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Research Article

Smart greenhouse fuzzy logic based control system enhanced with wireless data monitoring

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ABSTRACT

Greenhouse climate control is complicated procedure since the number of variables involved on it and which are dependent on each other. This paper presents a contribution to integrate greenhouse inside climate key's parameters, leading to promote a comfortable micro-climate for the plants growth while saving energy and water resources. A smart fuzzy logic based control system was introduced and improved through specific measure to the temperature and humidity correlation. As well, the system control was enhanced with wireless data monitoring platform for data routing and logging, which provides real time data access. The proposed control system was experimentally validated. The efficiency of the system was evaluated showing important energy and water saving.

1. Introduction

The management of production in a greenhouse requires decisions making on several times scales [1]. These decisions are mainly related to the crops growth conditions, the culture period and the control of the indoor environment. The regulation of the indoor environment can be performed with either passive means (mass storage, buried pipes, natural ventilation, shading devices, evaporative cooling, geothermal heating, etc.) or the use of mechanical and electric machines (heat pumps, fan) [2]. The quick and frequent responses are needed to make the system adaptable to alternating weather conditions [3]. Hence, high technology greenhouses systems, focused on creating a micro-climate more appropriate to enhance plant growth and reduce the cost of production as well the energy consumption of the system [4–7].

The control of the micro-climate in a greenhouse is a complex procedure because the number of involved variables which depend on each other [8]. Thus, the greenhouse is considered a complex non-linear system [9]. Fig. 1 summarizes the issues relating to the management of the indoor greenhouse climate.

To meet these requirements, various control strategies based on complex algorithms of artificial intelligence were discussed in the literature such as; fuzzy systems which have achieved significant results in the area of climate control for protected agriculture. It requires reliable information on the thermal behavior of the system. Indeed, many control techniques based on FLS are often used for this type of system. [10] introduced a decentralized decoupling fuzzy logic controller (FLC); the structure showed an effective set-point tracking, compared to conventional PID method. [11] studied the contribution of fuzzy logic control use to reduce energy consumption and environmental concerns. [12–15] presented a FLC to control a greenhouse irrigation system. [16] evaluated greenhouse FLC to conventional systems.

Other strategies have been developed such as: [17] have developed an adaptive control algorithm using neural networks. [18] creates a hybrid system using artificial intelligence to control the greenhouse climate. [19] Developed an expert system based controller to control optimal plants growth conditions. [20] introduced a multiple neural control for the greenhouse micro-climate which consists of the division of the greenhouse control phase in periods where a suitable controller is selected to drive the internal climate.

This work aims to improve the control of the indoor climate key's parameters of the greenhouse system (GHS). For instance, it contributes to enhance the control automation through wireless

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data monitoring platform. Both objectives contribute to a better handling of the energy consumption and the system water use.

First, fuzzy logic control technique was used to encounter the system non linearity and complexity. In particular, the temperature and humidity correlation was addressed and decoupling control strategy was introduced. Then, a smart automation system was involved and used for wireless data monitoring enabling a distant data access. This allows to create a database for a deeper data analysis and possible future performance enhancement. The smart automation system was experimentally set up for the GHS control. Its effectiveness was revealed through the impact on energy saving and water use.

2. Smart greenhouse control

2.1. Fuzzy logic control and contributions

This section describes the proposed solution, as depicted in Fig. 2, for the control of climatic parameters of the greenhouse (temperature, humidity, CO_2 rate, illumination). The solution is based on type-2 fuzzy logic systems [21,22] with particular attention to the following factors: efficiency, temperature and humidity correlation as well the system energy use. In fact, Type-2 fuzzy logic sets are involved to handle higher degree of uncertainty due to a dynamically changing environment [23, 24]. The membership functions of the inputs/outputs variables are constructed and elicited through a model simulation. The fuzzy sets are determined based on a deep human expertize and knowledge

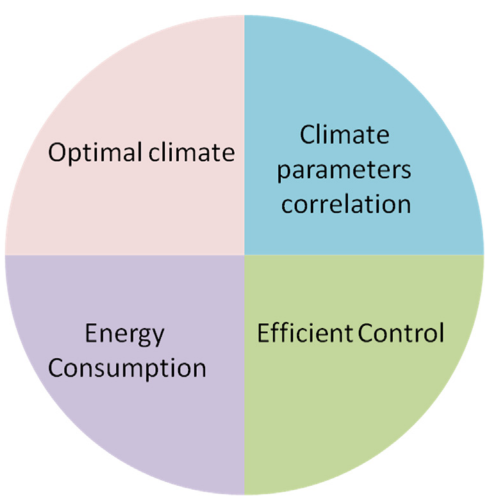

Fig. 1. Issues related to the control of the greenhouse.

on the thermal behavior of the GHS as well the usual operating ranges of the GHS.

The indoor climate control system is based on fuzzy controllers that manage the various decisions to achieve an optimal greenhouse climate depending on weather meteorological data and user instructions. These decisions are applied to the operational part of the system through variable frequency drives, as depicted in Fig. 3, which controls the climate electrical equipment. The FLC control system proposed will be detailed in the following paragraphs of this section.

2.1.1. Temperature FLC

The temperature FLC is shown in Fig. 4, the input variables are: (T_{in}–$T_{set\ point}$) difference between the inside air temperature T_{in} and the set point. (T_{ext}–$T_{set\ point}$) difference between the outside air temperature T_{ext} and the set point. The control variables are the ventilation rate and the heating rate.

Each of the two inputs is defined on five fuzzy sets {Negative Big «NB», Negative Medium «NM», Zero «Z», Positive Medium «PM», Positive Big «PB»}, the control variables are also on defined five fuzzy sets {Very Low «VL», Low «L», Medium «M», High «H», Very High «VH»}.

- **Membership functions:**

The membership functions associated with the fuzzy sets of the inputs variables and the control variables are presented in the following Figs. 5–8.

- **Inference rules**

The inference rules are, presented in Table 1, based on the Mamdani rules composition;

IF (T_{in} –$T_{set\ point}$) **is** (NB, NM, *Z*, PM, PB) **And** (T_{ext} – $T_{set\ point}$) **is** (NB, NM, *Z*, PM, PB) **Then** *Ventilation* **is** (VL, L, M, H, VH) **And** *Heating* **is** (VL, *L*, M, H, VH).

The following legend is used to index the inference rules in Table 1:

Control variables: Heating CH, ventilation *V*

Very Low: (− − −), Low: (− −), Medium: (+), High: (+ +), and *Very High (+ + +).*

2.1.2. Humidity FLC

The FLC of the indoor humidity, Fig. 9, of the greenhouse depends on the external humidity and its level inside the greenhouse. The input variables are: (H_{in}–$H_{set\ point}$) difference between the inside air humidity T_{in} and the set point. (H_{ext}–$H_{set\ point}$) difference between the outside air humidity H_{ext} and the set point. The control variables are the humidification and dehumidification rate.

- **The membership functions:**

The membership functions associated with the fuzzy sets of inputs and control variables are presented in the following Figs. 10–13.

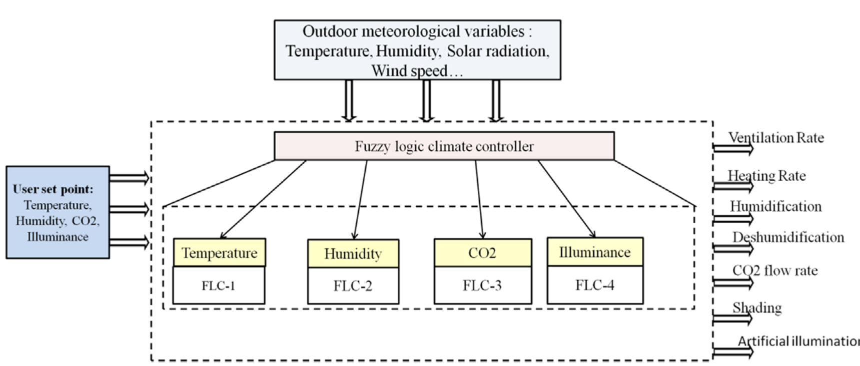

Fig. 2. Fuzzy logic based greenhouse control.

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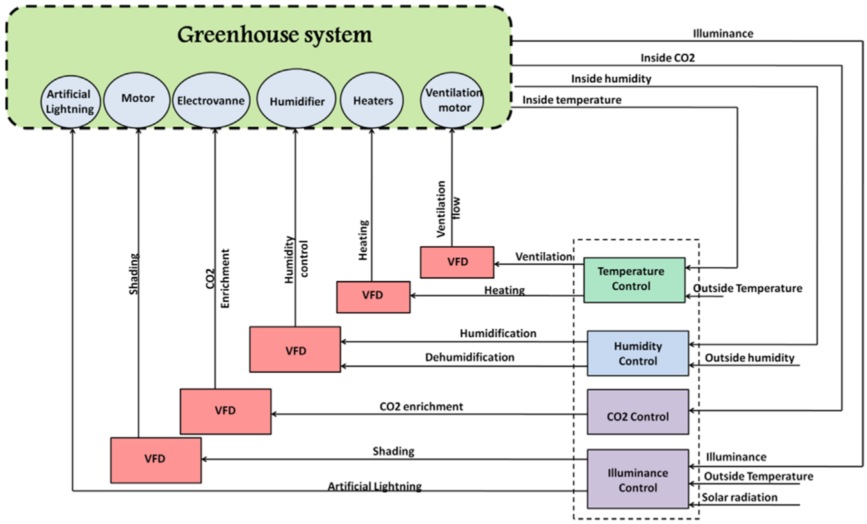

Fig. 3. Control of the greenhouse actuators.

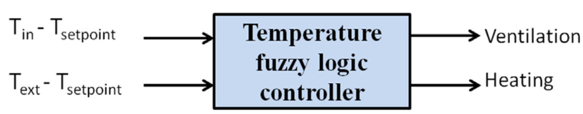

Fig. 4. Temperature fuzzy logic controller.

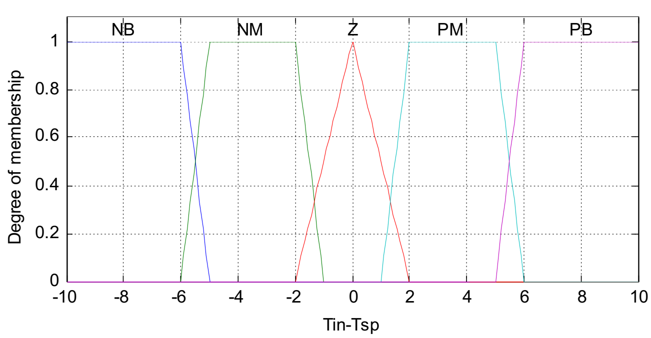

Fig. 5. Membership functions of the input variable «T_{in}–$T_{set\ point}$».

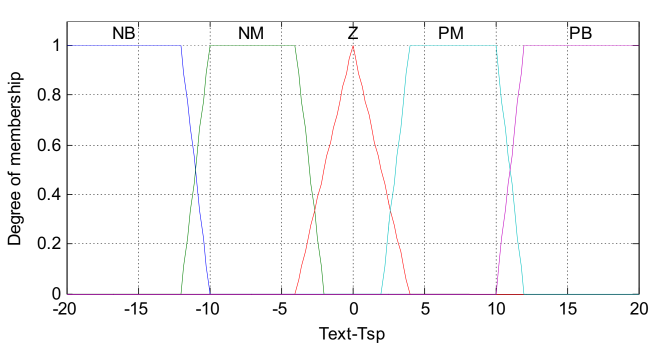

Fig. 6. Membership functions of the input variable «T_{ext}–$T_{set\ point}$».

Each of the two inputs is defined on five fuzzy sets {Negative Big « NB », Negative Medium «NM», Zero «Z», Positive Medium «PM», Positive Big «PB»}. As well, the control variables are defined five fuzzy sets {Very Low «VL», Low «L», Medium «M», High «VH», Very High «VH»}.

- **Inference rules**

The inference rules are shown in Table 2;

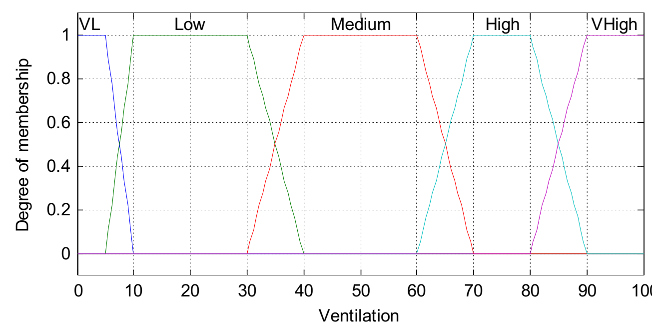

Fig. 7. Membership functions of the control variable «Ventilation».

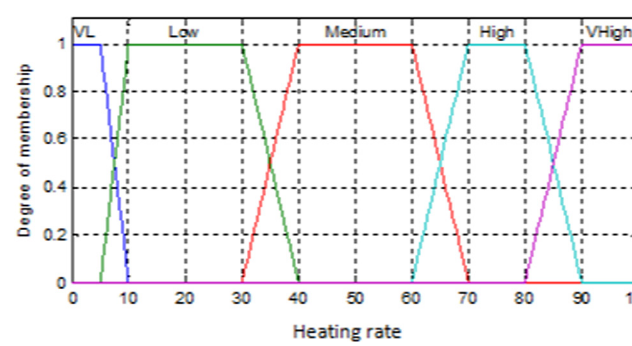

Fig. 8. Membership functions of the control variable «Heating».

IF (*H_{in}–H set point*) is (NB, NM, *Z*, PM, PB) **And** (*H_{ext}–H set point*) is (NB, NM, *Z*, PM, PB) **Then** *Humidification* is (VL, *L*, M, H, VH) **And** *Dehumidification* is (VL, *L*, *M*, *H*, VH).

The following legend is used:

Control variables: Humidification *H*, Dehumidification DH

Very Low (− − −), *Low* (− −), *Medium* (+), *High* (+ +), and *Very High* (+ + +).

2.1.3. CO_2 FLC

The CO_2 FLC, illustrate in Fig. 14, is described by two inputs variables and one output control variable CO_2 enrichment. The first input describes the error between the internal CO_2 levels and the set point, the second describes the variation of the error. The inputs are described by three fuzzy sets {Negative, Zero, Positive}. The CO_2 enrichment flow is described by four membership functions (Zero, Low flow, Medium flow, High flow).

Table 1
Inference rules of the temperature fuzzy controller.

Control variables		$T_{in} - T_{set\ point}$				
		NB	NM	Z	PM	PB
$T_{ext} - T_{set\ point}$	NB	CH (+++)	CH (++)	CH(+)	CH (−−)	CH (−−−)
	NM	CH (++)	CH (+)	CH (−−)	CH (−−−)	V (−)
	Z	CH (+)	CH (−−)	CH (−−−)	V (−−)	V(+)
	PM	CH (−−)	CH (−−−)	V (−−)	V (+)	V (++)
	PB	CH (−−−)	V (−−−)	V (+)	V (+++)	V (+++)

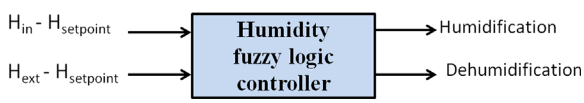

Fig. 9. Humidity fuzzy controller.

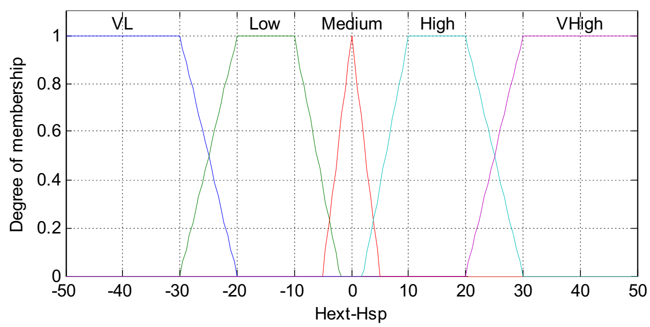

Fig. 10. Membership functions of the input variable «H_{ext}–$H_{set\ point}$».

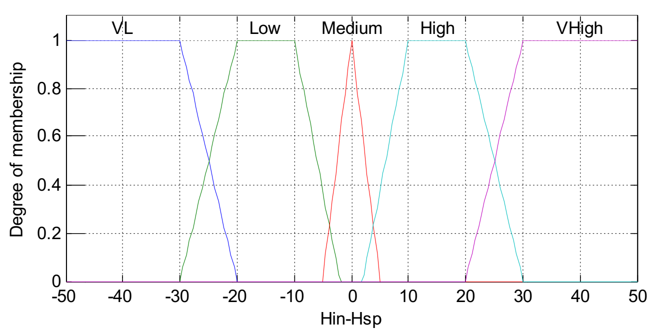

Fig. 11. Membership functions of the input variable «H_{in}–$H_{set\ point}$».

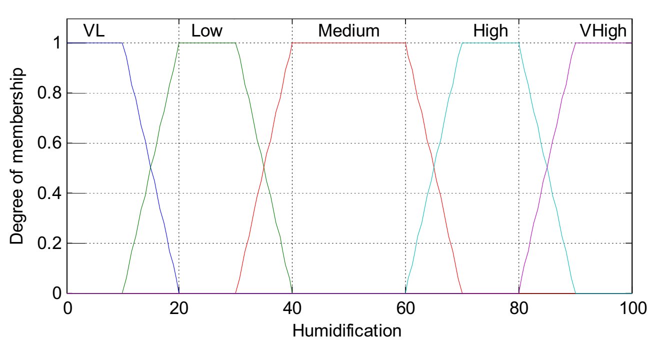

Fig. 12. Membership functions of the control variable «Humidification».

The membership functions of the input variables and output variables are shown in Figs. 15 and 16.

- **Inference rules**

The inference rules are shown in Table 3;

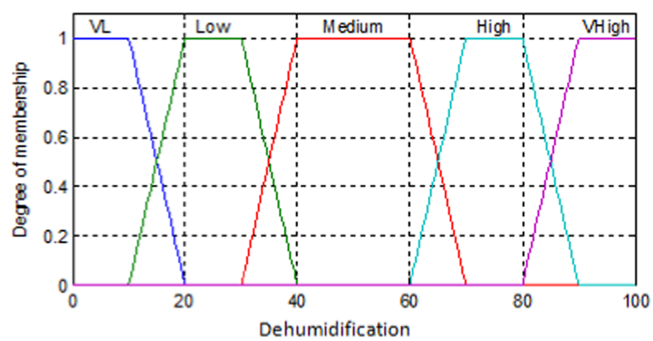

Fig. 13. Membership functions of the control variable «Dehumidification».

Table 2
Inference rules of the humidity fuzzy controller.

Control variables		H_{in}–$H_{set\ point}$				
H_{ext}–$H_{set\ point}$	NB	NB	NM	Z	PM	PB
	NM	H (+++)	H (++)	H (+)	H (−−)	H (−−−)
	Z	H (++)	H (+)	H (−−)	H (−−−)	DH (−−−)
	PM	H (+)	H (−−)	H (−−−)	DH (-)	DH (+)
	PB	H (−−)	H (−−−)	DH (−−)	DH (+)	DH (++)
	NB	H (−−−)	DH (+)	DH (++)	DH (+++)	DH (+++)

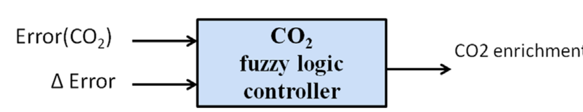

Fig. 14. CO_2 fuzzy logic controller.

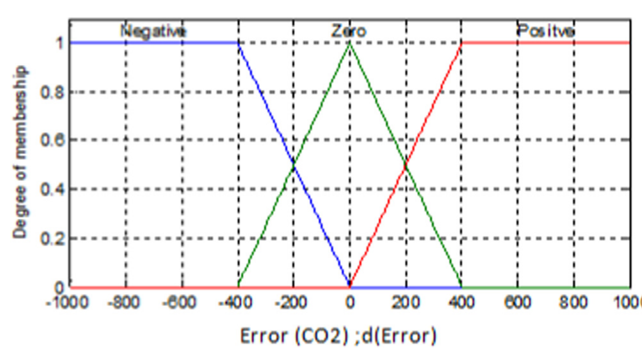

Fig. 15. Membership functions of the input variables « Error» and «ΔError».

2.1.4. Illuminance FLC

In this paragraph a FLC, Fig. 17, which controls the illuminance and shading inside the greenhouse, is developed. The inputs of the FLC are; The error on the illumination (the difference between the set and the actual value of the illumination inside the greenhouse), the solar radiation and the outside air temperature.

The control variables are the opening of the screen (for shade) and the artificial lighting. The associated membership functions

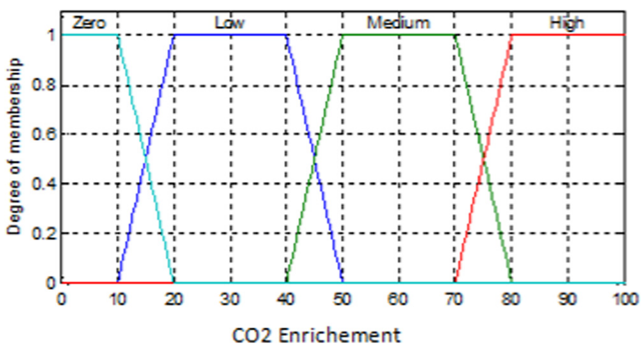

Fig. 16. Membership functions of the control variable «CO_2 enrichment».

Table 3
Inference rules of the CO_2 fuzzy controller.

Control variable		$CO_{2\ set\ point}-CO_{2in}$		
		N	*Z*	*P*
Δ Error	*N*	Zero	Zero	Low
	Z	Zero	Zero	Medium
	P	Zero	Low	High

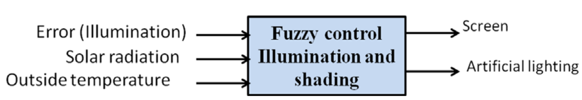

Fig. 17. Illumination and shading fuzzy logic controller.

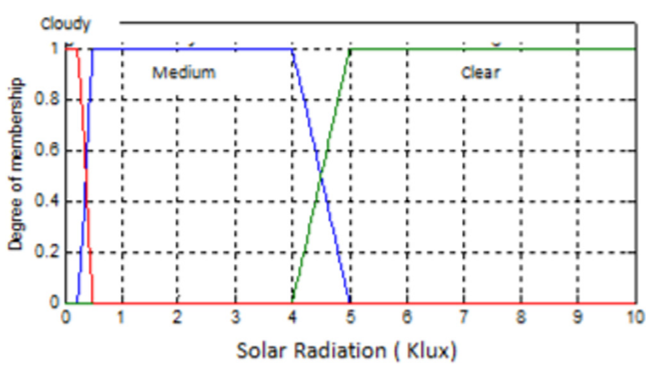

Fig. 18. Membership functions of the input variable «Solar radiation».

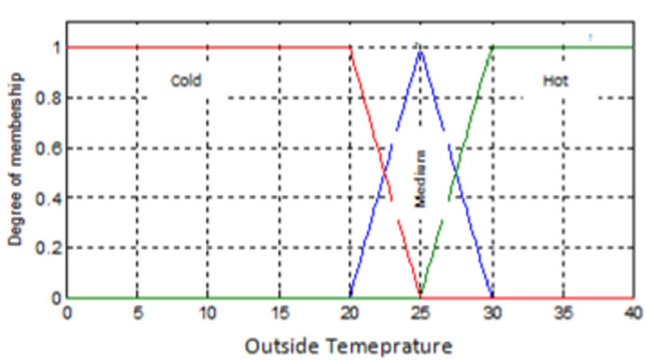

Fig. 19. Membership functions of the input variable «$T_{outside}$».

are shown in the following figures Figs. 17–20. The inputs are described by three fuzzy sets as follows: Illumination Error: {Negative, Zero, Positive}; Solar radiation: {Cloudy, Middle, Clear}; Outside temperature: {Warm, Medium, Cold}. The control

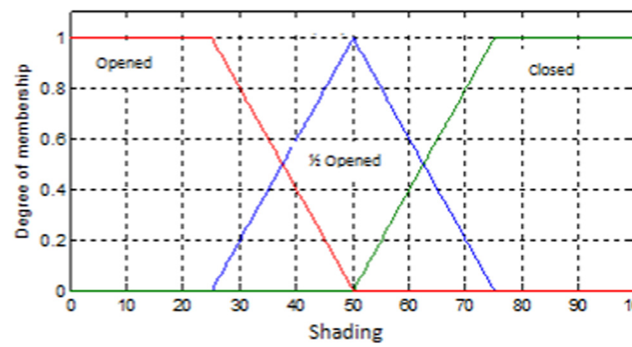

Fig. 20. Membership functions of the control variable «Shading».

Table 4
Inference rules of the fuzzy control of the illumination "Error (Illuminance) > 0".

Control variable		Solar radiation		
		Cloudy	Medium	Clear
$T_{outside}$	Cold	• Opened •Light ON	• Opened •Light ON	• Opened •Light OFF
	Medium	• Opened •Light ON	• ½ Opened •Light OFF	• ½ Opened •Light OFF
	Warm	• Opened •Light ON	• ½ Opened •Light OFF	• Closed •Light OFF

Table 5
Inference rules of the fuzzy control of the illumination "Error (Illuminance) < 0".

Control variable		Solar radiation		
		Cloudy	Medium	Clear
$T_{outside}$	Cold	• Opened •Light OFF	• Opened •Light OFF	• Opened •Light OFF
	Medium	• Opened •Light OFF	• ½ Opened •Light OFF	• ½ Opened •Light OFF
	Warm	• Opened •Light OFF	• ½ Opened •Light OFF	• Closed •Light OFF

Table 6
The fuzzy control rules of inference of the illumination "Error (Illuminance) = 0".

Control variable		Solar radiation		
		Cloudy	Medium	Clear
$T_{outside}$	Cold	• Opened • Light OFF	• Opened • Light OFF	• Opened • Light OFF
	Medium	• Opened • Light OFF	• ½ Opened • Light OFF	• ½ Opened • Light OFF
	Warm	• Opened • Light OFF	• ½ Opened • Light OFF	• Closed •Light OFF

variables: shading and lighting are associated with the following fuzzy sets: the screen: {Open, half open, closed}; and lighting: {On, Off}.

- **Inference rules**

The inference rules are presented from Tables 4–6.

► Error (Illumination): is Positive:
► Error (Illumination): is Negative:
► Error (Illumination): is zero:

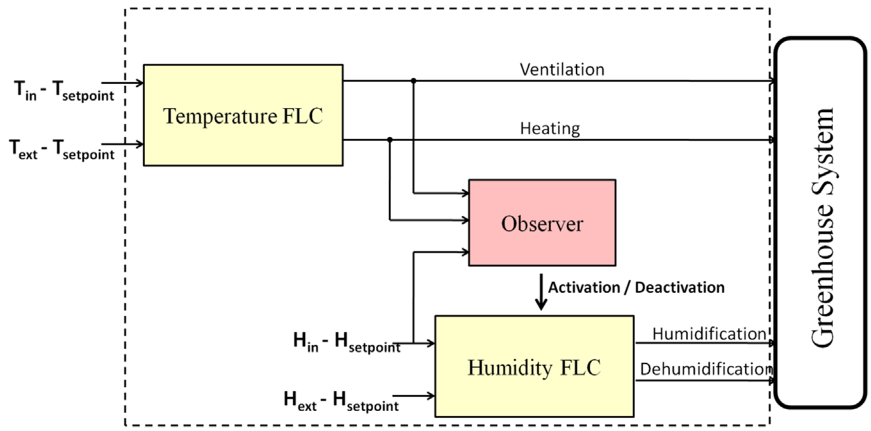

Fig. 21. Temperature and humidity control process.

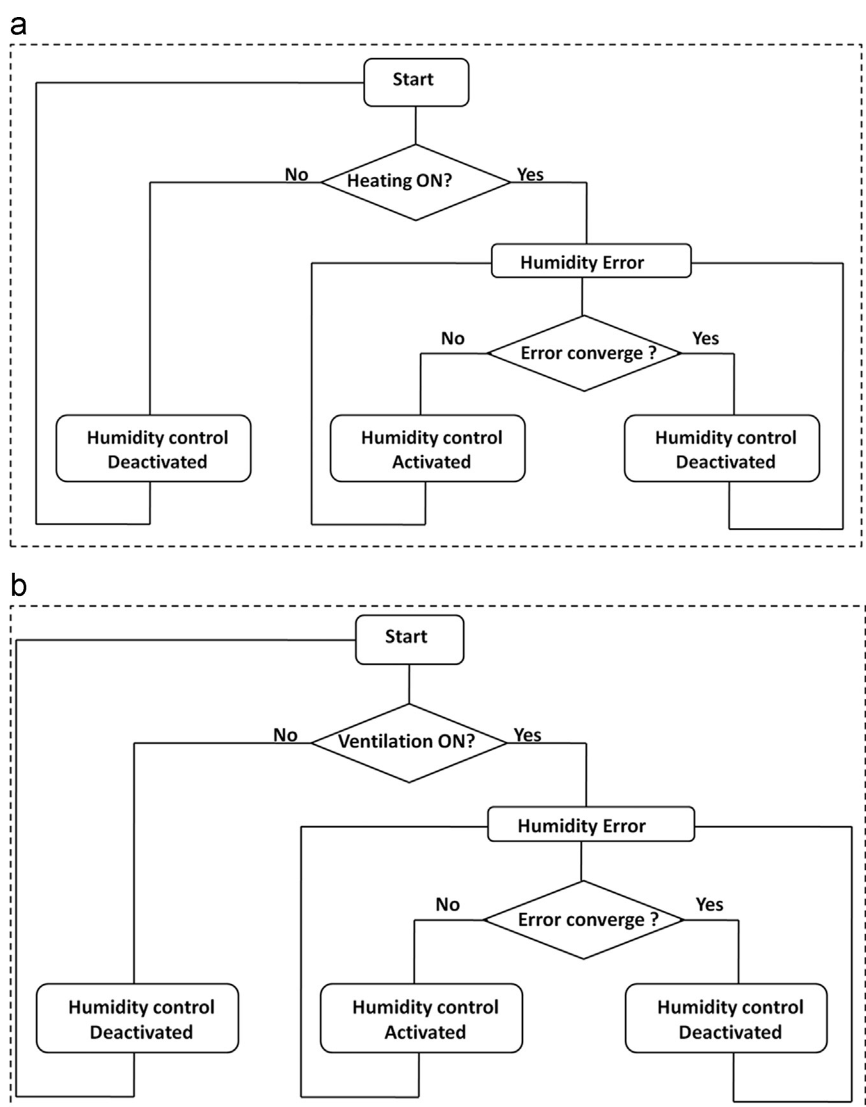

Fig. 22. Observer design flow: (a) heating case, and (b) ventilation case.

2.2. Design of the control process: system concept

The optimization of fuzzy control focuses on the correlation state between the temperature and the inside humidity [25]. This leads to select an appropriate combination of control decisions (ventilation, heating, humidification, and dehumidification). Indeed, an observer is developed and integrated into the control process as illustrated in Fig. 21. The observer design flow is shown in Fig. 22.

The role of the observer is to check the effect of ventilation and heating on the inside humidity, and to check if the error on moisture converge or diverge from the set point. When the error

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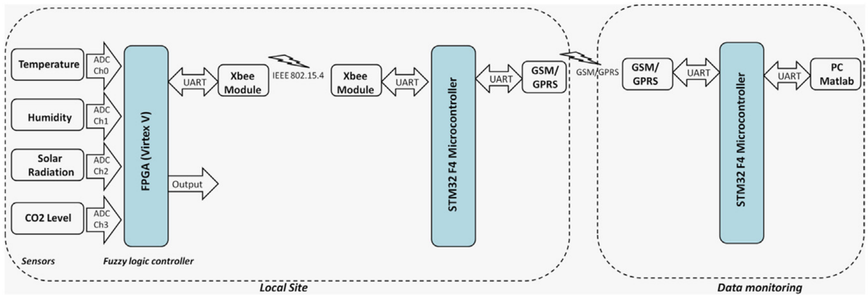

Fig. 23. Wireless data monitoring.

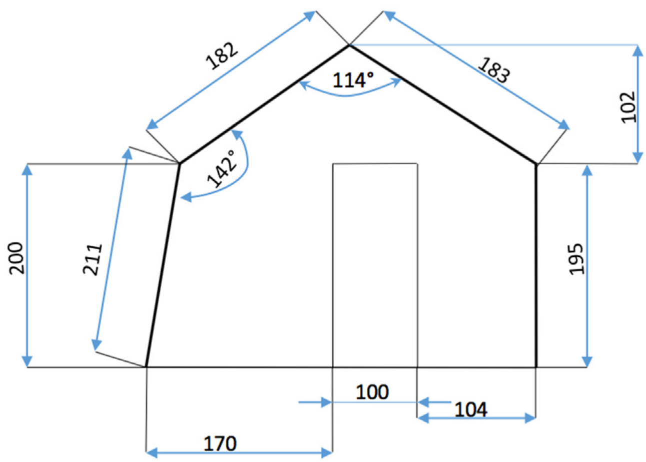

Fig. 24. Experimental greenhouse system.

converges under the effect of ventilation or heating, then it is unnecessary to activate the humidity control systems (humidifier, dehumidifier) since the ventilation (or the heating) is acting on the same sense of the humidity error convergence. Otherwise, if the error diverges the humidity control system is enabled.

2.3. Smart fuzzy logic based control system

2.3.1. System design

The system consists of FPGA-based fuzzy logic controller that manages the indoor keys climate parameters (Temperature, humidity, CO_2 level, and Illuminance). The inside data parameters is logged and monitored through a Zigbee-GSM/GPRS communication platform.

The system concept is based on two sub-systems as depicted in Fig. 23:

1. The local site: It consists of the controlling platform, the sensing part and a short range communication protocol through the Zigbee protocol.
2. Data logging and monitoring station: a long range communication protocol GSM/GPRS, for data routing and logging.

2.3.2. Wireless data monitoring

The local control platform is constructed around Virtex V FPGA board and an STM 32/F4 microcontroller. The fuzzy logic controllers were deployed on the FPGA board regarding to the complexity of the fuzzy logic algorithm, the parallel processing required for the inferences rules and the resources capacity of the FPGA. The main tasks of this board are:

1. The real time control of the inside greenhouse keys climate parameters.
2. Transmitting data to a local logging station through the STM 32 microcontroller and Zigbee modem for sort-range wireless connectivity IEEE802.15.4 compliant Zigbee protocol. This feature enables creating a database of the greenhouse inside climate for the efficiency and performance analysis of the control. In addition, this stage acts as a link between short-range and long-range networks.

A second station, for data logging and monitoring is deployed through a long-range communication protocols done over GSM/GPRS module which are interfaced to the station via STM32 microcontrollers. This feature enables long period data collection for advanced analysis, system performance optimization as well the distant real time access to data for the user.

3. Field sensors, calibration and data acquisition

A standard peak even span greenhouse for crop production (basil and similar crops), as depicted in Fig. 23, was selected in this work since it is one of the most common in Tunisia. It is located in the north of Tunis (36°41'46.68"N, 10°23'11.4"E).The glazing material used is the glass, the dimensions of the system are presented in the Fig. 24. The greenhouse is equipped by climate control equipment (ventilation system, electrical heaters, and fogging system for humidification), inside and outside climate sensors and a data acquisition module Fig. 25.

3.1. Temperature sensor

The greenhouse is equipped with a temperature sensor (LM35DZ) whose output voltage is proportional to the measured temperature (°C). The typical accuracy is ± 0.4 (°C) at a temperature of 25 (°C). The conditioning circuit is a non-inverting amplifier circuit whose gain is set by means of a potentiometer; Fig. 26 shows the circuit of the calibration curve (sensor+conditioner). The output voltage Vs changes as a function of temperature is linear.

The calibration performed on the sensor LM35DZ yielded the equation relating the variation of the output voltage Vs to the temperature T as depicted in Fig. 27.

$T = 10.48\ \mathrm{Vs} - 1.951$

3.2. Humidity sensor

To measure the relative humidity of the air, we installed a HIH-4000-001 sensor type from Sensors Honeywell. The calibration curve showing the variation of the output voltage Vs according to the humidity as depicted in Fig. 28, leads to the following equation:

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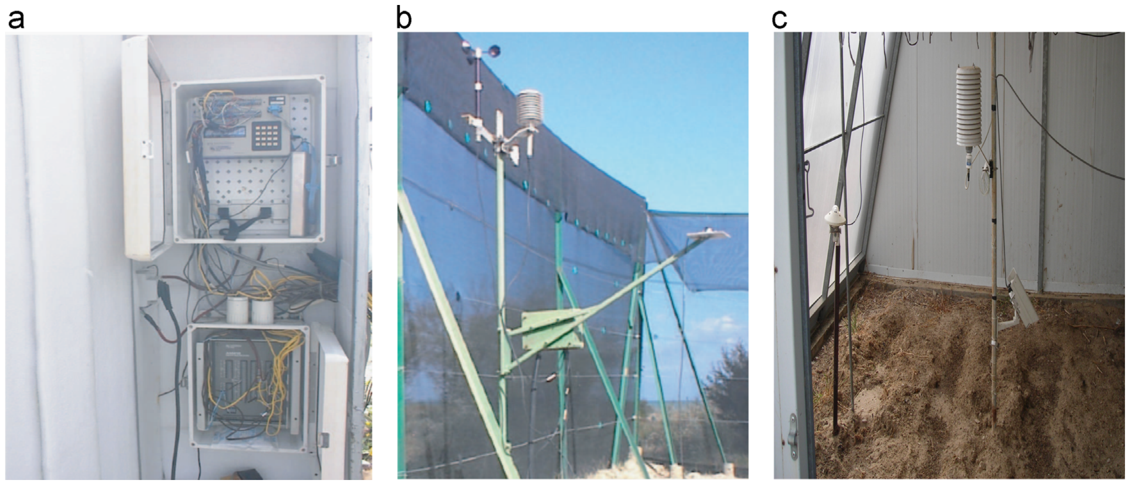

Fig. 25. (a) Data acquisition unit, (b) weather parameters sensors, and (c) inside climate parameters sensors.

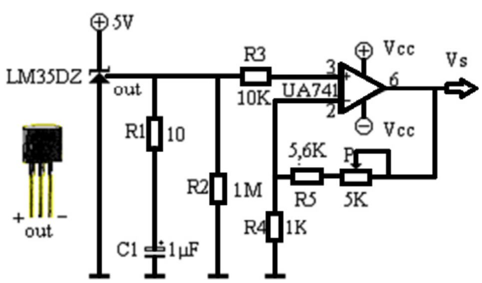

Fig. 26. Electronics associated with the temperature sensor LM35DZ.

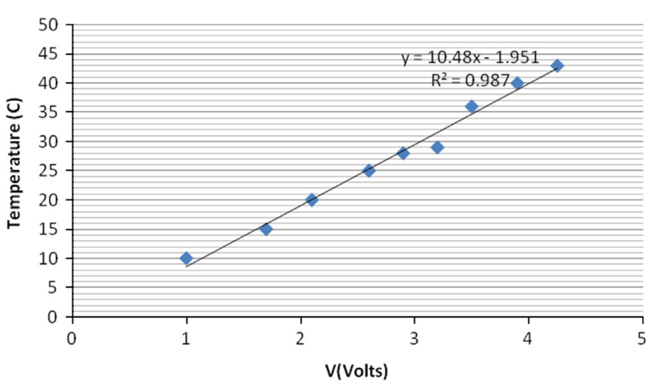

Fig. 27. Calibration curve of the temperature sensor.

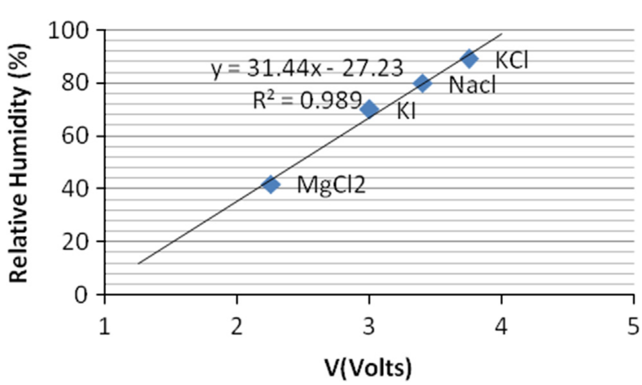

Fig. 28. Calibration curve of the Humidity sensor.

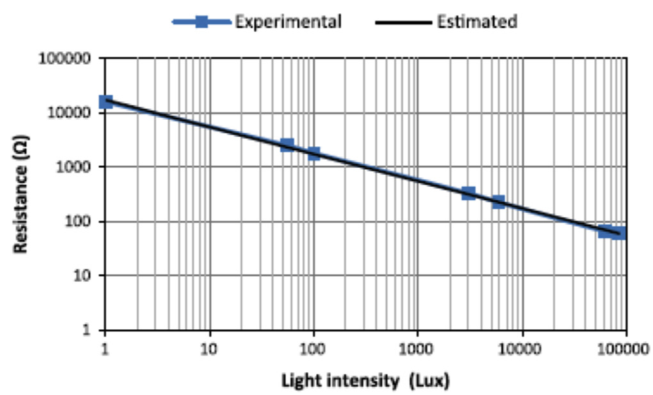

Fig. 29. Illuminance sensor calibration curve.

$RH = 31.44\ Vs - 27.23$ with a correlation coefficient, $R^2 = 0.98$.

3.3. CO_2 sensor

For measuring the CO_2 content, we used the TGS4160 sensor (Tagushi Gas Sensor, Japan) consisting of a sensitive element to CO_2 and a thermistor. Its sensing element is a solid electrolyte between two electrodes combined with the printed circuit. The CO_2 content according to the output voltage *Vs* of the circuit associated with the sensor is governed by the following equation.

$$CO_2(ppm) = 1000 \times Vs$$

3.4. Illuminance sensor

The illuminance sensor was calibrated using a light meter (RS 180–7133). The calibration results are depicted in Fig. 29 which spans a wide light intensity window from dark to full sun light.

3.5. Data acquisition

The data acquisition is performed through PCI-6024E acquisition borad. The PCI-6024E has various ranges of inputs/outputs amplitude (± 10 V, ± 5 V, 0.5 V, ± 0.05 V).The discretization of analog signals is done on 12 bit. The analog data acquisition is done via an analog multiplexer and the ADC performing quantization of the signal on n bits.

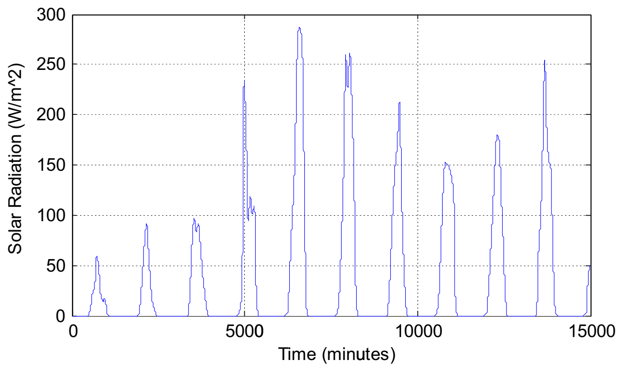

Fig. 30. Solar radiation over measurement period.

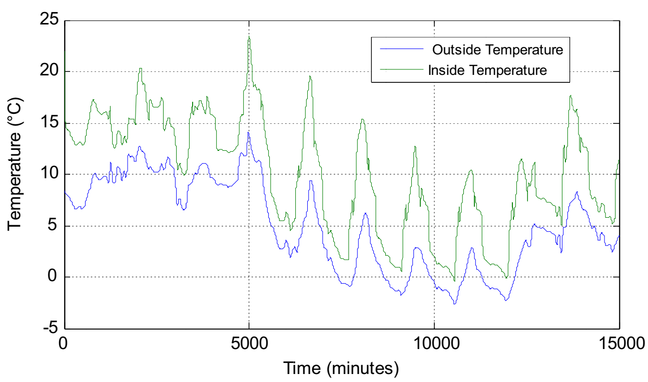

Fig. 31. Outside and inside GHS temperature.

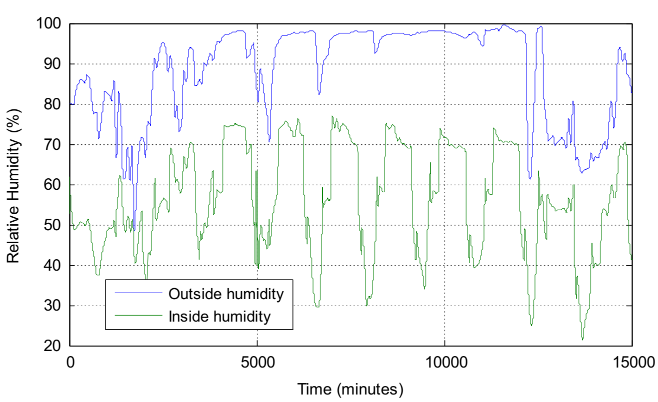

Fig. 32. Outside and inside GHS relative humidity.

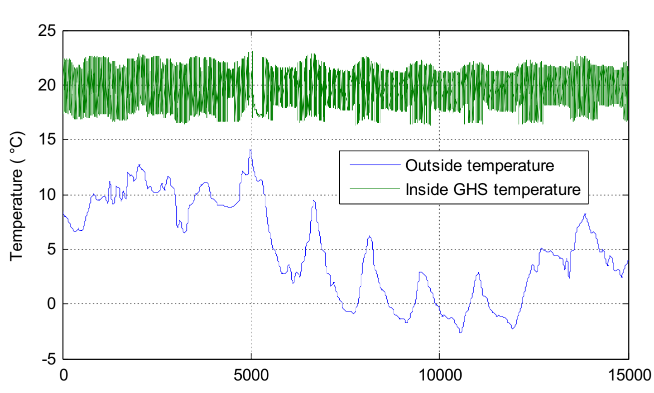

Fig. 33. FLC of the GHS temperature.

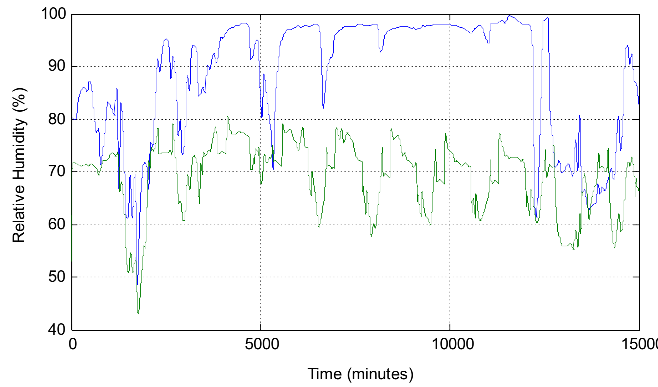

Fig. 34. FLC of the GHS humidity.

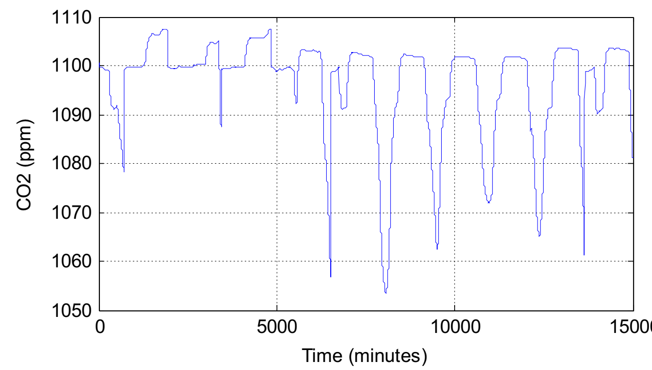

Fig. 35. FLC of the GHS CO_2 level.

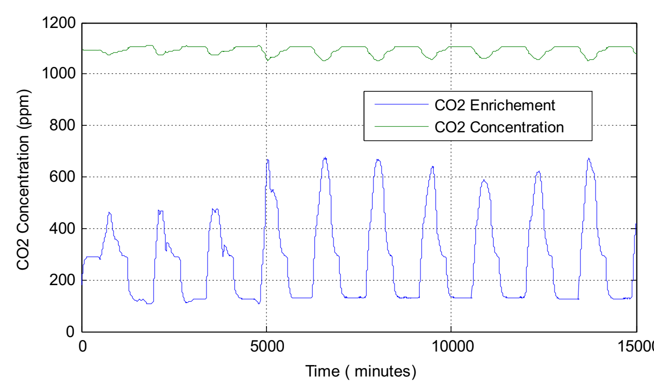

Fig. 36. CO2 Enrichment.

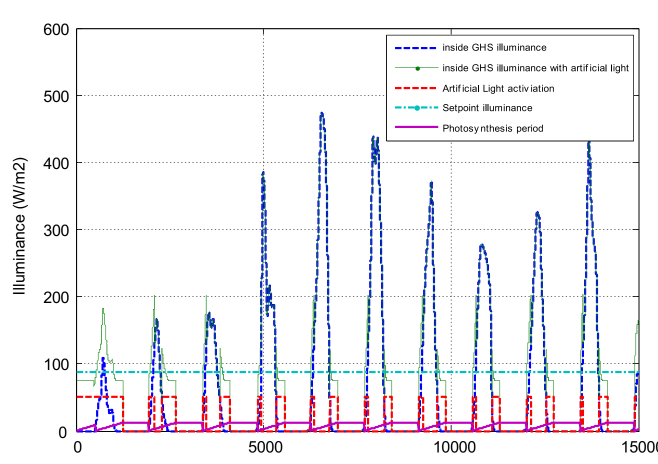

Fig. 37. FLC illuminance control.

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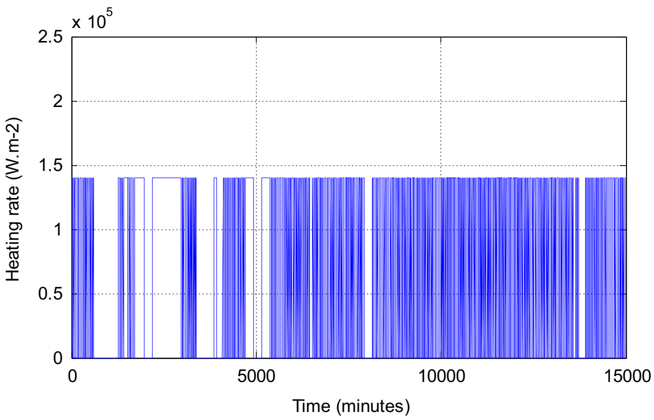

Fig. 38. GHS heating requirement.

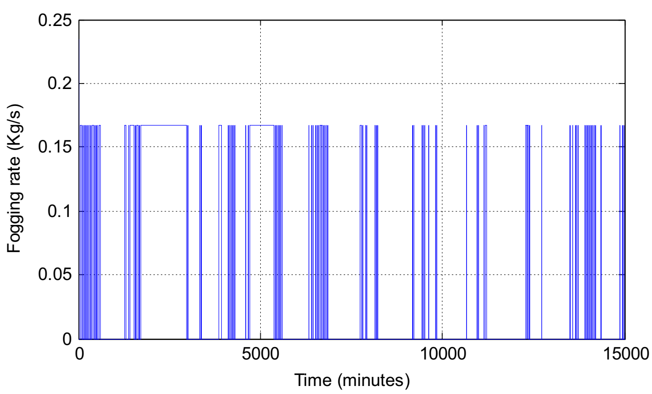

Fig. 39. Fogging rate without control process optimization.

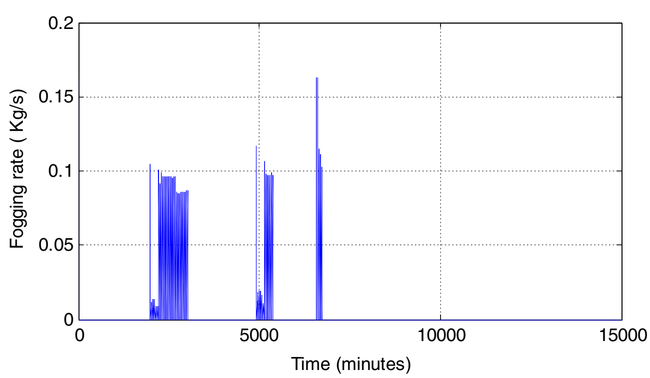

Fig. 40. Fogging rate with control process optimization.

4. Application to the control of the greenhouse

The developed FLC system control is applied to the GHS (Greenhouse System) during ten winter days starting from the 3rd of January 2015. For instance, the climate control system is evaluated when using the proposed FLC strategy. Figs. 30–32 show the outside weather data as well the inside greenhouse parameters without control; the solar radiation profile, the temperature and the relative humidity.

To check the GHS behavior, typical real-time data collected remotely during winter season as illustrated in Figs. 33–37. As expected, the measurement results, Figs. 33–37, showed that the FLC manage effectively the inside GHS climate. For instance, the inside GHS temperature and humidity are stabilized around experimental set points 20 (°C) and 70(%) respectively.

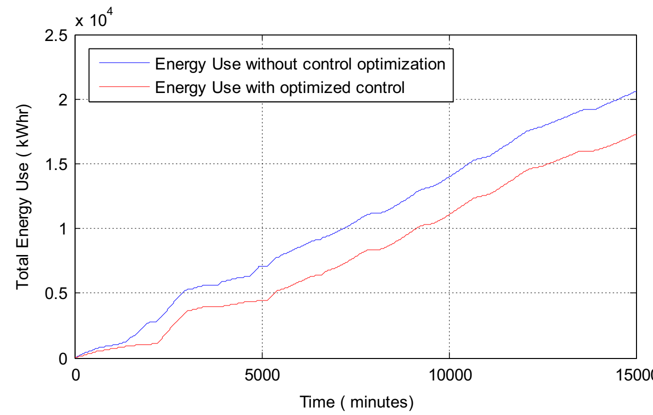

Fig. 41. Total energy use.

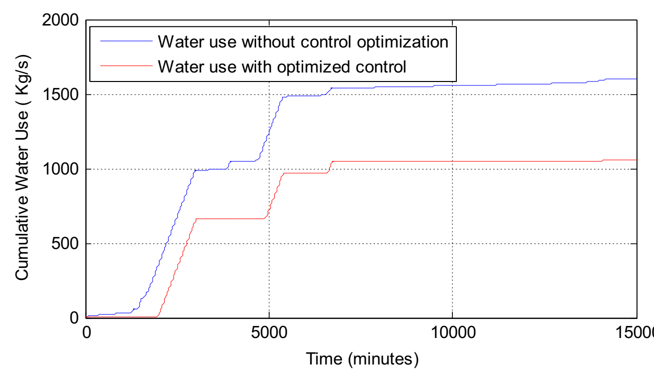

Fig. 42. Cumulative water use.

Regarding the CO_2, the optimal values are within the range of 800 ppm and 1500 ppm as a maximum value. In this work, a set point of 1100 (ppm) is applied to the control of CO_2 level. Figs. 35 and 36 show that, over time, the control of CO_2 levels is performed in a stable manner and at a relatively low rate which guarantees more savings on the use of CO_2 cylinders.

Fig. 37 shows the inside GHS illuminance without control, as well when the FLC control is applied through the artificial lightning. Results show that a required illuminance level 90 (W/m^2) [26] is achieved which contributes to enhance plants growth comfort conditions. Moreover, the activation periods of the artificial lightning, as depicted in Fig. 37, are in a good agreement with the plants photosynthesis period (12 h as a default value) which contributes to optimal photosynthesis activity. In fact, some plants photosynthesis period is longer than the solar radiation duration. Specially, during winter days when the daytime illuminance is not sufficient for some plants photosynthesis activity. Fig. 38.

The proposed control process is evaluated when the GHS temperature control is processed through the activation of the heating or the ventilation. In order to reveal the effectiveness of the control process, we focused on the operation time of the fogging system, as illustrated in Figs. 39 and 40, without optimization Fig. 39 as well when the proposed control process is applied Fig. 40. Results reveal that the operation time of the fogging system was significantly reduced which has an impact on the energy use and the water use.

5. Impact on energy savings and water use

The improved FLC control system was evaluated based on its impact on energy saving and water use. For instance, a comparative study of the energy and water consumption is performed to reveal the assessment of the improved system. As expected, the total energy use over the experience period was reduced by 22% as illustrated in Fig. 41. Moreover, the water use was reduced by 33%, illustrated in Fig. 42. This is explained by the improved micro-climate management approach which takes on account the correlation of the temperature and humidity leading to an optimal operation time of climate control actuators.

6. Conclusion

This works investigated environmental GHS keys parameters which affect the plants growth such as the temperature, the humidity, the CO_2 and the illuminance. A type-2 fuzzy logic systems were involved to manage the indoor climate with particular attention to the effectiveness, the energy use and the production costs. The indoor temperature and humidity correlation was also addressed. Indeed, an observer was integrated into the control process leading to appropriate control decisions. The system was enhanced by a smart data monitoring through a wireless data logging platform. This, allows a real-time data access and building database could be used for future enhancement of the system accuracy and decisions making. The experimental benchmark was described as well the field sensors, calibration and data acquisition.

Results have shown the effectiveness of the smart automation system on tracking the different parameters set points. The efficiency of the proposed control system was revealed through an evaluation on the energy saving and the water use. In fact, a comparative study on the GHS when the smart control is applied have shown that the energy saving and water use could achieve, respectively, 22% and 33%. Hence, the production costs could be reduced significantly with respect to sustainable development and environment.

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