{HCA} \cdot \text{DA} \cdot v_{atemp} + v_{steam} \cdot (\text{EEW0} + \text{HCS} \cdot v_{atemp}) \tag{17}$$

$$\text{HEXGROUND} = \text{HG} \cdot (x_{atempA} - v_{gtempA}) \tag{18}$$

$$\text{HExHull} = \text{GR} \cdot (\text{HW0} + \text{HW1} \cdot v_{wind}) \cdot (x_{atempA} - v_{atempA}) \tag{19}$$

$$\text{HCondEvap} = \frac{1}{3600} \cdot \text{EEW} \cdot \text{CondEvap} \qquad (\text{CondEvap from Eq. 8}) \tag{20}$$

$$\text{HHum} = \text{GH} \cdot (\text{EEW0} + \text{HCS} \cdot x_{atemp}) \cdot \dot{x}_{steam} \tag{21}$$

The heat capacity of the air and the plants (HCap) is determined by the heat capacity of the plants, the air, and the current amount of steam in the air. The heating from the sun (HSun) is calculated as the indoor sunlight intensity (x_{sun}) scaled by the thermic effect factor (TS). The heat exchange due to ventilation (HExVent) is influenced by the controlled ventilation (u_{vent}), the minimal air exchange (VM0), and the wind speed (v_{wind}). The difference between the energy contents of the indoor air (x_{energy}) and the outdoor air (v_{energy}) also influence this exchange. The exchange at the ground (HExGround) depends on the difference between the indoor air and the temperature of the ground. The exchange through the hull (HExHull) is determined by the difference between indoor and outdoor temperature and the wind speed (v_{wind}). Furthermore, the condensation or evaporation on the hull (HCondEvap) affects the indoor temperature. Finally, the change in humidity (HHum) affects the indoor temperature.

2.3 Indoor CO_2 concentration x_{CO2}

The CO_2 concentration in the greenhouse is influenced by three factors:

1. Artificially injected CO_2 (u_{CO2}).
2. CO_2 consumption by the plants through photo-synthesis and transpiration (CPhoto).
3. Exchange with the environment through ventilation (CExVent).

The change in indoor CO_2 concentration is modeled by the following equation.

$$\dot{x}_{CO2} = \frac{u_{CO2} - \text{CPhoto} - \text{CExVent}}{10^{-6} \cdot \text{DC} \cdot \text{GH} \cdot 3600} \tag{22}$$

where

$$\begin{aligned} \text{CPhoto} &= 100 \cdot \text{LeafSize[month]} \cdot \text{PM2} \cdot \\ &\quad \text{LeafCO2Ex[month]} \cdot \text{CPhGrow} \end{aligned} \tag{23}$$

$$\text{CPhGrow} = \begin{cases} \text{CPhCur} \cdot \text{CPhDec} & \text{if CPhCur} > 0 \\ \text{CPhCur} & \text{otherwise} \end{cases} \tag{24}$$

$$\begin{aligned} \text{CPhCur} &= c_1 \cdot (1 - \exp(-c_2 \cdot 0.5 \cdot x_{sun})) \cdot (1 - \exp(-c_3 \cdot x_{CO2})) \cdot \\ &\quad (x_{atemp} + c_4 \cdot (x_{atemp})^2) - c_5 \cdot (x_{atemp} + c_6 \cdot (x_{atemp})^2) \end{aligned} \tag{25}$$

$$\text{CPhDec} = \begin{cases} \exp(-c_7 \cdot (d_1 - f_{SD}(x_{steam}, x_{atempA}))^2) & \text{if } f_{SD}(x_{steam}, x_{atempA}) < d_1 \\ 1 & \text{if } d_1 \leq f_{SD}(x_{steam}, x_{atempA}) \leq d_2 \\ \exp(-c_8 \cdot (d_2 - f_{SD}(x_{steam}, x_{atempA}))^2) & \text{if } d_2 < f_{SD}(x_{steam}, x_{atempA}) \end{cases} \tag{26}$$

$$\text{CExVent} = (u_{vent} + \text{VM0} + \text{VM1} \cdot v_{wind}) \cdot \text{DC} \cdot 10^{-6} \cdot (x_{CO2} - v_{CO2}) \tag{27}$$

with $c_1 = 0.1381$, $c_2 = 8.687 \cdot 10^{-3}$, $c_3 = 3.697 \cdot 10^{-3}$, $c_4 = -1.9083 \cdot 10^{-2}$, $c_5 = 2.073 \cdot 10^{-3}$, $c_6 = 8.7525 \cdot 10^{-2}$, $c_7 = 0.0001$, $c_8 = 0.001$, $d_1 = 5$, and $d_2 = 10$.

The change in CO_2 concentration caused by photo-synthesis (CPhoto) is determined by the leaf size, the number of plants per m^2, the CO_2 exchange at the current month, and the growth conditions (GPhGrow). The growth depends on the indoor sunlight intensity (x_{sun}), the current CO_2 concentration (x_{CO2}), and the current indoor temperature (x_{atemp}). The growth is scaled by a factor (CPhDec) when the steam pressure is not in the optimal range between d_1 and d_2 (too dry or too moist). Note that negative growth occurs at night (x_{sun}=0) or at extreme temperatures. Negative growth is the situation where the plant's respiration is larger than its photosynthesis. The CO_2 balance is also influenced by the air exchange with the environment (CExVent), which is determined by the controlled ventilation (u_{vent}), the minimal air exchange (VM0), and the wind speed (v_{wind}). The environment CO_2-level (v_{CO2}) can be kept constant at $v_{CO2} = 340$ ppm.

2.4 Accumulated biomass x_{biom}

The change in biomass depends on the photo-synthesis of the plants (CPhoto). It is modeled by the following equation.

$$\dot{x}_{biom} = \text{CPhoto} \cdot \frac{30}{44 \cdot 3600} \tag{28}$$

Note that x_{biom} models the dry weight of the crop, here tomatoes. Naturally, the biomass represented by x_{biom} must be positive, which is achieved by a simple constraint $x_{biom} \geq 0$ in the simluator.

2.5 Accumulated profit x_{profit}

The change in profit is modeled as the income minus the expenses.

$$\dot{x}_{profit} = \dot{x}_{biom} \cdot \text{DWF} \cdot v_{Ptom} \cdot 10^{-3} - \frac{u_{CO2} \cdot v_{PCO2} \cdot 10^{-3}}{3600} - \frac{u_{heat} \cdot v_{Pheat}}{3600} \tag{29}$$

In our implementation, the prices are kept constant to $v_{Ptom} = 12$ DKK/kg, $v_{PCO2} = 4$ DKK/kg, and $v_{Pheat} = 0.0002$ DKK/(W·h).

2.6 Condensation on greenhouse hull x_{cond}

The change in the condensation amount on the greenhouse hull is modeled by the following equation.

$$\dot{x}_{cond} = \frac{\text{CondEvap}}{3600} \tag{30}$$

Note that the condensation amount on the hull is limited between 0 and 25 g/m^2 (CHM in Table 3). The simulator must implement this constraint.

3 Implementation specific details

The simulator is implemented in Java 1.3 and is integrated with EVALife's EA-library (available at `www.evalife.dk`). The code is approximately 1200 lines long including the Runge-Kutta approximation. The simulator is available upon request (`ursem@daimi.au.dk`) except for the weather data, which is copyrighted by the Danish Meteorologic Institute, DMI (`www.dmi.dk`). For comparative studies we recommend to purchase the data for the measuring station Aarslev, Denmark, 2000 from DMI, which is available to researchers for about 900 DKK (110$). Please contact Rasmus K. Ursem (`ursem@daimi.au.dk`) if you decide to purchase this weather data, since the data contains a few gaps and it would be important to use the exact same data in a comparative study.

4 Conclusions

In this report we have described a rather complex greenhouse simulator, which has been translated from German and reimplemented in Java based on a MatLab version. The main purpose of the simulator is to serve as a benchmark problem for experimental control techniques. Another objective with the report was to describe the minor modifications we have made to the original version.

References

[Pohlheim and Heißner, 1996] Pohlheim, H. and Heißner, A. (1996). Optimale Steuerung des Klimas im Gewächshaus mit Evolutionären Algorithmen: Grundlagen, Verfahren und Ergebnisse. Technical report, Technische Universität Ilmenau.

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Appendix A: Physical constants, auxiliary variables, and functions

Description	Variable	Unit	Value
Gas constant for steam	RWS	[J/(g·K)]	0.46152
Heat capacity for air	HCA	[J/(g·K)]	1.006
Heat capacity for steam	HCS	[J/(g·K)]	1.8631
Heat capacity for water	HCW	[J/(g·K)]	4.1868
Evaporation energy for water 20°C	EEW	[J/g]	2453
Evaporation energy for water 0°C	EEW0	[J/g]	2501
Density of air at 20°C and 760 Torr	DA	[g/m^3]	1204
Density of CO_2 at 20°C and 760 Torr	DC	[g/m^3]	1840

Table 2: Physical constants.

Description	Variable	Unit	Value
Plants per m^2	PM2		1
Transmission degree for glass	TG		0.71
Thermic degree for sunlight	TS		0.6
Coefficient for water injection	CW	[1/Pa]	0.0005
Greenhouse height	GH	[m]	3
Ratio glass surface/ground surface	GR		1.64
Heat exchange coeff. at no wind	HW0	[W/(m$^2 \cdot$ K)]	3
Heat exchange gradient at nonzero wind	HW1	[(W/(m$^2 \cdot$ K))/(m/s)]	0.2
Heat exchange coeff. at ground	HG	[W/(m$^2 \cdot$ K)]	3
Maximal condensation on greenhouse hull	CHM	[g/m^2]	25
Minimal air exchange at no wind	VM0	[m^3/(m$^2 \cdot$ h)]	2
Minimal air exchange gradient	VM1	[(m^3/(m$^2 \cdot$ h))/(m/s)]	2
Leaf size to water equivalent factor	LSW	[g/m^2]	1000
Dry weight factor for crop (tomatoes)	DWF		10

Table 3: Greenhouse constants.

Description	Variable	Unit	Function
Absolute temperature for x_{atemp}	x_{atempA}	[K]	$x_{atemp} + 273.15$
Absolute temperature for x_{htemp} (Eq. 11)	x_{htempA}	[K]	$x_{htemp} + 273.15$
Absolute temperature for v_{atemp}	v_{atempA}	[K]	$v_{atemp} + 273.15$
Absolute temperature for v_{gtemp}	v_{gtempA}	[K]	$v_{gtemp} + 273.15$
Indoor sunlight intensity	x_{sun}	[W/m^2]	TG$\cdot v_{sun}$
Outdoor steam density	v_{steam}	[g/m^3]	$\dfrac{v_{RH} \cdot f_{SSP}(v_{atempA})}{100 \cdot v_{atempA} \cdot \mathrm{RWS}}$

Table 4: Auxiliary variables.

The following equations are used multiple times in the differential equations describing the greenhouse state.

Month	1	2	3	4	5–10	11	12
LeafSize[·]	0.5	0.5	0.8	1.5	2.0	1.0	0.5
LeafTrans[·]	0.015	0.015	0.015	0.015	0.015	0.015	0.015
LeafCO2Ex[·]	1.0	1.0	1.0	1.0	1.0	1.0	1.0

Table 5: Plant growth variables.

Saturation steam pressure over water [Pa]

Saturation steam pressure in Pa over water at temperature T in Kelvin.

$$f_{SSP}(T) = \exp\left(a_1/T + a_2 + a_3 \cdot T + a_4 \cdot T^2 + a_5 \cdot \log T\right) \tag{31}$$

where T is the temperature in Kelvin, $a_1 = -6094.4642$, $a_2 = 21.1249952$, $a_3 = -0.02724555$, $a_4 = 0.0000168534$, and $a_5 = 2.4575506$.

Steam pressure [Pa]

$$f_{SP}(S, T) = S \cdot T \cdot \mathrm{RWS} \tag{32}$$

where S is the steam density (e.g., x_{steam}), T is the temperature in Kelvin, and RWS is the gas constant (see Table 2).

Saturation deficit [hPa]

$$f_{SD}(S, T) = \frac{f_{SSP}(T) - f_{SP}(S, T)}{100} \tag{33}$$

where S is the steam density (e.g., x_{steam}) and T is the temperature in Kelvin.

Relative humidity [% r.H.]

$$f_{RH}(S, T) = 100 \cdot \frac{f_{SP}(S, T)}{f_{SSP}(T)} \tag{34}$$

where S is the steam density (e.g., x_{steam}) and T is the temperature in Kelvin.

Appendix B: Translation details

The greenhouse simulator described in this report is, as mentioned, translated from the German description found in (Pohlheim and Heißner, 1996). This appendix summarizes the translation of the variables and their units. The section is mainly intended for readers who want to verify the translation and seek additional information in the original description. Please, note that there might be minor differences between this description and the original description. These differences may be due to a rewriting of the equations for clarification, to remove typos, and to describe extensions suggested in the presented simulator.

English	German	Unit
u_{heat}	Q	[W/m^2]
u_{vent}	LR	[m^3/(m$^2 \cdot$ h)]
u_{CO2}	W	[g/(m$^2 \cdot$ h)]
u_{water}	RM	[g/(m$^2 \cdot$ h)]
x_{steam}	DDI	[g/m^3]
$\dot{x}_{steam}$	DDDI	[g/(m^3·s)]
x_{atemp}	TEMI	[°C]
$\dot{x}_{atemp}$	DTEMI	[°C/s]
x_{CO2}	CI	[ppm]
$\dot{x}_{CO2}$	DCI	[ppm/s]
x_{biom}	BIOM	[g/m^2]
x_{profit}	GEWI	[DKK/m^2]
x_{cond}	KS	[g/m^2]
x_{htemp}	TEMG	[°C]
x_{sun}	I	[W/m^2]

English	German	Unit
v_{sun}	IGLOB	[W/m^2]
v_{atemp}	TEMA	[°C]
v_{gtemp}	TEMB	[°C]
v_{RH}	FA	[% r.H.]
v_{wind}	U	[m/s]
v_{CO2}	CA	[ppm]
v_{Pheat}	PR3	[DKK/(W·h)]
v_{PCO2}	PR2	[DKK/kg]
v_{Ptom}	PR1	[DKK/kg]
v_{steam}	DDA	[g/m^3]
x_{atempA}	TAI	[K]
x_{htempA}	TAG	[K]
v_{atempA}	-	[K]
v_{gtempA}	-	[K]

Table 6: Translation details for control, state, and environment variables. Furthermore, the auxiliary variables calculated from other variables are listed.

English	German	Unit
RWS	RWS	[J/(g·K)]
HCA	CPL	[J/(g·K)]
HCS	CPD	[J/(g·K)]
HCW	CPW	[J/(g·K)]
EEW	VDW	[J/g]
EEW0	VDW0	[J/g]
DA	DL	[g/m^3]
DC	DC	[g/m^3]
LeafSize	A	
LeafCO2Ex	P0	[g/(dm$^2 \cdot$ h)]
LeafTrans	V0	[g/(dm$^2 \cdot$ h)]
DWF	-	

English	German	Unit
PM2	n	
TG	BQ	
TS	KI	
CW	KR	[1/Pa]
GH	GH	[m]
GR	GF	
HW0	KW0	[W/(m$^2 \cdot$ K)]
HW1	KW1	[(W/(m$^2 \cdot$ K))/(m/s)]
HG	KB	[W/(m$^2 \cdot$ K)]
CHM	KSM	[g/m^2]
VM0	-	[m^3/(m$^2 \cdot$ h)]
VM1	-	[(m^3/(m$^2 \cdot$ h))/(m/s)]
LSW	KP	[g/m^2]

Table 7: Translation details for physical constants, plant constants, and greenhouse constants.

English	German	Unit
$f_{SSP}(x_{atempA})$	PSI	[Pa]
$f_{SSP}(x_{htempA})$	PSG	[Pa]
$f_{SSP}(v_{atempA})$	PSA	[Pa]
$f_{SP}(x_{steam}, x_{atempA})$	PDI	[Pa]
$f_{SD}(x_{steam}, x_{atempA})$	SDI	[hPa]
$f_{RH}(x_{steam}, x_{atempA})$	FI	[%.r.H.]

English	German	Unit
c_7	EE_1	
c_8	EE_2	
d_1	$SDIG_1$	
d_2	$SDIG_2$	

Table 8: Translation details for auxiliary variables and functions.

English	German	Unit	English	German	Unit
TRANS	trans	$[g/(m^2 \cdot h)]$	HCAP	CG+ (seite 6)	$[J/(K{\cdot}m^2)]$
TRGROW	VREL		HSUN	qglob	$[W/m^2]$
TRCUR	VRELC		HEXVENT	qluwe	$[W/m^2]$
TRSTD	VSTAN		x_{energy}	HI	$[J/m^2]$
WATERINJ	lube	$[g/(m^2 \cdot h)]$	v_{energy}	HA	$[J/m^2]$
ENVEXC	wadawe	$[g/(m^2 \cdot h)]$	HEXGROUND	qboden	$[W/m^2]$
CONDEVAP	kondverd	$[g/(m^2 \cdot h)]$	HEXHULL	qduga	$[W/m^2]$
COND	konden	$[g/(m^2 \cdot h)]$	HCONDEVAP	qkonden	$[W/m^2]$
TRPO	trpoko	$[m/h]$	HHUM	GH+ (seite 6)	$[W/m^2]$

Table 9: Translation details for auxiliary variables for $\dot{x}_{steam}$ and $\dot{x}_{atemp}$.

English	German	Unit
CPHOTO	gawe	$[g/(m^2 \cdot h)]$
CPHGROW	FREL (in german simulator code)	
CPHCUR	FICT	
CPHDEC	FSD	
CEXVENT	kodiwe	$[g/(m^2 \cdot h)]$

Table 10: Translation details for auxiliary variables for $\dot{x}_{CO2}$.