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Improving automatic climate control with decision support techniques to minimize disease effects in greenhouse tomatoes

Joaquín Cañadas *, *Jorge Antonio Sánchez-Molina*, *Francisco Rodríguez*, *Isabel María del Águila*

Department of Informatics, University of Almería, 04120 Almería, Spain
The Agrifood Campus of International Excellence (ceiA3), Spain

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ABSTRACT

Crop growth in greenhouses is basically determined by the climate variables in the environment and by the amounts of water and fertilizers supplied by irrigation. The management of these factors depends on the expertise of agricultural technicians and farmers, usually assisted by control systems installed within the greenhouse. In this context, decision support features enable us to incorporate invaluable human experience so that we can take quick and effective decisions to ensure efficient crop growth. This work describes a real-time decision support system for greenhouse tomatoes that supports decisions at three stages – the supervision stage identifies climate sensor faults, the control stage maintains climate variables at setpoints, and the strategic stage identifies diseases affecting the crop and changes climate variables accordingly to minimize damage. The DSS was implemented by integrating a real-time rule-based tool into the control system. Experimental results show that the system increases climate control effectiveness, while providing support in preventing diseases which are difficult to eradicate. The system was tested by simulating the appearance of the disease and observing the real system response. The main contribution has been to demonstrate that production rules, which are mature and well-known in the artificial intelligence domain, can act as a shared technology for the whole system. This means that fault detection, temperature control and disease monitoring features are not dealt with in isolation.

1. Introduction

Crop growth is basically determined by the climate variables in the environment and by the amounts of water and fertilizers that can be supplied by irrigation. Therefore, crop growth can be managed by controlling these variables [19]. This makes a greenhouse ideal for growing crops because it is enclosed; and these variables can be manipulated for optimal plant growth and development [3].

Having ideal climatic conditions present in the greenhouse might be optimal for plant growth but they also favor the proliferation of pests and diseases. This is the case with the

* Corresponding author at: Department of Informatics, University of Almería, 04120 Almería, Spain.
E-mail addresses: jjcanada@ual.es (J. Cañadas), jorgesanchez@ual.es (J.A. Sánchez-Molina), frrodrig@ual.es (F. Rodríguez), imaguila@ual.es (I.M. del Águila).
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disease caused by the fungus *Botrytis cinerea* [8] (i.e. *Botrytis*), which thrives on humidity in the air. The lack of ventilation in Mediterranean greenhouses [6,4] means that condensation in production processes under plastic is ever-present and, consequently, can cause severe damage [24,17].

Artificial intelligence and decision support systems (DSS) have the potential of being successful methods for analyzing and modeling environmental system activities [12,33,39,31,7]. These systems are becoming a means of integrally managing the necessary decision-making information in specific fields, a real alternative for acquiring the necessary expert criteria and making them accessible in the specific domain [23]. Furthermore, they offer a highly specialized criterion when an expert's opinion is needed, without needing them to attend. [27,2].

Applying DSS to the supervision and control of greenhouse crop growth has come about because it is possible to incorporate these systems into the automation of the growing processes [18,2,42]. Greenhouse climate control systems automate growth using devices installed in the greenhouse which collect sensor data. Most of the advanced commercial climate control systems currently in use contain multiple heuristic rules and usually manage hundreds of defining parameters related to weather trajectories and actuators [17]. Current approaches focus not only on production processes, but also on the agricultural marketing chain (right through from seed germination to consumer sales [32]).

This paper describes a decision support system built for greenhouse horticultural production that has been applied to three decision stages: supervision, control, and strategic. The supervision stage identifies climate sensor faults, the control stage maintains climate variables at setpoints, and the strategic stage identifies diseases affecting the crop and changes the climate variables accordingly to minimize damage. Sensor fault detection [5,25,41,15], greenhouse climate control systems [33,21,35] and disease monitoring [27,2,16,22] are in themselves complex problems that have been widely addressed in the literature. While most of the previous approaches focused on just one of the problems in isolation, the goal of this work is to demonstrate how fault detection and control functionalities can be incorporated into an integrated system using a mature and experienced method, such as rules, as a common design and implementation technology for the whole DSS. The aim is to provide an integrated system for climatic growth control incorporating fault detection, control and expert supervision techniques in order to prove that DSS can supplement automated control systems in intensive knowledge tasks where the variables decisively influence crop growth.

The DSS was evaluated in the greenhouse at the Cajamar Foundation's Experimental Station (in south-east Spain), where the system was tested by simulating the appearance of disease and observing the real system response.

The rest of the paper is structured into four sections. Section 2 describes the study area, the knowledge acquired and the task workflow that defines the system architecture. The subsystems that deal with each stage are described in Section 3. Section 4 includes the main results and validation processes and, finally, Section 5 gathers together the conclusions and possible future research.

2. Materials and methods

2.1. Study area and host system

The data used in this research was acquired from the Cajamar Foundation's Experimental Station greenhouses in El Ejido, Almería Province, Spain (2° 43″W, 36° 48″N, and 151 m a.s.l.). The crops grow in a multispan "Parral-type" greenhouse (Fig. 1). The greenhouse is 877 m^2 (37.8 × 23.2 m) and has a polyethylene cover, automated ventilation with windows in the north and south walls, a roof-flap window in each span, 20 × 10 threads × cm^{-1} mesh "bionet" anti-insect screens, and night heating generated by a 95 kW hot-air heater programmed to keep the minimum temperature above 14 °C. The greenhouse orientation is east to west, whilst crop rows are aligned north to south. The growing conditions and crop management are very similar to those in commercial tomato greenhouses. The climate parameters inside the greenhouse are monitored continuously. Outside the greenhouse, a weather station measures air temperature, relative humidity, solar and photosynthetic active radiation (PAR), rain detection, wind direction and speed. The cover temperature sensors were located on the east (two sensors) and west (two sensors) sides. During the experiments, the indoor climate variables were also recorded; in particular, air temperature and relative humidity with a ventilated psychrometer (model MTH-A1, ITC, Almería, Spain), solar radiation with a pyranometer (model MRG-1P, ITC, Almería, Spain), and photosynthetic active radiation (PAR) with a silicon sensor (PAR Lite, Kipp-Zonnen, Delft, The Netherlands).

The adaptive proportional-integral controller (PI controller) manages daylight air temperature and humidity by means of the top and side windows. Potentiometers show the window position at any control instant. The night air temperature and humidity are controlled by the windows and the heating system. The ventilation and heating setpoints are 25 ° C and 14 °C, respectively. All the actuators are driven by relays designed for this task. Minute by minute climate data were recorded on a personal computer. The data acquisition system is made up of two National Instrument Compact-Field points connected by an Ethernet protocol.

2.2. Knowledge acquisition

Temperature is the climate variable that most influences crop growth. It is also the most controlled variable inside greenhouses in south-east Spain since the existing structures and installed actuation systems make it possible [11]. Due to the favorable weather conditions in this region, the energy necessary to reach the optimal temperature during the day is provided by the sun; thus, it is only under extreme conditions when this needs to be supplemented. The problem for daytime temperature control is keeping the temperature from exceeding the optimal. Of the several available greenhouse cooling approaches [34,1], natural ventilation is the most commonly used actuation system in the area; this promotes air exchange between the greenhouse's interior and exterior. The relationship between the interior and exterior air temperature is known. However, this relationship can undergo wind

Fig. 1 – Greenhouse facilities used for the experiments in this study. From left to right and from top to bottom: Greenhouse, CO_2 sensor, solar and PAR radiation, heating system, solar and PAR radiation inside the greenhouse, and the tomato crop rows.

and/or rain disturbance [11], which have opposing effects: the higher the wind speed, the quicker the air is renewed; whereas when it rains, the ventilation windows must be completely closed, regardless of the indoor temperature.

At night, the crop remains inactive so it is unnecessary to maintain a high temperature. Sometimes, on cloudless winter nights, thermal inversion phenomena occur when the indoor temperature is lower than the outdoor temperature. Greenhouses cool slowly because windows are closed at night minimizing conduction losses, whilst the thermal plastics used are fairly opaque to infra-red radiation so radiation losses are low. Even so, by the end of the night, when the thermal energy has been released to the atmosphere, the indoor temperature is very similar to that outdoors. Nonetheless, thermal inversion phenomena are quite unusual, and their effects are limited even more so nowadays by the use of new thermal plastics and heating systems.

On the other hand, optimum crop development conditions might also be ideal for the development of cryptogamic diseases that should be avoided at all cost. *Botrytis* is caused by the fungus *Botrytis cinerea* [8]; it is one of the most common and widely distributed diseases, inflicting heavy economic losses on growers due to its high treatment cost. It develops under high humidity conditions, producing a conspicuous fruitful layer of gray mold on the tissues affected [8]. The best approach for controlling this disease has been prevention: increasing natural or forced ventilation (when outdoor conditions are more favorable), heating (increasing the temperature reduces the risk of condensation) and using desiccants, etc. These precautions reduce the risk of near water vapour saturation conditions, decreasing the presence of condensation under the roof or on the plants [8]. Once this disease appears, it can only be kept from spreading to other plants by controlling humidity and hands-on labor, and by applying fungicides.

Table 1 shows a list of the main diseases whose infection capacity can be reduced by lowering environmental humidity, thus making them eligible for decision support system consideration.

2.3. Tasks control architecture

Greenhouse horticultural production has commonly been approached using a hierarchical control architecture [32,30], where the system is supposed to be divided into different time scales and the control system is divided into two different layers to achieve optimal crop growth. In our work, this structure has been added to/modified so as to include three different modules (marked in red in Fig. 2). The DDS is structured on three decision stages: supervision, control, and strategic (see Fig. 2). These three stages have been translated into three layers of actions (i.e. subsystems):

1. *Alarm advice subsystem*. The alarms supervision stage detects and diagnoses failures in the various sensors used for cultivation control, and makes decisions according to the failure detected, reconfiguring the system so it continues functioning [13].
2. *Temperature control subsystem*. The control stage is designed as a rule-based system and acts directly on the actuators installed in the greenhouse, controlling the climate parameters (temperature) [14,26].
3. *Disease management subsystem*. The disease management strategic stage takes data from pest and disease samples detected on the crop [40], modifying the climate parameters to minimize proliferation of the harmful agents and their effect on the crop.

Table 1 – Main diseases for which ventilation is used as a preventive control.

Disease	Causal agent	Species	Symptoms	Preventive control	Crops
Alternariosis	*Alternaria spp*	Fungus	Leaves: Brownish spots, yellowish rounded concentric edges	Ventilation	Several
Gray mold	*Botrytis cinerea Pers.*	Fungus	Soft gray rot of leaves, stems and fruit especially in wounds, cuts, etc.	Ventilation and irrigation	Several
Pepper blight	*Phytophthora capsici sp. Leonina*	Fungus	Irreversible wilt of the aerial part of plant. Swelling of roots and cankers at crown	Ventilation and irrigation	Pepper and tomato
Soft rot	*Erwinia carotovora pv. carotovora*	Bacteria	Water rot and soft rot with distinctive odor	Ventilation and irrigation	Several
Oidiopsis	*Leveillula taurica*	Fungus	White powdery rot that turns yellow on surface, white on the lower side of leaf	Ventilation	Several
Black rot	*Xantomonas campestris p.v. vesicatoria*	Bacteria	Small spots with yellow edges, translucent with brown center	Ventilation and irrigation	Several
Mildew terrestre	*Phytophthora nicotianae*	Fungus	Damage to crown causing wilting, and even death	Ventilation and irrigation	Several
Black spot	*Pseudomonas syringae*	Bacteria	Small black spots surrounded by a yellow halo	Ventilation and irrigation	Several
Gummy stem canker	*Didymella bryoniae*	Bacteria	Round brownish spots on cotyledons	Ventilation and irrigation	Tomato and melon
Mildew	*Pseudoperonospora cubensis*	Fungus	Yellow spots in rings limited by the nerves	Ventilation	Cucurbitaceas

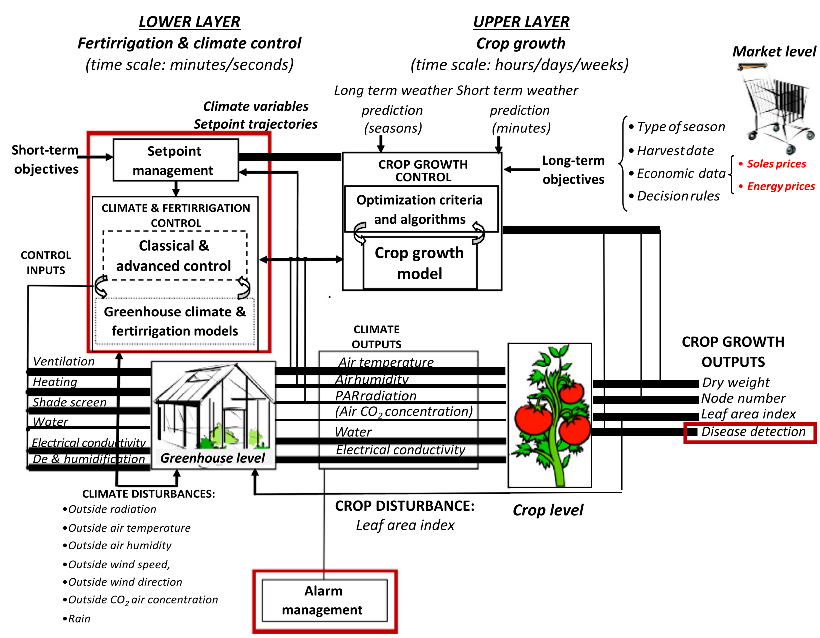


Fig. 2 – Decision stages and workflow.

The control stage was solved with a control task [30], which consisted of detecting any discrepancies in the sensor measurements and their setpoints, and then acting accordingly on the actuators to modify the conditions. The supervisor and strategic stages were solved as an expert supervision task [38]. A generic supervisory task is the set of actions performed to ensure that the system works properly, even in anomalous situations. To carry this out, it has to rapidly and reliably detect any anomalous situation; following this, it has to identify why this situation occurred and then work out how to prevent it from happening again.

3. System description

The DSS was implemented by integrating a real-time rule-based tool with a SCADA (Supervisory Control and Data Acquisition) control system installed in the greenhouse [30]. The inputs are the variables that can be acted on (windows,

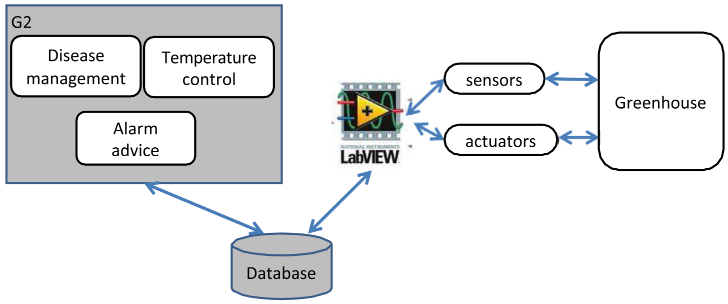


Fig. 3 – System Architecture.

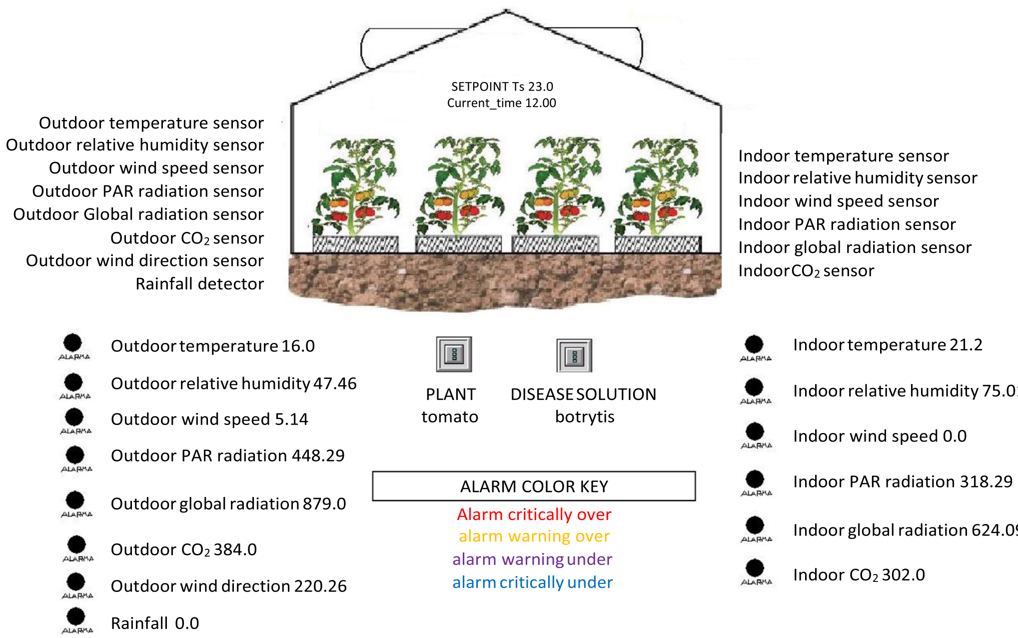


Fig. 4 – Control panel.

irrigation valves, heating, etc). The disturbances are the variables that cannot be manipulated but can be measured; hence their effect on the system is taken into account (e.g., weather, pests and diseases). Finally, the outputs are the variables to be controlled (interior temperature, relative humidity, water, nutrients and so forth).

G2 by Gensym Corporation [10] was used to implement the decision support system. This real-time rule-based tool has an excellent object-oriented graphical environment, with rapid prototyping facilities enabling easy modeling and simulation. Taking the knowledge of agricultural experts as the starting point, rule-based knowledge bases were designed for each of the three stages. In addition, fuzzy control techniques were applied to optimize decision rules. Integration with the climate control system was achieved using a SCADA system; this interacts with the devices installed in the greenhouse and enables communication between G2 and the LabView tool (see Fig. 3). LabView is in charge of gathering data from the greenhouse sensors and communicating the right signals to the greenhouse actuators. G2 contains all the decision-making rules and procedures necessary for control, system supervision and user interaction. Both applications were connected via a database.

Fig. 4 shows a screenshot of the user interface; specifically, it shows the alarm supervision panel. A range of colors is used to highlight the type of alarm for failures detected in the sensor measurements. The system shows the alarms in real time, recording the event and the time at which they occurred in a database. The diagnosis alarm is given in a message window to inform the human operator.

3.1. *Alarm advice*

Two types of alarms can be found when working with sensors in industrial systems: *electrical signals* and *physical variables*. The purpose of *electric signal alarms* is to extract as much information as possible from the electrical signals regarding the failures they detect and to monitor whether the sensors are functioning properly. Alarms related to *physical variables* are set by the users based on their knowledge of the measurements the sensor should show. The diagnosis is made when the sensors read outside of their ranges, considering the time

Table 2 – Rules for Alarm advice.

Type alarm	Rules
Electrical signal alarms	FOR ANY outdoor temperature sensor WHEN Outdoor temperature >= 10 V THEN change the color of the outdoor temperature alarm to red AND message = 'CRITICAL WARNING: The outdoor temperature sensor is outside its maximum range'
Poor signal alarms	FOR ANY radiation sensor WHEN time = 'night' AND radiation >0 THEN change the color of the radiation alarm to red AND message = 'Failure signal condition in radiation sensor, filter failure'
Poor calibration alarms	FOR ANY sensor in the global radiation class WHEN Radiation < 0 OR Radiation < 1200 THEN change the color of the global radiation alarm to red AND message = 'Failure in global radiation sensor'
Inadequate differ-ential value alarms	FOR ANY indoor CO_2 sensor WHEN abs (previous-state – current-state) >60 THEN change the color of the indoor CO_2 alarm to brown AND message = 'Signal failure, increase in value read over previous valor read is out of range' AND current-state = previous-state FOR ANY indoor CO_2 sensor WHEN previous-state – current-state = 0 THEN change the color of the indoor CO_2 alarm to brown AND message = 'Signal failure: Values constant in last readings'

Table 3 – Types of sensors outputs.

Type of sensor	Measurement range	Output
Temperature	[−20...65] °C	[0...10] V
Relative humidity	[0...100]%	[0...10] V
PAR radiation	[0...1000] W m^{-2}	[4...20] mA
Global radiation	[0...2000] W m^{-2}	1 mV per W m^{-2}
CO_2 concentration	[0...3000] ppm	[0...10] V
Wind speed	[0...33] m s^{-1}	[0...5] V
Wind direction	[0...360]°	[0...5] V
Rain	Yes/no	0 (no) or 1 V (yes)

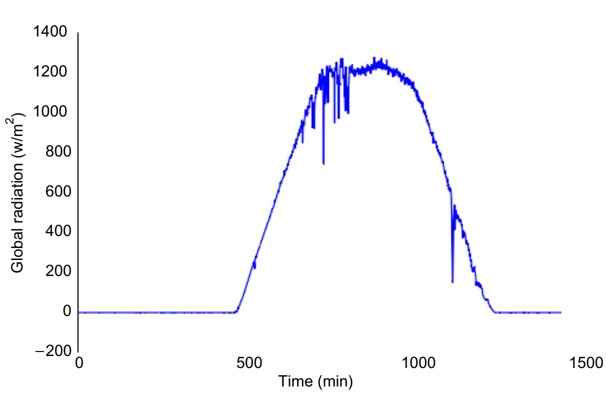
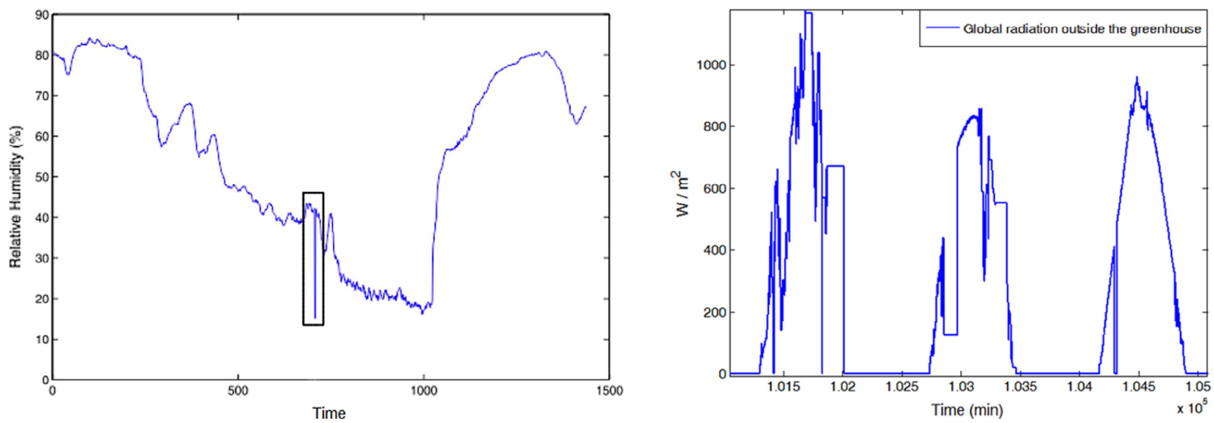


Fig. 5 – Calibration failure in radiation sensor, values >1200 W/m^2 (Date: 14 April 2013).

of day and other disturbances affecting the greenhouse. This type includes alarms for *poor signal condition*, *poor calibration* and *inadequate differential values*.

Table 2 includes a sample rule for each type of alarm. Electric signal alarms need to know the minimum and maximum value of the output signal provided by the manufacturer. The first rule in Table 2 is an example that shows whether outdoor temperature sensor data are correct for an analogical output that exceeds the maximum 10 V value. Similar rules have been designed to detect whether the signal is within its maximum and minimum for each of the sensor types installed in the greenhouse (see Table 3). How they are processed depends on the type of signals and knowledge of the process.

Alarms for poor signal are fired when the sensors show insufficient or inadequate ranges for the time of day, or when conditions or disturbances affecting the greenhouse appear.



(a) Inadequate differential values in relative humidity sensor (b) Errors in indoor global radiation

Fig. 6 – Differential values.

An example is global radiation at night. The failure occurs when radiation sensors show a signal greater than zero during the night; or the contrary, very weak or no signals during the day (see the second rule in Table 2).

An *Alarm for poor calibration* is diagnosed when the sensor value shows it is out of calibration or out of order, or when two identical sensors show very different values even though they should be the same. Fig. 5 shows a day on which the radiation exceeds the maximum, over 1100 W/m^2, and the sensor is considered to have a problem, as this value is too high for southeastern Spain. The third row in Table 2 shows the rule designed to identify a failure from poor radiation sensor calibration, where values are below 0 W m^{-2} or over 1200 W m^{-2}.

Alarm for inadequate differential value occurs when the difference between the current sensor value and the previous one is over a certain limit; this is considered erroneous because sensor signals are continuous. The fourth example in Table 2 shows the rule that detects a failure from inadequate differential values in the CO_2 sensor. Once the detection occurs, a rule performs the reconfiguration by eliminating the current measurement and keeping the previous one. Similar failure rules have been defined by differential values for temperature, relative humidity (Fig. 6a), PAR radiation, global radiation, and CO_2 sensors, according to Table 4.

When the system detects an alarm, the failure is diagnosed, showing why the alarm has been triggered and then the system proposes a reconfiguration that can be carried out automatically; or else shows a message allowing the operator to carry out the reconfiguration. An example of this is the case of two CO_2 sensors, one showing values within the set parameters, and the other showing lower values. The diagnosis identifies the sensor as out of calibration and reconfigures the system by discarding the data from the sensor that is out of calibration. Another common error in these types of readings is when the system saves readings that are constant over a period of time (Fig. 6b); that is to say, the readings do not change but remain constant, which is uncommon in systems subjected to strong outside disturbances. Any of the rules used in these types of alarms is the last rule in Table 2. This kind of error might happen because the acquisition system enters a state in which the sensors do not acquire new readings and the last one remains as a residual.

Table 4 – Differential values for sensors measurements.

Type of sensor	INCREMENTAL VALUE
Temperature	±0.6 °C
Relative humidity	±8% saturated air
PAR radiation	±150 W m^{-2}
Global radiation	±300 W m^{-2}
CO_2 concentration	±60 ppm

3.2. *Temperature control*

In greenhouse crop production, the indoor climate can be manipulated in terms of temperature, humidity, radiation and CO_2 concentration [36]. Temperature is perhaps the most important, as described in Section 2.2. Due to the variations in plant growth, two daily setpoints are defined, one for the nighttime and another higher one for the daytime. Natural ventilation is used to lower the greenhouse temperature. Sometimes, however, ventilation windows have to be completely closed due to extreme wind speeds. If the indoor temperature is lower than the setpoint, the ventilation is closed. At night, the crop is inactive so it is not necessary to maintain a high indoor temperature; thus, a lower setpoint is established to reduce energy consumption and lower the production cost (i.e. the fuel used for heating, which is one of the highest costs in automated greenhouse production). One might observe that these actuation systems do not act simultaneously since their effects are opposite – using ventilation during the daytime when the temperature has to be lowered, while using heating at night when the temperature has to be raised.

Therefore, four sensors are used in the daytime greenhouse temperature control system: temperature (outdoor and indoor), wind speed (outdoor) and rainfall (outdoor). The controller was designed as a decision table, in which the controller output indicates the greenhouse window aperture percentage (Table 5) and the following variables intervene:

Table 5 – Control decision table: percentage of window aperture.

Rain	Wind speed	Error	Error action	Wind speed disturbance	Tin–Tout disturbance	Disturbance action	Final action
Yes							0%
No	XL						0%
	ƒ = XL	No error					0%
	ƒ = XL	S	25%	S	S	15%	40%
	ƒ = XL	S	25%	S	M	10%	35%
	ƒ = XL	S	25%	S	L	−5%	20%
	ƒ = XL	S	25%	M	S	10%	35%
	ƒ = XL	S	25%	M	M	5%	30%
	ƒ = XL	S	25%	M	L	5%	30%
	ƒ = XL	S	25%	L	S	0%	25%
	ƒ = XL	S	25%	L	M	−5%	20%
	ƒ = XL	S	25%	L	L	−10%	15%
	ƒ = XL	M	50%	S	S	25%	75%
	ƒ = XL	M	50%	S	M	25%	75%
	ƒ = XL	M	50%	S	L	25%	70%
	ƒ = XL	M	50%	M	S	20%	70%
	ƒ = XL	M	50%	M	M	20%	75%
	ƒ = XL	M	50%	M	L	20%	60%
	ƒ = XL	M	50%	L	S	10%	60%
	ƒ = XL	M	50%	L	M	8%	58%
	ƒ = XL	M	50%	L	L	5%	55%
	ƒ = XL	L	75%	S	S	25%	100%
	ƒ = XL	L	75%	S	M	25%	100%
	ƒ = XL	L	75%	S	L	15%	90%
	ƒ = XL	L	75%	M	S	15%	90%
	ƒ = XL	L	75%	M	M	5%	80%
	ƒ = XL	L	75%	M	L	10%	85%
	ƒ = XL	L	75%	L	S	15%	90%
	ƒ = XL	L	75%	L	M	10%	85%
	ƒ = XL	L	75%	L	L	10%	85%
	ƒ = XL	XL	100%	S	S	0%	100%
	ƒ = XL	XL	100%	S	M	0%	100%
	ƒ = XL	XL	100%	S	L	−5%	95%
	ƒ = XL	XL	100%	M	S	−10%	90%
	ƒ = XL	XL	100%	M	M	−5%	95%
	ƒ = XL	XL	100%	M	L	−10%	90%
	ƒ = XL	XL	100%	L	S	−2%	98%
	ƒ = XL	XL	100%	L	M	−5%	95%
	ƒ = XL	XL	100%	L	L	−10%	90%

S – small or low; M – medium; L – high; XL -very high.

- Outdoor rain and wind speed.
- Error (Setpoint – Tin): the difference between the greenhouse setpoint temperature (Setpoint) and the indoor temperature (Tin).
- Temperature disturbance (Tin–Tout): the difference between the indoor greenhouse and outdoor temperatures
- Action: corresponds to the controller output indicating the greenhouse window aperture percentage.

It starts by determining the error (Setpoint – Tin), which determines a first action in the form of a window aperture percentage. This first action is adjusted to the wind speed and the Tin–Tout disturbance, thus finding a final window aperture value.

A fuzzy control is used to improve the dynamic behavior of the control system [37], using the linguistic labels employed by the expert when eliciting knowledge. This fuzzy logic controller is able to convert a linguistic control strategy into an automatic control strategy thus obtaining more intelligent responses to the imprecision and conditions of the outside world in an attempt to imitate human behavior [26]. As Fig. 7 shows, fuzzification transforms the numerical values into linguistic labels, which are used in the DSS

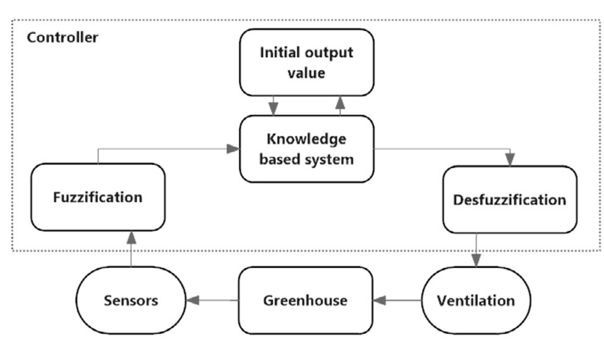
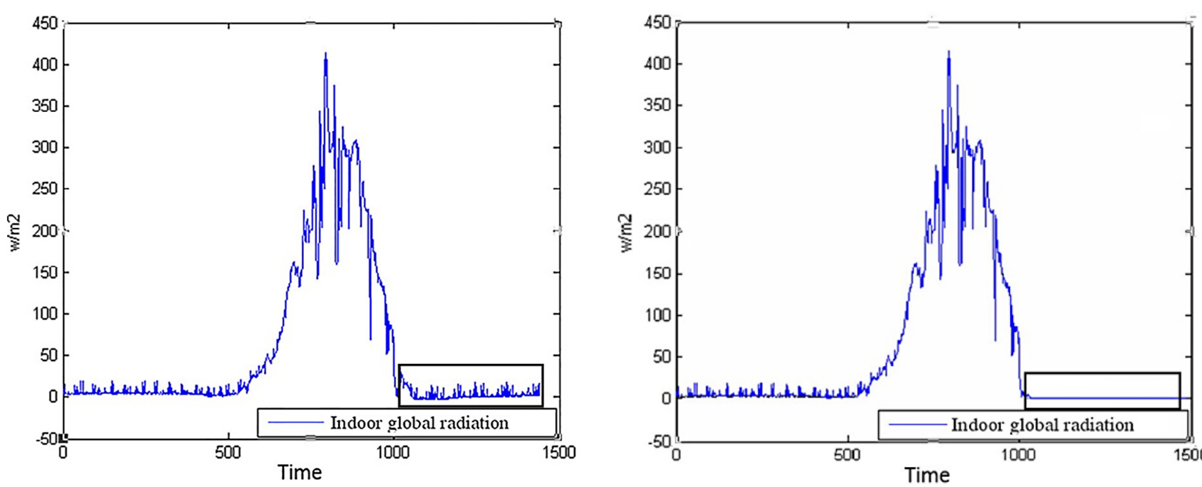


Fig. 7 – Fuzzy control process.

Table 6 – Fuzzy trapezoidal membership functions.

Label	Range	Trapezoidal parameters [α β γ δ]
Wind speed		
Low	[0 ... 4] m/s	[0 0 4 5]
Medium	[4...8] m/s	[3 4 8 9]
High	[8...12] m/s	[7 8 12 13]
Very high	>12 m/s	[11 12 $+\infty$ $+\infty$]
Error (Setpoint – Tin)		
No error	>0 °C	[−0.1 0 $+\infty$ $+\infty$]
Small	[−0.2...0] °C	[−0.3 −0.2 0 0.1]
Medium	[−0.4...−0.2] °C	[−0.5 −0.4 −0.2 −0.1]
High	[−0.6...−0.4] °C	[−0.7 −0.6 −0.4 −0.3]
Very high	<−0.6 °C	[$-\infty$ $-\infty$ −0.6 −0.5]
Differential temperature (Tin – Tout)		
Low	[0...5] °C	[0 0 5 6]
Medium	[5...10] °C	[4 5 10 11]
High	>10 °C	[9 10 $+\infty$ $+\infty$]



(a) No system intervention (b) With system intervention

Fig. 8 – Example of errors in outdoor global radiation.

decision-making rules; and later, the numerical value to be applied by the actuator is determined by defuzzification. Three inputs are fuzzified: wind speed, error and differential temperature. The membership degree of each input in a fuzzy set is determined by trapezoidal functions. Table 6 shows the linguistic terms and value ranges for wind speed, error and differential temperature.

The defuzzification rule shown below is an example of a rule obtained from the control decision table (see Table 5):

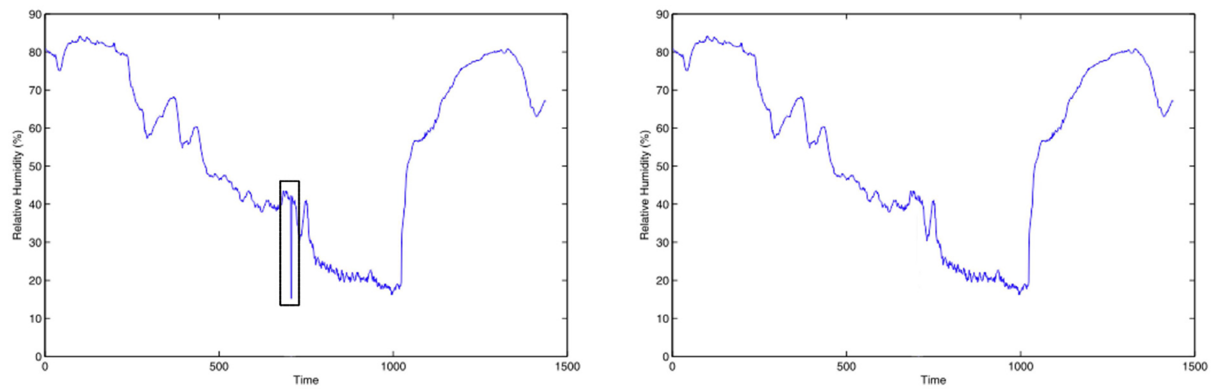
```
IF label-Error-Value = 'small'
AND label-Wind-Speed = 'low'
AND label-Dif-Temperature = 'low'
THEN Aperture = 40
```

3.3. *Disease management*

The purpose of disease management was not to develop a detailed crop disease diagnostic system as other studies have done [20,9,29,28] but to focus on the design of the production system reconfiguration when a disease is detected. This reconfiguration acts on the climate control system, modifying the climate control conditions inside the greenhouse (in our case, the setpoint temperature), to minimize the spread of the disease and its effects on the crop. Table 1 includes the diseases that could be avoided by reconfiguring the system in order to ventilate it.

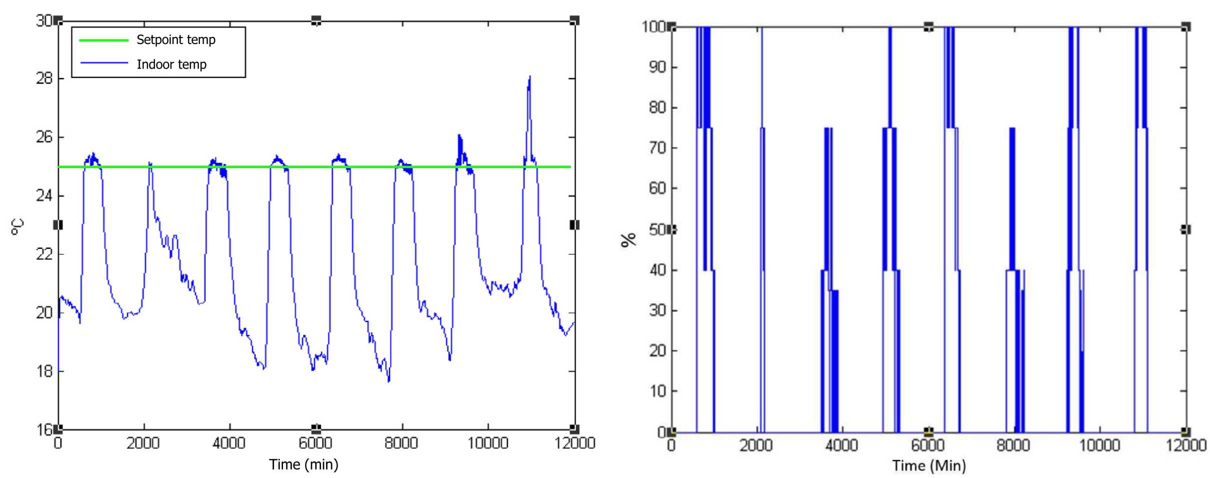
In the detection stage, the grower or agricultural technician has to input the data regarding the diseases into the system, previously collected in a sampling process performed during their visit to the crop; this might include the presence a certain color spots, a virus or a pest. The diagnostic rules for identifying the disease have been designed according to these sampling data. The reconfiguration consists of modifying the greenhouse's climate control system setpoint temperature to minimize the effects of the diagnosed disease.

The example below shows the type of rule that detects tomato diseases by the color of spots on the fruit. The disease is diagnosed, and then the system responds depending on the

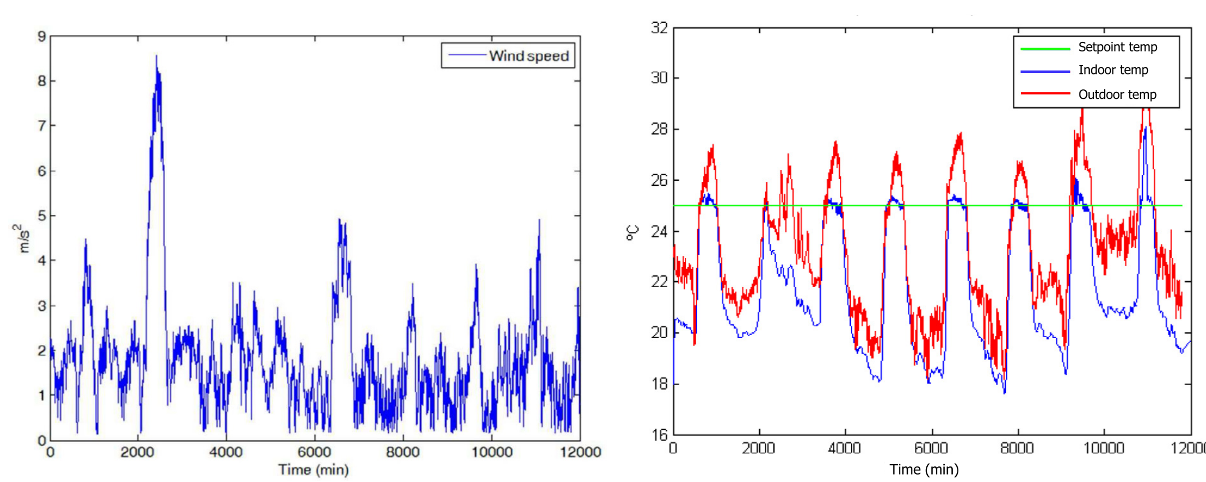


(a) No system intervention (b) With system intervention

Fig. 9 – Example of errors in the greenhouse's relative humidity.



(a) Greenhouse temperature (b) Percentage aperture of windows

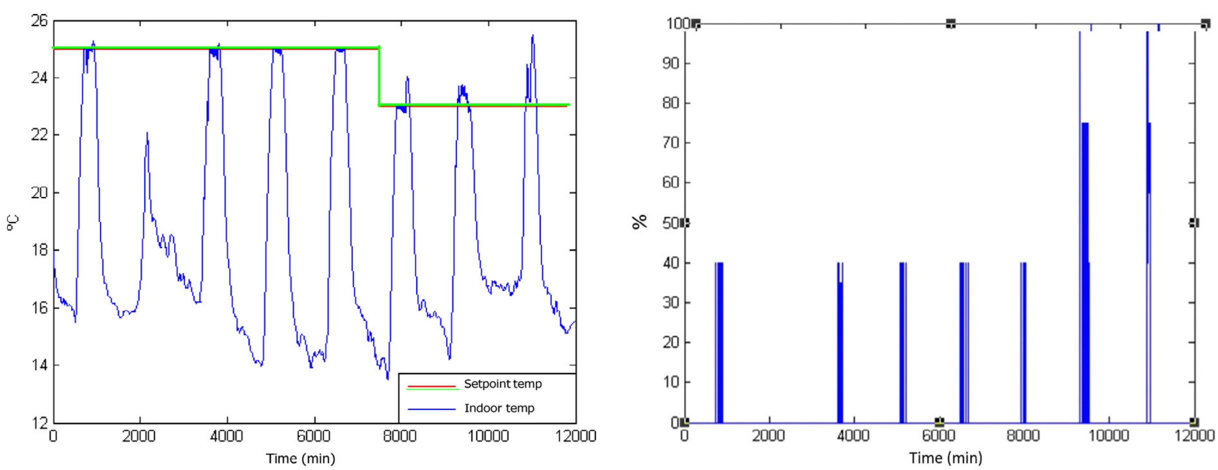


(c) Wind speed (d) Temperature control

Fig. 10 – Temperature control test (8 test days).

Table 7 – Disease control study table.

Day	Detection: Spot color	Diagnosis: Disease	Reconfiguration
1			25
2	White	Oidiopsis	25 (Not included)
3			25
4			25
5			25
6	Gray mold	*Botrytis*	23
7	Gray mold	*Botrytis*	23
8	Gray mold	*Botrytis*	23



(a) Indoor and set point temperatures with *Botrytis*

(b) Percentage aperture of windows

Fig. 11 – Disease control test (8 test days).

color of the spots. If *Botrytis* is diagnosed, the first action would be to lower the setpoint two degrees to increase the window aperture and thereby reduce the risk of accumulating humidity inside the greenhouse. The system would use the following rule for the diagnosis:

```
IF crop = 'tomato'
AND color-spots = 'gray mold'
THEN disease = 'Botrytis'
```

When the disease has been detected, the expert decides that the greenhouse setpoint temperature (Ts) should be lowered 2 °C, as shown in the following example of the reconfiguration rule:

```
IF crop = 'tomato'
AND disease = 'Botrytis'
THEN Ts = Ts − 2
```

4. Results and discussion

The system validity has been independently assessed for each of the three actuation stages. The data anomalies read from the sensors were identified by the alarm system and the system was reconfigured, allowing it to keep working. Next, the fuzzy control rules correctly changed the state of the climate actuators, and the presence of diseases appropriately modified the climate control setpoint variables.

As a result of the processes executed to check the alarm subsystem, alarms have been classified into two categories depending on the influence a sensor error has on the system – low level and critical level alarms. Critical level errors have an important effect on the greenhouse and on the crop itself. Alarms for temperature, CO_2, rainfall, radiation and wind speed sensors are in this category; for example, proper functioning of the rainfall sensor is essential because errors in measurement would indicate rain and therefore close the zenith windows when they should be open; this would negatively affecting crop growth by keeping the temperature control system from performing correctly.

On the other hand, low level errors do not have such an important effect (for example, errors in the PAR radiation signal, wind direction or ground temperature) since these have very little influence on crop growth control, and such measurements are more of interest for system modeling. Wind direction has a varying effect depending on the type of greenhouse, and the position of the zenith windows (whether they face in the same direction as the wind or in other directions). In the case of the greenhouse where the tests were performed, the sensor is less important because all the zenith windows are facing west, which means that at high wind speeds (>7 m/s), they are closed to prevent damage to the plastic or to the structure itself.

Looking at radiation, there is one basic sensor that controls ventilation, heating and CO_2 enrichment. Fig. 6b shows the data acquired by this outdoor global radiation sensor for one full day; these data has been chosen because two different errors can be distinguished in them:

- Failures in electrical signal: One can observe how, at several times during daylight hours, radiation was recorded as 0, which implies that the data acquisition system did not receive a signal from the sensor.
- Incorrect differential values: As shown in the example above, the radiation sensor constant data alarm was triggered several times during the day. The graph shows how radiation remained constant for several minutes, which is incorrect behavior for this type of sensor.

Fig. 8 shows the mean radiation for the indoor sensor on the following day of experiments (Day 2) – starting at minute 1000, the signal is corrected after applying the system filter. With this filter engaged, the radiation drops to 0, the real night-time value. In this case the correction made in the humidity sensor, Fig. 9 shows the filter action, which displays an error due to incorrect differential values, as shown in Fig. 9.

Fig. 10 is a set of graphs showing temperature control results. These show the different variables used in control, such as the temperature setpoint and indoor greenhouse temperature (Fig. 10a), the outdoor temperature (Fig. 10d), and the wind speed (Fig. 10c). They also show the windows' aperture percentage (Fig. 10b), which is the control system actuation mechanism.

The controller output data (the ventilation output) are watched to check that the control system is working properly – if the indoor temperature is above the setpoint, the system opens the greenhouse windows. This output can be modified by the action of other variables such as the wind speed or the difference between indoor and outdoor temperatures. The setpoint and indoor greenhouse temperature make it possible to check controller behavior and the influence of the variables. In this figure, the greenhouse setpoint temperature is 25 °C and the temperature variation inside the greenhouse covers 8 days in the month of November. The controller was acting correctly because, when the indoor temperature was around the setpoint, the system managed to keep it so. The exception was on the last day when the indoor temperature considerably exceeded the setpoint; this was because the temperatures were too high and the system became saturated.

In Fig. 10b, the window aperture, which varies from 0 to 100, is shown for those same days. The aperture percentage is above zero when the indoor temperature is higher than the setpoint temperature. The other variables mentioned above, such as wind speed, as represented in Fig. 10c, are taken into consideration. The wind speed was not very high, so it did not affect control very much, except on the second day when the wind was strong and a slight window aperture lowered the indoor temperature. Another variable that influences the control system is the difference between indoor and outdoor temperature. It can be seen that, even though the outdoor temperature is above the setpoint, the indoor temperature is kept close to it, showing that the control system was working properly.

The disease management results show that the control system was still working correctly when there was a disease in the crop. To demonstrate this, the results are shown for a period when diseases were detected. In the case of gray mold spots, the system diagnosed *Botrytis*, and the reconfiguration consisted of lowering the setpoint temperature two degrees to minimize damage.

(Table 7) summarizes the disease management system working over the eight days of testing. The setpoint temperature in the greenhouse was 25 °C. During the test the crop showed characteristic symptoms of the disease known as oidiopsis (caused by the fungus Leveillula taurica), which was not included in the decision support systems, so it was eliminated from the study table. On Day 6, gray mold spots characteristic of *Botrytis* were detected on the crop surface, from which point the system was reconfigured lowering the setpoint for ventilation to 23 °C.

Fig. 11 shows how *Botrytis* was detected; and on days 6–8, its presence caused the greenhouse setpoint temperature to be lowered by two degrees. It also shows how the control system continued working, keeping the indoor temperature around the new setpoint 11a. Fig. 11b also shows the controller output on those eight days as the system was reconfigured based on the crop condition.

By lowering the set point temperature as a result of the disease, the ventilation was opened wider, increasing the air exchange with the outdoors. This exchange favored outdoor ambient conditions, which in the western part of Almería Province are usually less favorable than indoor conditions for the development of the disease; that is to say, low mean humidity with wind and high temperatures almost all year round. With this action, absolute humidity is lowered and DPV increases, avoiding values near water vapour saturation and reducing condensation on both the greenhouse roof and the plants.

5. Conclusions

This article presented a decision support system applied to the supervision and control of climate conditions in greenhouse crops. It has shown the feasibility of decision support systems in supplementing automated control systems for intensive knowledge tasks where the variables decisively influence crop growth.

The developed system assists growers in decision-making, providing additional real-time information to the climate control systems as well as a variety of solutions to problems that arise in the automated monitoring of climate conditions during the growing period.

Three action stages were implemented in the system. The alarm supervision stage identified failures in the climate sensors, providing a diagnosis that assisted the grower in understanding the nature of the error. Furthermore, reconfiguration was implemented making it possible for the system to remain functional in spite of the error detected. The temperature control stage managed the temperature inside the greenhouse by governing window aperture ventilation. The resulting graphs show that the control system was working properly. Finally, the disease management stage detected and diagnosed various diseases affecting the crop. In addition, it automatically reconfigured the system for *Botrytis*.

In this work, fault detection, greenhouse climate control and disease diagnosis have been addressed in an integrated fashion. However, since they are sufficiently complicated to be tackled independently with new and more precise methods, future planned work will investigate several different lines more comprehensively, for each of the action layers implemented in the system. One such improvement will include more climate parameters in the control layer, such as CO_2, radiation, etc., so there is more information for decision-making. We also intend to include more variables in the disease management making more precise diagnosis possible based on new symptoms. The possibility of providing a list of plant health-care and biological control products for fighting the diagnosed diseases is likewise being considered.

In future works, we still need to carry out the quantitative estimation of the effect of different actions on the evolution of pests and diseases in horticultural crops. In order to develop this subsystem in our paper, we were only able to modify the various climate setpoints as examples of applying expert systems to supervise and control greenhouse crop growth. This paper is focused on DSS implementation and its proposal for carrying out logical actions in different situations.

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