Description of a Crop Growth Model for the Management of Supplemental Lighting in Greenhouses

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Summary. A dynamic management strategy for supplemental lighting in greenhouses was developed. It makes use of a plant growth model and of a rule-based decisionmaking protocol within the framework of a generic greenhouse climate management software system. The model, an adapted version of SUCROS87, tracks plant growth and predicts dry weight production based on measured or estimated values of light intensity, temperature, and CO₂ concentration. A set of logical predicates (rules) implements the strategy's behavior. Optimization of lamp use was conducted as a function of economic criteria that enable a comparison between the additional income associated with yield increases due to supplemental lighting and incurred cost increases. Although the model is not perfectly reliable in its predictions, the system can be used to simulate the effect of changes to economic parameters on the decisions of the management strategy. The dynamic strategy described here differs

from conventional supplemental lighting scenarios in the sense that it increases the length of the period of supplemental lighting when the daily solar light integral is low, and reduces or eliminates the use of supplemental lighting when the weather forecast predicts that the daily solar light integral will exceed plant requirements.

In greenhouse production, the creation of an artificial climate often requires large energy inputs. Careful management of energy costs requires the use of computerized systems that continuously monitor and change important climatic parameters. The operation of the current generation of commercial climate control systems is based on the observance of production guidelines (or blueprints) set by the producer for relatively long periods (several days). These guidelines are generally the result of the experience of hundreds of producers over several years. The guidelines aim at maintaining climatic conditions that ensure a good growth rate and avoid extreme conditions.

Although very useful, existing systems do not maintain optimal growth conditions at all times, and the particular needs of an individual producer are not always met by the functions provided by the control system. Further, these systems are essentially static (Udink ten Cate, 1980) and cannot take into account the continuous changes affecting the greenhouse environment. Challa and Schapendonk (1986) showed that the optimal climatic set points vary over short periods of time (within the same day) as a function of both outside climatic parameters and plant development stage. Further, the expenses associated with maintaining the settings varies with season and cost of inputs.

Research on more-flexible control systems has led to the study and development of dynamic systems based on explanatory models of growth and development and on models of greenhouse mass and energy balances (Challa et al., 1988; Gauthier and Guay, 1990).

Researchers have recognized the need for multilevel control systems that can synchronize the reactions of system components to the producer's ultimate objective (Udink ten Cate et al., 1978). These systems demand considerable processing power. A distrib-

uted system in which several computers are used is one answer to the growing information-processing requirements (Bakker et al., 1988; Hooper, 1988).

A working group in the Netherlands recognized the important role that can be played by optimization calculations within dynamic climate management strategies. They proposed an approach based on several levels of control (Udink ten Cate et al., 1978). Decisions are based on output from specialized simulation models (Challa and Schapendonk, 1986; Heuvelink and Challa, 1989), and may be subject to considerations involving economic optimization and user preferences (Challa et al., 1988). The environmental conditions are then optimized over short time intervals (a few minutes).

At Laval Univ., a dynamic greenhouse climate management software system has been developed. The system, called GX (Gauthier, 1993a, 1993b), defines a general architecture that may accommodate different decision-support or decisionmaking modules such as mathematical models and rule bases. GX can be used as an on-line system (i.e., for the real-time management of greenhouse climates). It also can be used in a totally virtual mode to simulate and assess the effect of various management strategies. To that end, it contains models of the mass and energy exchange processes that are used to simulate the greenhouse climatic environment and its response to the control strategy under study.

This article presents results obtained with GX following the development and simulated use of a supplemental lighting management strategy. This strategy is based on the use of a general model of plant growth, SUCROS87, that was adapted to the use of artificial lighting, and on a series of management rules supplied by a domain expert (i.e., a grower that has several years of experience working with supplemental lighting). The number of rules was kept at a minimum in order to limit the overall complexity of the knowledge base and to facilitate modifications.

This article describes the operation and use of a crop growth model and of management heuristics (informal or learned behavioral knowledge) for the operation of supplemental lighting systems in greenhouses.

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The GX dynamic climate management system

The GX program was developed using the Smalltalk-V (Digitalk, Los Angeles) object-oriented programming environment. The interested reader can refer to more-specialized sources (Goldberg and Robson, 1983; Meyer, 1988) for a comprehensive introduction to object-oriented programming concepts in general, and to Smalltalk systems in particular.

GX has an open architecture and is described in detail elsewhere (Gauthier and Guay, 1990; Gauthier, 1993a, 1993b, 1993c, 1993d). In the GX system, a greenhouse complex consists of several zones (Fig. 1). Climatic zones (called production zones) may be divided into several irrigation zones. The external zone represents the context (climatic and economic) in which the greenhouse complex is operated. Each zone has a number of attributes or associated objects describing its current state (temperature, light level, relative humidity, crop, etc.).

Figure 2 presents the principal components that are necessary to implement a control strategy. In GX, a control strategy is represented by a program structure called a scenario. The activation of a scenario leads to the creation of a series of databases that will contain a historic record of measurements, parameters, and statis-

Fig. 2. Relations between the principal components of the GX dynamic scenario for the management of supplemental lighting.

tics. These values then may be used by the scenario's decisionmaking protocols.

Supplemental lighting control strategy

The approach chosen for the implementation of the supplemental lighting control strategy is based on

the use of a small number of simple management rules that call on agents (essentially subprograms) for the execution of precise tasks such as the calculation of the photosynthesis rate.

The developed production scenario (called **ScenarioSucros**), uses two agents (Fig. 2). Both are derived from the SUCROS87 model that was adapted (Carrier et al., 1993) to incorporate the use of supplemental lighting. This adaptation consisted mainly in changing the integration time step from 1 day to 1 h.

Plant growth simulator.

A FORTRAN version of SUCROS87 (Spitters et al., 1989) was converted to Smalltalk for this project. This conversion also provided the opportunity to separate the two major functions logically—plant growth prediction and the calculation of physical parameters.

The agent or module used for the calculation of the physical parameters (**SucrosAstro**) was broken down into sub-functions, each calculating a base parameter such as atmospheric transmissivity and day length. These calculations serve more-complex tasks, such as the prediction of the quantity of light for the next day based on the day of the year and the weather forecast (essentially based on a clearness index). Breaking down the model into smaller independent components enables it to be used in ways that were not

a GXSystem

Fig. 1. Relations between the principal components of the GX greenhouse climate management system. Boxes represent system entities and the bulleted lists are the parameters that describe these entities.

foreseen in the original model, such as calculating the time of sunrise and sunset.

The **SucrosTomato** agent is used to compute plant growth rate based on models of the biochemical processes. This function also was broken down into subfunctions that conduct the base calculations for photosynthesis. The quantity of photosynthates produced each hour under the prevailing environmental conditions are determined by combining the various subfunctions. This quantity then is distributed to the various plant organs and used for the calculation of the fresh weight accumulated in the fruit. In the control strategy, this is calculated twice, once with supplemental light and once without. These values then are transformed into gross income (before marketing) and compared to the cost increment due to electricity consumption and additional packaging costs (due to increased yields) associated with the use of supplemental lighting. Other cost increases are assumed to be negligible.

Scripts. Each type of scenario has its own set of scripts. Generally, the role of a script is to establish the set-point for each of the different climatic parameters (air temperature, relative humidity, CO₂ concentration, light intensity). The supplemental lighting script for **ScenarioSucros (Sucros-PAR)** conducts economic optimization by comparing the difference in yields calculated by the agent **SucrosTomato** for the two situations considered (with and without supplemental lighting). These differences are translated into profits or losses through a simple economic model. **SucrosPAR** also queries agent **SucrosAstro** for the value of certain scenario parameters such as times of sunrise and sunset and quantity of light predicted for the next day.

The decisions taken by the scripts lead to modifications to the program structures representing measurement and regulation equipment. In general, the decision is taken in two steps. In the first step, the various scripts and their associated rules are consulted on a round-robin fashion to determine the desired value or state of a climatic parameter (e.g., temperature). Different scripts and rules can attempt to set the desired value of the same physical parameter. In such a case, the value established by the rule that had the

highest priority rating becomes effective.

In the second step, the set-points to be used by the regulatory equipment are determined from the previously established desired states or values. Desired values and set-points are assessed periodically (every 15 min in this study). Only the set-points have a direct impact on the greenhouse climate.

For the purpose of this work, a rule set that establishes the desired state for the high-intensity discharge (HID) lamps was defined. It calls upon the crop growth model to obtain most of the facts needed to reach a decision and incorporates security barriers for the decisionmaking process. Essentially, the rule set establishes the desired value for PAR (*DesiredPAR*) inside the greenhouse. This value is either 0 or 90 W·m⁻² (360 mmol·m⁻²·s⁻¹) and is defined as the minimum level of PAR that ultimately is desired in the greenhouse at a given time. In other words, if the PAR inside the greenhouse falls significantly below this critical value, the lamps eventually are switched on. Obviously, when the value of *DesiredPAR* is 0 W·m⁻², the lamps cannot be switched on. In fact, the value of the *DesiredPAR* parameter is used by the regulation subsystem to establish the lamp state (on or off) based on criteria such as the elapsed time since the last state change and the average PAR inside the greenhouse over the last 30 min. During the night, if the desired PAR is 90 W·m⁻² and the installed HID lamp intensity is less (e.g., 20 W·m⁻²), the regulation subsystem will keep the lights on because the measured or calculated light level will be below the desired light level.

The devised script contains eight rules that are used to determine the *DesiredPAR* (see Table 1 for the definition of the variables used in these rules). The first rule is as follows:

RULE 1:

IF: TotalDailyLight > MaxDailyLight
THEN: DesiredPAR := 0
JUSTIFICATION: Light integral exceeded for the day

TotalDailyLight is calculated using the measured PAR value and compared to *MaxDailyLight*. Parameters such as *MaxDailyLight* can be modified by the grower. When the rule is triggered (i.e., if the premise is true),

the desired PAR is set to 0 W·m⁻². Bruggink and Heuvelink (1987) determined that tomato plants do not benefit from supplemental lighting when the sum of daily light energy reaching the crop exceeds 13.8 mol·m⁻² (3 MJ·m⁻² of PAR).

Once a day, **SucrosAstro** is used to obtain the values of the *TotalDailyLightForecast*, *Sunrise*, and *Sunset* parameters. The second rule then compares the anticipated light integral to the maximum desired light integral and sets the *DesiredPAR* accordingly.

RULE 2:

IF: TotalDailyLightForecast > MaxDailyLight
AND: CurrentTime < Sunset
THEN: DesiredPAR := 0
JUSTIFICATION: Light integral for the day will be exceeded

A statistic representing the average light intensity over the last 30 min (the *MeanLight30Min*) is maintained and used in rule 3. It should be noted that rule 3 has no utility under normal economic conditions. In fact, the crop growth model is able to determine the critical level where it is not profitable to use supplemental light (rule 8). This type of rule, typical of current control strategies, was included as a safeguard and to reassure growers.

RULE 3:

IF: MeanLight30Min >= MaxInstantLight
THEN: DesiredPAR := 0
JUSTIFICATION: Maximum instantaneous light intensity was reached

One of the characteristics of the dynamic supplemental lighting management strategy is that it can change the photoperiod from day to day. It has been established that a photoperiod of 20 h or more can be harmful to tomato plants (Vézina et al., 1991). A maximum photoperiod duration thus constitutes one of the limits that the system cannot exceed, whatever the results of the economic optimization calculations (rule 4).

RULE 4:

IF: Photoperiod >= MaxPhotoperiod
THEN: DesiredPAR := 0
JUSTIFICATION: Desired photoperiod was reached

It is normally essential to use the

Table 1. Names and descriptions of variables used in the scripts and scenario for supplemental light management.

Variable	Description	Units
CurrentTime	Normal (solar) time at which the rule is evaluated	h
DesiredPAR	Desired state (ON or OFF) for HID lamps	---
EndOfWorkShift	Time of the end of the working day (defined by grower)	h
IntensitySolarRad	Intensity of the global solar radiation measured outside	W·m ⁻²
MaxDailyLight	Maximum PAR light energy in the greenhouse that a tomato plant can use in 1 day (defined by grower)	MJ·m ⁻²
MaxInstantLight	Maximum instantaneous level of light intensity where it is uneconomical to use lamps (defined by grower)	W·m ⁻²
MaxPhotoperiod	Maximum duration of photoperiod in the greenhouse (defined by grower)	h
MeanLight30Min	Mean global light intensity during the previous 30 min	W·m ⁻²
MinPhotoperiod	Minimum duration of photoperiod in the greenhouse (defined by grower)	h
Photoperiod	Photoperiod measured since the start of the day	h
PredictedProfit	Calculated profit (or loss) associated with the use of supplemental lighting	\$/m ²
Sunrise	Calculated time of sunrise	h
Sunset	Calculated time of sunset	h
TotalDailyLight	Integral for PAR light energy in the greenhouse measured during the day	MJ·m ⁻²
TotalDailyLightForecast	Integral for PAR light energy in the greenhouse for the next day as calculated by the program	MJ·m ⁻²
VisibleLightThreshold	Light level where it becomes difficult to distinguish objects (defined by grower)	W·m ⁻²

lamps until the end of the working day. Rule 5 is thus triggered when the sun provides insufficient light and the current time is smaller than the *EndOfWorkShift*. The grower thus has the potential of overriding the economic optimization by setting the value of the *EndOfWorkShift* parameter. This rule originally was considered important. However, recent discussions with growers leads us to reassess the usefulness of this rule, because both the work patterns and lighting regimes have been modified to accommodate the needs of pollination bumble bees. It appears that the use of supplemental lighting past the time of sunset jeopardizes the bees' ability to regain their hives at the end of the day.

RULE 5:

IF: IntensitySolarRad < VisibleLightThreshold
 AND: CurrentTime < EndOfWorkShift
 AND: CurrentTime > Sunrise
 THEN: DesiredPAR := 90
 JUSTIFICATION: Keep lamps on until the end of the working day

Rule 4 establishes the maximum photoperiod duration. Large variations in photoperiods may not be beneficial for the plants. Thus, rule 6 ensures a minimal photoperiod duration based on the parameter *MinPhotoperiod*. In the province of Quebec, the electricity rates can make it more economical to use supplemental light in the morning (from midnight to 0600 HR) than during the evening (1600 HR until mid-

night). The first part of the rule calculates the latest time in the morning at which the lighting can be turned on and still respect minimal photoperiod duration, assuming that the lights will be turned off at sunset or at the end of the working day at the latest.

RULE 6:

IF: CurrentTime >= (max(Sunset, EndOfWorkShift) - MinPhotoperiod)
 AND: CurrentTime < Sunrise
 THEN: DesiredPAR := 90
 JUSTIFICATION: Lamps turned on to ensure a minimum photoperiod

The last two rules use the agent **SucrosTomato** to determine the profitability of supplemental lighting. These rules have a lower priority than the preceding rules and only serve when none of the other rules are triggered.

RULE 7:

IF: PredictedProfit >= 0
 THEN: DesiredPAR := 90
 JUSTIFICATION: It is profitable to use the HID lamps

RULE 8:

IF: PredictedProfit <= 0
 THEN: DesiredPAR := 90
 JUSTIFICATION: It is not profitable to use the HID lamps

In GX, it is the scenario that consults the rule base. The rule base is consulted at regular intervals (i.e., every 15 min) and only the rules for which the premises are true are triggered.

Precision of the SucrosTomato model

To be useful for management purposes, a crop growth model must be reliable. The weekly mean yield predicted by the model was compared to actual yields for a greenhouse tomato crop grown between 31 Oct. 1990 and 8 Feb. 1991. The mean difference was 0.41 kg·m⁻² per week, which is roughly equivalent to the difference between yield under supplemental lighting (at an intensity of 100 mmol·m⁻²·s⁻¹ of HPS for a 17-h photoperiod) and yield without supplemental lighting for the same period of the year (0.45 kg·m⁻² per week) (Vézina et al., 1991). Hence, the precision of the model is inadequate.

As GX makes decisions based on economic criteria, the profit associated with the use of supplemental lighting should be greater than the model's error margin (converted into commercial value). If not, a profit calculated by **SucrosTomato** may be a loss in reality.

The profit (or loss) attributed to the model's error margin (P_{err}) is expressed in \$/ha and calculated by subtracting the packaging costs associated with the quantity of fruit produced from the gross revenue from product sales [Eq. 1]. The additional cost of electricity is not included because the extra yield due to overestimates by the model does not depend on the quantity of energy used.

$$P_{err} = E * H * (1/\rho) * (P - C_{pack}) \quad [1]$$

where:

E = error in dry weight calculations attributed to model ($\text{g} \cdot \text{h}^{-1} \cdot \text{ha}^{-1}$),

H = duration of the simulation (h),

ρ = dry weight to fresh weight ratio (3.5%),

P = product price on fresh weight basis (\$/g), and

C_{pack} = cost of packaging/handling on fresh-weight basis (\$/g)

The additional profit due to HID lighting (P_{light}) in \$/ha may be calculated by subtracting the costs of packaging and electricity from the extra revenue associated with supplemental lighting.

$$P_{\text{light}} = [\Delta P_F \cdot H \cdot (P - C_{\text{pack}})] - (W_{\text{lamp}} \cdot n \cdot 0.001 \cdot C_{\text{elect}} \cdot H_{\text{light}}) [2]$$

where:

ΔP_F = production surplus associated with supplemental lighting (g fresh weight/h per ha),

W_{lamp} = power absorbed by an HID lamp (W),

n = number of lamps/ha,

C_{elect} = cost of electricity (\$/kWh), and

H_{light} = duration of lighting (h).

Ideally, the comparison of measured data with data from the model

should be made for short periods where $H = H_{\text{light}}$. Thus, it would be possible to compare the difference in yield between a crop receiving supplemental lighting and a crop not receiving supplemental lighting. However, there are no measured values of ΔP_F for such short periods. In this study, the results of an experiment conducted over a period of 9 weeks was used to determine the value of $\Delta P_F \cdot H$. During this period, measurements were taken every week (Vézina et al., 1991). The plots received 0 and $100 \text{ mmol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ of supplemental PPFD for a 17-h photoperiod. Despite the fact that the lamps in the plots with lighting were turned off when solar light levels were sufficient and that the photoperiod was 1 h longer than the photoperiod used in the dynamic strategy, we believe that the results of the study by Vézina et al. (1991) may help judge the model's precision.

For example, if $W_{\text{lamp}} = 480 \text{ W}$ and $n = 2000$ lamps/ha, we can assume a photosynthetic photon flux density equal to $100 \text{ mmol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ (HPS lamps). Supposing that $C_{\text{elect}} = 0.032$ \$/kWh, $C_{\text{pack}} = 0.001$ \$/g, $P = 0.003$ \$/g, $H = 336 \text{ h}$ (14 days), and the mean error attributed to the model (E) is 860 g dry weight/h per ha (obtained by comparing measured and

calculated values and shown in Carrier et al., 1994), the resulting error is $16,512$ \$/ha. On the other hand, the increased profit due to supplemental lighting is $14,129$ \$/ha, based on 9 h of lighting/day ($H_{\text{light}} = 126 \text{ h}$). Thus, under these conditions, the error due to the model (in dollar terms) would be greater than the increased profit due to supplemental lighting.

Behavior of GX with ScenarioSucros

The behavior of the dynamic management strategy was studied through simulations in order to verify the integrity of the decisionmaking process. A conventional strategy with a fixed, 16-h photoperiod also was simulated for comparison purposes. In the conventional, so-called static, strategy, the lamps were turned on at 0200 HR in the morning and were turned off when the outside global radiation intensity reached a threshold value of $125 \text{ W} \cdot \text{m}^{-2}$. In the springtime, the lamps were turned on a little later to compensate for the increase in day length and turned off at the same outside radiation level.

Simulations were run to determine whether the dynamic management strategy behaved differently from the conventional strategy. In Fig. 3,

Fig. 3. Simulated effect of the static and dynamic control strategies on PAR light levels for 2 Jan. 1990. The dynamic strategy used supplemental light for as long as it was judged profitable.

the behavior of the two strategies for the conditions measured on 2 Jan. 1990 is compared. The light energy for the day was low and the instantaneous maximum intensity (PAR in the greenhouse) seldom exceeded 100 $\text{W}\cdot\text{m}^{-2}$. Under these conditions, the calculations by **Sucros Tomato** showed that it was profitable to use supplemental lighting for a large part of the day. The conventional system turned off the lamps at a predetermined instantaneous intensity. In both cases, the lamps were turned on again at the end of the day to allow greenhouse workers to continue working.

The sensitivity of the dynamic strategy can be appreciated from the fact that for the conditions of 2 Jan. 1990, when the price of tomatoes was set at \$4.00 /kg, the strategy calculated a profit and the lamps were used for >12 h. However, when the price was \$2.00 /kg for the same day, the HID lamps were not used because the program determined that it was not profitable to do so. For the same day, the program calculated a loss when the intensity of supplemental lighting was fixed at 50 $\text{mmol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ (10 $\text{W}\cdot\text{m}^{-2}$), whereas it predicted a profit at 100 $\text{mmol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ (20 $\text{W}\cdot\text{m}^{-2}$).

Table 2 contains a summary of the results obtained from the simulation of the behavior of the two strategies for meteorological conditions measured at Laval Univ. between 28 Feb. and 27 Mar. 1990. As can be observed, the dynamic strategy resulted in a greater amount of PAR energy while using less supplemental lighting. The dynamic nature of the optimization strategy is illustrated by the fact that standard deviation values for photoperiod and hours of supplemental lighting are greater in the dynamic strategy than in the static strategy. In other words, while the static strategy used a fixed photoperiod resulting in unproductive use of supplemental lighting, the dynamic strategy made more rational use of the electrical energy needed to operate the HID lamps by consider-

ing predicted light levels and a cost-benefit analysis approach to decision-making. The dynamic nature of the optimization strategy is also well-illustrated in Fig. 4. As the amount of anticipated and received solar radiation increases, the number of hours during which supplemental PAR is used decreases. The same trend occurs with the photoperiod.

For example, on 1 Mar., the lamps were not turned on in the early part of the day because the anticipated light integral was greater than *MaxDaily-Light*. However, the lamps were turned on later in the day (at 1200 HR) because it was estimated to be profitable to do so. On the next day (2 Mar. 1990), very little light was anticipated and the lamps were switched on at 0130 HR and kept on all day. In fact, on that day, the light integral was not reached.

The variability in supplemental PAR and photoperiod was much lower with the static strategy because the lamps always were switched on at the same time of day and were switched off when the radiation was above the threshold value or at the end of the day.

Discussion

As can be seen from the values presented in Table 2, the dynamic strategy could result, during certain parts of the year, in significant electrical energy savings while maintaining the same or even better light regimes. It is not clear if variations in photoperiod can seriously affect crop growth, but, because the amplitude of these variations can be limited by the greenhouse manager, this should not pose any serious problem.

The strategy presented herein only manages supplemental lighting. A natural extension to the management of supplemental lighting would be the optimization of thermal/shading screen control because such screens have an affect on light levels when used during the day and on heat loss during

the night. In fact, because the lamps contribute significantly to greenhouse heating (Brault et al., 1989), their effect on the greenhouse heat balance should be taken into account when decisions are being made about changing the state of the lamps. Another aspect that should be considered for optimization purposes is the future worth of a crop's net growth rate, because the market price of produce such as tomatoes tends to vary significantly throughout the year and today's fruit growth is next month's sale. A model to predict the evolution of market prices is thus an important piece of the optimization puzzle.

Many other environmental parameters affect crop growth and energy consumption. For example, CO_2 and relative humidity levels have an impact on crop growth and can be controlled or affected by ventilation. Other considerations linked to pest management, pollination by bumble bees, and marketing can come into play and influence the decisionmaking protocol. Hence, decisions based solely on profit vs. loss considerations cannot always be used.

Conclusion

The simulation capabilities of the GX system provides a powerful tool for the development, validation, and analysis of dynamic strategies. The results presented here showed that the integration of a growth model and management rules can be used effectively for the dynamic management of supplemental lighting in greenhouses. True optimization could be realized by taking into account the effect of HID lamps on the greenhouse sensible and latent heat balances. In fact, the approach used for this study, which consisted in the integration of heuristics and analytical models, holds promise for the future because considerable efforts are being put into the development and improvement of greenhouse heat exchange and crop growth models.

In other words, computers and their associated software can automatically and dynamically manipulate climatic and environmental set-points. This can result in significant reductions in costs and in increases in productivity. In fact, we have shown how software can be used to make better (read, more-profitable) use of existing technology such as supplemental light-

Table 2. Comparison of radiation integrals, supplemental light use, and photoperiods obtained from simulations of the behavior of the static and dynamic strategies for meteorological conditions measured at Laval Univ. between 28 Feb. and 27 Mar. 1990.

	Total PPFD ($\text{mol}\cdot\text{m}^{-2}$)		HID usage (h)		Photoperiod (h)	
	Static	Dynamic	Static	Dynamic	Static	Dynamic
Average	13.8	16.6	13.1	6.5	15.0	13.1
Sum	386.4	465.5	366.5	180.8	419.5	366.2
SD	2.8	4.6	1.1	4.4	0.3	2.0

Fig. 4. Behavior of the dynamic strategy for meteorological conditions measured at Laval Univ. between 28 Feb. and 12 Mar. 1990.

ing. There are many opportunities for such improvements, but one of the limiting factors has been the cost of developing, validating, and implementing the required computer programs, models, and knowledge bases. However, because software development tools are getting more and more powerful, we can envisage a rapid increase in the use of "knowledge-intensive" environment control systems.

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