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Improving Energy Efficiency in Greenhouse Industry

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Abstract: - This paper proposes an automated system for greenhouse management, in order to develop control techniques for regulation of internal microclimate, fitting with different production strategies. The option in the selection of control logics, allows operator to pursue energy saving politics, for the conditioning systems management, time production shortening, or quality products improvement. The adoption of a specific procedure may be the most advantageous condition in the economical management and it will be valued each time by operator, to follow different marketing situations.

Key-Words: - **E**nergy savings, Control system, Greenhouse, Microcontroller, Temperature, Carbon dioxide.

1 Introduction

The economic growth that many countries of the world have experienced over the last two decades has resulted in a corresponding upsurge in energy usage.
While the demand for energy within economies keeps growing, escalating global oil prices, increasing energy-related pollution and the need to address greenhouse mitigation responsibilities, have increased the real and opportunity cost of energy usage. The growth of the cost of energy usage has led to re-evaluate the levels of energy use per a unit of output and of energy efficiency in all countries.
Obviously, the process of reduction and rationalization of the energy consumption is interesting mainly the most energy intensive industries, and among these the greenhouse industry, in particular.
The greenhouse industry is an important user of energy all over the world. Greenhouse growers use a considerable amount of energy (about 8-16 TeraJoule/hectare/year, depending on latitude and weather condition) for maintaining optimal growing conditions (temperature, humidity, CO_2 concentration) to achieve full yield potential.
Energy, mainly natural gas or coal, is the second largest cost for protected crop growers. Heating is mainly used at night and during winter to reduce thermal differentials in order to control the environment and boost production. Heating is often combined with ventilation techniques to control humidity and reduce the need for fungicides. Fuel, typically gas, is also burned during the day to produce CO_2, with the energy stored in large thermal water tanks for use as heating later in the day.
Moreover, it is worth to note that the greenhouse area is in continuous expansion, especially in the Mediterranean basin, due to the enlarging demand of vegetables for the export and domestic markets, resulting from economic development.
This will prompt growth in energy consumption.
From these considerations it is clear as profitability of greenhouse firms is largely dependent on energy costs. World growers are aware of the rising costs of energy and many are already trying to operate as energy efficiently as possible. Mainly, the growers are considering the lowering their greenhouse temperature setpoints and adjusting their production strategies to reduce their annual heating costs.
But, it is worth to note that greenhouse temperature influences energy consumption as well as other fundamental issues, as crop timing and plant quality. So, when determining a growing temperature, it is important to understand how temperature influences plant growth and development so that growers can optimize their production schedules and still produce high quality plants on time.
In this scenario, this paper aims at providing guidelines for designing a control system architecture to improve greenhouse energy efficiency and improve their environmental performance (i.e. reduce CO_2 emissions). Because the largest portion of energy intake is used for climate control, in this paper the attention is mainly focused on heating.
The proposed control system tries to find an advantageous match between greenhouse management, in terms of energy efficiency, maintenance and primary resources consumption, and the profits due to products sale.
From the consideration that greenhouse is a complex system emerges the need to have new flexible control systems, which fit to biological cultivation requirements, climatic aleatority and different control methodologies. The use of microcontroller or PC based systems can realize more complex climatic conditioning procedures and cultivation methods than a traditional system does, where, usually, there's a single parameter control, like temperature, or a time-programmed control.
A traditional system, sufficient for a limited or not very sensitive production, is not enough today, in a wide-scale production scenarios, based on special cultivations, more sensitive to climatic changes, for example floriculture, and finalized to product sale. Also Mediterranean greenhouse industries are changing their conventional production

strategies, migrating from the adaptation of the crops to a suboptimal environment, using limited greenhouses climate control, to the creation of an optimal environment for crops, using better equipped greenhouses with improved climate management, obtaining an increase of product quality. Achieving an economic compromise between the higher costs of improved greenhouses and their increased agronomic production are requiring different solutions, according to the local technical and socioeconomic conditions. Diverse studies have been made to improve the greenhouses technological level, including greenhouse design and climate management, crop techniques and practices (cultivars, cycles, plant protection, irrigation, substrates) in the various conditions of the Mediterranean basin. The cultural level of the growers, in the different countries, can be a limiting factor to improving the technological level of the greenhouses and great efforts are been made to transfer the technological knowledge to the growers, providing them with the methodology of optimization of their production systems.

The implementation of multiple parameters threshold logic or fuzzy logic, at the control stage, may better meet the biological needs of a particular cultivation.

So, it involves in a production quality improvement and resources optimization both biological, that concern, strictly, cultivation phase (water, fertilizer and pesticide savings) and energetic, used for conditioning systems operations.

These last ones, actually, are the most important items in the economical balance.

This paper proposes an automated system for greenhouses management, in order to develop control methods for the regulation of internal microclimate, to comply different production strategies. The option in the selection of control logics, allows operator to pursue energy saving politics, for the conditioning systems management, time production shortening, or quality products improvement.

2 Production Time, Energy Consumption and Crop Quality

The proposed system automates maintenance and management procedures of greenhouses conditioning systems and gives the way to develop particular control logics, to comply with specific production choices.

The control involves production time, energy consumption and crop quality, in fact, they represent the main items in the production costs and returns balance.

Phenological models show that time to flower decreases as greenhouse temperature increase; this is true both for plants with a short flowering time and with a long ones. Sperimentations confirm a 3.9 days advantage on crop time every 1°C temperature increase; others show 2-10 days advantage every 1°C [1]. Obviously, this difference depends on specific cultivation. Time-temperature relation is generally hyperbolic.

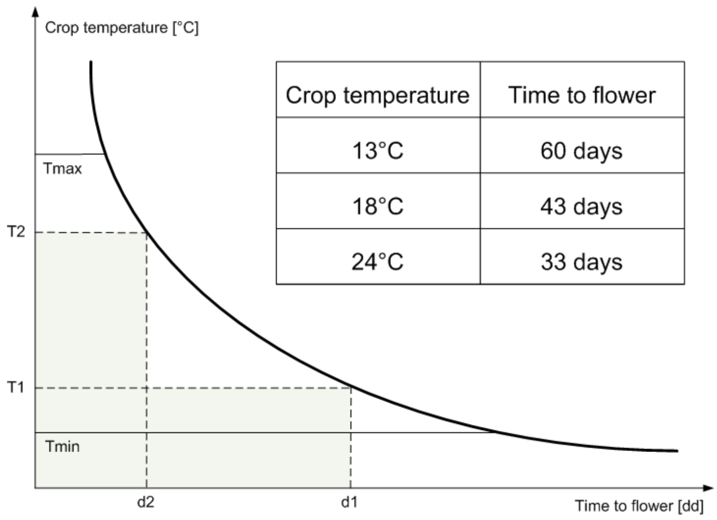

Fig.1: Crop days needed for three different rose cultivar in three different daily thermical levels [2].

In Fig.1, it is shown how to plan time production by controlling the greenhouse internal temperature, Ti.

Within the temperature range, $T_{min} \div T_{max}$, of the greenhouse during the winter, plants develop leaves and flowers progressively faster as temperature increases. Thus, turning down the temperature during the day or night will delay crop timing. The production time will increase when the plants are grown at cooler-than-normal temperatures. So, to finish a crop on the same time as last year, it is necessary to begin growing the crop earlier in the year.

But when temperature decreases under a specific temperature, called base temperature, Tb, the plants cease to develop. The base temperature varies from crop to crop.

Temperature has effects also on plant quality, in fact, for many crops, plant quality at the same stage of development increases as growing temperature decreases. If plants are grown at similar light intensities but at different temperatures, marketable plants grown at cooler temperatures often have thicker stems, greater branching, more roots, and more, larger flowers. Therefore, one of the benefits of growing at cool temperatures is that overall plant quality could be improved even though crop timing is delayed.

>From the strong dependence of plants growing process from temperature derives the need to have heavy heating system.

Greenhouse energy requirement is the sum of different terms: conduction/convection through glazing, infiltration of outside air, conduction into the ground, radiation loss to the sky. Approximately, thermical balance can be written as [3]:

$$\frac{dT_i(t)}{dt}=\frac{1}{C_{gr}}[(\Lambda(t)+k_r)\cdot(T_o(t)-T_i(t))+h(t)+ \quad (1)$$
$$+k_s\cdot(T_s(t)-T_i(t))+\eta\cdot G(t)]$$

The heating, h(t), needed to maintain a stationary thermical regime into the greenhouse, $T_i(t)=T_i$=const (internal air temperature), is:

$$h(t)=(\Lambda(t)+k_r)\cdot(T_i-T_o(t))+k_s\cdot(T_i-T_s(t))+$$
$$-\eta\cdot G(t) \quad (2)$$

where k_r and k_s are the roof and the soil heat transfer coefficient, $T_0(t)$ is the outside temperature, G(t) the incoming solar radiation, η the radiation efficiency, Λ(t) is the ventilation transfer coefficient and $T_S(t)$ the soil temperature.
This requirement increases with increasing set-point temperature, and it must be evaluated all along flowering time, inversely proportional to the fixed temperature. Totally energy requirement, H, for crop phase completion, is obtained by integration of h(t) on crop timing. Approximately, it is the product of days to flower and energy consumption per day at that temperature. Researches [4-9] have suggested control regimes which can save greenhouse heating energy by reducing the temperature set-point, when heat losses are high (windy, low outside temperature), and increasing it, when the losses are lower.
Finally, product quality is seen as the interaction between photosynthesis and respiration phase. Concerning initial and final products, photosynthesis may be described as in the figure below:

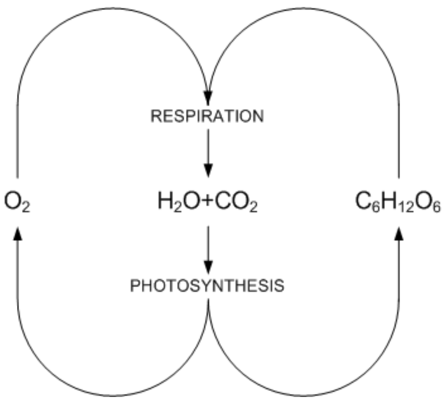

Fig. 2: Photosynthesis and respiration products

Into the phase of photosynthesis, CO_2 and H_2O combine producing carbohydrates and molecular oxygen; contrarily, into the phase of respiration, there is the production of CO_2 and H_2O from carbohydrates and oxygen. This process may be controlled modifying CO_2, radiation and temperature levels: for example, a proportional increase of temperature and CO_2, fitting radiation increasing, produces a more efficient photosynthesis; otherwise, the shortage of only one parameter causes its reduction.

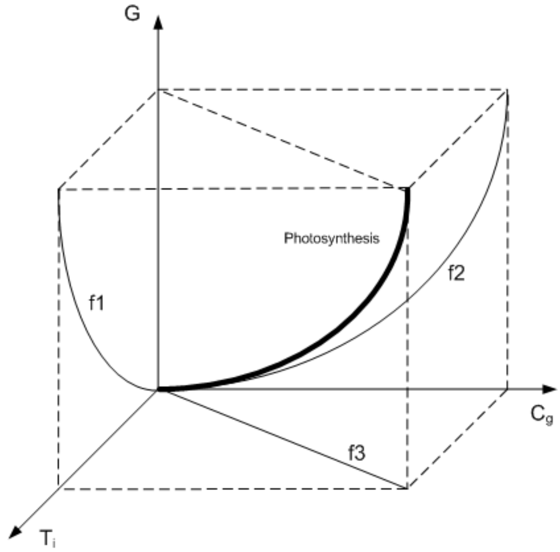

Fig. 3: Photosyntesis balance

Fig.3 shows the relations between parameters needed for photosynthesis with the curves:
f_1 (radiation-temperature),
f_2 (radiation-carbon dioxide),
f_3 (temperature-carbon dioxide).
Therefore, it is convenient to increase temperature set-point and CO_2 concentration with increasing radiation and decreasing them, all through the night, to reduce respiration phase. In facts, this last one is unfavorable for biological growth due to carbohydrates consumption.
Carbon dioxide concentration balance may be written as:

$$\frac{dC_g(t)}{dt}=\frac{a_g}{v_g}\cdot[\Phi_v(t)\cdot(C_o(t)-C_g(t))+c_i(t)+ \quad (3)$$
$$+\theta_c(t)-\Omega_c(t)]$$

where a_g and v_g are the greenhouse area and volume respectively, $C_0(t)$ and $C_g(t)$ the outside and greenhouse carbon dioxide concentration, $c_i(t)$ the carbon dioxide injection, $\Phi_v(t)$ the ventilation, finally, $\theta_c(t)$ and $\Omega_c(t)$ are the photosynthesis and respiration.
So, it can be defined a cost function as [3]:

$$J(t)=-[\alpha_1\Delta_g(t)-\alpha_2c_i(t)-\alpha_3h(t)] \quad (4)$$

where α_1 is the price of product, α_2 and α_3 are the cost of carbon dioxide and the heating respectively.
The term:

$$\Delta_g(t)=g_c\ [\Omega_c(t)-\theta_c(t)] \quad (5)$$

where gc is the growth conversion efficiency, represents the respiratory cost of the growth.

3 Modeling

Control system takes part in the regulation of internal temperature, T_i, and internal carbon dioxide concentration, C_g, to fit the particular productive strategy according with operator's choices.
Regulation of the greenhouse temperature is realized with a boiler system, to increase it, and with a forced ventilation system, to decrease level to the outside temperature; in the same way, CO_2 concentration level is regulated, indirectly, with a propane boiler and a ventilation system.
Therefore, control logic realizes the following productive strategies:

- *Production time shortening*, increasing the set-point temperature, T_i, fitting with the time-temperature models, as seen in paragraph 2. Then, the control system sets:

$$\begin{cases} T_i = T_{\max} \\ C_i = f_2(G) \end{cases} \tag{6}$$

Similarly, it is possible to program a different crop time opportunely regulating temperature set-point.

- *Production cost lowering*, by minimization of the cost function (4). J-function must be evaluated during the whole growth time, integrating its addends on interval $0 \div t_{END}$. When the heating is working, the system is in a stationary thermical regime, $T_i(t)=T_i=$const; so, integrating (2) from 0 to t_{END}, where:

$$t_{END} = \frac{const}{T_i} = \frac{A}{T_i} \tag{7}$$

is just the hyperbolic relation in Fig.1, it results:

$$H \cong A \cdot k_r \cdot (1 - \frac{\overline{T_o}}{T_i}) + A \cdot k_s \cdot (1 - \frac{\overline{T_s}}{T_i}) - \frac{\eta \cdot A \cdot \overline{G}}{T_i} \tag{8}$$

neglecting ventilation term, which is little incisive. $\overline{T_o}$, $\overline{T_s}$, $\overline{G}$ are the mean outside temperature, the mean soil temperature and the mean radiation, respectively, evaluated during the whole crop time. Energy requirement, for heating system, increases with set-point temperature increasing, as shown in Fig.4.
Minimum of heating energy requirement, H, is obtained for the minimum temperature of phenological model. It involves in a minimization of CO_2 consumption, but also in photosynthesis reduction, which has negative repercussions on profits.

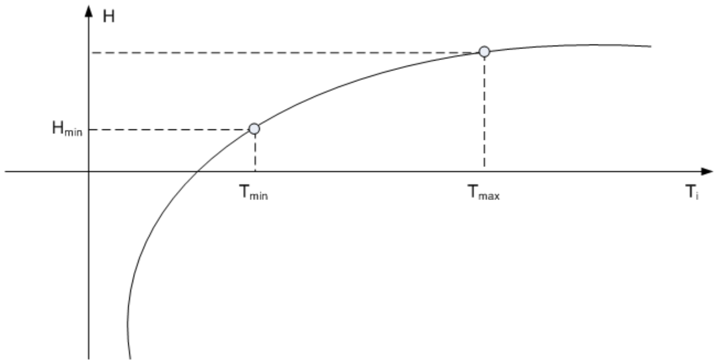

Fig. 4: T_i dependence of heating energy

Finally, minimization of J-function is obtained balancing positive effects, due to the lowering of instantaneous energetic consumption and negative ones, due to photosynthesis reduction. This last one produces a delay in crop time.
Generally, you can find uncertain and contrasting results about these matters: [10] shows total energy consumption to flower a crop was lower with a higher greenhouse temperature from January to May; more than 30% energy can be saved to produce this crop in a 25°C greenhouse compared to a 15°C. Contrarily, in autumn it is preferred a lower temperature. Of course, the growing periods between them are different. On the other side, [4-9] suggest control regimes which can save greenhouse heating energy by reducing the temperature set-point when heat losses are high.
Divergence of these results is due, certainly, to complexity in finding a exhaustive mathematical model which holds in account all interactions between possible variables.
In this exposure, the (8) gives a condition to determine the optimal set-point temperature, according with a particular production strategy. So, the greenhouse temperature is setted to the minimum value, according with the specific phenological model.
Therefore, the system sets:

$$\begin{cases} T_i = T_{\min} \\ C_i = f_2(G) \quad con \quad C_i \le f_3(T_{\min}) \end{cases} \tag{9}$$

- *Photosynthesis improvement*, by regulating temperature and carbon dioxide according to the radiation:

$$\begin{cases} T_i = f_1(G) \quad con \quad T_{\min} \le T_i \le T_{\max} \\ C_i = f_2(G) \quad con \quad C_i \le f_3(T_{\max}) \end{cases} \tag{10}$$

Moreover, a combination of *Production time shortening* and *Photosynthesis improvement* control can ensure ulterior control modes in production strategies.

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During the night hours or in the absence of solar radiation, carbon dioxide enrichment system in turned off; so, *Photosynthesis improvement* control is disabled and control system only operates on temperature.

4 Energy Management

Control system, here proposed, is planned for an agricultural production plant with several automatized greenhouse modules, working under the super-vision of a central unit.

Temperature and carbon dioxide values for each module can be setted through the central system which determines them to suite a particular production strategy, as seen before. Starting from given configuration of whole plant, system can also limit total heating energy requirement, $H_{TOT}(T_i)$ to a setted thresholds value, so to reduce total energy consumption.

Whenever whole plant energy level, which is the sum of N greenhouse modules, exceeds its own limit, central system provides in lowering temperature set-points for each module. It determines which modules are involved and calculates adjustments on temperature's setting values. This decision is the result of an interaction between particular parameters assigned to each module:

P → *Priority*;

Δ → *Tolerance* [°C],

These parameters are chosen according to economical and productive matters. Whenever a change in the set-points value occurs, it can determine both a delay in crop time and in product quality. So, priority scheme determines an operative hierarchy, on the other side, tolerance parameters set the maximum range in temperature modifications.

The following table shows plant initial settings:

Tab. 1: Starting configuration

Module	T	T_{min}	P	Δ	H
1	T_1	$T_{min,1}$	P_1	Δ_1	H_1
2	T_2	$T_{min,2}$	P_2	Δ_2	H_2
3	T_3	$T_{min,3}$	P_3	Δ_3	H_3
4	T_4	$T_{min,4}$	P_4	Δ_4	H_4
..					
..					
N	T_N	$T_{min,N}$	P_N	Δ_N	H_N

T_i, in the column T, are the setpoints that central system calculates to fit operator's particular strategy for the specific module. If there is no limit on total energy consumption, they are sent to local units; contrarily, supervision-system executes the following algorithm, in order to find an appropriate matching between local requirements (crop time, energy requirement or photosynthesis) and global requirements (total energy):

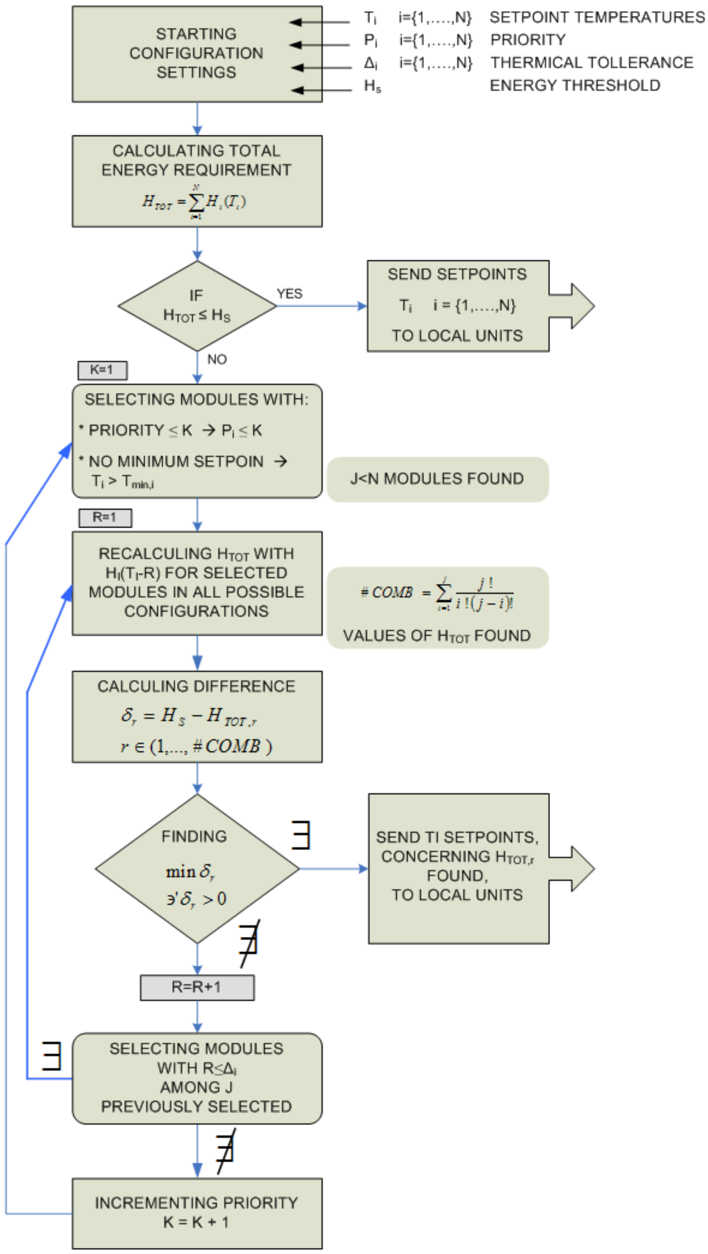

Fig. 5: Decisional algorithm

Initially, system calculates H_{TOT} from temperature set-point in Tab.1. If H_{TOT} exceed the thresholds H_S, system selects modules with a lower priority and sets, for these modules, iteratively, T_i=T_i-R (lowering 1°C temperature) System examines all possible combinations between selected and no-selected modules, each time recalculating H_{TOT}. So, it is obtained a set of:

$$\#COMB = \sum_{i=1}^{j} \frac{j!}{i!\cdot(j-i)!} \qquad (11)$$

values for H_{TOT}. If no-one fits with energetic threshold, system decrements again temperature set-points, according with the tolerance ranges. Whenever there is still no acceptable solutions, system iterates algorithm including next higher priority modules.

Therefore, system determines new temperature set-points for some greenhouse module so that total energy requirement does not exceed energy threshold, and, at same time, with a minimum difference between H_S and H_{TOT}. This last condition produces a lower perturbation of starting situation, which is the optimum operation mode with no limit on totally energy requirement.

The pattern of temperature set-points, according with estimated H_{TOT} value, is posted to local units, which control sensors and conditioning systems to maintain the particular thermical regime.

4 Controlling

Each module automation is realized with microcontrollers which both monitorize internal and external greenhouse climatic parameters and ensure conditioning systems operations.

We have used the *ZWorld - Rabbit2000*, which is a *Dynamic_C*-programmable microcontroller, mounted on *BL2100* motherboard, both for local and central units. *BL2100* is equipped with several digital and analogical I/O, used for linking field devices, sensors and actuators, with local controllers. To maintain a setted value, for example temperature, system turns on and off the boiler through appropriate relays whose switching signal is directly generated by microcontroller. Similarly, sensors are directly linked with motherboard I/O by analogical connections; moreover, *Rabbit* microcontroller is equipped with an Ethernet I/O. Control software was developed in *Dynamic-C*, which is the programming language for *Rabbit* processors.

Local microcontrollers need for set-points of temperature and carbon dioxide to work. They are calculated and posted from central unit, as seen before. So, boiler and CO_2 enrichment system are turned on and off according with a threshold control logic.

Heating system, as shown in Fig.6, is turned-on when temperature is lower than T_i-Δ/2, and off when it is higher than T_i+Δ/2. Δ is small enough not to alter the purposes of control method; it's used to avoid continuous ignitions and extinctions of heating system due to a fluctuating temperature near to the setted threshold. Similarly, local units regulate CO_2 concentration.

The particular value of T_i, in the phenological range T_{min}÷T_{max}, which ensures production success, and CO_2 concentration, determine a variation in energy requirement, crop time, finally, in product quality.

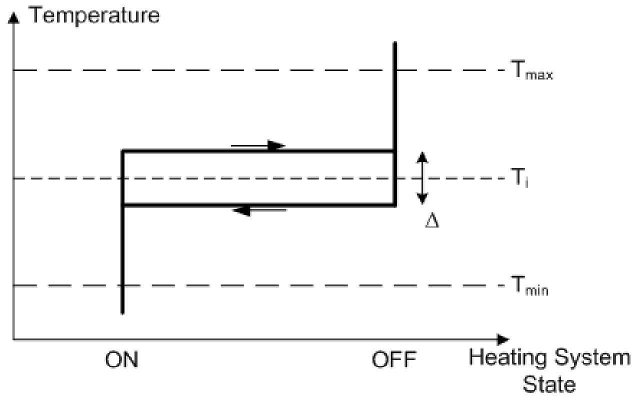

Fig.6: Heating system control logic

Supervision system calculates the optimal setpoints of temperature and carbon dioxide, according with operator's productive strategies. Moreover, if operator specifies an ulterior threshold, limiting total energy requirement, and total energy requirement exceeds it, central supervision system modifies local temperature setpoints, as seen in the previous paragraph, so that an acceptable compromise between local strategies and total energy consumption can be found.

Therefore, control phase is stratified into two levels:

- lower level, where local units supply for maintaining greenhouse temperature and CO_2 concentration to the setpoint values;
- upper level, where central unit calculates setpoints values according with operator's productive strategy and post them to local units.

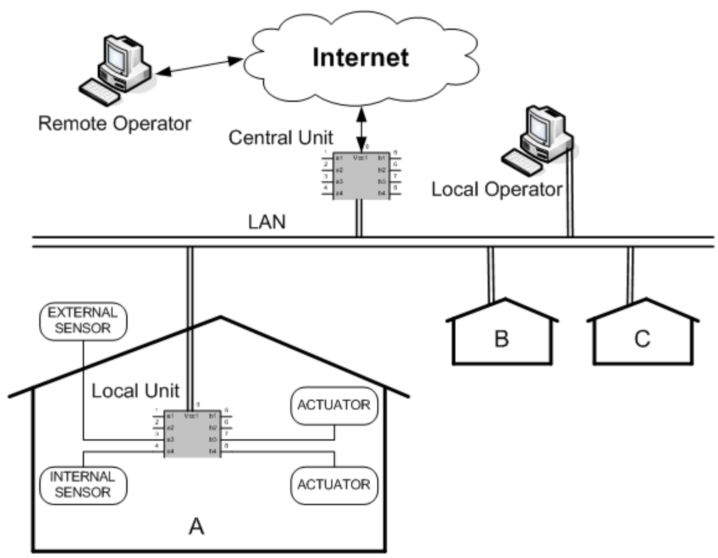

Fig.7: Global System Network

Central and local units communicate over a LAN through Ethernet connections, based on TCP/IP protocol; central unit is web-server configured, allowing an access to the global control system from local network or internet. User operates with an HTML interface specifying his options for each greenhouse module and whole system; in addition, climatic values and conditioning systems state can be read, remotely, with a minimum delay, to control the correct system operation.

6 Conclusion

The need to find a reasonable compromise in the management of a greenhouse industry, between energy savings and productive matters, concerning product quality and time production, was treated in this paper. Today, this is a problem of great interest, both because the demand for energy in this productive sector is increasing, and for the development of agricultural techniques which ensure improvements in products quality and growth cycles shortening, that are significant matters in the agricultural market.

Control system here proposed, works locally, on each greenhouse module, maintaining the particular microclimate into the greenhouse, and globally, searching for optimal sets of temperature and CO_2 concentration, which ensure operator choices. Furthermore, control system is able to limit energy requirement for whole plant.

Algorithm proposed has a deterministic approach to the problem: it examines all possible combinations of set-point values and greenhouse modules, searching for lowering energy consumption. Once it has been found, relative temperatures become setpoints values for the local controllers.

Solutions proposed, regarding possible operative modes for local systems, move from phenological considerations about the growth of plants, and mathematical models which describe thermical and CO_2 balance. Obviously, model goodness is directly proportionate to how it fits a real system.

Because the modeling approach is founded on the theory exposed in [3], [4], further improvements in those models will produce more precision in the results furnished by proposed control system.

Moreover, an experimental campaign is actually in progress using a test greenhouse at disposal at University of Salerno and with collaboration of some greenhouse industry operators.

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