An object-oriented greenhouse simulation software system - Part II: Description, validation and use of a simple model

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Gauthier, L. 1993. **An object-oriented greenhouse simulation software system - Part II: Description, validation and use of a simple model.** Can. Agric. Eng. **35**:223-228. A simple model of greenhouse heat and mass exchanges was written in the Smalltalk object-oriented programming language and was integrated into a general greenhouse climate control and management software system (GX). The structure, operation and performance of the heat and mass exchange simulation subsystem is described and sample results of its use are given. The results show that the GX simulator can emulate the behavior of the greenhouse ecosystem and of its climate control system. Hence, by using the GX simulation subsystem, the results from a simulation using one control strategy can be compared to results from a simulation run with a different strategy. One can then determine the potential savings in terms of energy or other inputs (CO_2, water, etc.) associated with the use of a given strategy. The GX-based simulator has shown potential for both teaching and research applications.

Keywords: greenhouse, simulation, object-oriented programming, knowledge systems, smalltalk

Un modèle simplifié des échanges thermiques et massiques en serre a été écrit dans le langage orienté-objet Smalltalk. Ce modèle est en fait intégré dans le progiciel GX de contrôle et de gestion du climat en serre. La structure, l'opération et les performances du simulateur sont décrits et des résultats de simulation sont présentés. Ceux-ci démontrent que le simulateur GX peut émuler le comportement d'une serre et de son système de régulation du climat. Aussi, les résultats d'une simulation utilisant une certaine stratégie de contrôle peuvent être comparés aux résultats obtenus sous une stratégie différente. Les économies potentielles en énergie ou en intrants divers (CO_2, eau, etc.) associées à une certaine stratégie peuvent ainsi être estimés. Le simulateur possède donc un potentiel intéressant comme outil de formation et de recherche.

INTRODUCTION

In part one of this series of articles (Gauthier 1993c), a software architecture (GX) for the simulation of greenhouse system behaviors was presented and discussed. This architecture facilitates the representation of various greenhouse systems and can be used to simulate their behavior. In fact, as discussed in Gauthier (1993a, 1993b, 1993c), it allows the implementation and validation of dynamic and knowledge-based control strategies. In this article, the operation and use of the heat and mass exchange simulation subsystem that was built and tested using the GX programming environment is presented.

DESCRIPTION OF MODEL

As introduced in Gauthier (1993c), GX can accommodate different models by virtue of its object-oriented architecture. As long as the model provides the proper interface or data exchange protocol, several different models can coexist in the system and the user can choose, at run time, the model that is the most appropriate for the task. This functionality was used to implement two different models of greenhouse thermal exchanges: a static one based on the equations presented by Duncan et al. (1981) and ASAE (1988) and a dynamic one based on work done by de Halleux (1989). Only the first one will be presented and discussed.

BASIC EQUATIONS

Heat balance

In the static model, the change in greenhouse air temperature, T_g, is modeled using the following differential equation (Duncan et al. 1981):

$$\frac{dT_g}{dt} = \frac{Q_{net}}{CP_{gh}} \tag{1}$$

where:

Q_{net} = heat gains - heat losses ($W \bullet m^{-2}$), and
CP_{gh} = thermal inertia of greenhouse ($J \bullet {}^{o}C^{-1}$).

Equation 1, when solved, produces:

$$T_g = T^* + (T_g - T^*) \exp(-\Delta t / C_t) \tag{2}$$

where:

$$C_t = \frac{CP_{gh}}{UA} \tag{3}$$

$$T^* = T_g + \frac{Q_{net}}{UA} \tag{4}$$

$$Q_{net} = (Q_f + Q_s + Q_h) - (Q_{cr} + Q_i + Q_v + Q_{gr}) \tag{5}$$

in which:

U = overall heat transfer coefficient ($W \bullet {}^{o}C^{-1} \bullet m^{-2}$),
A = exposed greenhouse surface area (m^2),
Q_f = heating system input (W),
Q_h = heat supplied by high intensity discharge lamps (W),
Q_s = solar gain (W),

Q_i = sensible and latent heat transfers through infiltration (W),

Q_v = heat loss through ventilation,

Q_{gr} = heat loss to soil (W), and

Q_{cr} = conductive and radiant losses (W).

The various Q terms are described below.

Q_f is the heating system output and is computed by the regulation subsystem emulator (Gauthier 1993c) which estimates the current heat demand as a percentage of the maximum heating capacity. This fraction is then used to calculate the actual heat output of the heating apparatus.

Q_h is the heat supplied by high intensity discharge (HID) lamps and is computed by multiplying the state of the lighting system (0 or 1) by the heat output of the installed lighting system. It is assumed that the heat supplied by the lamps is equal to five times the amount of photosynthetically active radiation (PAR) they produce (de Halleux 1989).

Q_s is the solar gain and is calculated by using a fraction of the outside solar radiation (global spectrum). This fraction is based on accepted or measured values of transmissivity for a given greenhouse structure in the presence or absence of shading screens.

Q_i accounts for sensible and latent heat transfers through infiltration and is calculated as the product of air density ($kg \bullet m^{-3}$), air specific heat ($kJ \bullet kg^{-1} \bullet {}^{o}C^{-1}$), air infiltration rate ($m^3 \bullet s^{-1}$) and the difference between the inside and outside air temperatures (^{o}C). The specific heat of the air was assumed constant and equal to 1 $kJ \bullet kg^{-1} \bullet {}^{o}C^{-1}$.

Q_v is the heat loss through ventilation and is computed as for infiltration. However, the rate of ventilation is established by the regulation subsystem emulator based on the calculated air temperature and the ventilation set point.

Q_{gr} is the heat loss to the soil and is calculated based on an equation proposed by Roberts et al. (1985) which is the product of a constant value (1.384), the greenhouse perimeter, and the temperature differential.

Q_{cr} is the lumped conductive and radiative losses and is computed with the approach proposed in ASAE (1988) which is based on the use of the overall heat transfer coefficient, U, expressed in $W \bullet m^{-2} \bullet {}^{o}C^{-1}$. The value of U was adjusted to account for the difference in heat loss rates due to the presence or absence of thermal screens.

At each time step, new values for outside air temperature, solar radiation and controlled heat inputs (from heaters and HID lamps) are asserted. These are then used to compute the net heat loss of the greenhouse (Eq. 5) which is in turn used to calculate a new value for the inside temperature (Eq. 3).

Mass balance

Since the simulator is used to test the integrity and behavior of the logic implemented in control strategies, it was important to simulate the variations of water vapor and CO_2 concentrations which occur in greenhouses. Hence, simple and more or less intuitive models of mass exchanges were integrated into the simulation subprogram, but their impact on the heat balance was neglected. The water vapor exchange rate ($kg \bullet s^{-1}$) is based on calculated values of the overall ventilation, crop transpiration (an on/off type of parameter), fogging, and condensation rates. Similarly, a CO_2 balance was incorporated into the program to simulate the effect of photosynthesis, respiration, carbon dioxide injection and ventilation rates on the CO_2 content of the air.

MODEL ORGANIZATION

To implement the model, a Smalltalk class was defined: **StaticHeatXChgSimulator**. It is a subclass of the abstract classes: **GXZoneSimulator** and **ShelteredZoneSimulator**. The attributes (instance variables) of a ShelteredZoneSimulator appear in Gauthier (1993c). When an instance of this class is created, it is associated to a **Zone** instance and initial values are assigned to the ***timeStep***, ***previousTime*** and ***client*** variables. The ***machines*** variable is also initialized with instances of the class **FiniteStateMachine** (Gauthier 1993c) and the ***coefficients*** and ***constants*** variables contain collections of values which reflect the characteristics of the zone being modeled. In Table I, the names and roles of the principal methods associated with the **StaticHeatXChgSimulator** class are listed.

The simulator is run by sending it the message ***tic: aTimeInSeconds*** where ***aTimeInSeconds*** is the current simulation time expressed in seconds past midnight. The corresponding method or procedure computes new values for the variables ***airTemp***, ***co2***, ***par***, and ***relHum*** and the finite state machines are run. The latter will adjust controlled variables (heater output, vent openings, state of HID lamps, CO_2 injection valves, etc.) based on the difference between setpoint values and calculated values.

VALIDATION OF THE SIMPLE MODEL

Tests were conducted to validate the model. The output of the simulator was compared to measurements taken in a single-bay, stand-alone, Venlo type greenhouse located on the Laval University campus. This greenhouse was heated with an

Table I: List of methods or procedures associated with the StaticHeatXchgSimulator class

Method selector	Description
calculateCO_2	Compute new CO_2 concentration
calculateRelHum	Compute new relative humidity level
calculatePAR	Compute new PAR level
calculateScreenPos	Compute new screen position
calculateTranspRate	Compute new crop transpiration rate
calculateAirTemp	Compute new air temperature
foggingFSM	Create and return the FSM for the fogging system
airHeatingFSM	Create and return the FSM for air heating system
co2FSM	Create and return the FSM for CO_2 injection system
screenFSM	Create and return the FSM for the thermal screen
hidFSM	Create and return the FSM for HID lamps
ventilFSM	Create and return the FSM for the ventilation system

electric furnace and equipped with HID lamps (20 W•m^{-2}), thermal screens, and a fogging system. The greenhouse measured 6.4 m by 24 m with a height of 4 m to the gutters. Energy consumption was recorded through the use of two pulse generating kilowatt-hour meters connected to a CR10 data logger (Campbell Scientific, Logan, UT). The total energy consumption over a 15 minute period was logged by the CR10 and transferred to a desktop computer for analysis on a daily basis. Air temperature and relative humidity sensors were also connected to this data logger and average values over a fifteen minute period were recorded.

The outside climatic conditions were measured by a separate installation which recorded 15 minute averages for air temperature, relative humidity and solar, PAR, and infrared radiation. Table II contains the values of the model parameters used for the validation results presented in the next section.

COMPARISON OF MEASURED AND CALCULATED VALUES

Figures 1 and 2 show results for a simulation that was run using climatic data for 3 days in January and 3 days in May of 1992. The measured and calculated temperatures (15 minute averages) are shown in Fig. 1 while the energy consumptions and ventilation demands (hourly averages) are shown in Fig. 2. Based on these results, the simulator was judged sufficiently accurate to be used for control strategy assessment.

TIME REQUIRED FOR SIMULATIONS

The amount of time required to run simulations using the **StaticHeatXchgSimulator** was recorded on several occasions. Since OS/2 is a multitasking system which can make use of virtual memory, the values can only serve as an indication of the type of performance that can be expected. When simulating a single zone with a 60 second time step on a 33 MHz, 486 computer containing 12 megabytes of RAM and running OS/2 version 1.3, the time required to simulate one hour varied between 0.5 and 1.0 minutes. The differences can be explained by the presence of other applications on the host computer, by the number of dynamic GX windows open at the time the simulation is run and by the complexity of the scenario that is being executed. Such results are adequate when GX is used as a teaching tool since it gives students the opportunity to visualize the behavior of the system. When the end results are of interest (i.e., the files containing the simulation results), a simulation can be run as a background task.

USE OF THE SIMULATOR FOR CONTROL STRATEGY ASSESSMENT

Figure 3 contains sample results from a simulation run using a scenario in which the nighttime setpoints were established so as to maintain a constant 24 hour average air temperature of 20°C (de Koning 1988). Weather data representing climatic conditions in Quebec City for a ten day period in October were used. Figure 3A and Table III indicate that the nighttime setpoint was related to the daytime temperature.

The code fragment which produces the dynamic behavior captured by the chart of Fig. 3A is shown in Fig. 4. It consists of three rules with different priorities and premises. For rule #3 to fire, the parameters and statistics labeled *Avg24hAirTemp*, *AvgDayTemp*, and *DayLength* must be defined. Rule #3 establishes the nighttime temperature to a value that is greater or equal to 14°C and that ensures an average 24 hour air temperature equal to the value of

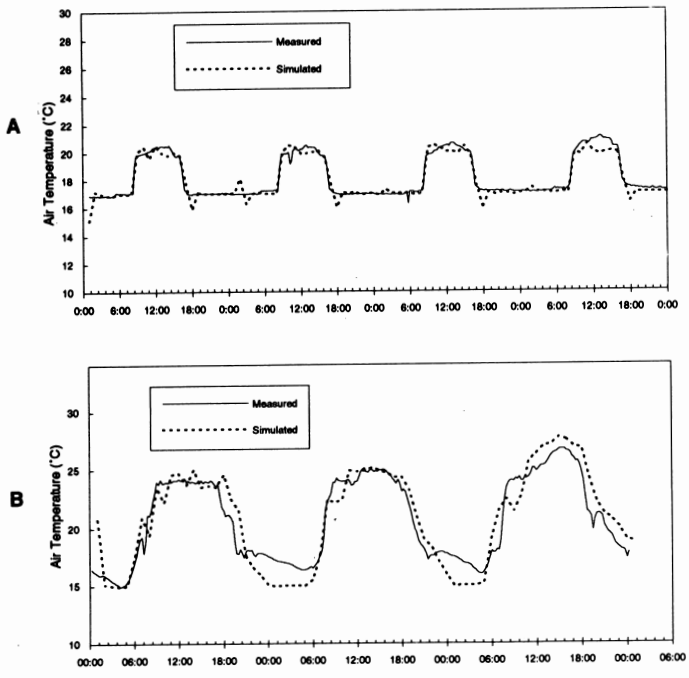

Fig. 1. Comparison of measured and calculated values of greenhouse air temperature for (A) winter and (B) spring conditions.

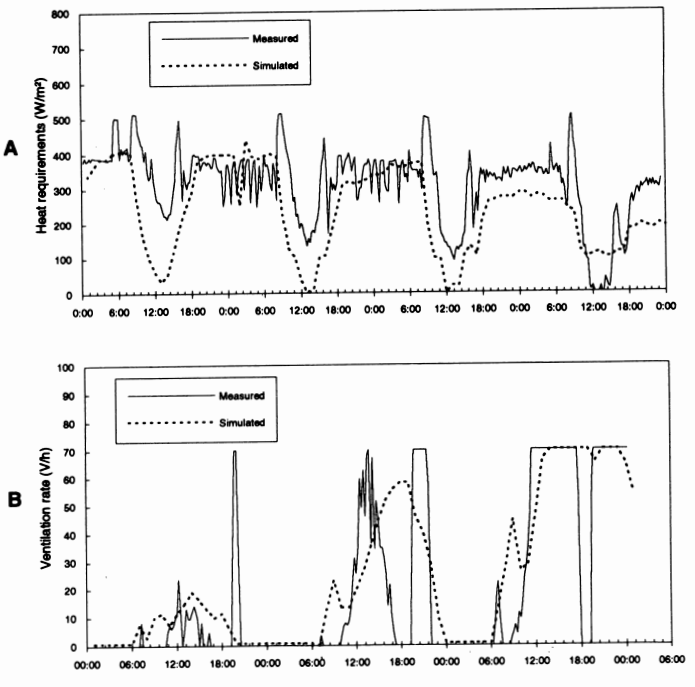

Fig. 2. Comparison of measured and calculated values of heat demand in the winter (A) and ventilation demand in the spring (B).

Table II: List of parameter definitions and values used to run the simulator validations

Parameter	Definition	Value (units)
N_o	Volume changes per hour (above freezing)	0.72 h^{-1}
N_f	Volume changes per hour (below freezing)	0.5 h^{-1}
CP_{gh}	Greenhouse thermal inertia	5 $kJ \cdot {}^{\circ}C^{-1}$
Cp_{air}	Air specific heat	1 $kJ \cdot kg^{-1} \cdot {}^{\circ}C^{-1}$
Rho	Air density	1.293 $kg \cdot m^{-3}$
U_o	Overall heat transfer coefficient (thermal screens retracted)	3.0 $W \cdot m^{-2} \cdot {}^{\circ}C^{-1}$
U_s	Overall heat transfer coefficient (thermal screens deployed)	2.1 $W \cdot m^{-2} \cdot {}^{\circ}C^{-1}$
A	Surface area of greenhouse floor	154 m^2

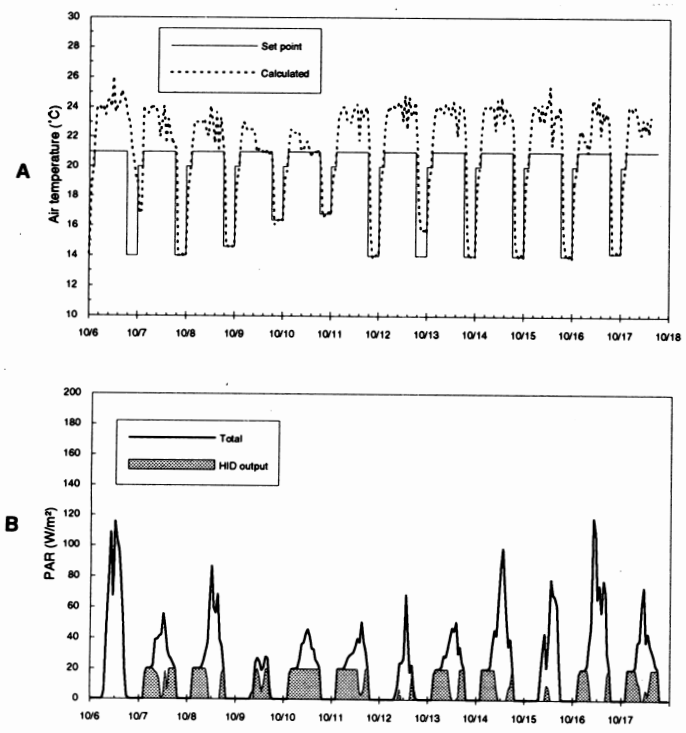

Fig. 3. Profiles for air temperatures (A) and photosynthetically active radiation (B) produced by a GX simulation using weather data from a ten day period in October.

Avg24hAirTemp. For the results presented here, this parameter was fixed to 20°C.

The PAR pattern (Fig. 3B) reflects the utilization of supplemental light from 200h to 1800h (the lamps were switched off when the natural light levels reached a certain threshold value or when a certain light integral was obtained). The total calculated PAR radiation shown in Table III is thus the sum of the artificial and natural radiations that reached the canopy and was calculated using the measured global radiation and the greenhouse transmissivity coefficient which varied based on screen position. As it can be observed from Fig. 3B, the lamps were kept on throughout the daytime on October 9 and 10 while they were switched off early on the 6th and on the 16th. Figure 3B actually reflects the effect of a fairly sophisticated supplemental lighting control strategy that is based on the use of a crop growth model that generates estimates of the marginal rate of return associated with the use of supplemental lighting (Carrier and Gauthier 1993).

The CO_2 enrichment strategy can be assessed from Table III: the average CO_2 level increases with the amount of light except for the day of October 6 when the recourse to ventilation did not allow for CO_2 enrichment.

Table III also contains the daily average for relative humidity and vapor pressure deficit (VPD). The latter was regulated so as to obtain a smooth increase from one day to the other while aiming for a desired value of 0.4 kPa. Hence, from October 7 to 13, the VPD gradually increased but it decreased again after the 13th due to ventilation. The use of a fogging system could help maintain the VPD close to its desired value. This can be achieved through simple changes to the fogging system control strategy.

For the simulation results presented above, the IU emulator reproduced the behavior of the heating, cooling and supplemental lighting systems. By examining Fig. 5 we can observe the simultaneous use of ventilation and heating which can be explained partly by dehumidification needs (especially at night) and partly by simulator idiosyncrasies. Better response can be obtained by decreasing the simulation time step at the expense of simulation speed.

SUMMARY AND CONCLUSIONS

The simulation results presented above shows how GX can be used as a research and teaching tool. By modifying the logic or the parameters that a control strategy makes use of, one can study and document the strategy's behavior before it is actually deployed. This is because GX emulates, with a certain a degree of fidelity, the behavior of the greenhouse ecosystem and of its climate control system. Hence, by using the GX simulation subsystem, the results from a simulation using one control strategy can be compared to results from a simulation run with a different strategy. One can then determine the potential savings in terms of energy or other inputs (CO_2, water, etc.) associated with the use of a given strategy. With the use of an accurate crop growth model, the yields and hence, the profitabilities of different control strategies can also be compared. The GX simulator has potential for both teaching and research applications. Better physical and biological models should make it an even more useful tool.

Table III: Average and total values obtained from a simulation using weather data from a ten day period in October in Quebec City

	Air Temp (°C)			RH (%)	VPD (Pa)	CO_2 (ppm)	PAR (MJ/m^2)	Photo (h)
Date	24h	Night	Day	24h	24h	24h	24h	
10/06	23.1	15.5	24.5	84	510	500	3.3	16.1
10/07	20.0	19.6	21.6	98	40	636	1.8	16.1
10/08	20.5	17.5	22.3	95	130	652	2.3	16.1
10/09	20.1	16.5	21.5	93	160	622	1.5	16.1
10/10	20.2	17.5	21.5	94	150	652	1.7	16.1
10/11	21.0	17.5	23.2	91	230	633	1.7	16.1
10/12	21.4	16.2	23.5	86	390	599	1.8	16.1
10/13	21.1	17.3	23.5	88	340	629	1.8	16.1
10/14	20.9	16.0	23.3	92	230	640	2.5	16.1
10/15	20.6	16.0	23.0	96	130	660	2.3	16.1
10/16	20.5	15.8	22.7	95	150	673	2.9	16.1
Average	20.9	16.9	22.8	92	220	627	2.1	16.1
STDEV	0.9	1.2	1.0	4.3	140	46.5	0.6	0.0

RULE-1 **"Set daytime air temperature setpoint to 21 °C"**
IF: {*PAR* value in Zone is > = 10};
THEN: {Set *DesiredValue for AirTemp in Zone* to: 21 °C with a priority of: 5
because: 'PeriodOfDay = Daytime'}.

RULE-2 **"Set default nighttime air temperature setpoint to 18.5 °C"**
IF: {*PAR* value in Zone is < 5};
THEN: {Set *DesiredValue for AirTemp in Zone* to: 18.5 °C with a priority of: 6
because: 'PeriodOfDay = Nighttime'}.

RULE-3 **"Set nightime air temp. setpoint based on 24 avg temp."**
IF: {*PAR* value in Zone is < 5};
AND: {*Avg24hAirTemp* < > nil};
AND: {*AvgDayTemp* < > nil};
AND: {*DayLength* < > nil};
THEN: {Set *DesiredValue for AirTemp* in Zone to:
((((*Avg24hAirTemp* * 24) - (*AvgDayTemp* * *DayLength*)) / (24 - *DayLength*)) max: 14) with a priority of: 7
because: 'Nighttime temp. regime based on 24 hr avg'}.

Fig. 4. Pseudo-code for the GX rule set that implements the air temperature regulation script used in the simulation results presented in Fig. 3.

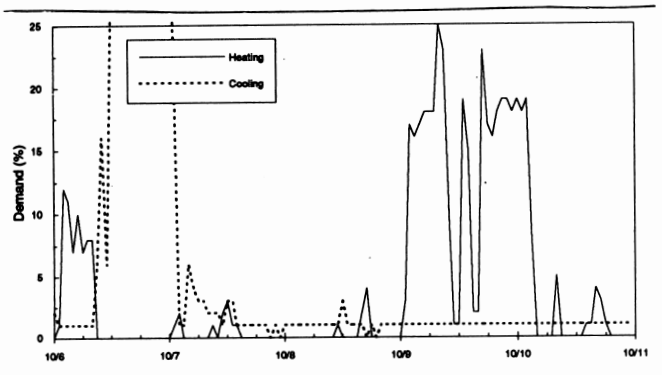

Fig. 5. Simulated heating and cooling demands expressed as percentages for a five day period in October.

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