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Module 6: CLIMATE MANAGEMENT

Presentation

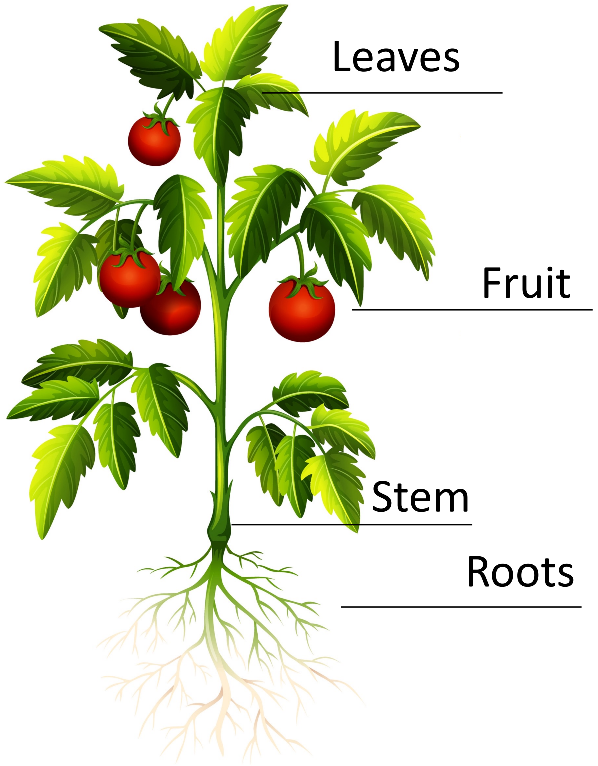
Motivation

Crop growth control in greenhouse

Crop growth

Increased biomass or the physical dimensions of plants

[Bidwell, 1974]



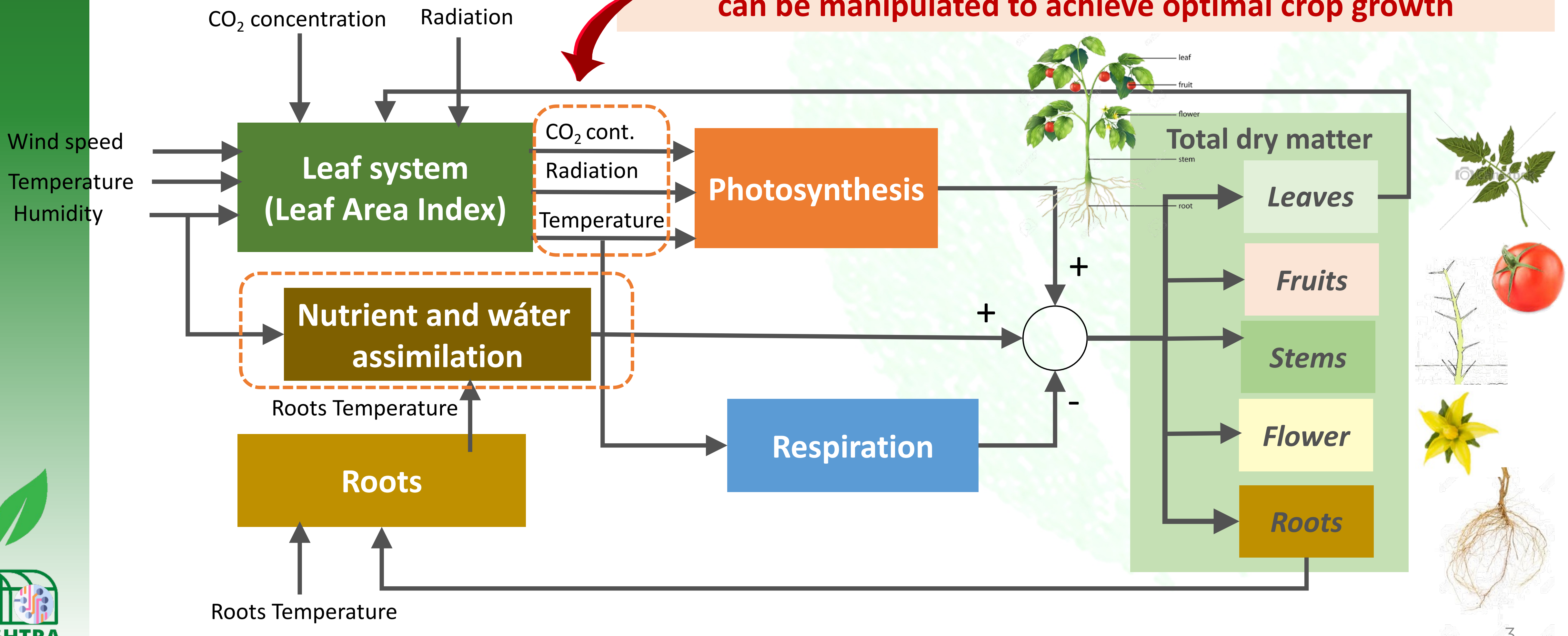
How can it be measured?

- Number and size of leaves (Leaves Area Index, LAI).
- Dry matter (material that results from drying plants)
- Fresh weight (actual plant weight composed of dry matter and water)

Motivation

Crop growth control in greenhouse

A greenhouse is a closed enclosure where weather conditions can be manipulated to achieve optimal crop growth



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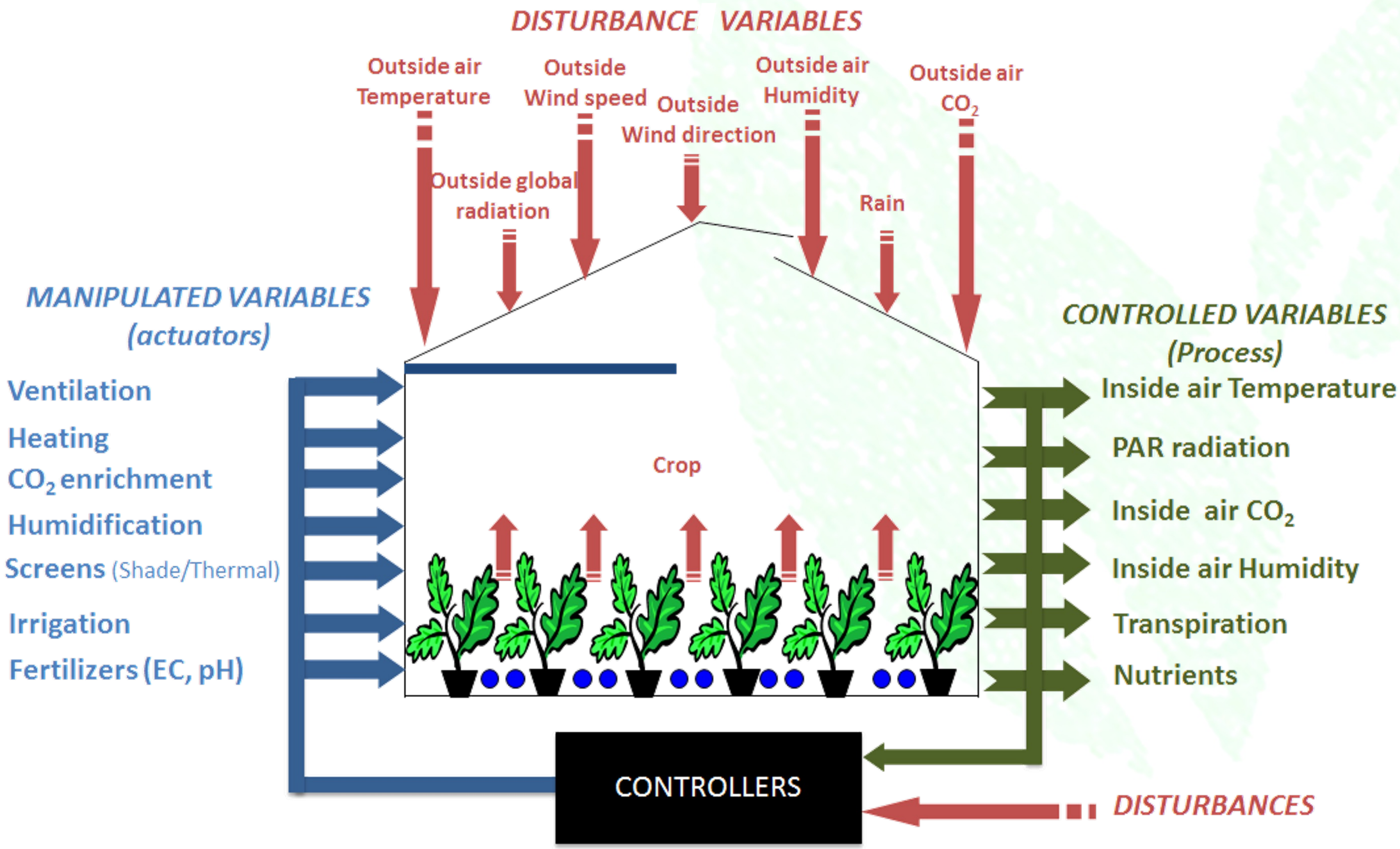
Motivation

Crop growth control in greenhouse



Motivation

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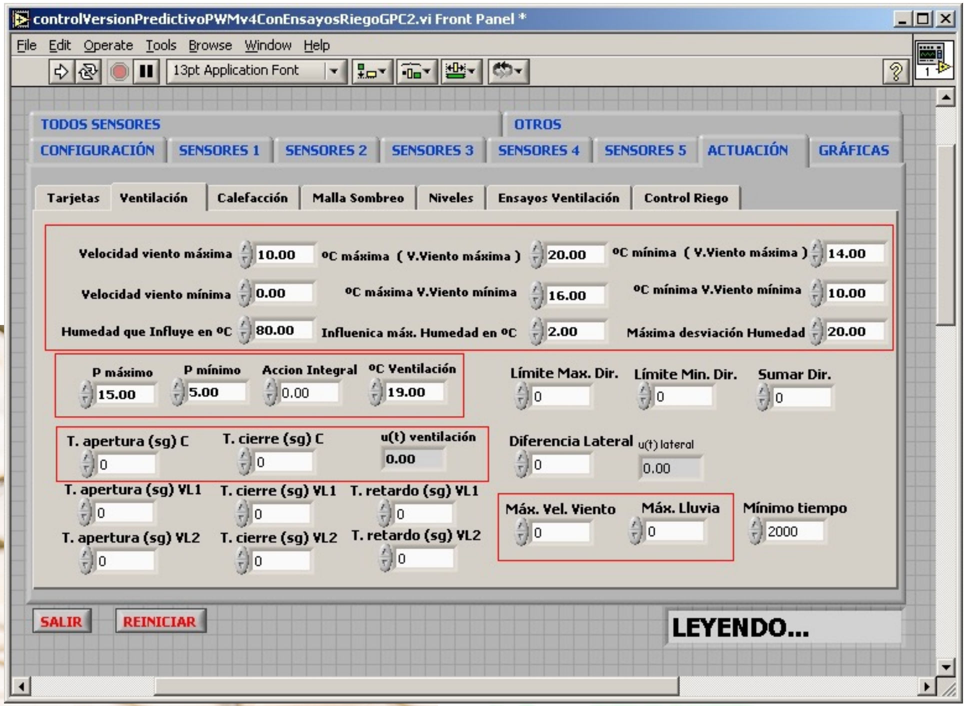
Motivation



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Objectives

- To explain the advantages and the need for the **application of automatic control techniques** in the fundamental processes of greenhouse crop production, specifically the control of climatic variables, irrigation and fertilizer injection.
- To describe the **necessary elements** (sensors, controllers and actuators) that form this particular type of control systems.
- To show the **necessity of using advanced control techniques** such as gain scheduling control, cascade control or parallel feedforward control to improve disturbance rejection, as well as to describe the principles of operation of these techniques.
- Show the need to use **new approaches** to climate-based crop growth control considering economical, quality and energy saving aspects.

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Competences/Skills

- Competency to the sensors and actuators that acting together and fulfilling a certain objective.
- Competency to the basis of climate control.
- Competency to the control algorithms design for the main climate variables.
- Competency to distinguish the different trends in crop growth control
- Competency to choose the most important variables that influence growth and know how to control them to obtain maximum economical profit.
- Competency to recognize that there are situations in which the climate control can be forced and other in which this is not profitable

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Lessons

6.1. Measurement

Introduce and motivate the student to understand the importance of measuring climate variables and what the measurement process looks like.

6.2. Greenhouse climate variable control

Show the commercial controllers and advanced control algorithm for certain variables, and learn about its advantages and disadvantages.

6.3. Climate-based crop growth control

Crop control algorithms as a method to obtain input savings in greenhouses. These algorithms are also used to efficiently manage the consumption systems, such as the control of climate actuators.

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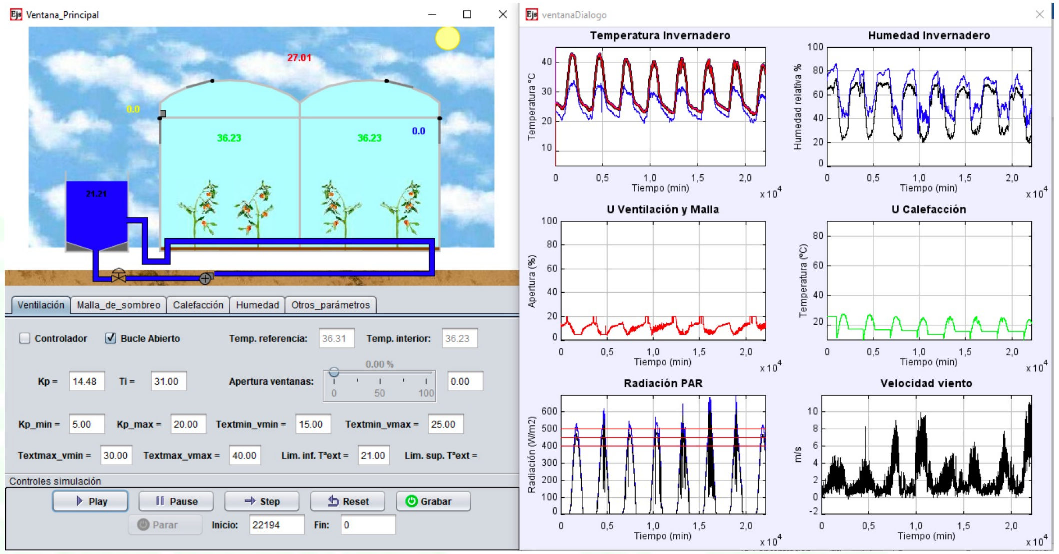
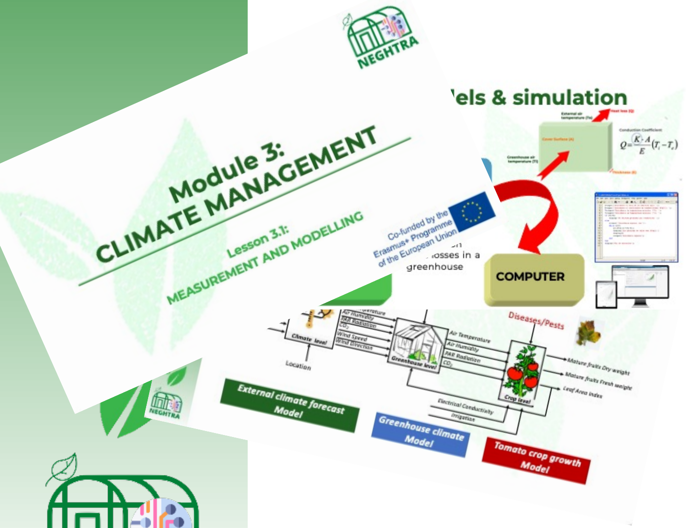
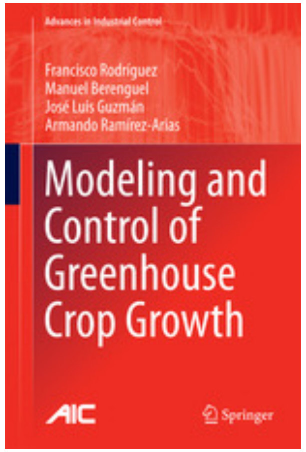
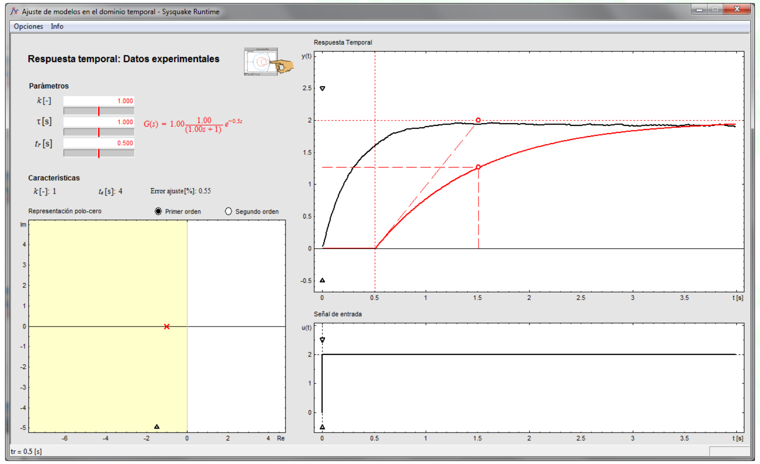
Learning material

- Presentations and videos
- Books
- Interactive tools
- Greenhouse climate control Virtual lab
- UAL Greenhouse climate data bank









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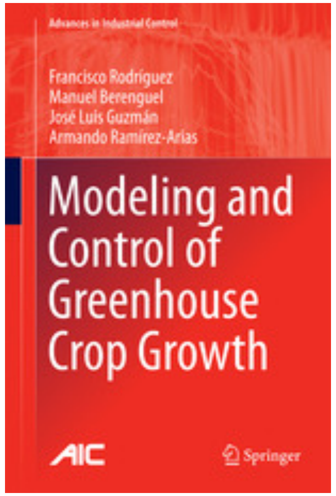
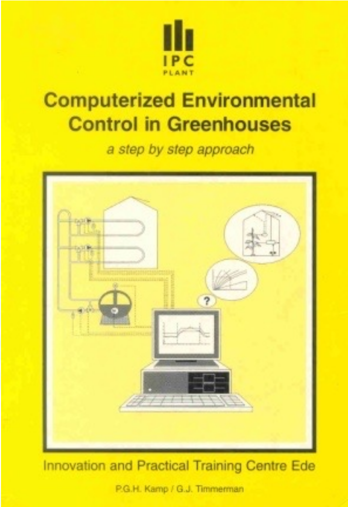
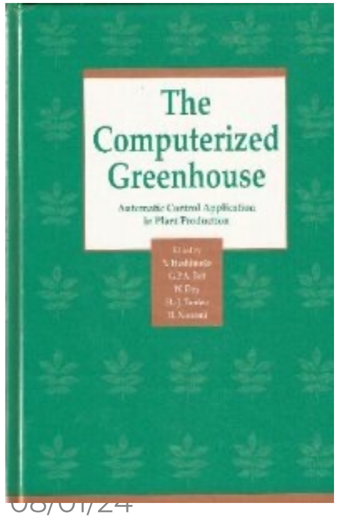
Sources

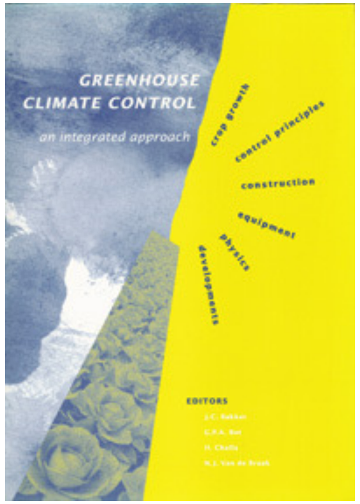


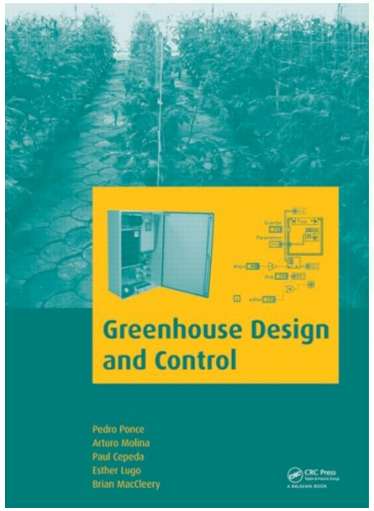
Rodríguez, F., Berenguel, M., Guzman, J.L., Ramírez-Arias, A..; 2015; *Modelling and Control of Greenhouse Crop Growth*; Springer International Publishing; London (UK); 250 pp.

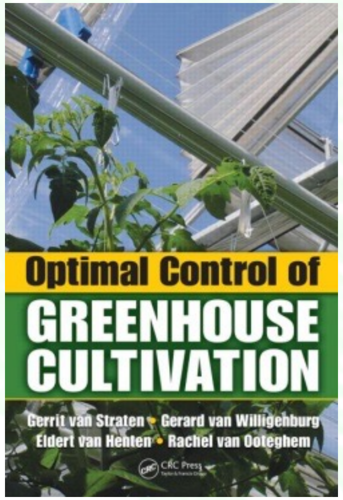
Kamp, P.G.H.; Timmerman, G.J.; 1996; *Computerized environmental control in greenhouses. A step by step approach*; IPC Plant; Ede;; 273 pp. .

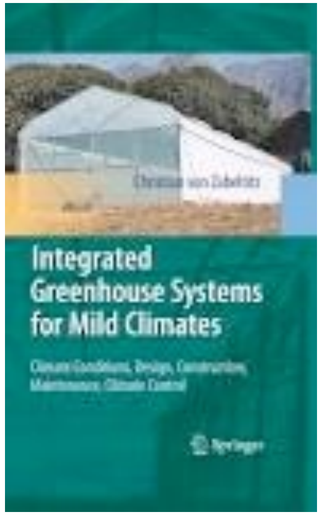












08/01/24

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Module 6:
CLIMATE MANAGEMENT

Lesson 6.1:
Measurement and modelling

Theme 6.1.1:
Fundamentals of measurement

Basic concepts

Measurement Process

Conclusions

NEGHTRA

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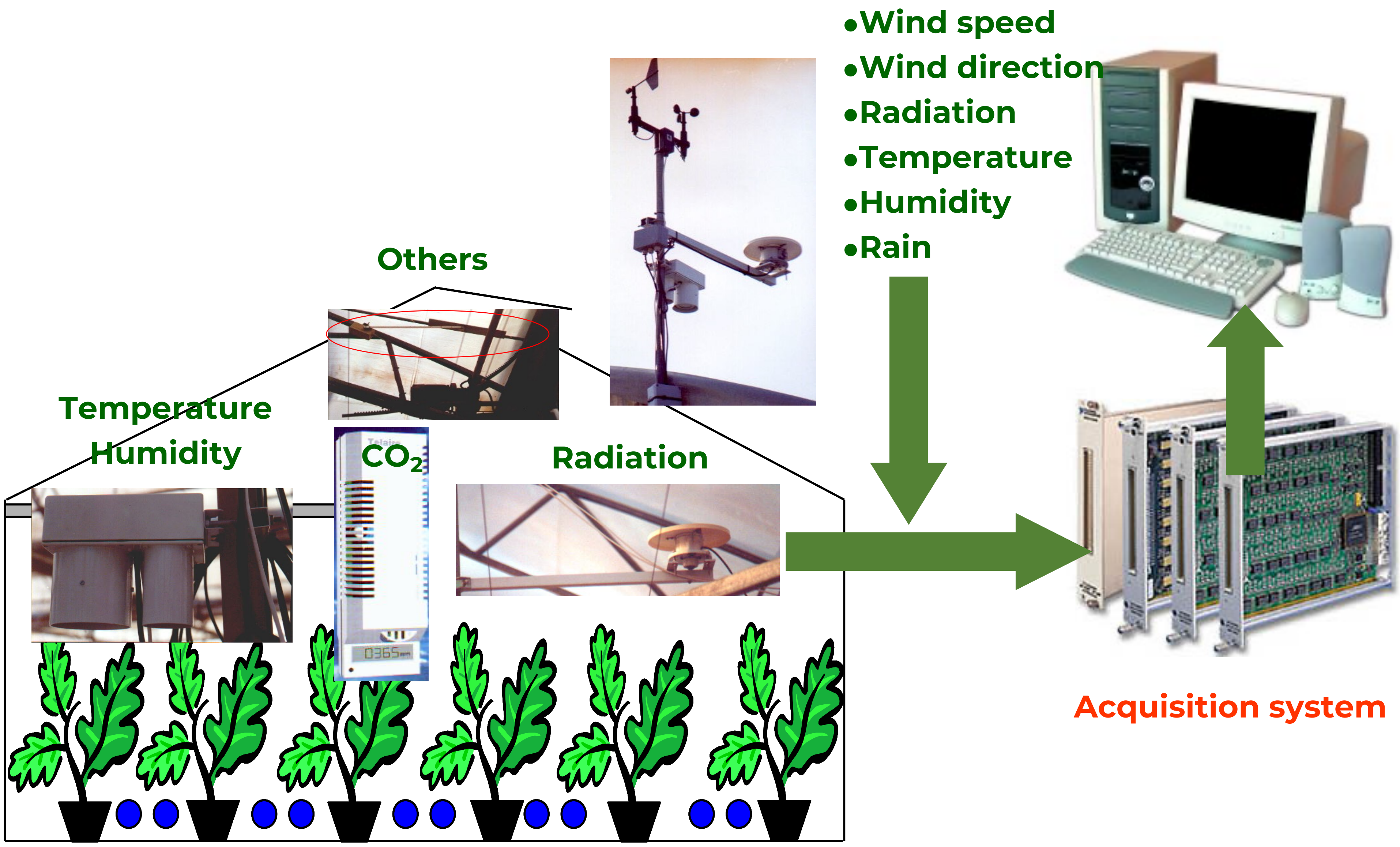
Greenhouse climate management



Basic concepts

Measurement Process

Conclusions

What is a sensor?

A measuring instrument or sensor that performs an estimation of the variable, converting a physical or chemical signal into an electrical signal.

Climate
Temperature
Relative humidity
CO_2
Global radiation
PAR radiation
Wind speed
Wind direction

Soil & water
Water content
Tensiometers
EC
pH
Temperature
Nutrients - Ions

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Measurement Range

Range is the scope of variable values that can be measured by the sensor. It is specified by a lower and an upper limit.

Temperature and humidity sensor

Temperature	
Measuring range	0 ... +60 °C

This sensor takes correct measurements between 0 and 60 ºC

Is it a good choice for a greenhouse?

Definitions and basic concepts

Span: is defined as the difference between the upper and lower values of the range.

Precision: The reference accuracy is the maximum limit of the measurement error, when the instrument is used under nominal conditions.

***Accuracy*:** is the degree to which the measurement it provides approximates a standard or ideal measurement value. It is usually expressed in terms of standard deviation or range.

Important when choosing instrumentation

Sensor Accuracy

Accuracy is the degree to which the measurement the sensor provides approximates a standard or ideal measurement value. It is usually expressed in terms of standard deviation or range.

Is 0.2-0.5 ºC of temperature or 5% relative humidity correct?

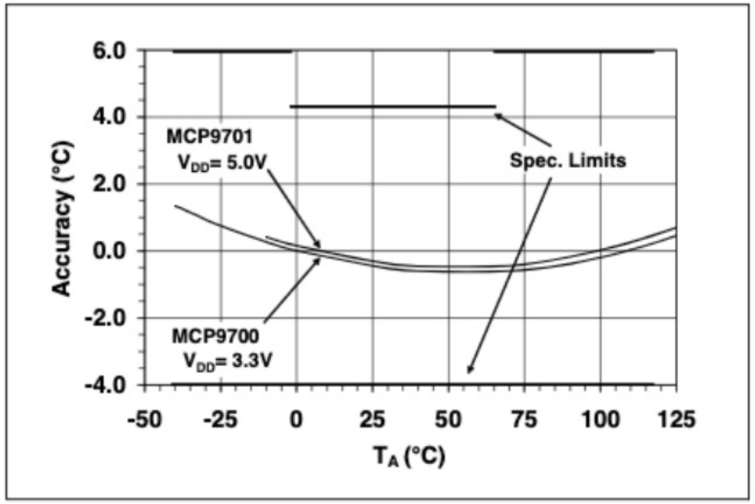
Vapour pressure measurement (kPa) with temperature and humidity sensor

HUMIDITY (%RH) \ TEMPERATURE (°C)	0	10	20	30	40	50	60	70	80
100	± 0.03	± 0.05	± 0.09	± 0.16	± 0.27	± 0.44	± 0.69	± 1.33	± 2.38
90	± 0.03	± 0.05	± 0.09	± 0.15	± 0.26	± 0.42	± 0.66	± 1.26	± 2.24
80	± 0.03	± 0.04	± 0.07	± 0.12	± 0.21	± 0.34	± 0.63	± 1.20	± 2.10
70	± 0.02	± 0.04	± 0.07	± 0.12	± 0.20	± 0.32	± 0.50	± 1.13	± 1.96
60	± 0.02	± 0.03	± 0.06	± 0.11	± 0.18	± 0.30	± 0.47	± 1.06	± 1.82
50	± 0.02	± 0.03	± 0.06	± 0.10	± 0.17	± 0.28	± 0.45	± 0.99	± 1.68
40	± 0.02	± 0.03	± 0.05	± 0.09	± 0.16	± 0.26	± 0.42	± 0.76	± 1.54
30	± 0.01	± 0.03	± 0.05	± 0.09	± 0.15	± 0.24	± 0.39	± 0.69	± 1.40
20	± 0.01	± 0.02	± 0.04	± 0.08	± 0.14	± 0.23	± 0.36	± 0.62	± 1.26
10	± 0.01	± 0.02	± 0.04	± 0.07	± 0.12	± 0.21	± 0.33	± 0.55	± 1.13
0	± 0.01	± 0.02	± 0.04	± 0.06	± 0.11	± 0.19	± 0.30	± 0.48	± 0.99

METER

ATMOS 14
GEN 2

Temperature sensor



MICROCHIP

MCP9700/01

Definitions and basic concepts

Repeatability: This characteristic indicates the degree of consistency of the instrument, i.e., to what degree the device provides equal readings when the measured variables take the same value and the measurement conditions are the same. If the measurement conditions are not required to be identical, this characteristic is called reproducibility.

Deadband: The deadband of a measuring instrument is the range of variation of the measured variable that does not produce a perceptible change in the output of the instrument. The most common cause of deadband is static friction. The deadband of a measuring device is usually specified as a percentage of its range.

Definitions and basic concepts

Linearity: This term is applied to functions or curves and measures the degree to which they can be approximated by a straight line. It is usually expressed as the maximum error that would be made in approximating the function by a straight line. Linearity is a desirable quality in most measuring instruments, since it implies similar sensitivity over the entire measuring range.

Bias: It is a constant error that affects the measurement over its entire range. It is an error that is not random and can be corrected by calibrating the instrument.

Derive: It is the variation experienced by some of its characteristics in a given period of time. Drifts are due to changes that some components or materials of the instrument undergo when the temperature or humidity varies.

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Instruments classification

Types of measurements

Directs: the meaning of the measurement and the purpose of the processing operation are identical.

Tesiometer (Pa)

IRROMETER

Indirect: the meaning of the measurement and the purpose of the processing operation are not same, but are related to each other.

Potencimeters (mv or mA) to measure Windows oppenings (% or º)

BOURNS

Steps in the measurement process

Example: Pressure

Variable to measure

(Bar)

Sensor

Telemecanique Sensors

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Steps in the measurement process

Example: Pressure

Main	
Range of product	OsiSense XM
Product or component type	Electronic pressure sensors
Pressure sensor type	Pressure transmitter
Pressure switch type of operation	Pressure transmitter
Device short name	XMLR
Pressure sensor size	10 bar 145 psi 1 MPa
Maximum permissible accidental pressure	40 bar 580 psi 4 MPa
Destruction pressure	40 bar 580 psi 4 MPa
Controlled fluid	Fresh water (0...80 °C) Air (-20...80 °C) Hydraulic oil (-20...80 °C) Refrigeration fluid (-20...80 °C)
Fluid connection type	G 1/4A (male) conforming to DIN 3852-E
[Us] rated supply voltage	24 V DC SELV, voltage limits: 17...33 V

Telemecanique Sensors

Steps in the measurement process

Example: Pressure

Variable to measure (Bar) → **Sensor** → **Transducer** → Electric signal (“low quality”) (mV)

Telemecanique Sensors

HK INSTRUMENTS
USER-FRIENDLY MEASURING DEVICES

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Steps in the measurement process

Example: Pressure

Variable to measure

(Bar)

Sensor → **Transducer** → **Conditioner Transmitter**

Electric signal ("low quality")

(mV)

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Steps in the measurement process

Example: Pressure

Variable to measure
(Bar)

Electric signal
("low quality")
(mV)

Electric signal
("high quality")

Monitoring

Sensor → Transducer → Conditioner Transmitter → Monitoring

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Basic concepts

Measurement Process

Conclusions

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Steps in the measurement process

Example: Pressure

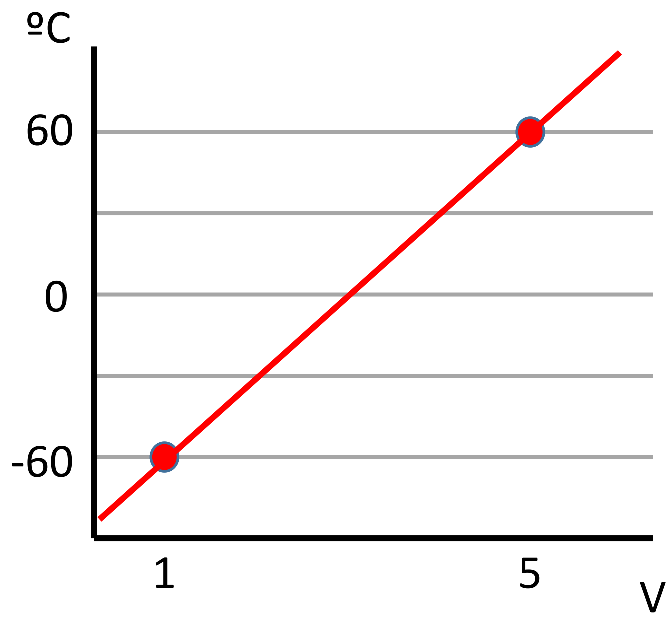
Variable to measure (Bar) → **Sensor** → **Transducer** → Electric signal ("low quality") (mV) → **Conditioner Transmitter** → Electric signal ("high quality") → **Monitoring** / **Controller Data logger**

Steps of a measurement process

Calibration: is defined as the set of operations that aim to determine the relationship between the values indicated by a measuring instrument and the true values of the measured variable.

Temperature sensor:
Output: 1-5V
Range: -60 to 60ºC

Linear



Y = m X + b

$$m = \frac{\Delta Y}{\Delta X} = \frac{60 - (-60)}{5 - 1} = 30$$

B= Y - m X= 60 – 30 · 5 = -90

Y= 30 X - 90

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Steps of a measurement process

Calibration: is defined as the set of operations that aim to determine the relationship between the values indicated by a measuring instrument and the true values of the measured variable.

Soil water content

$$Y = 4.3\ 10^{-6}\ X^{3} - 5.5\ 10^{-4}\ X^{2} + 2.92\ 10^{-2}\ X - 5.3\ 10^{-2}$$

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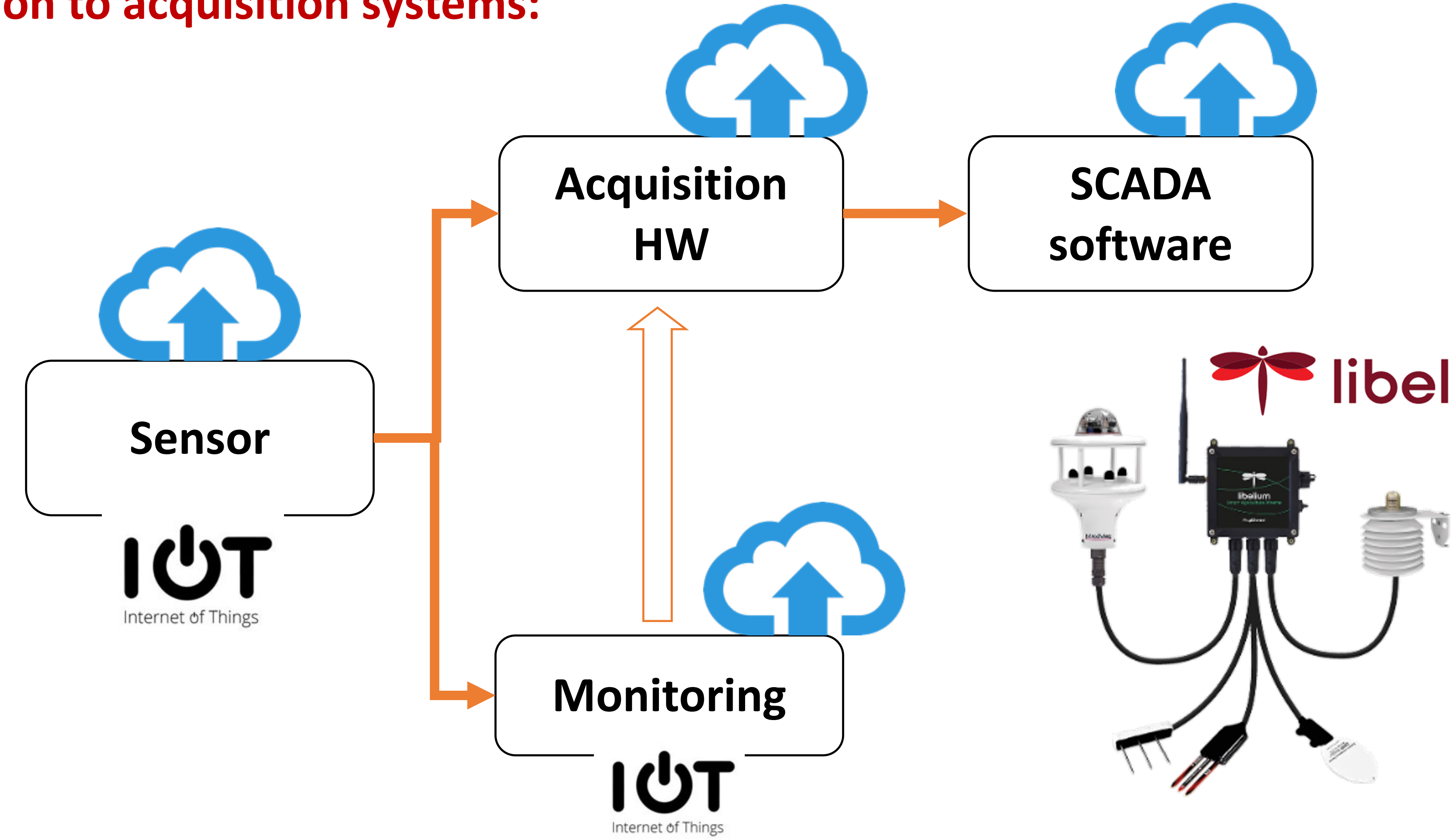
New trends

Connection to acquisition systems:



Operation conditions

Operating temperature range	-20...+60 °C
Storage temperature range	-30...+70 °C
Operating humidity range	0...100 %RH non-condensing

CAMPBELL SCIENTIFIC
WHEN MEASUREMENTS MATTER

Temperature
Relative humidity
CO_2

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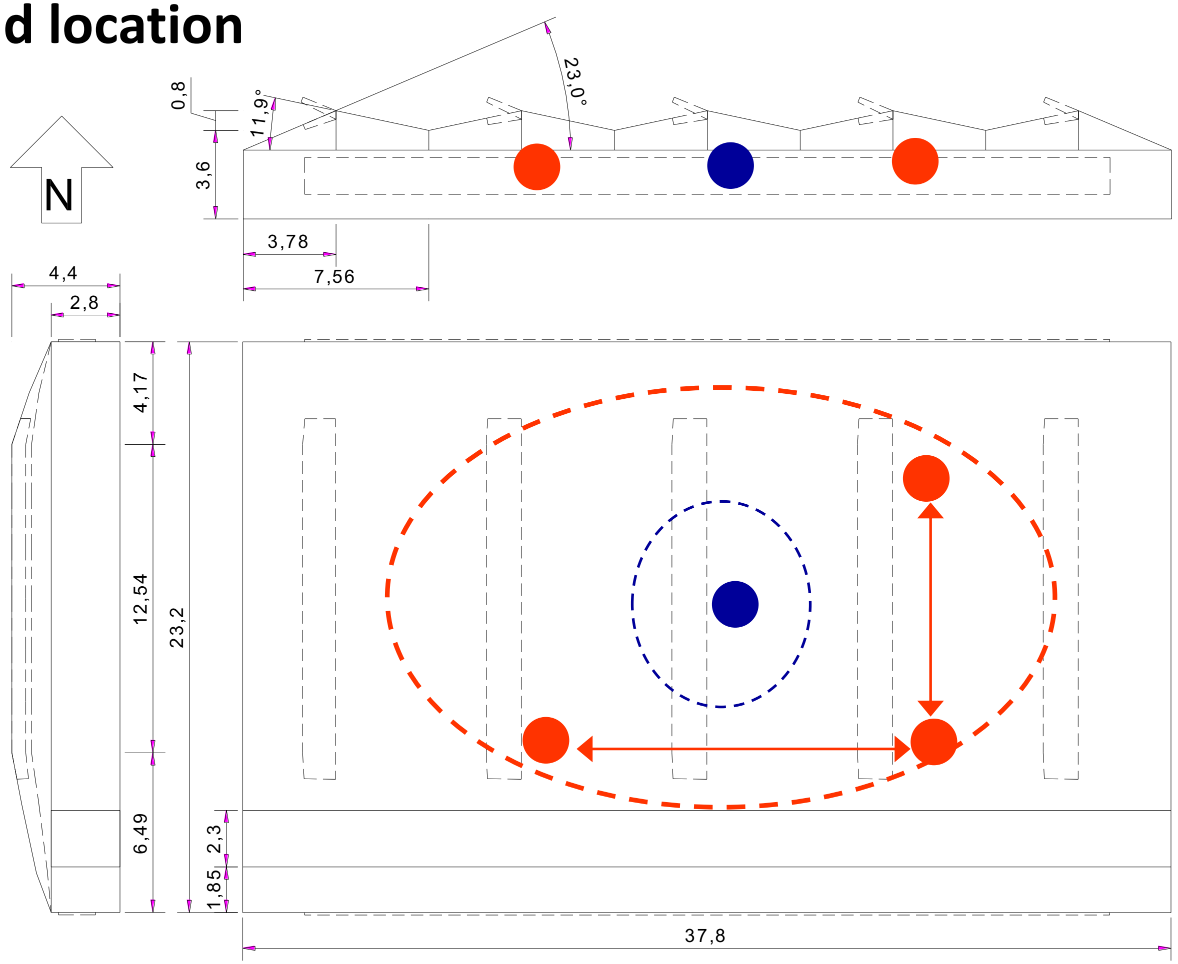
Basic concepts

Measurement Process

Conclusions

Operation conditions

Number and location



Standard
(one in the middle)

Ideal
(Three in "L")

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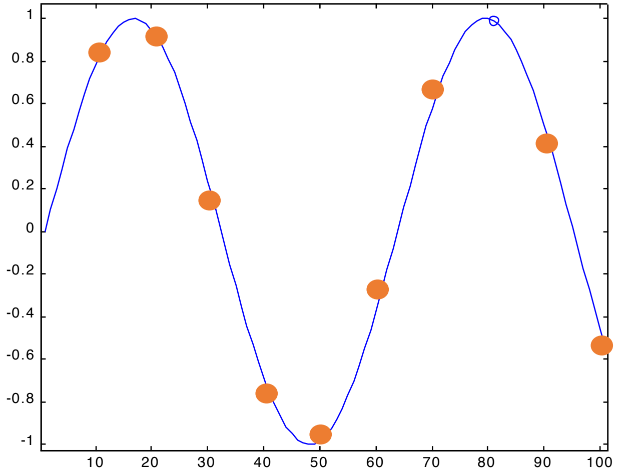
Operation conditions

Data adquisition

CAMPBELL SCIENTIFIC
WHEN MEASUREMENTS MATTER



Sampling theorem of Nyquist-Shannon

The sampling frequency of a continuous signal must be at least twice the highest frequency.

Conclusions

- To control a variable, it is necessary to measure it with sensors.
- The sensor converts a variable into an electrical signal.
- To work with this signal, other systems are required such as a signal conditioner or a transmitter.
- One must be aware of the sensor features to ensure that they can withstand the extreme conditions possible in a plastic greenhouse.
- A price/performance ratio has to be decided upon before choosing and buying an acquisition system.

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Module 6: CLIMATE MANAGEMENT

Lesson 6.1: Measurement and modelling

Theme 6.1.2: Climate sensors

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Internal climate sensors

External climate sensors

Best Practices

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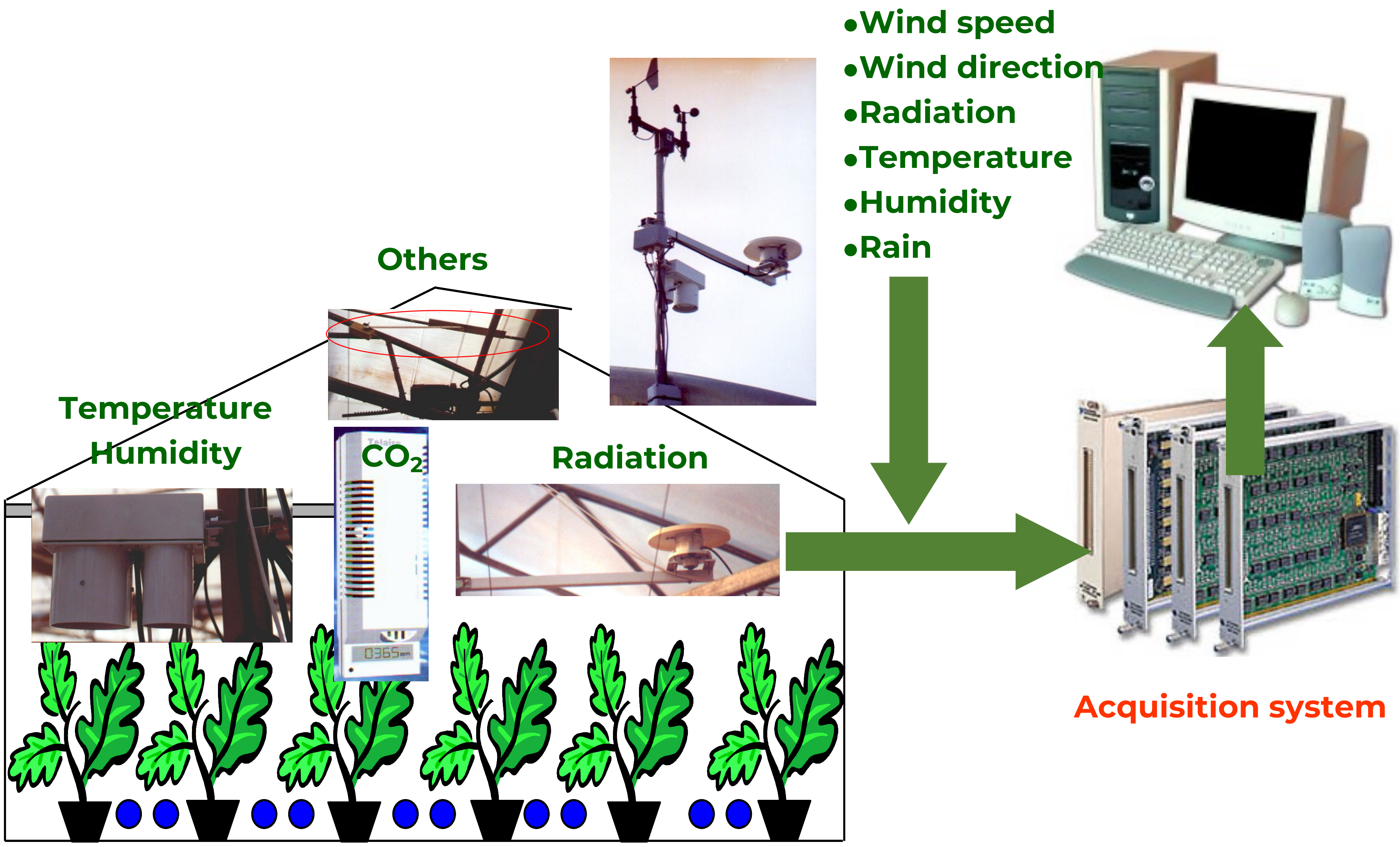
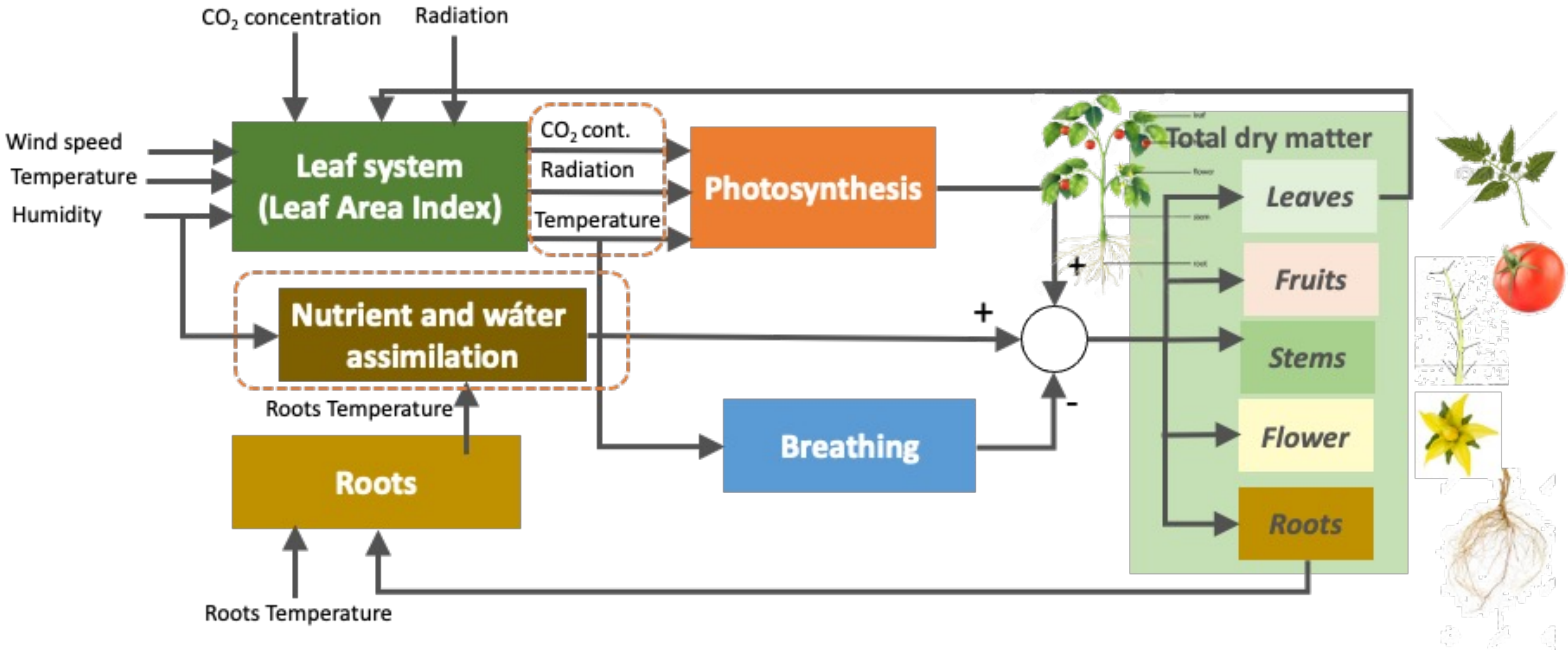
Greenhouse climate management



Internal climate sensors



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Temperature sensors

Humidity sensors

Radiation sensors

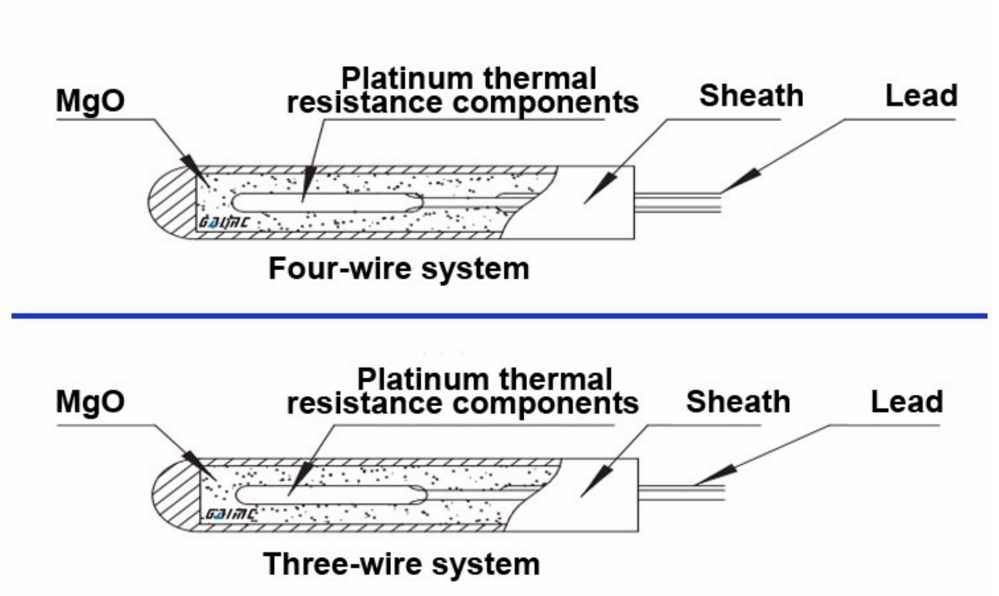
Conclusions

Temperature sensors

Metal Resistors.

The resistance of a metal changes when its temperature varies

$$R(T) = R_o \cdot (1 + A \cdot T + B \cdot T^2 + C.T^3 + \ldots)$$



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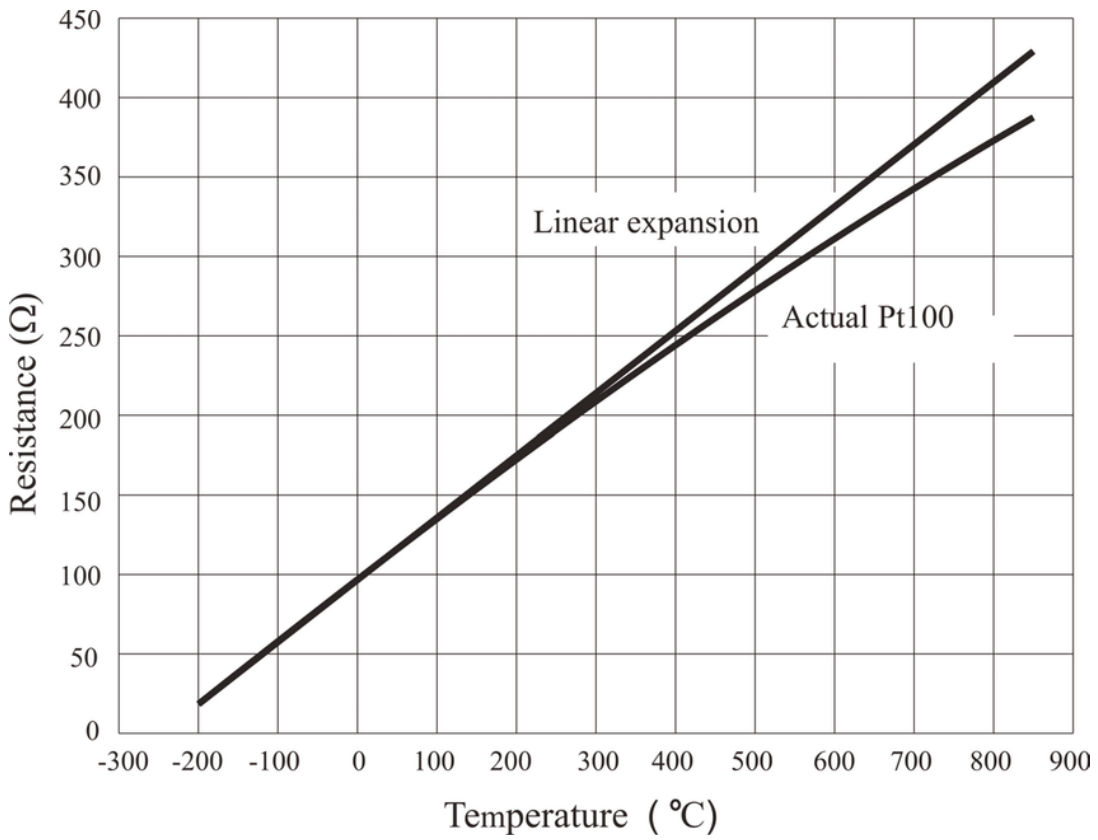
Temperature sensors

Metal Resistors. Pt-100

The resistance of a metal changes linearly when its temperature varies



Temperature sensors

Metal Resistors. Pt-100

HANNA instruments

Sonda Pt100 de 4 hilos de Aire/Gas

- **Características**

- Rango: -30 a 350ºC
- Precisión: +/- 0,25 ºC, +/- 3% de lectura
- Mango de la Sonda: Carilon
- Sonda: Acero Inoxidable AISI 316
- T. de Respuesta: 30 segundos

Thies CLIMA

Order No.	Technical Data	
2.1265.20.000	Operating voltage	12 V AC/ 6 VA or
		24 V AC/ 11 VA or
		24 V DC/ 8 W
2.1265.22.000	Operating voltage	12 V DC/ 4 W
	Measuring element	Pt 100 acc. to IEC 751
	Accuracy	± 0,15 K
	Ventilation	6 m/s
	Electr. connection	4-lead circuit
	Connection	plug
	Dimension	Ø 160 x 435 mm
	Weight	3,5 kg

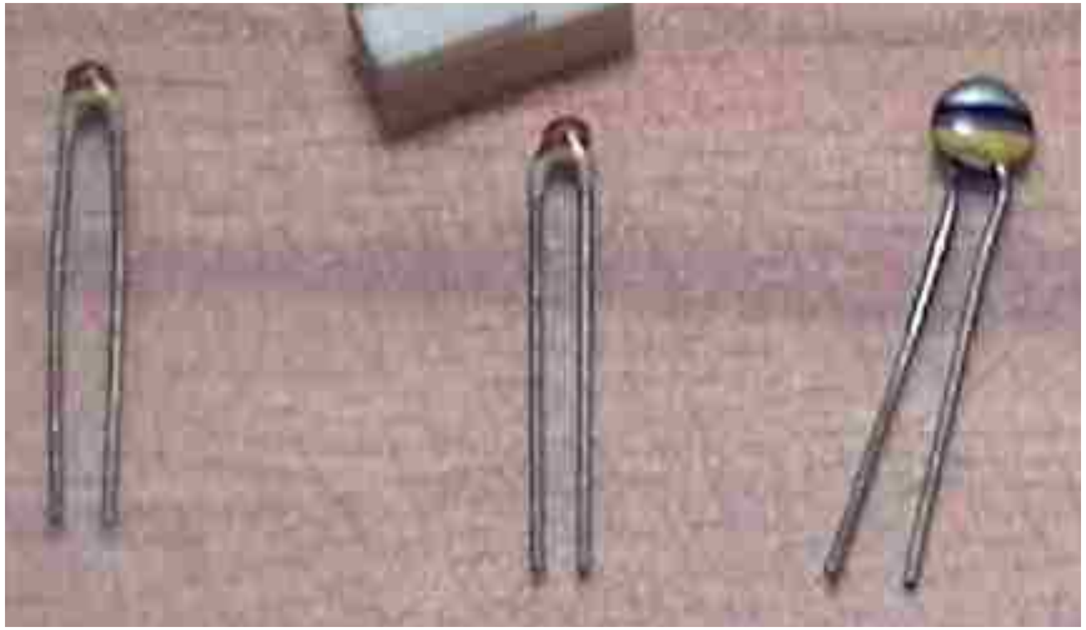
Temperature sensors

Thermistors

The resistance of a semiconductor changes when its temperature varies:

- PTC. Increases resistance when temperature increases
- NTC. Decreases resistance when temperature increases

$$\frac{1}{T} = A + B \ln R + C (\ln R)^3$$



Temperature sensors

There are two kinds of temperature sensors:

Metal Resistors. Pt-100

The resistance of a metal changes when its temperature varies

Thermistors

The resistance of a semiconductor changes when its temperature varies

Feature	Metallic	Thermistor
Stability	Good	Reasonable
Repeatability	Good	Reasonable
Accuracy	Low	High
Temperature Range	High	Low
Price	Medium/High	Low

Humidity sensors

Hygrometers

Human hair, some animal tissues or some synthetic materials present different elasticity with moisture, so if we measurements the length, we have a humidity sensor

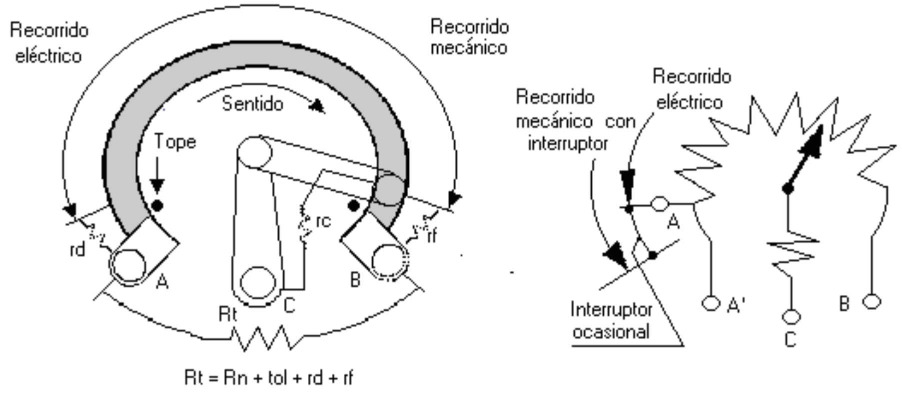
Transforms moisture into displacement

Humidity sensors

Hygrometers

Human hair, some animal tissues or some synthetic materials present different elasticity with moisture, so if we measurements the length, we have a humidity sensor

Transforms moisture into electrical measurement by means of potentiometers (variable electrical resistance used to generate a variable voltage)



Humidity sensors

Psychrometers

It Is based on the temperature measurement of the dry thermometer and the wet thermometer (from a distilled water tank)

↓

Transforms moisture into electrical measurement by

two temperature sensors:

- One to measure dry (air) temperature
- Other to measure the humid temperature (wet bulb)

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Humidity sensors

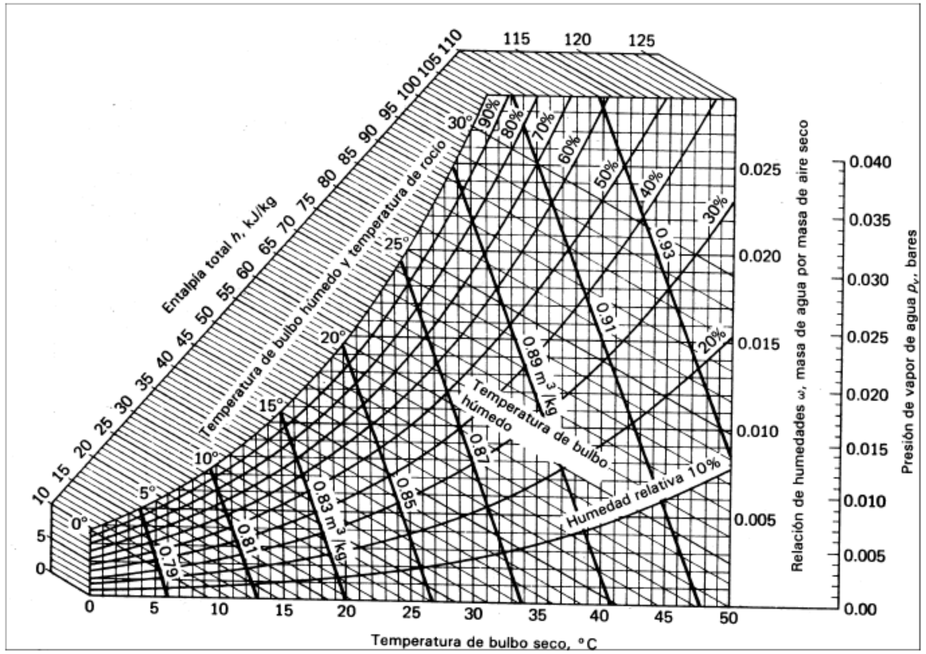
Psychrometers

It Is based on the temperature measurement of the dry thermometer and the wet thermometer (from a distilled water tank)

Diferencia entre el termómetro seco y el húmedo

°C (1)	0		1		2		3		4		5		6		7		8		9		°C (2)
18	100	95	90	85	80	76	71	65	61	57	53	49	45	40	37	32	28	24	20	16	
19	100	95	90	85	81	77	72	66	62	58	55	51	47	42	38	34	30	27	23	20	
20	100	95	90	85	82	77	72	68	63	60	56	52	48	44	42	37	32	29	25	22	
21	100	95	91	86	82	78	73	69	64	60	57	53	49	45	43	38	34	31	27	24	
22	100	95	91	87	82	78	74	70	65	62	57	54	51	47	45	40	37	33	29	26	
23	100	95	91	87	83	79	75	70	66	63	58	56	52	48	46	41	38	35	31	28	
24	100	95	92	87	83	79	76	71	67	63	60	57	53	50	48	43	39	37	33	30	
25	100	96	92	87	83	80	76	72	68	63	61	58	54	51	48	45	41	38	35	32	
26	100	96	92	87	84	80	77	73	69	65	62	58	56	52	48	46	42	39	37	33	
27	100	96	92	88	84	81	77	73	70	66	62	59	57	53	50	47	43	39	37	33	
28	100	96	92	88	84	81	78	74	70	67	63	60	57	54	51	48	45	42	38	36	
29	100	96	92	88	85	82	78	75	71	67	64	61	58	55	52	49	46	43	40	38	
30	100	96	93	89	85	82	78	75	72	68	65	62	58	56	53	50	47	44	42	39	
31	100	96	93	89	86	82	79	76	73	69	66	63	60	57	54	51	48	45	43	40	
32	100	96	93	89	86	83	79	76	73	70	67	63	60	58	55	52	49	47	43	41	

(1)Temp. termómetro seco; (2) Humedad relativa en %



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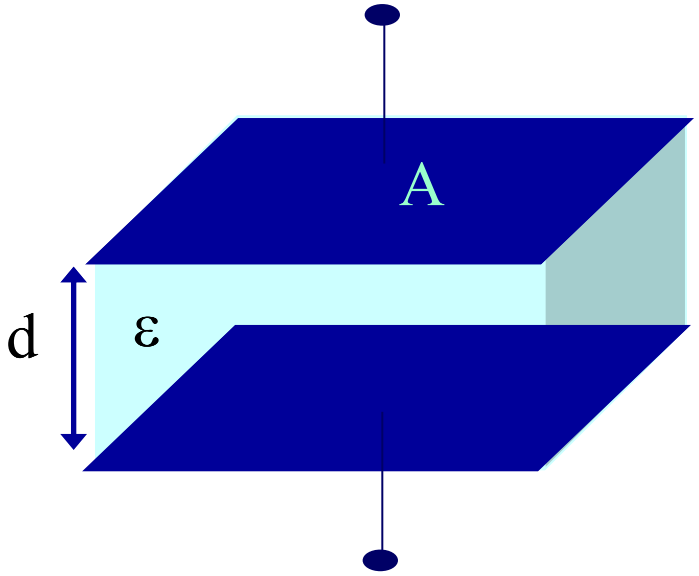
Humidity sensors

Capacitive Sensors

The capacity of the capacitors can vary depending on the humidity of the Dielétrico

Transforms moisture into electrical magnitude



$$C = \varepsilon \frac{A}{d}$$

The Dielectric constant

It is humidity function

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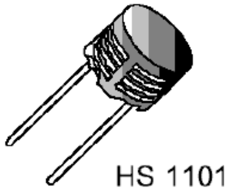
Humidity sensors

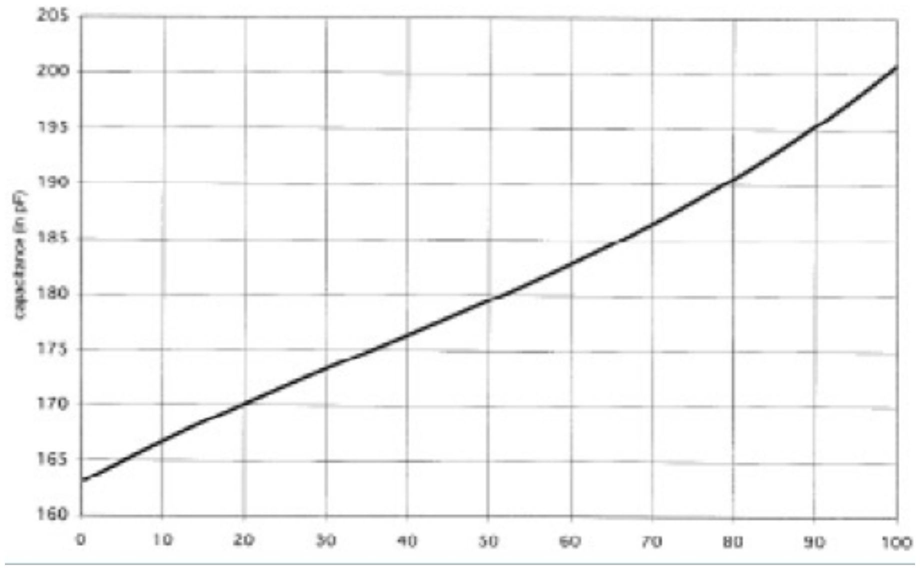
Capacitive Sensors

The capacity of the capacitors can vary depending on the humidity of the Dielétrico

Transforms moisture into electrical magnitude

HUMIREL





Humidity sensors

There are three kinds of humidity sensors:

Hygrometers

Human hair, some animal tissues, and some synthetic materials vary their elasticity based on the moisture level - so if we measure the length, we have a humidity sensor.

Psychrometers

These sensors measure the temperatures of a dry thermometer and a wet thermometer (from a distilled water tank), so really they are two temperature sensors.

Capacitive sensors

The capacity of the capacitors can vary depending on the environmental humidity

Sensor	Price	Accuracy	Comments
Hygrometer	Medium	± 2 %	Affected by low humidity
Psychrometer	High	± 1.5 ºC	Good performance from 0 to 100%
Capacitive sensor	Low	± 1.5 %	Malfunctions when saturated

Temperature sensors

Humidity sensors

Radiation sensors

Conclusions

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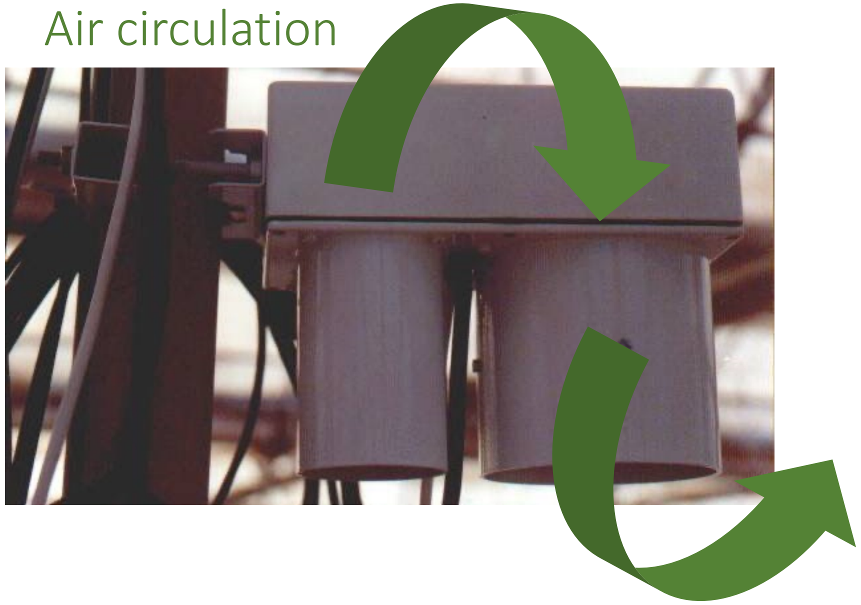
Best Practices

Temperature and humidity

- Use direct radiation protection

Thies CLIMA

- Use forced ventilation with the sensors located into the greenhouse



- Accuracy: 0.3 ºC and 3 % for humidity

HUMIDITY (%RH) \ TEMPERATURE (°C)	0	10	20	30	40	50	60	70	80
100	± 0.03	± 0.05	± 0.09	± 0.16	± 0.27	± 0.44	± 0.69	± 1.33	± 2.38
90	± 0.03	± 0.05	± 0.09	± 0.15	± 0.26	± 0.42	± 0.66	± 1.26	± 2.24
80	± 0.03	± 0.04	± 0.07	± 0.12	± 0.21	± 0.34	± 0.63	± 1.20	± 2.10
70	± 0.02	± 0.04	± 0.07	± 0.12	± 0.20	± 0.32	± 0.50	± 1.13	± 1.96
60	± 0.02	± 0.03	± 0.06	± 0.11	± 0.18	± 0.30	± 0.47	± 1.06	± 1.82
50	± 0.02	± 0.03	± 0.06	± 0.10	± 0.17	± 0.28	± 0.45	± 0.99	± 1.68
40	± 0.02	± 0.03	± 0.05	± 0.09	± 0.16	± 0.26	± 0.42	± 0.76	± 1.54
30	± 0.01	± 0.03	± 0.05	± 0.09	± 0.15	± 0.24	± 0.39	± 0.69	± 1.40
20	± 0.01	± 0.02	± 0.04	± 0.08	± 0.14	± 0.23	± 0.36	± 0.62	± 1.26
10	± 0.01	± 0.02	± 0.04	± 0.07	± 0.12	± 0.21	± 0.33	± 0.55	± 1.13
0	± 0.01	± 0.02	± 0.04	± 0.06	± 0.11	± 0.19	± 0.30	± 0.48	± 0.99

METER

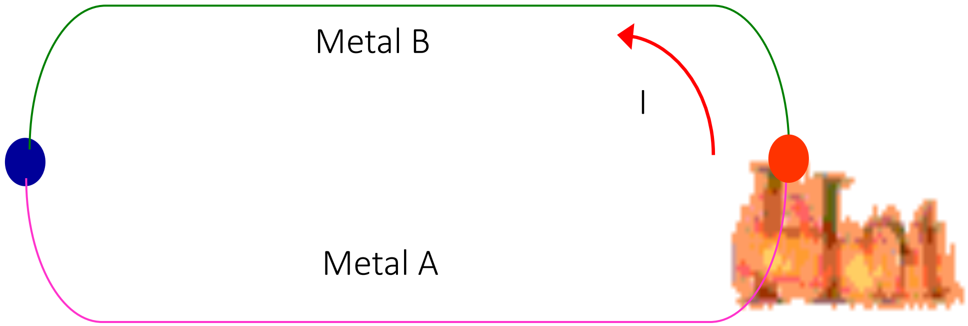
ATMOS 14
GEN 2

Radiation sensors

Based on thermo-elements

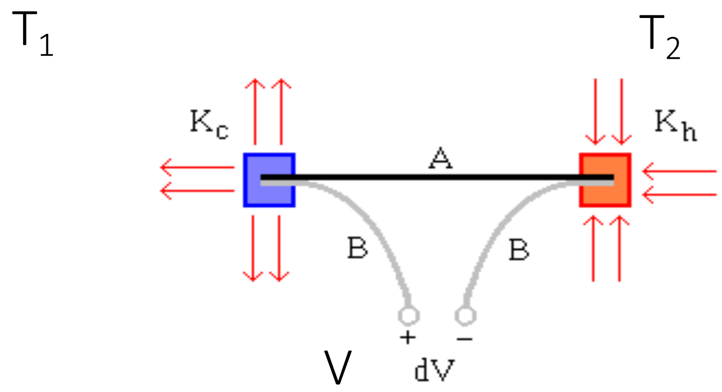
The resistance of a metal changes when its temperature varies

If There are two metals (A and B) welded at their ends and there is a temperature difference between them, an electric current will circulate



By the Seebeck effect a thermocouple (current generator) arises:

$$V = C_{Seebeck} \cdot (T_2 - T_1)$$



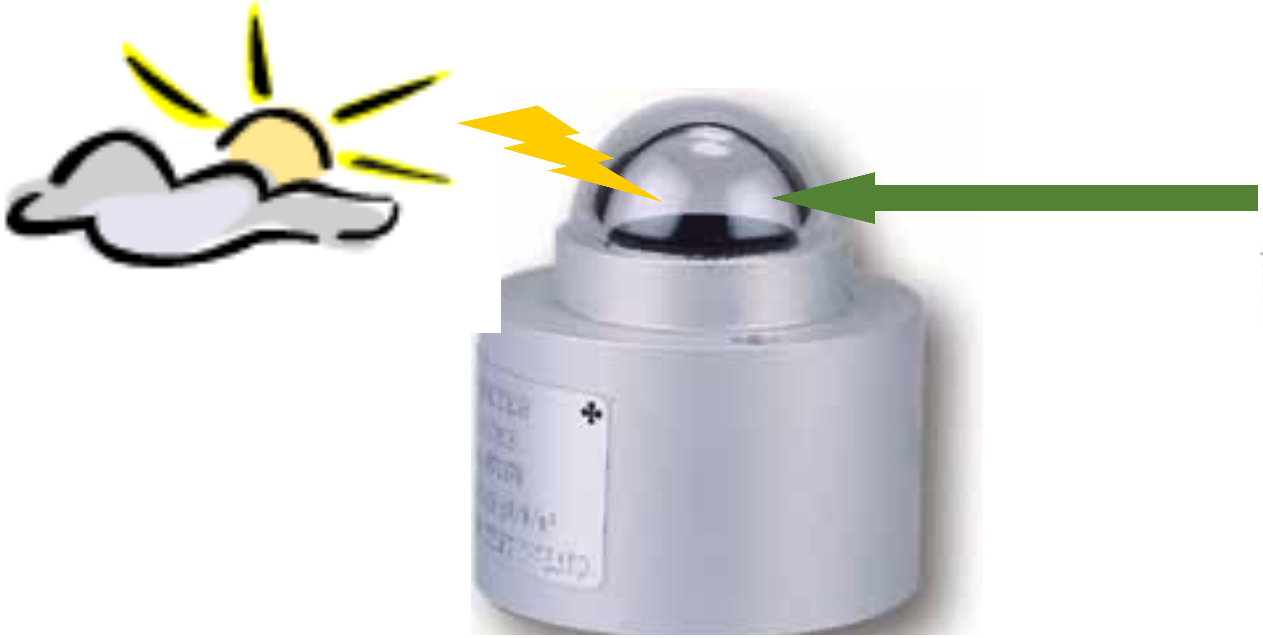
Radiation sensors

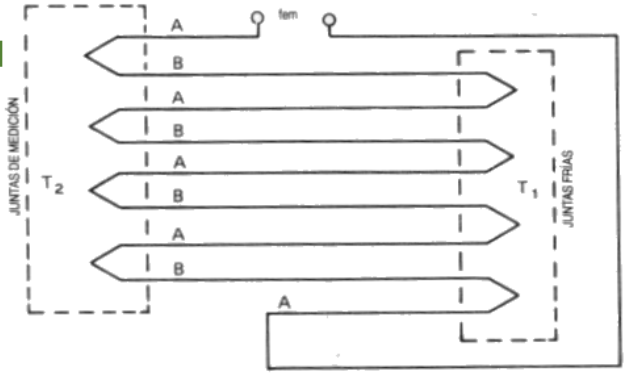
Based on thermo-elements

The resistance of a metal changes when its temperature varies

The radiation Is measured indirectly from the temperature.

The Total Radiation pyrometer is formed by a pyrex, silicon or calcium fluoride lens that concentrates the radiation of the hot object into a thermopile made up of several small sized thermocouples and assembled in series. The radiation is focused directly affecting the hot joints of the thermocouples.





Temperature sensors

Humidity sensors

Radiation sensors

Conclusions

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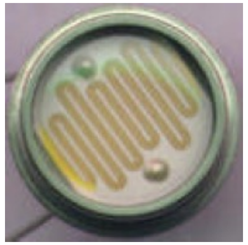
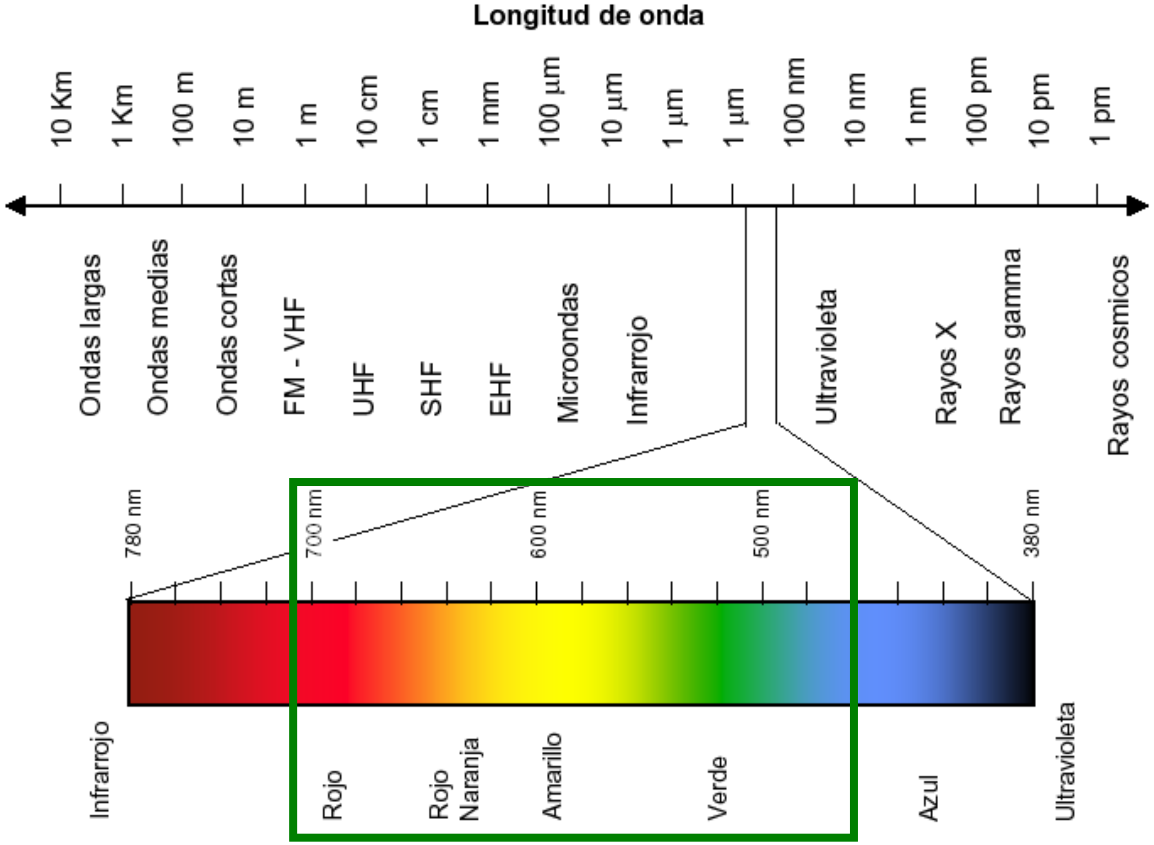
Radiation sensors



Based on photocells

They are semiconductors whose resistance varies according to the incident radiation.

PAR radiation
(Photosintetically Active Radiation)



Radiation sensors

There are two kinds of radiation sensors:

Based on thermo-elements

The resistance of a metal changes when its temperature varies

Based on photocells

The resistance of a semiconductor changes when its temperature varies

Sensor	Price	Comments
Thermo-elements	High	• All Spectrum (from UV to IR) • Slow
Photocells	Medium	• Very Fast • Too Much Noise

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Temperature sensors

Humidity sensors

Radiation sensors

Conclusions

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Best Practices

Radiation

- Shadows should be avoided

- they must be well levelled.

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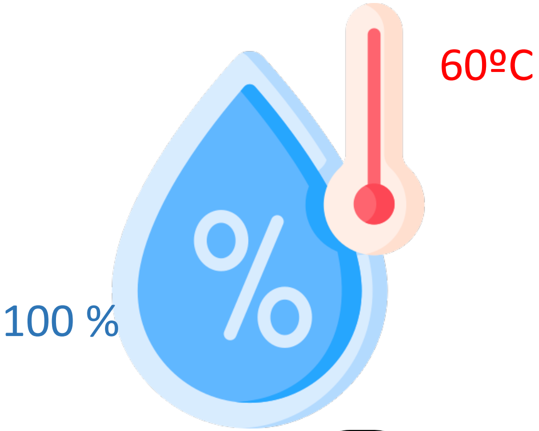
Best Practices

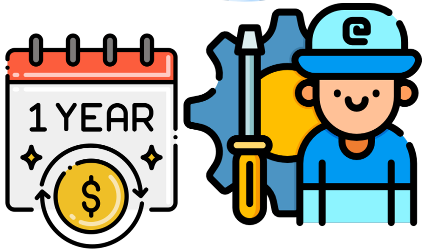
- All the electronic systems must be protected according to international IP67 standard (UNE EN 60529:2018)

- Operation temperature: +60 ºC.



- Operation relative humidity: 100% with condensation.

- Maintenance of the measuring systems must be carried out at least once a year or when indicated by the manufacturer.



- It is advisable to place the external climate station one metre above the ridge of the greenhouse

Conclusions

- To control the greenhouse climate, one must measure the temperature, relative humidity, global or PAR radiation, and CO_2.
- The most suitable sensor should be selected according to the application for which it is needed.
- It is advisable to follow the best practices advice so that the measurement system performs well.
- All parts of the measuring system must be properly maintained.

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Module 6: CLIMATE MANAGEMENT

Lesson 6.1: Measurement and modelling

Theme 6.1.2: Climate sensors

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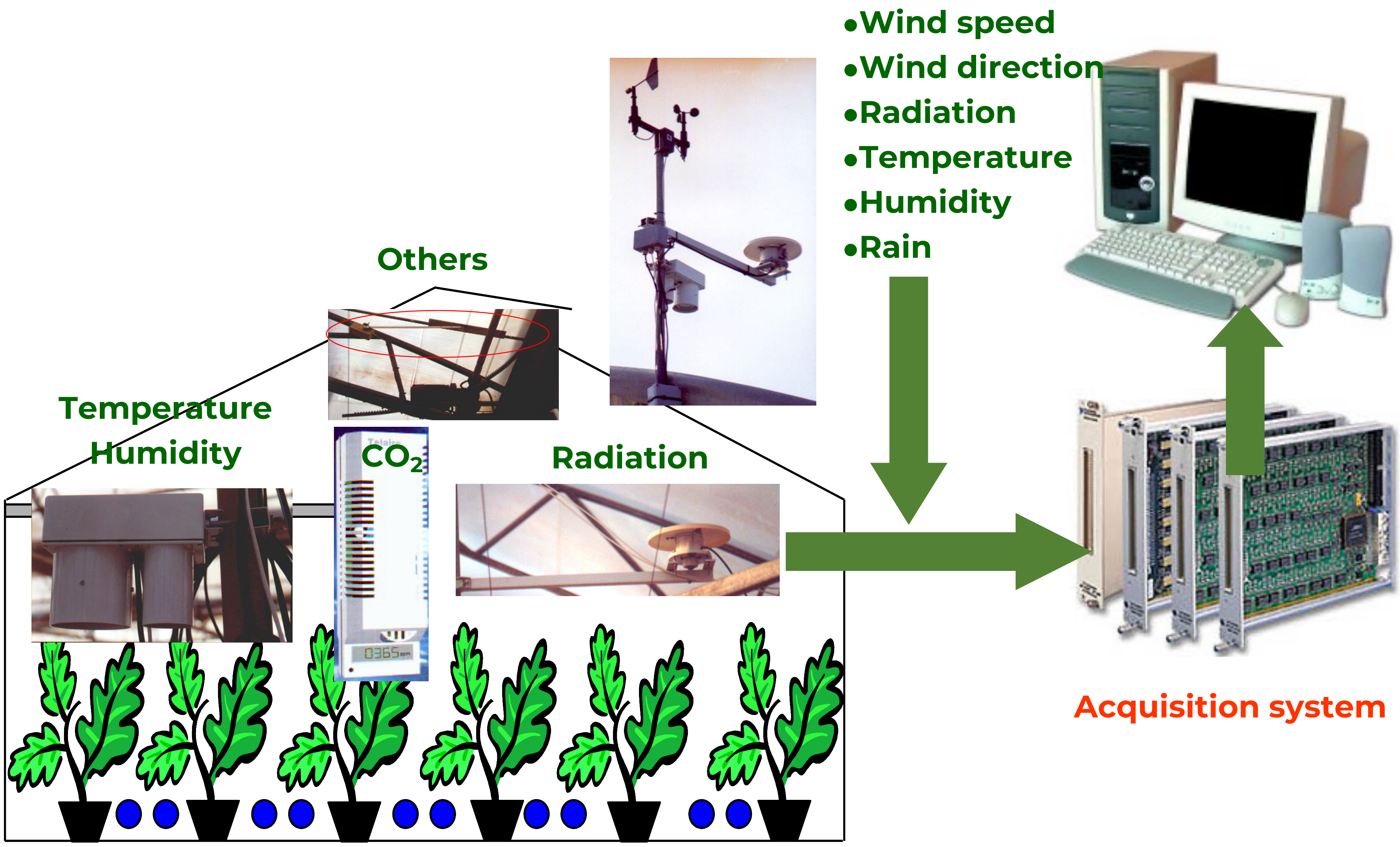
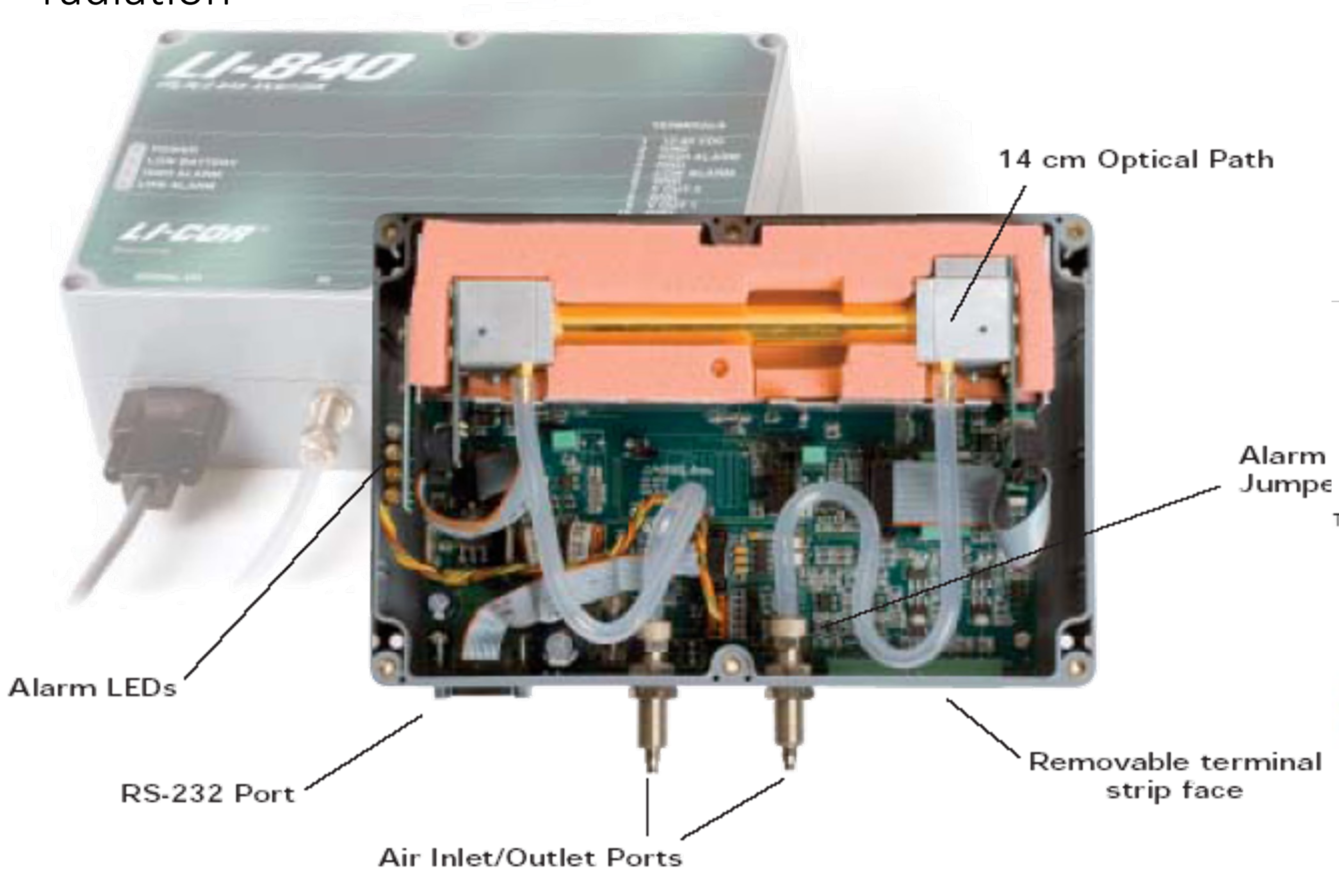
Greenhouse climate management



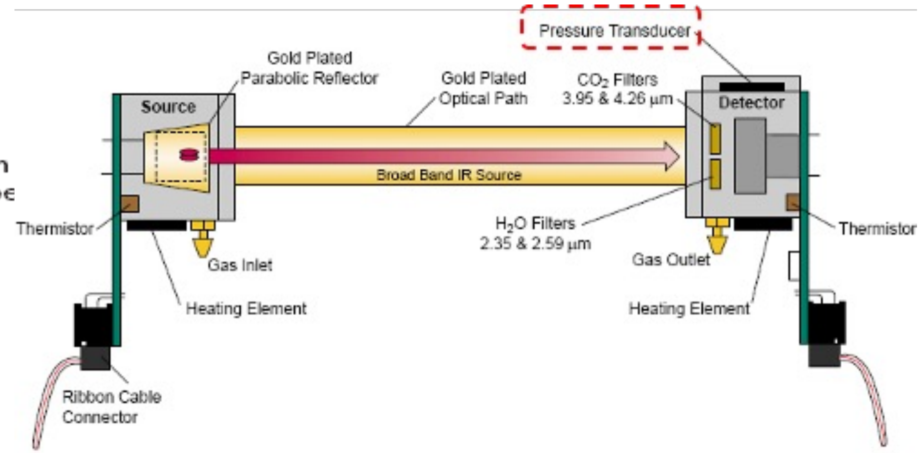
CO_2 concentration sensors

NDIR technique (Non-Dispersive Infrared Radiation)

These are based on the properties of the gas molecules (such as CO_2) to absorb the infrared radiation



LI-COR



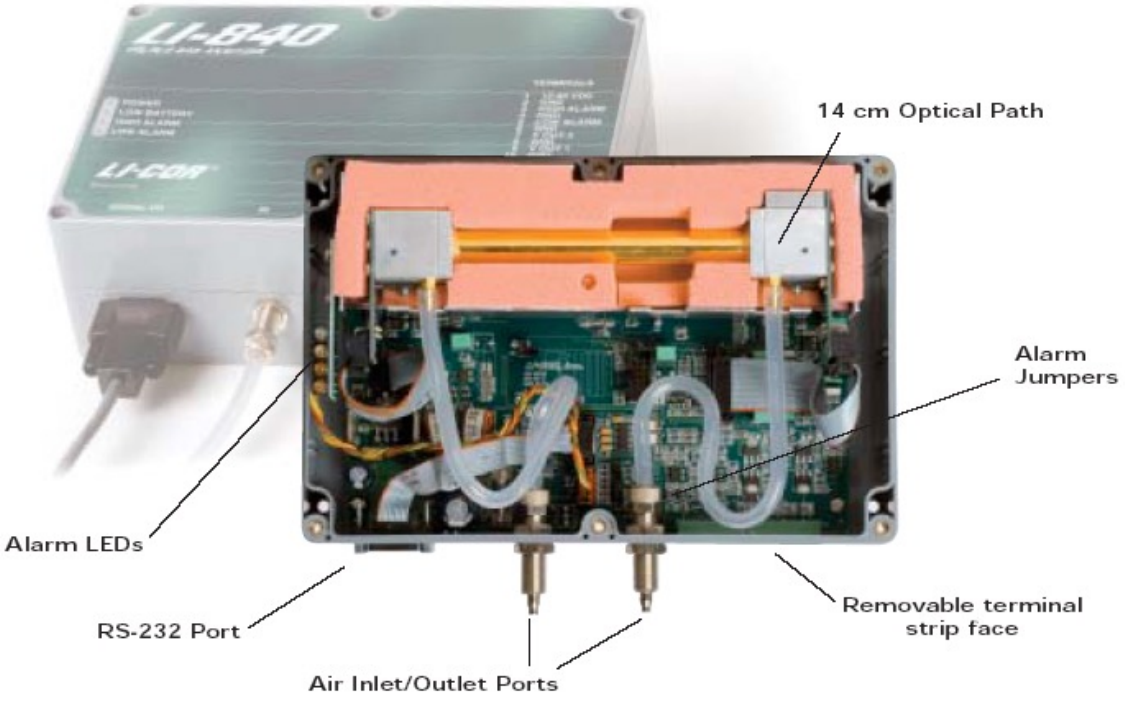
CO_2 concentration sensors

NDIR technique (Non-Dispersive Infrared Radiation)

They are based on the properties of the gas molecules (as CO_2) to absorb the infrared radiation

LI-COR®

As a gas detector a pressure sensor is usually used because when the sample is absorbed the Infrared radiation, it modifies the pressure of the chamber



Wind speed and direction

Mechanical sensor: Anemometer and vane

Converts wind velocity into a mechanical variable and then into an electrical variable

Spinning speed

Axis Position

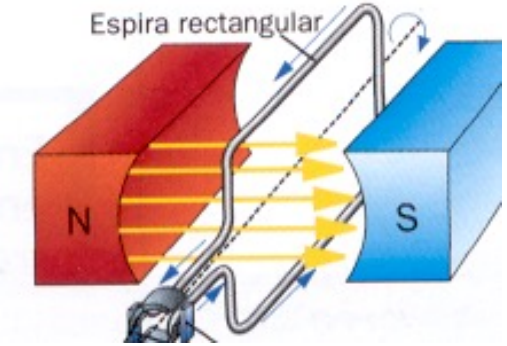
An electrical signal is required!

Wind speed and direction

Mechanical sensor: Anemometer

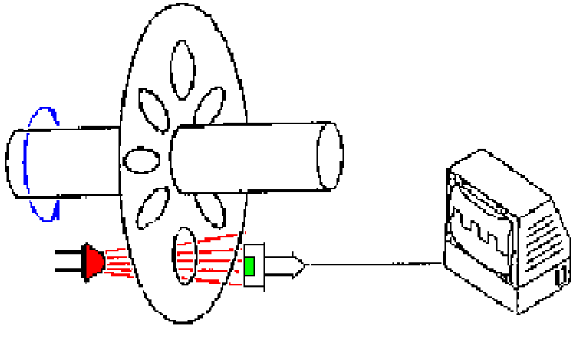
Convert wind velocity into a mechanical variable and this into a electrical variable

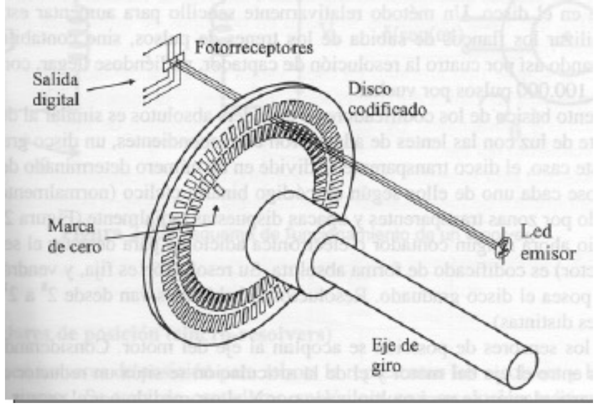
Dynamo. Produces Direct current



Spinning Speed

Incremental Encoder. Produces a series of pulses





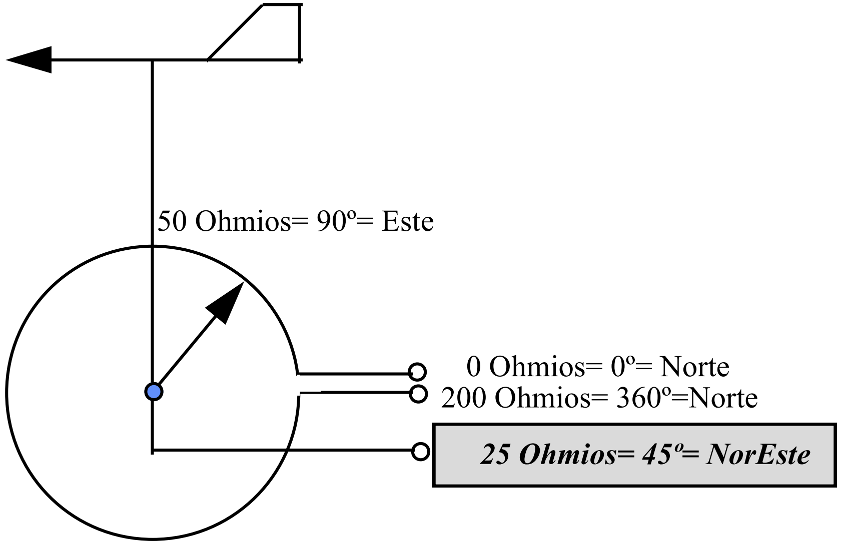
Wind speed and direction

Mechanical sensor: Vane

Turn the wind direction into a mechanical variable

Axis Position

Potentiometric



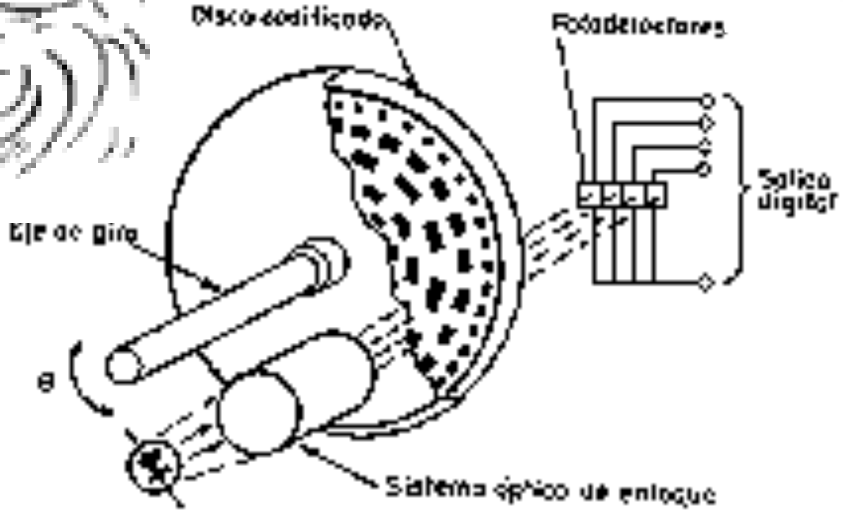
Wind speed and direction

Mechanical sensor: Vane

Turn the wind direction into a mechanical variable

Axis Position

Absolute encoders

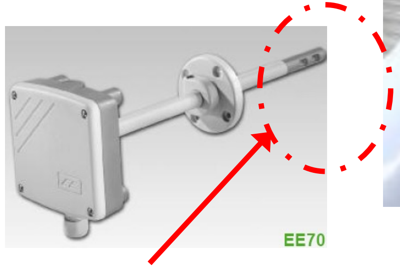


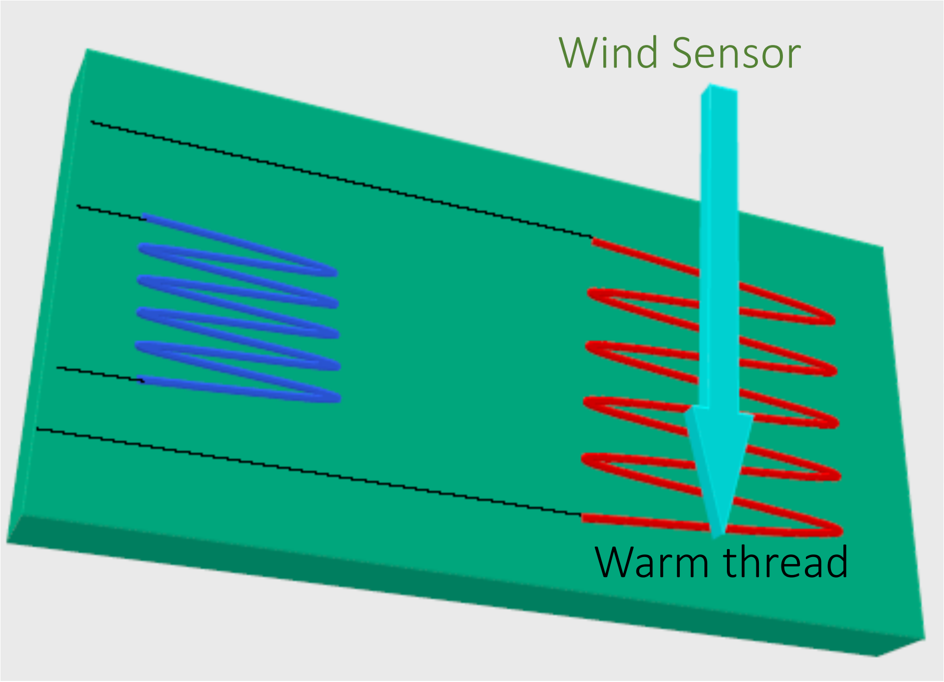
Wind speed and direction

Thermal sensor: Anemometer and vane

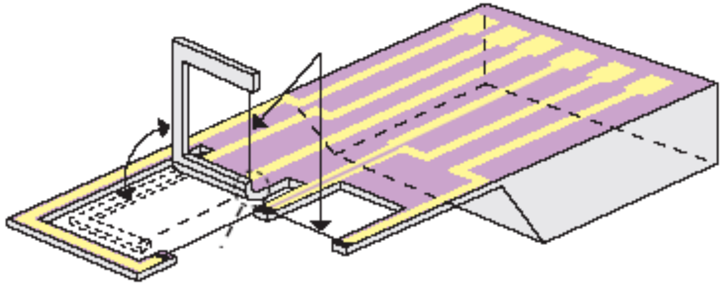
Convert wind speed into temperature measurement

Platinum or tungsten Yarn





They make up the measurements on two axes

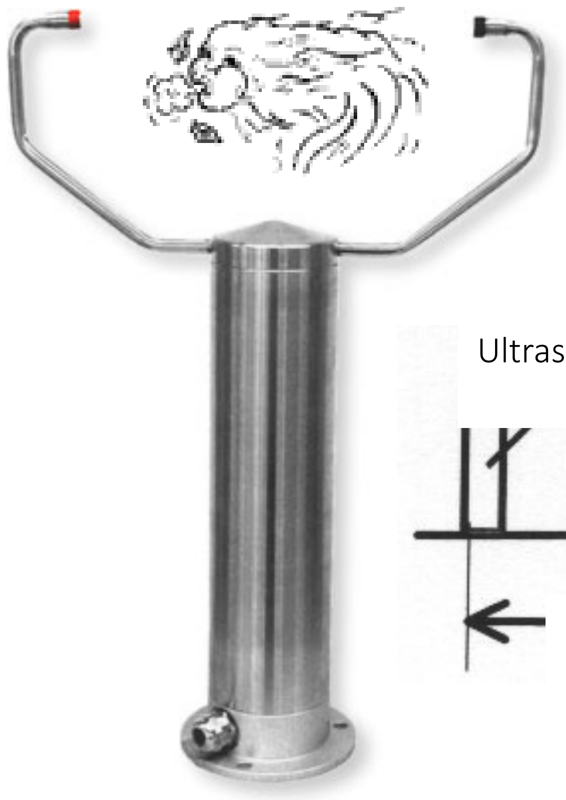


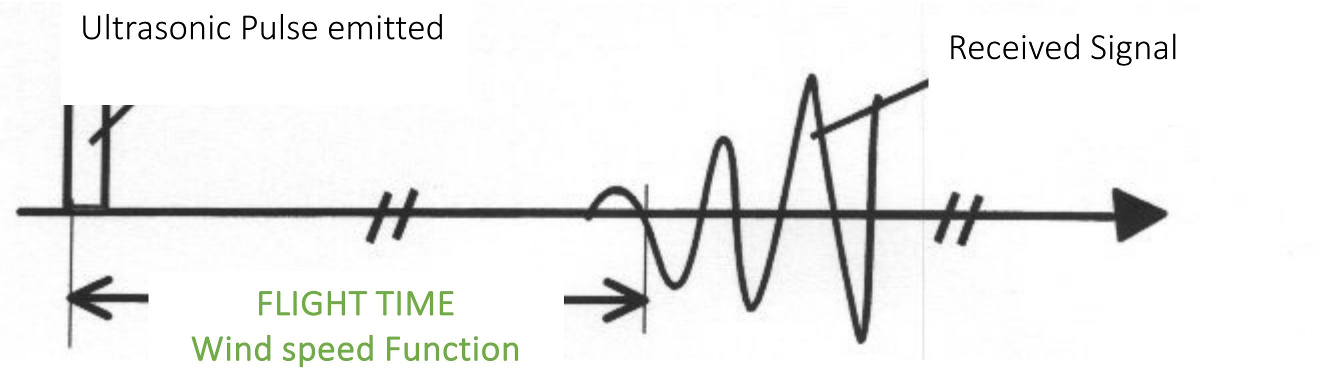
Wind speed an direction

Ultrasonic Sensors: Anemometer and vane

Turn wind speed into time

Turn wind speed into time



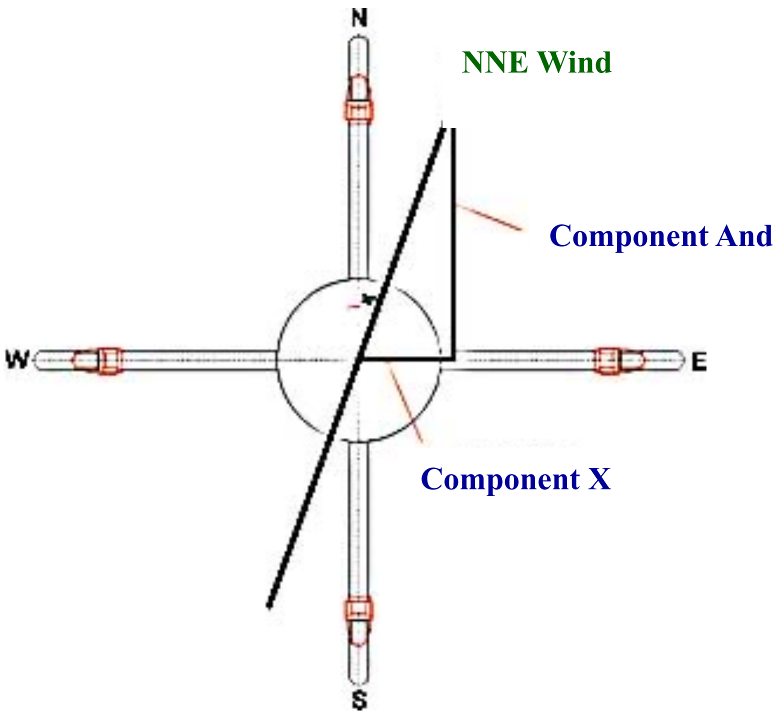


Wind speed and direction

Ultrasonic Sensors: Anemometer and vane

Convert wind speed into temperature measurement

They make up the measurements on two axes



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Wind speed and direction

There are three kinds of wind sensors:

Mechanical

Convert wind velocity into a mechanical variable

Thermal

Convert wind speed into temperature measurement

Ultrasonic

Turn wind speed into time

Sensor	Price	Accuracy	Comments
Mechanical	Low	Low	Simple, need a minimum to start moving
Ultrasonic	High	High	Complex, sensitive to Orientation, measures very low wind speeds
Thermal	Middle	Middle	Very Fast , sensitive to orientation, it Is affected by thermal drifts, measures very low wind speeds

Internal climate sensors

External climate sensors

Best Practices

Conclusions

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Rain detector

This functions by producing a short circuit in an electronic system

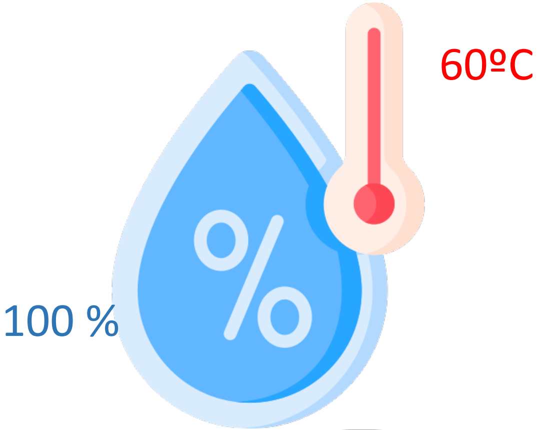
nesa®

They must be heated to avoid water detection via condensation, such as from the dew at sunrise.

Best Practices

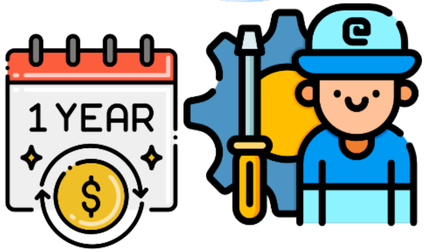
- All the electronic systems must be protected according to international standard IP67 (UNE EN 60529:2018)

- Operating temperature: +60 ºC.



- Operating relative humidity: 100% with condensation.

- Maintenance of the measuring systems must be carried out at least once a year or when indicated by the manufacturer.



- It is advisable to place the external climate station one metre above the greenhouse ridge.

Conclusions

- CO_2 variable is an important variable that should be measure to know about the growth conditions
- The external climate variables need to be measured.
- This measured are important for control and modelling purposes.
- The different technologies used to measure has influence in precision and price
- All parts of the measuring system must be properly maintained.

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Module 6:
CLIMATE MANAGEMENT

Lesson 6.1:
Measurement and Modelling

Theme 6.1.4:
Modelling Fundamentals

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Systems and models

Systems

A part of the real world in which interest is shown

Model

A simplified representation or abstraction of a real system, process or theory, in order to:

- Increase understanding.
- Make predictions.
- Design a control system.

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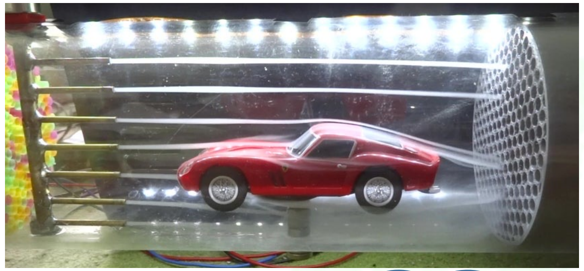
Types of models

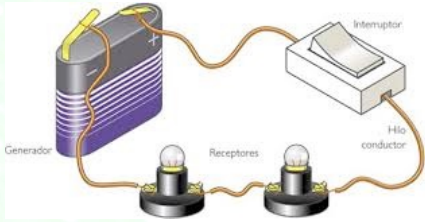


Physical models

They consist of the representation of physical systems described by measurable variables.

Mental models

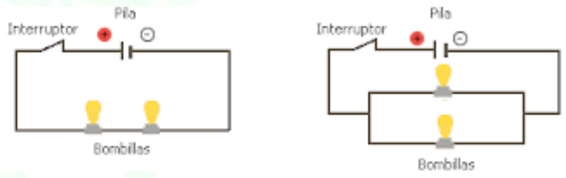
They are heuristic or intuitive processes that exist only in our minds..



Symbolic models

These models include symbols, together with logical and mathematical operations that can be used to formulate a solution to a problem.

- **Non-mathematical Symbols**



Systems & Models

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Types of models

Symbolic models

These models include symbols, together with logical and mathematical operations that can be used to formulate a solution to a problem.

Mathematical Symbols

Example: Greenhouse air temperature

$$\underbrace{c_{c-esp,a}\, c_{den,a} \frac{c_{vol,inv}}{c_{area,s}} \frac{dX_{t,a}}{dt}}_{\text{Air heat}} = \underbrace{c_{cv,cb} \frac{c_{area,cb}}{c_{area,s}} \left(X_{t,cb} - X_{t,a}\right)}_{\text{Cover}} + \underbrace{c_{cv,s} \left(X_{t,s} - X_{t,a}\right)}_{\text{Soil}} + \underbrace{2 V_{LAI}\, c_{cv,c-a} \left(X_{t,a} - X_{t,c}\right)}_{\text{Crop}} + \underbrace{c_{cv,cal} \frac{c_{area,cal}}{c_{area,s}} \left(X_{t,cal} - X_{t,a}\right)}_{\text{Heating}} -$$

$$V_{h,efec} = c_{w,v} \left[sin(\psi) - sin(\psi - U_{\alpha}) \right]$$

$$\underbrace{-\left\{ \frac{c_{largo,vent}\, c_{desc}\, P_{t,e}}{3 c_g \left(X_{t,a} - P_{t,e}\right)} \left[\left[V_{h,efec}\, c_g \frac{X_{t,a} - P_{t,e}}{P_{t,e}} + c_{viento} P_{v,e}^2 \right]^{3/2} - \left(c_{viento} P_{v,e}^2\right)^{3/2} \right] \right\} c_{den,a}\, c_{c-esp,a} \cdot \left(X_{t,a} - P_{t,e}\right)}_{\text{Natural Vents}} - \underbrace{c_{ren,hora} \frac{c_{vol,inv}}{c_{area,s}} c_{den,a} \left(X_{t.a} - P_{t,e}\right)}_{\text{Leaks}} +$$

$$\underbrace{+ V_{lt,vap-a} \frac{c_{cv,cb\text{-}a}}{c_{c\text{-}esp}} \frac{V_{area,cb}}{V_{area,s}} \left(V_{Hsat,cb} - X_{H,a}\right)}_{\text{Cover latent heat}} + \underbrace{V_{lt,vap} \frac{\frac{V_{cv,s}}{V_{c\text{-}esp}}}{1 + c_{rd,s} \frac{V_{cv,s}}{V_{d,vap} V_{c\text{-}esp}}} \left(V_{Hsat,s} - V_{Hab,aire}\right)}_{\text{Soil latent heat}} + \underbrace{\frac{V_{r,est} V_{rn,c} \frac{V_{pcsv}}{c_{pt}} + 2 c_{clv} V_{LAI} \left(V_{Hsat,a} - X_{H,a}\right)}{\left(1 + \frac{V_{pcsv}}{c_{pt}}\right) V_{r,est} + V_{r,cl}}}_{\text{Crop transpiration}}$$

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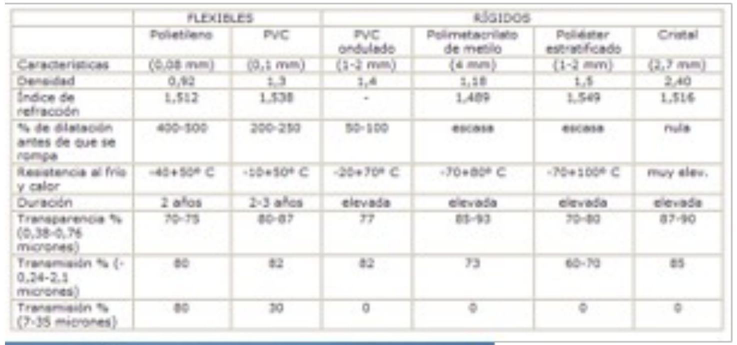
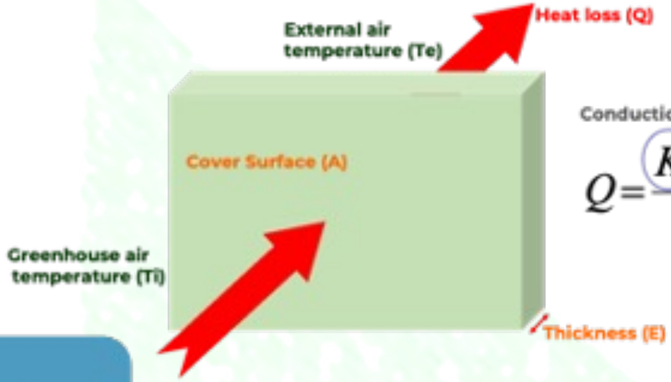
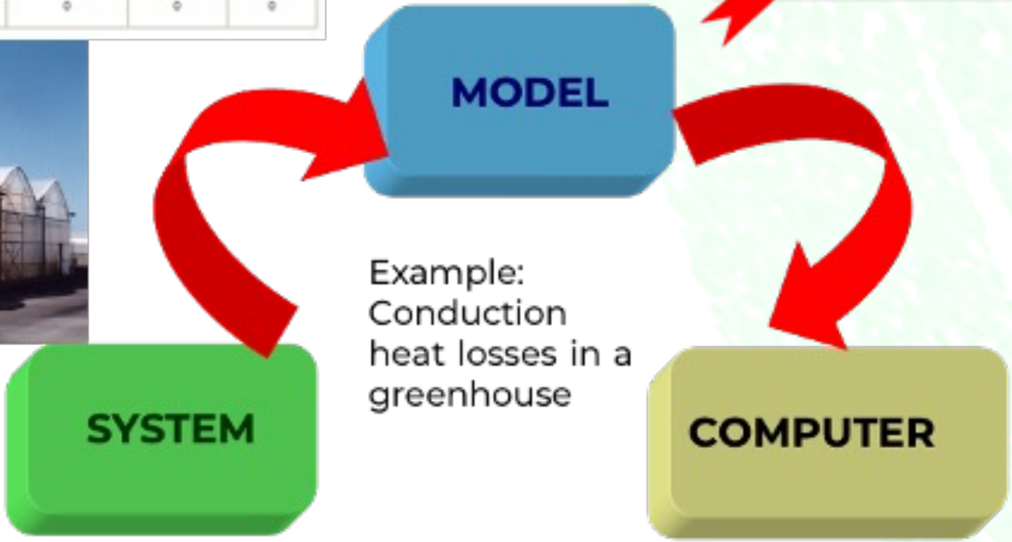
Systems, models & simulation



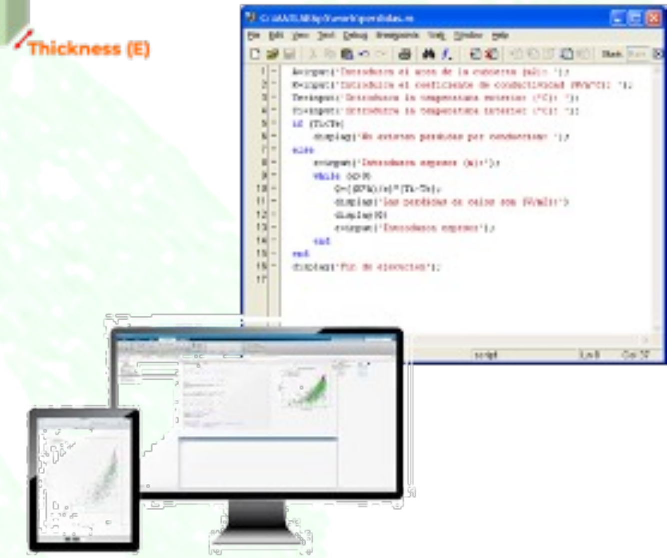
	FLEXIBLES		RÍGIDOS			
	Polietileno	PVC	PVC ondulado	Polimetacrilato de metilo	Poliéster estratificado	Cristal
Características	(0,08 mm)	(0,1 mm)	(1-2 mm)	(4 mm)	(1-2 mm)	(2,7 mm)
Densidad	0,92	1,3	1,4	1,18	1,5	2,40
Índice de refracción	1,512	1,538	-	1,489	1,549	1,516
% de dilatación antes de que se rompa	400-500	200-250	50-100	escasa	escasa	nula
Resistencia al frío y calor	-40+50º C	-10+50º C	-20+70º C	-70+80º C	-70+100º C	muy elev.
Duración	2 años	2-3 años	elevada	elevada	elevada	elevada
Transparencia % (0,38-0,76 micrones)	70-75	80-87	77	85-93	70-80	87-90
Transmisión % (-0,24-2,1 micrones)	80	82	82	73	60-70	85
Transmisión % (7-35 micrones)	80	30	0	0	0	0



$$Q = \frac{K \cdot A}{E}(T_i - T_e)$$



Example: Conduction heat losses in a greenhouse



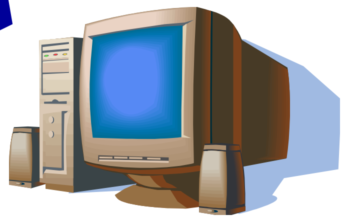
Model validation

A valid representation of reality is sought → Real data should be similar to those estimated by the model.

Example: Greenhouse air temperature

$$c_{c-esp,a}\, c_{den,a} \frac{c_{vol,inv}}{c_{area,s}} \frac{dX_{t,a}}{dt} = Q_{cv,cb-a} + Q_{cv,s-a} + Q_{cv,p-a} + Q_{cv,cal-a} - Q_{ven} - Q_{fugas} - Q_{lt,cb} - Q_{lt,s} - Q_{lt,c}$$

Implementation



Estimated Temperature

Measured Temperature

Estimated temperature ≅ Measured temperature

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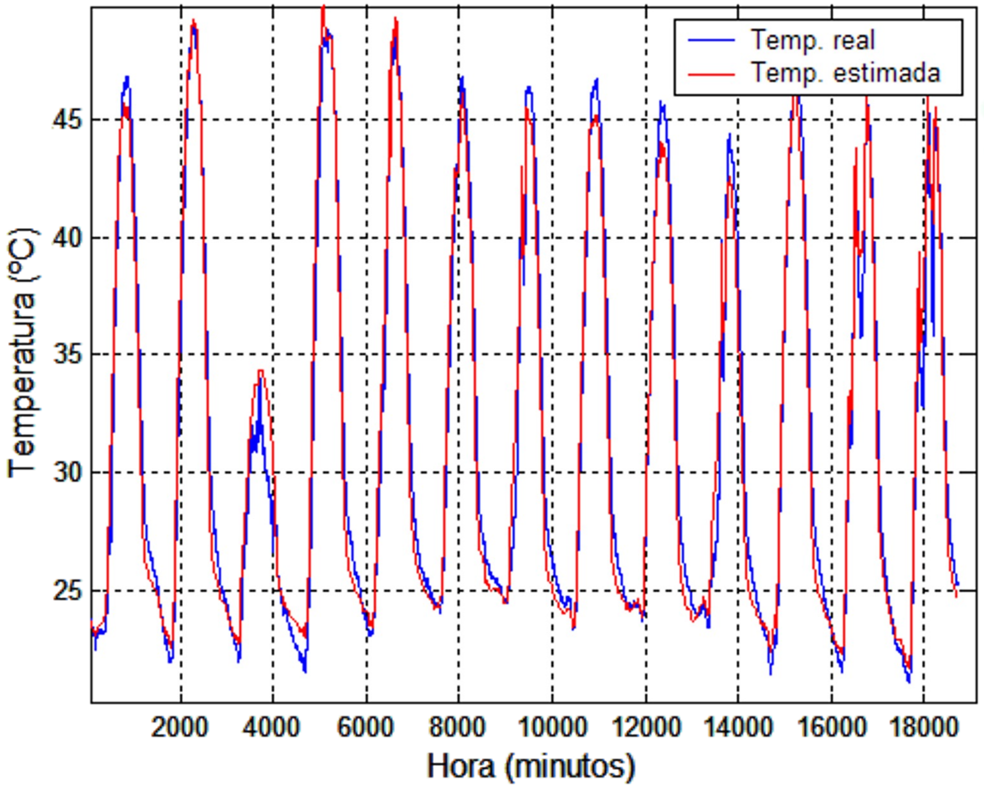
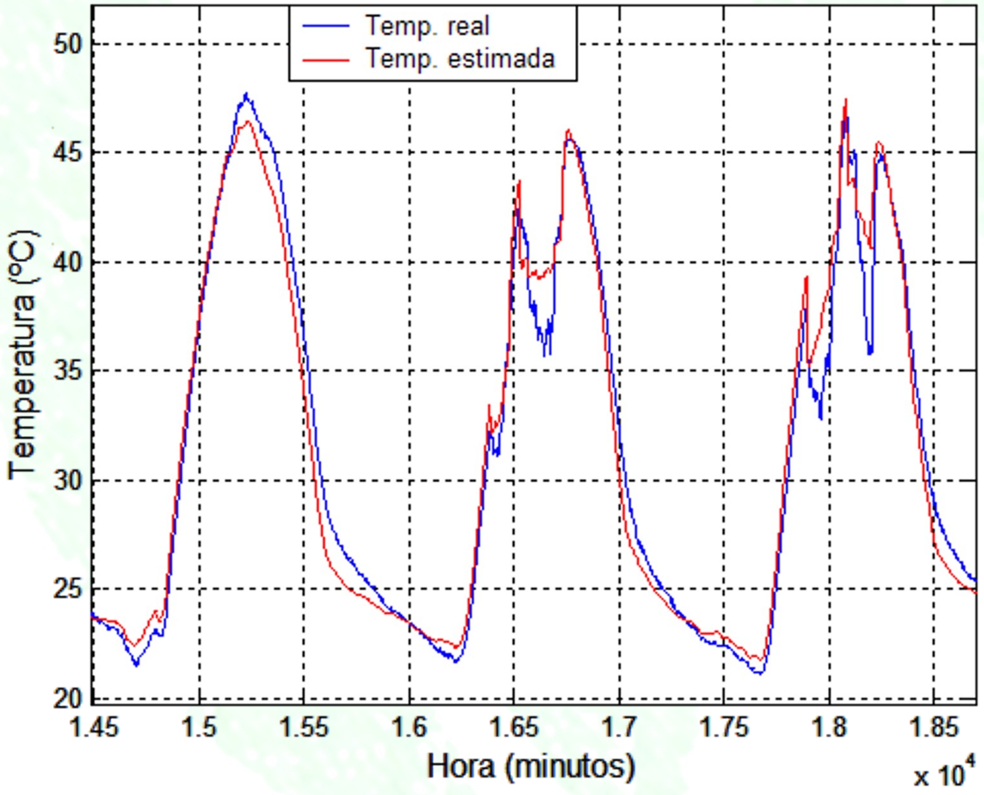
Model validation

Actual data should be similar to those estimated by the model.





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Systems & Models

Model calibration & validation

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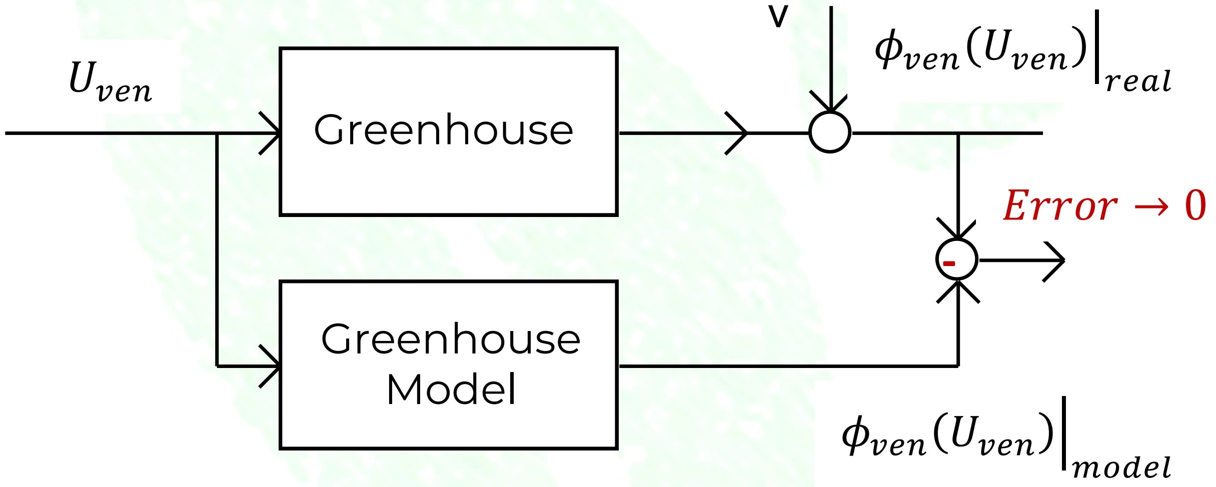
Model calibration

The models usually contain parameters whose values are unknown.

$$\phi_{ven}(U_{ven}) = \alpha U_{ven}^{\beta}$$

A process of identification of these parameters and validation of the models themselves is generally required.



Systems & Models

Model calibration & validation

Use cases

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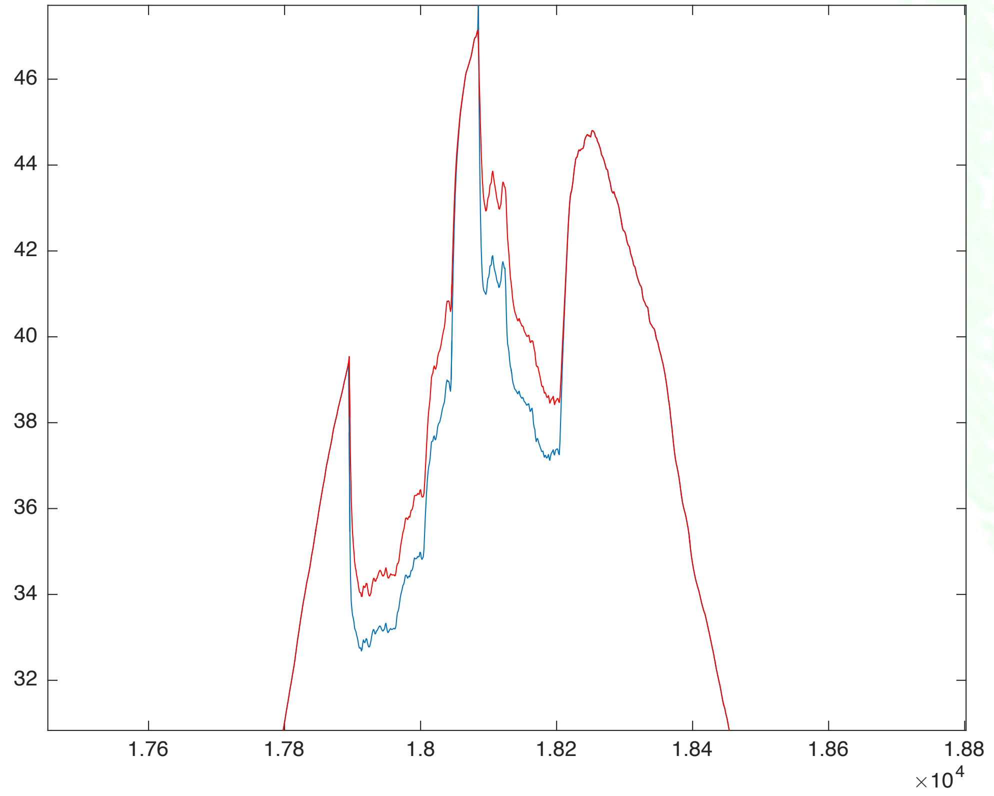
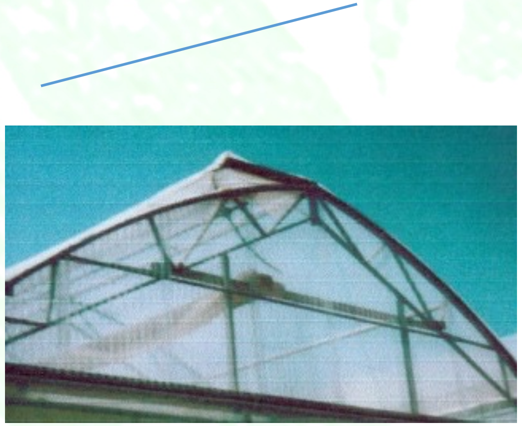
Use cases

Greenhouse structure design or actuator sizing

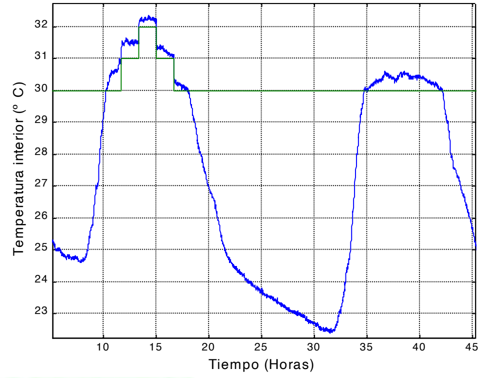




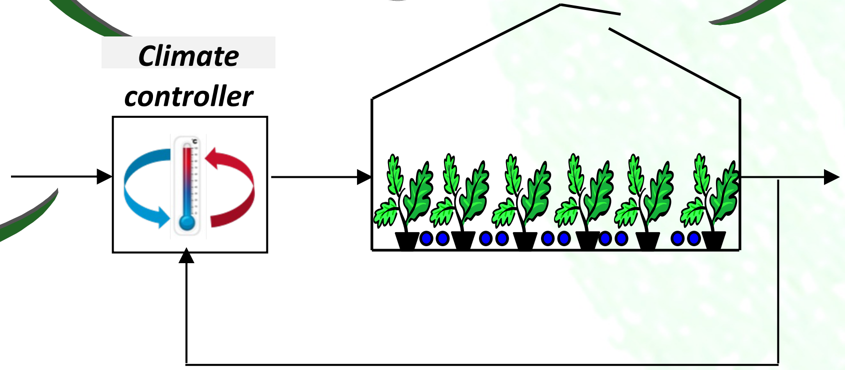
Use cases

Climate controller design

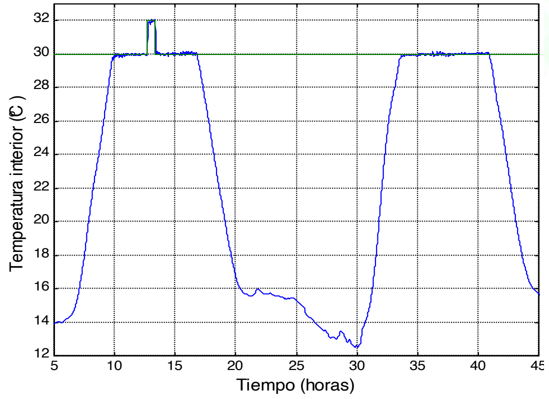
Adaptative control



Gain Scheduling control



Robust Control



Predictive control

Feedforward control

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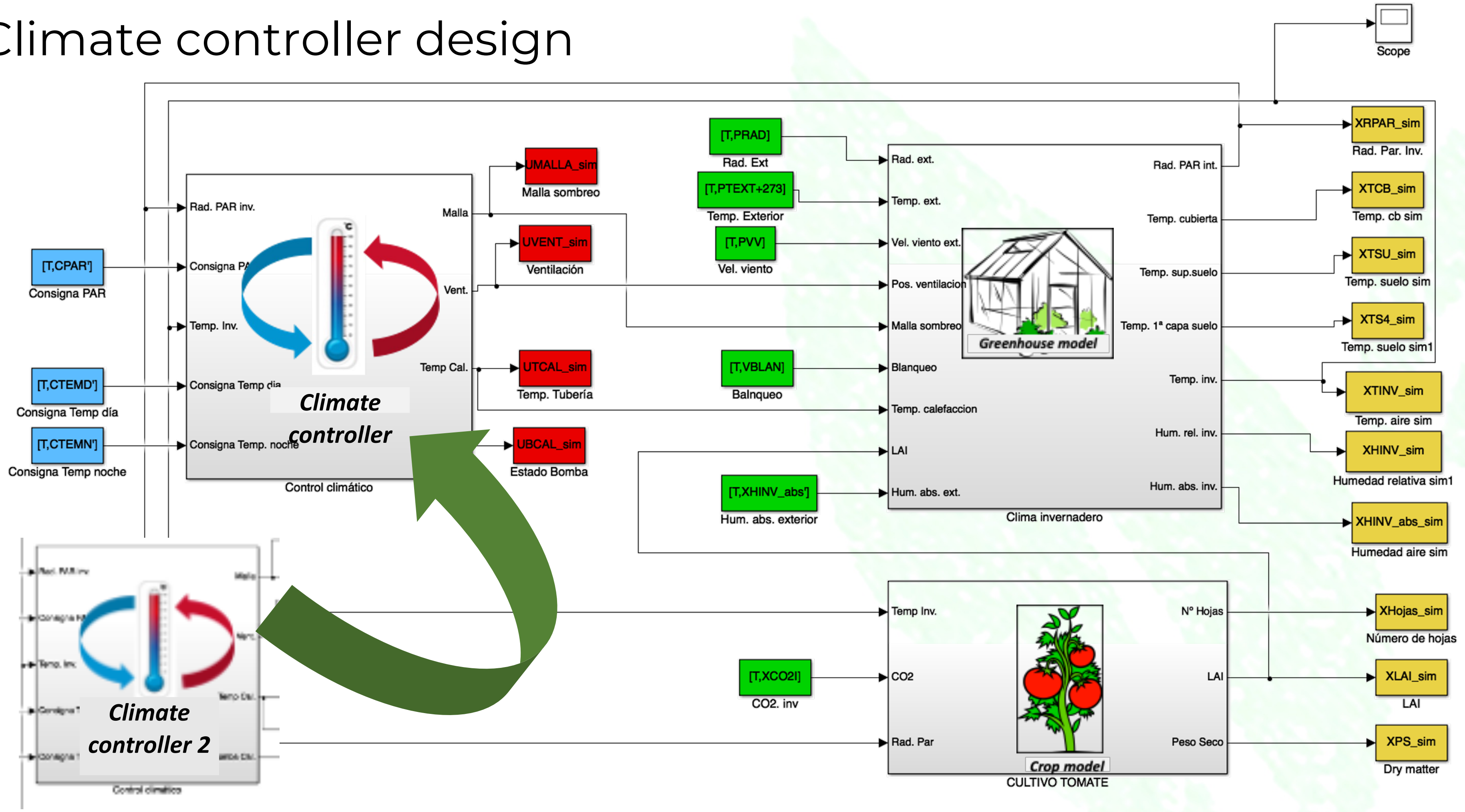
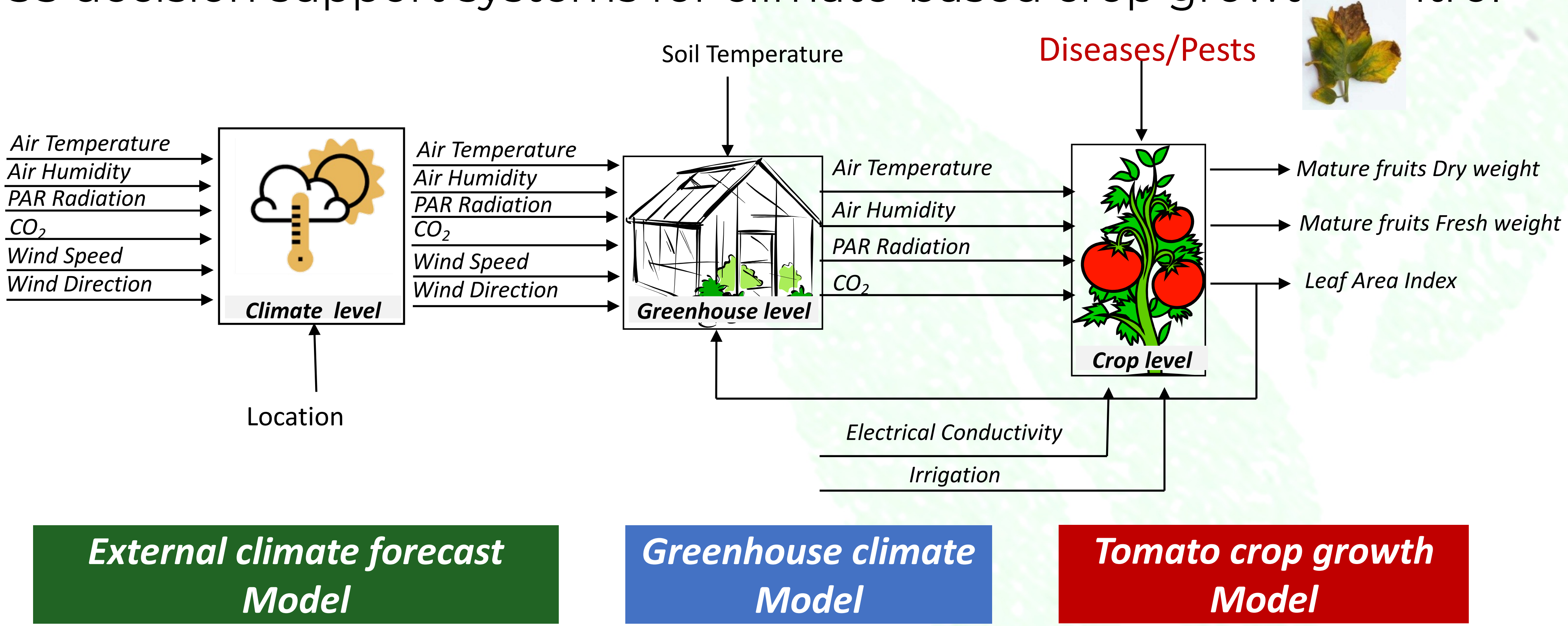
Climate controller design



Use cases

DSS decision support systems for climate-based crop growth control



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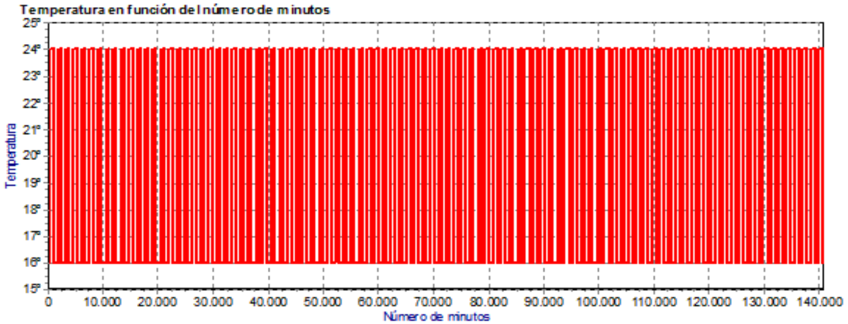
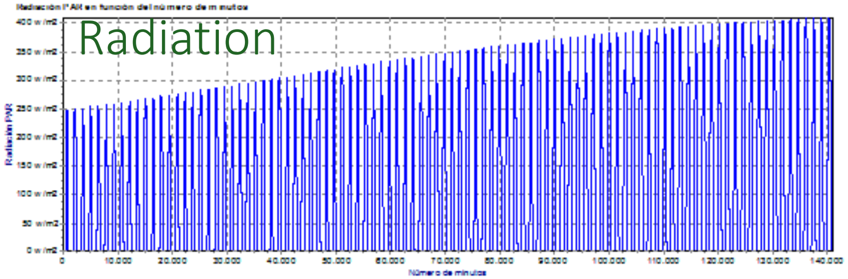
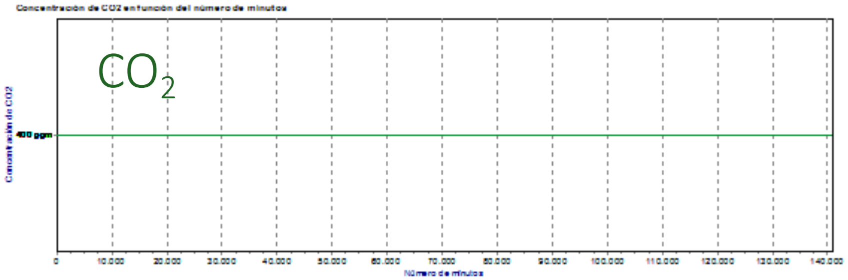
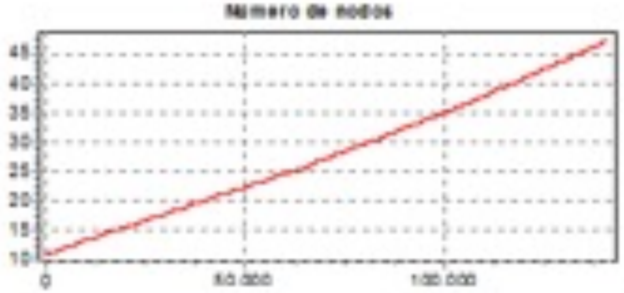
DSS decision support systems for climate-based crop growth control

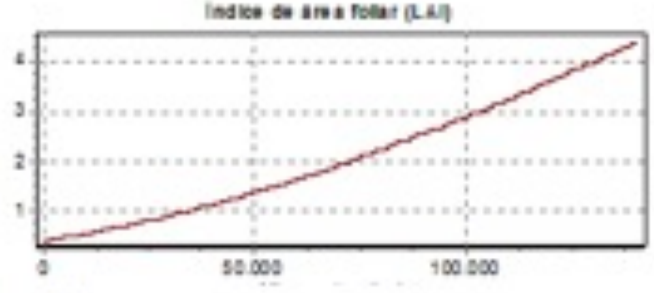
Temperature strategy 1

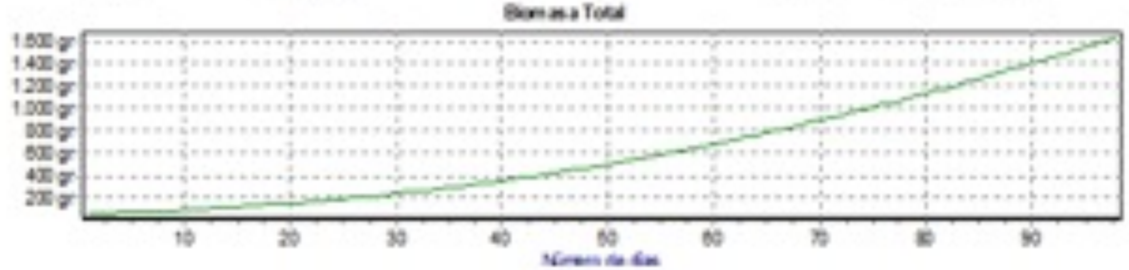


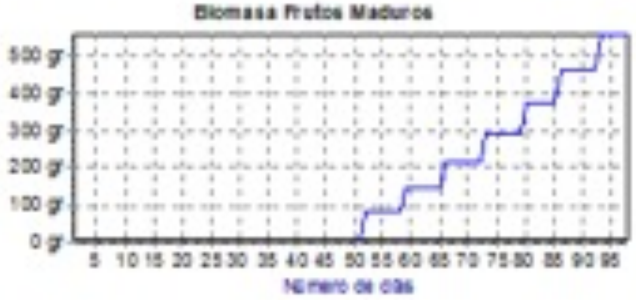


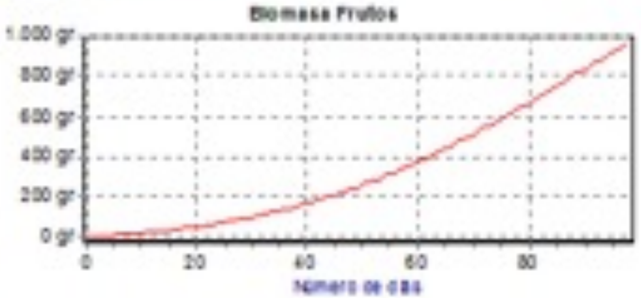






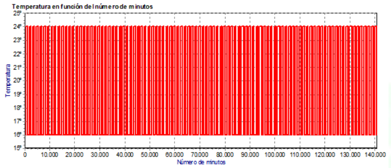


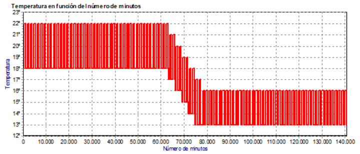


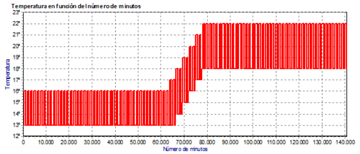


Use cases

DSS decision support systems for climate-based crop growth control



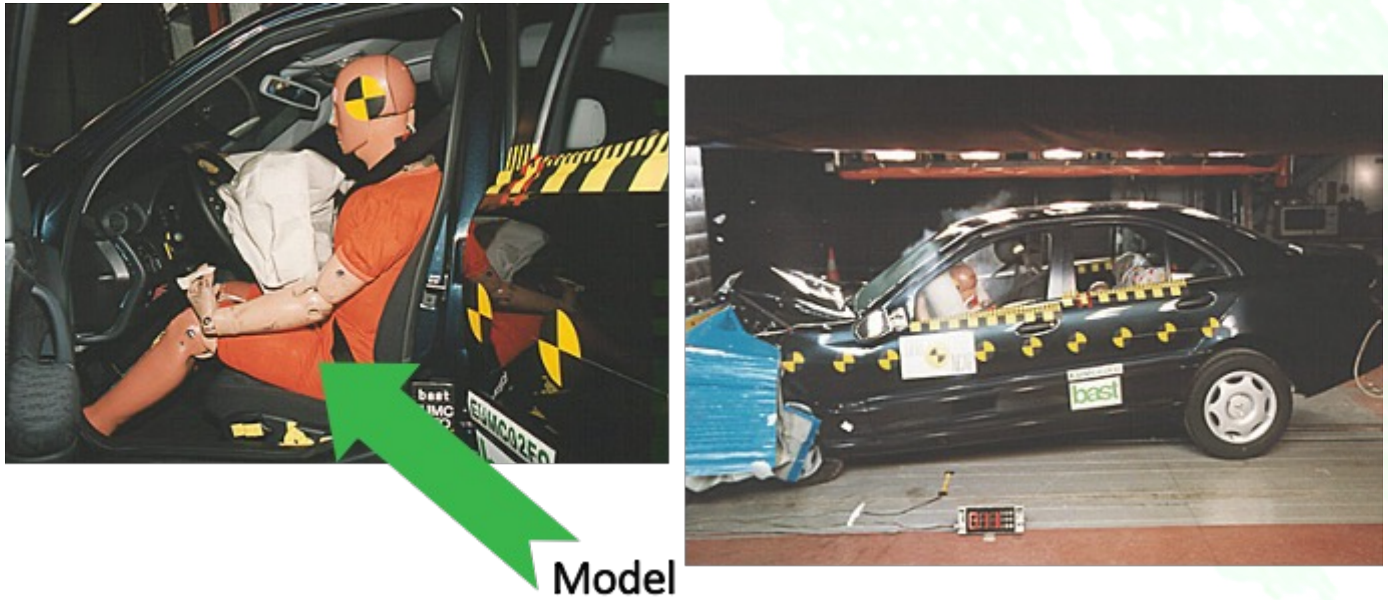




	Temperature Strategy 1	*Temperature Strategy 2*	*Temperature Strategy 3*
Number of nodes	47,41	43,97	43.68
Leaf Area Index	4,41	3,98	3,95
Total Dry Matter	1,621 Kg/m^2	1,689 Kg/m^2	1,538 Kg/m^2
Fruit Dry Matter	0,967 Kg/m^2	0,783 Kg/m^2	0,836 Kg/m^2
Ripe Fruit Dry Matter	0,559 Kg/m^2	0,443 Kg/m^2	0,261 Kg/m^2

Conclusions

- The main advantages and benefits of the use of model are:
  - They help to evaluate the outcome of a real-world decision without actually making it
  - They allows the organization of knowledge and observations about the system as well as the possible logical deductions that can be made from this organization.
  - In general, they are cheaper than experimenting with the real system.



Conclusions

- The use of models is agriculture sector is needed because evaluate the outcome of a real-world decision without actually making it saving time and money.
- All models need to be calibrated and validated. For example, a greenhouse temperature model is the same for all greenhouses, but its parameters are different for each one.
- There are several success stories of the use of models in greenhouse agriculture.
- The use of models is mandatory to crop growth control

Co-funded by the Erasmus+ Programme of the European Union

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Module 6: CLIMATE MANAGEMENT

Lesson 6.1: Measurement and Modelling

Theme 6.1.5: First principles model

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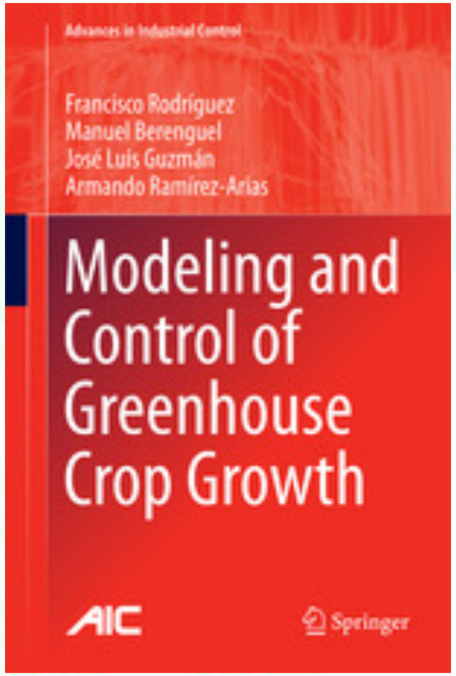
- General considerations for Greenhouse climate modelling
- Climate variables first principles models
- Model implementation
- Model calibration and validation
- Conclusions

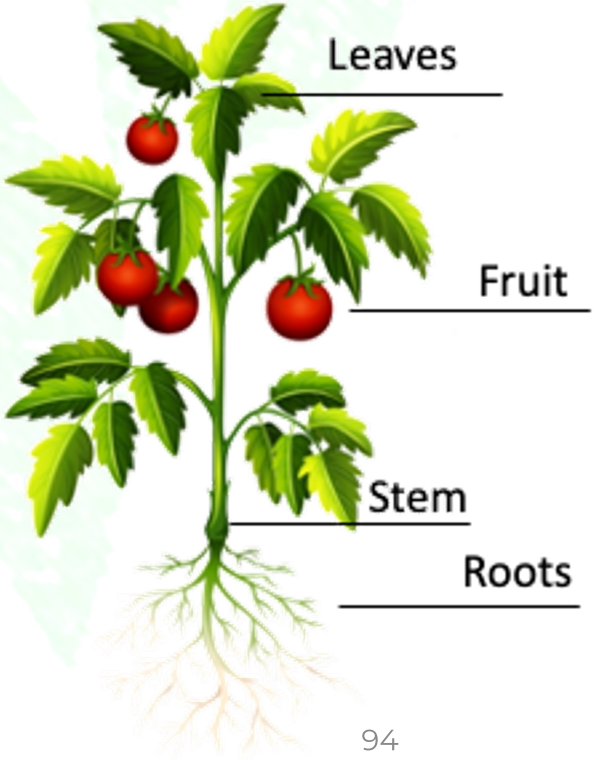


Crop growth control

The crop growth can be defined by biomass increment of the physical dimensions of the plants [Bidwell, 1974]

How it can be measured?

- Number and size of leaves
- Dry matter (matter resulting of drying the plants)
- Fresh weight (weight of the plant composed by dry matter and water)



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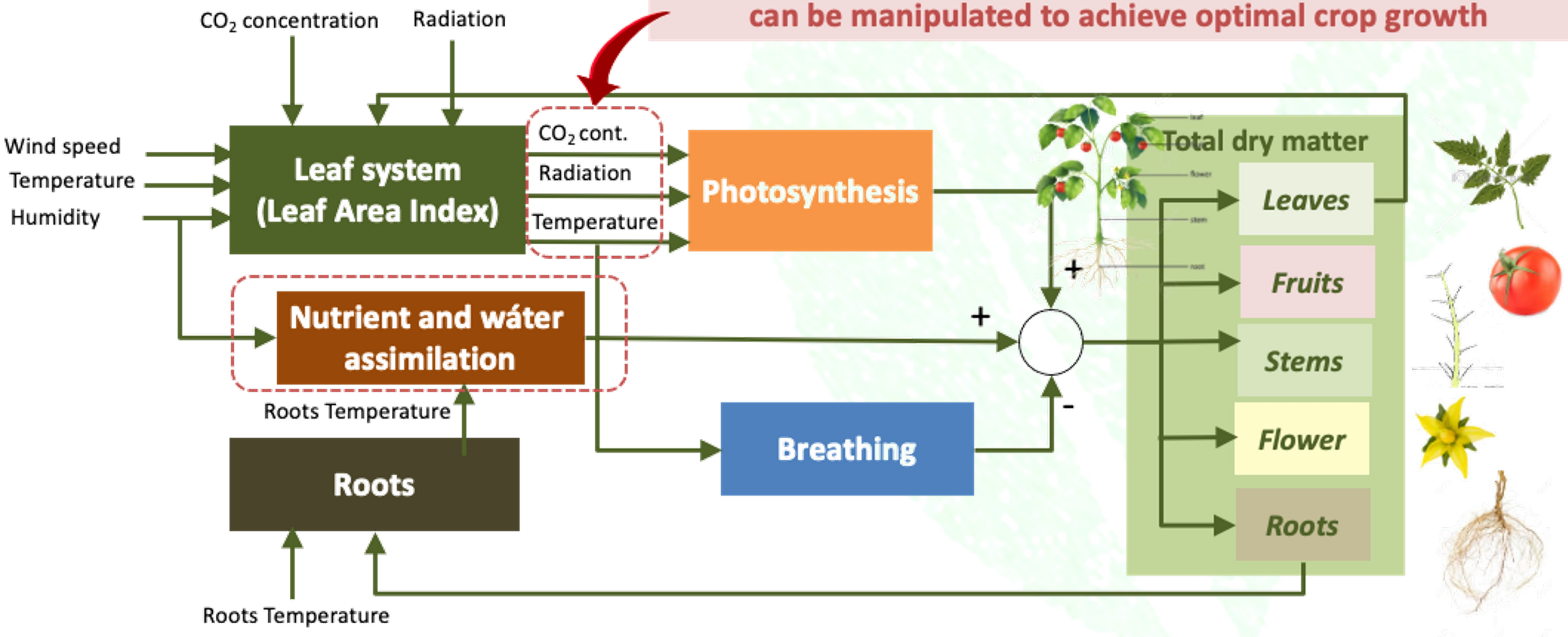
Crop growth control

A greenhouse is a closed enclosure where weather conditions can be manipulated to achieve optimal crop growth



Greenhouse climate variables

The variables that describe the greenhouse climate and its influence on the crop growth are:

- Air temperature
- CO_2 concentration
- PAR radiation on the crop

Indirectly, the humidity of the air affects the development and growth of the crop as it influences the transpiration of the crop.

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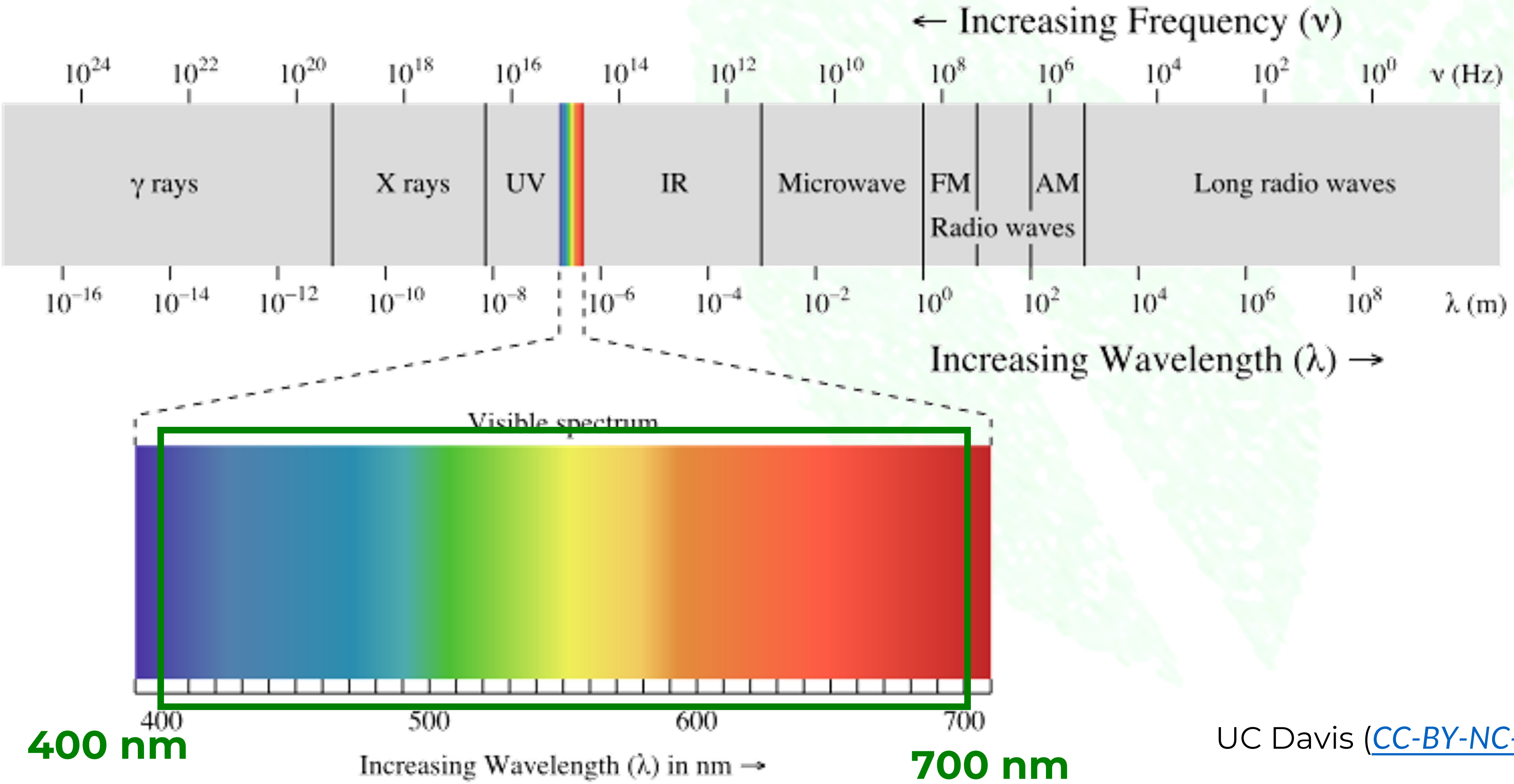
Greenhouse climate variables

Photosintetically Active Radiation (PAR radiation)

The spectral range of solar radiation from 400 to 700 nanometers that photosynthetic organisms are able to use in the process of photosynthesis.



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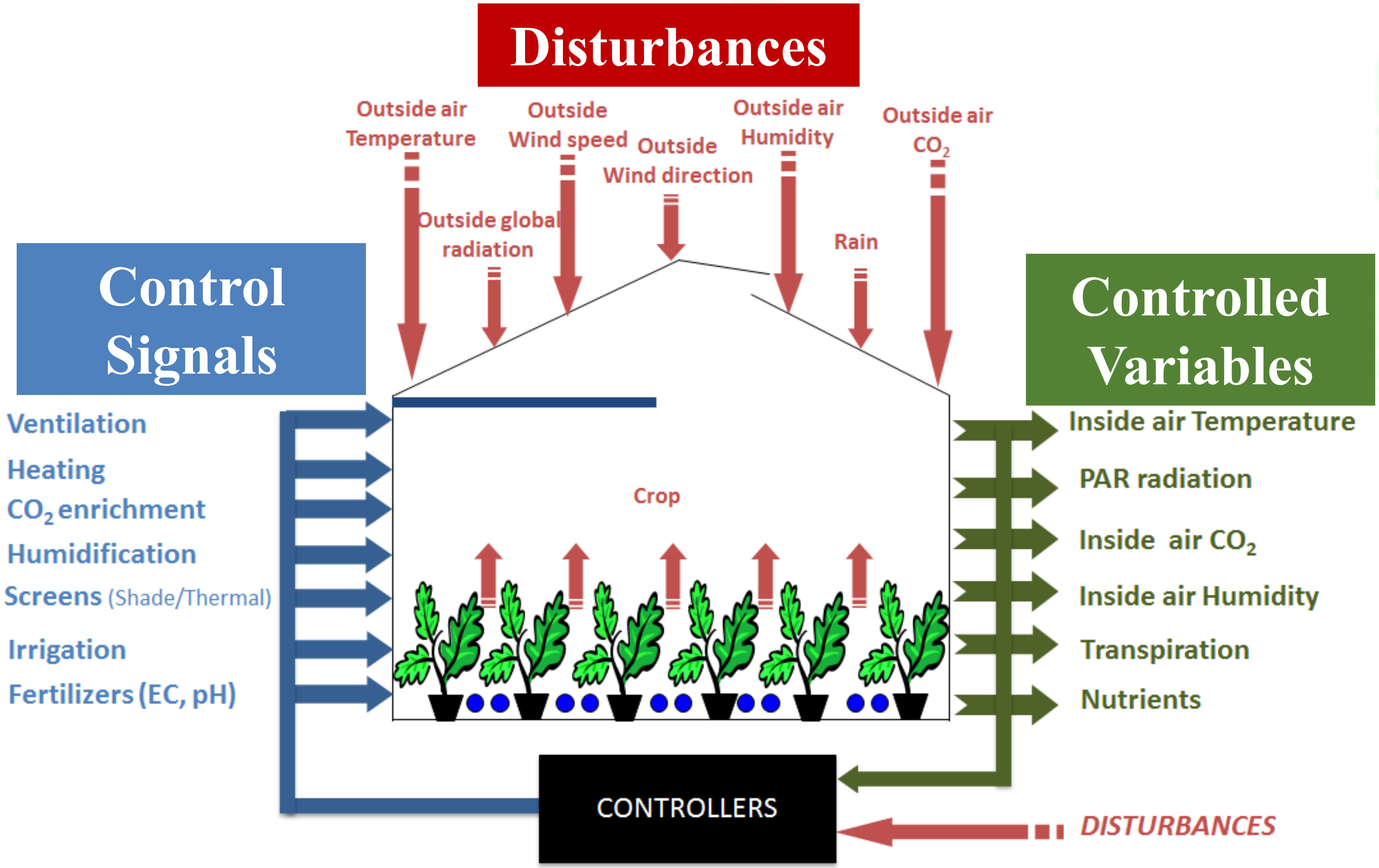
Greenhouse climate variables control



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General considerations

The dynamic behaviour of the microclimate inside a greenhouse is a combination of physical processes involving:

- Energy balance (radiation and heat)

$$\frac{\mathrm{d}Q_{\mathrm{tot,vol}}}{\mathrm{d}t} = c_{\mathrm{h,vol}}\frac{\mathrm{d}X_{\mathrm{T,vol}}}{\mathrm{d}t} = Q_{\mathrm{in,vol}} - Q_{\mathrm{out,vol}} + Q_{\mathrm{gen,vol}}$$

- Mass balance (water vapor and CO2 fluxes).

$$\frac{\mathrm{d}M_{\mathrm{tot,vol}}}{\mathrm{d}t} = c_{\mathrm{vol}}\frac{\mathrm{d}X_{\mathrm{c,vol}}}{\mathrm{d}t} = M_{\mathrm{in,vol}} - M_{\mathrm{out,vol}} + M_{\mathrm{gen,vol}}$$

General considerations

The transport phenomena to be considered are as follows:

- Basic heat transfer processes
  - Conduction.
  - Convection.
  - Absorption, reflection and transmission of solar radiation.
  - Emission, absorption, reflection and transmission of thermal radiation
- Basic processes of combined heat and mass transfer
  - Condensation of water vapour
  - Evaporation of water vapour
  - Crop transpiration
- Effects of actuation systems
  - Ventilation systems.
  - Heating systems.
  - Shading and thermal screens.
  - Etc.

General considerations

Subsystems of a greenhouse

- Cover. It is a solid and homogeneous medium which partially transmits solar and thermal radiation.
- Crop. It is a living organism that is an open thermodynamic system that extracts and provide energy from and to the surrounding environment
- Air. It is a gaseous medium joining the different solid elements in the greenhouse.
- Soil. It is a porous medium responsible for the greenhouse thermal inertia, absorbing energy during the day and emitting it overnight

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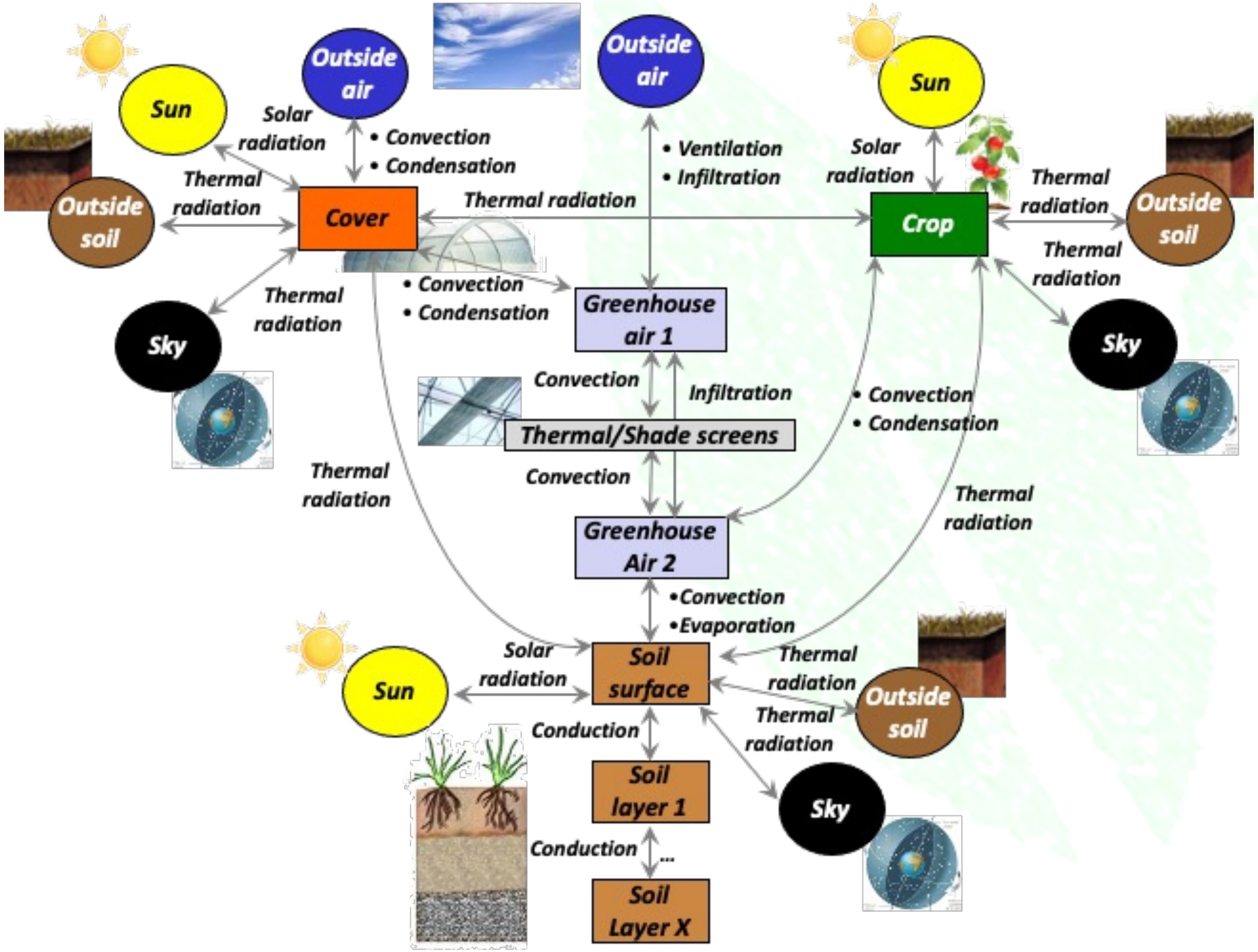
General considerations



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General Hypotheses

- The greenhouse is divided into four elements : Cover, internal air, soil surface, and one soil layer.
- The external element that interact with greenhouse are: external air, crop, deep soil layer, sky (celestial vault) and Fertigation ponds and channels (i.e. NFT systems)
- The state variables of the model are: greenhouse air temperature ($X_{T,a}$), CO2 concentration ($X_{co2,a}$) and humidity (absolute $X_{Ha,a}$ and relative $X_{Hr,a}$), cover temperature ($X_{T,cv}$), soil surface temperature ($X_{T,ss}$), and first soil layer temperature ($X_{T,sl}$) and the PAR radiation onto the canopy ($X_{rp,a}$).

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General Hypotheses

- The exogenous and disturbance inputs acting on the system are the outside air temperature ($D_{T,e}$), absolute humidity ($D_{Ha,e}$) and CO2 concentration ($D_{CO2,e}$) , wind speed ($D_{ws,e}$) and direction ($D_{wd,e}$), sky temperature ($D_{T,sky}$), outside global solar radiation ($D_{rs,e}$), PAR radiation ($D_{rp,e}$), greenhouse whitening (D_{wh}), the transpiration rate inside the greenhouse via the leaf area index (D_{LAI}) and the temperature of the deepest soil layer ($D_{T,s2}$).
- The control inputs of the system are: the position of the natural ventilation (U_{ven}), the position of the shade screen (U_{shd}), the heating system (U_{heat}), the humidifier system (U_{hum}), the dehumidifier system (U_{dhum}), and the CO_2 enrichment system(U_{CO2}),

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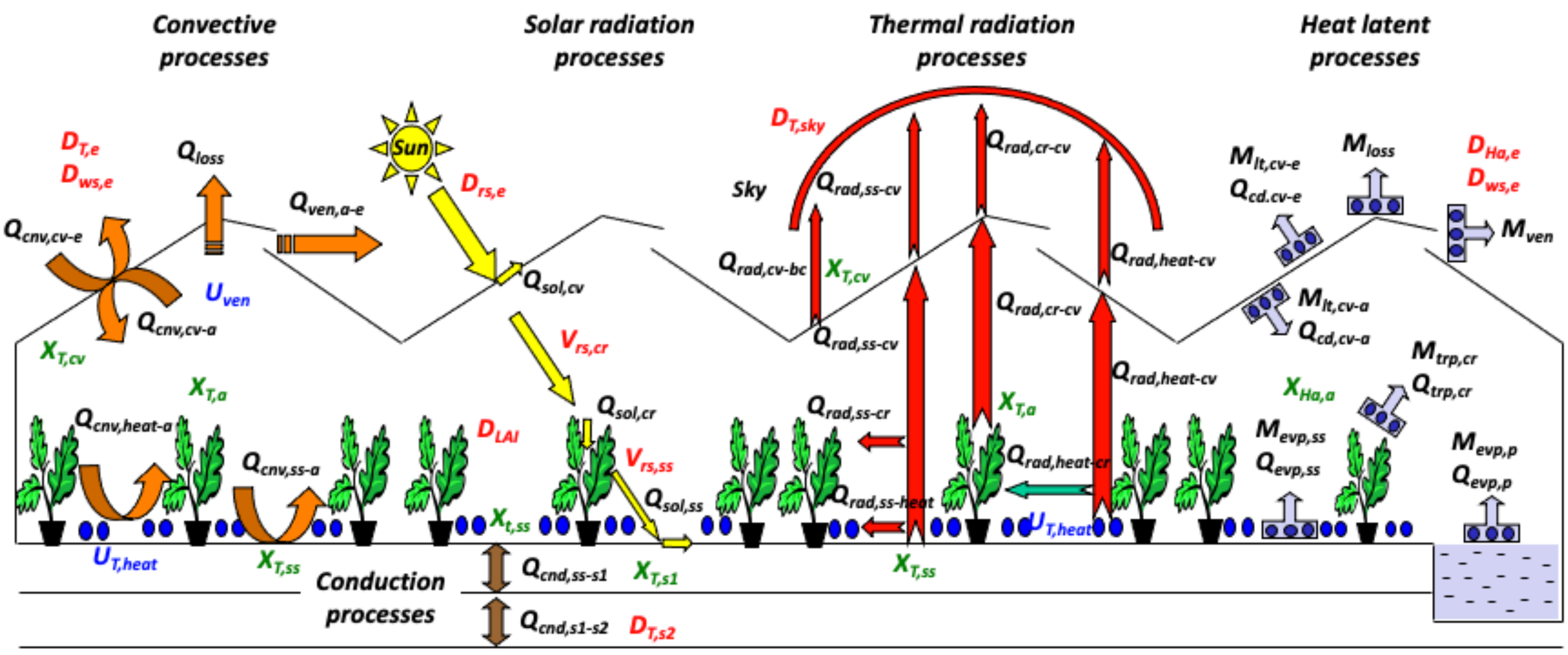
General Hypotheses



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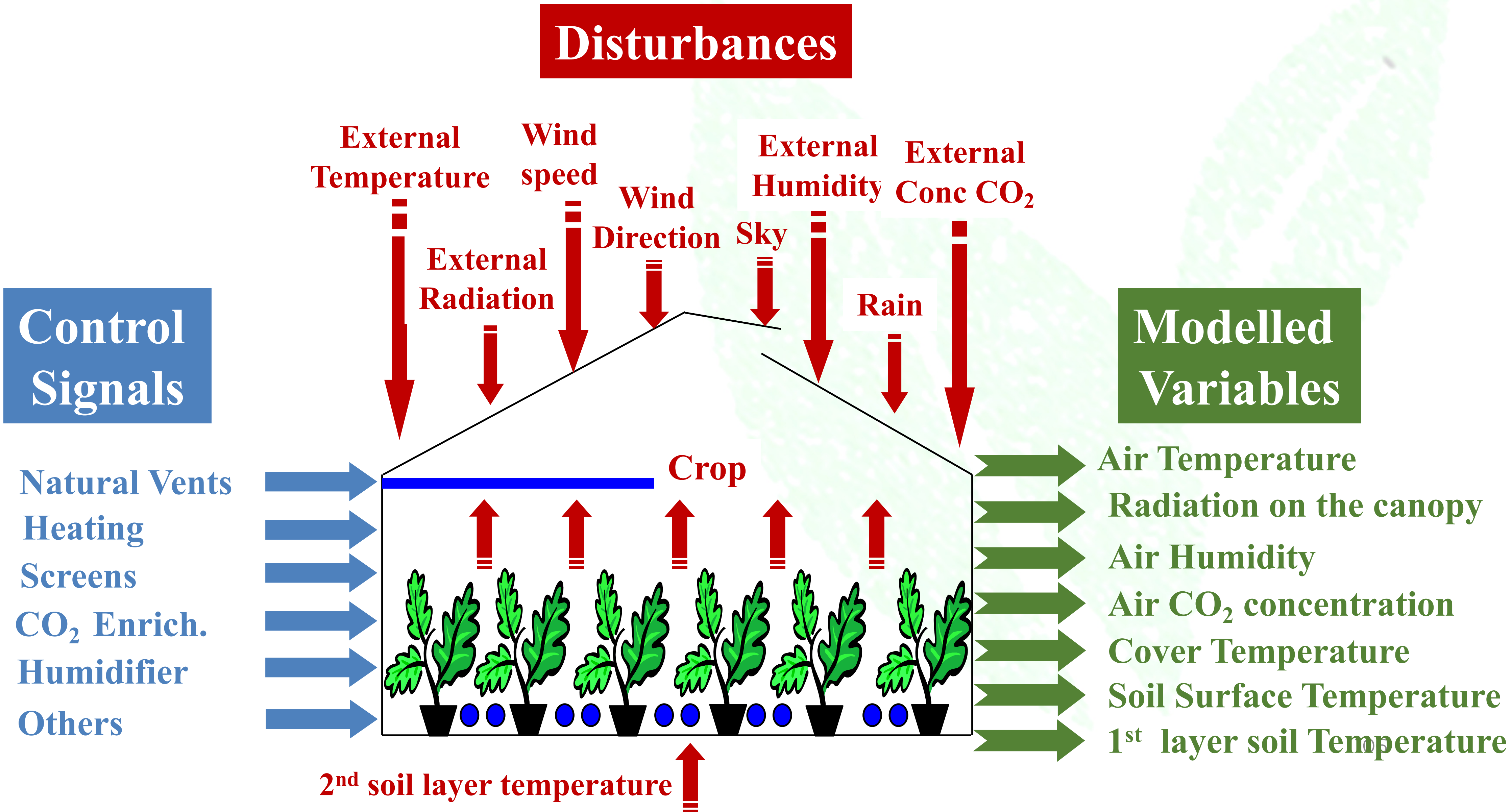
General Hypotheses



General Hypotheses

The greenhouse dynamics are defined by a system of 6 ODEs given as:

$$\frac{\mathrm{d}\mathbf{X}}{\mathrm{d}t} = f\left(\mathbf{X}, \mathbf{U}, \mathbf{D}_m, \mathbf{V}, \mathbf{C}, t\right) \text{ with } \mathbf{X}(t_i) = \mathbf{X}_i$$

Where:

$X=X(t) \in R^n$	is a n-dimensional vector of state variables (n=6)
$U=U(t) \in R^m$	is a m-dimensional vector of input variables (m= 7)
$D=D(t) \in R^o$	is an o-dimensional vector of measurable disturbances (o= 8)
$V=V(t) \in R^p$	is a p-dimensional vector of system variables
$C \in R^q$	is a q-dimensional vector of system constants
t	is the time
X_{ti}	is the known initial state at the initial time
t_i	is the initial time
$f{:}R^{n+m+o+p+q} \rightarrow R^n$	is a nonlinear function based on mass and heat transfer balances.

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General Hypotheses

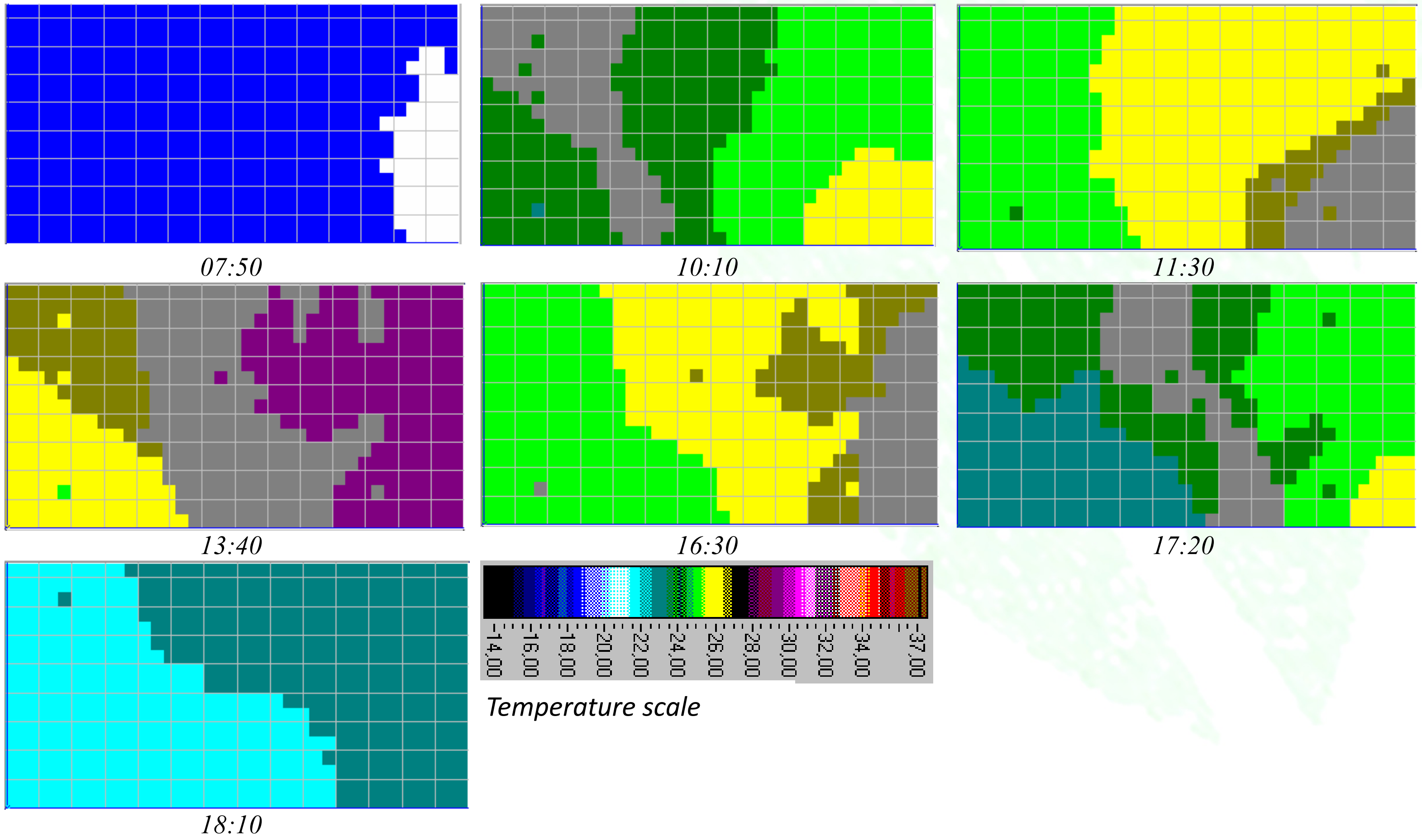
- The heat fluxes are one-dimensional.
- The temperature models are based on a heat transfer balance where the following physical processes are included: Solar (*sol*) and thermal radiation (*rad*) absorption, heat convection (cnv) and conduction (*cnd*), crop transpiration (*trp*), condensation (*cd*), and evaporation (*evp*).
- To design the humidity model, a mass balance is used based on artificial water influxes, exchange with the outside, crop, condensation, and evaporation.

General Hypotheses

- The models of short and long wave radiation do not consider reflection, and the air is inert to these processes.
- The physical characteristics of the different elements, such as density or specific heat are considered constant in the temperature range the greenhouse evolves.
- The thickness of the cover is in microns, so the conductive heat flow is quantitatively negligible compared to other heat flows that appear in the cover temperature models. So, it is accepted that the temperatures of both cover surfaces are similar.

General Hypotheses

- A uniform homogeneous distribution of variables is considered in the cover, air and soil



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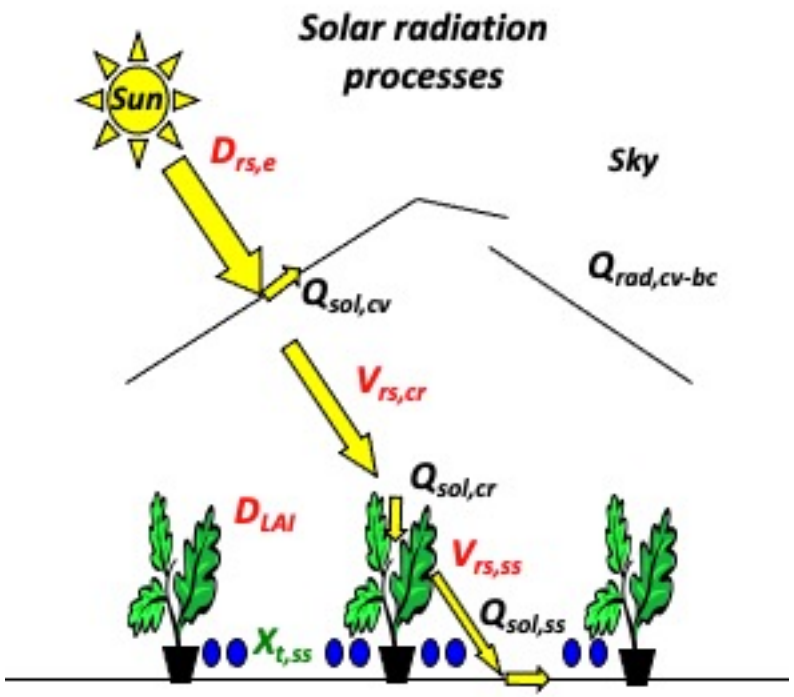
Radiation (Global and PAR) model

- The PAR radiation onto the canopy is similar to the PAR radiation outside the greenhouse dimmed by the different physical elements that absorb the radiation



$$X_{\mathrm{rp,a}} = V_{\mathrm{tsw,g}} D_{\mathrm{rp,e}}$$

$$V_{\mathrm{tsw,g}} = \begin{cases} c_{\mathrm{tsw,cv}} & \text{no shade, no whitening} \\ c_{\mathrm{tsw,cv}} c_{\mathrm{tsw,wh}} & \text{no shade, whitening} \\ c_{\mathrm{tsw,cv}} c_{\mathrm{tsw,shd}} & \text{shade, no whitening} \\ c_{\mathrm{tsw,cv}} c_{\mathrm{tsw,wh}} c_{\mathrm{tsw,shd}} & \text{shade, whitening} \end{cases}$$

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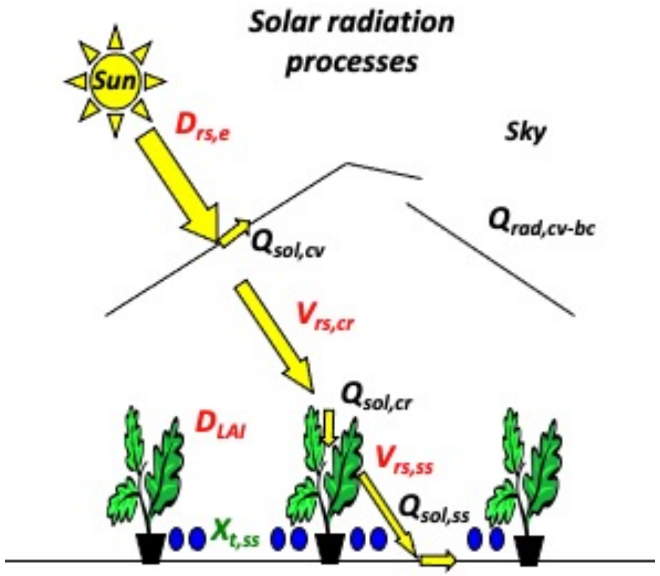
Radiation (Global and PAR) model

- The solar radiation absorbed by the cover is determined by the shortwave radiation cover material absorptivity and the whitening.
- The solar radiation absorbed by the soil surface is determined by the shortwave radiation cover material absorptivity, the shade screen, whitening and the crop status (defined by LAI),



$$Q_{\mathrm{sol,cv}} = c_{\mathrm{asw,cv}} D_{,\mathrm{e}}$$

$$Q_{\mathrm{sol,ss}} = c_{\mathrm{asw,ss}} V_{\mathrm{rs,cr}} \exp\left(-c_{\mathrm{extsw,cr}} D_{\mathrm{LAI}}\right)$$

$V_{rs,cr}$ is the solar radiation that reaches the top of the canopy based on the solar radiation absorption by the physical elements that the radiation crosses

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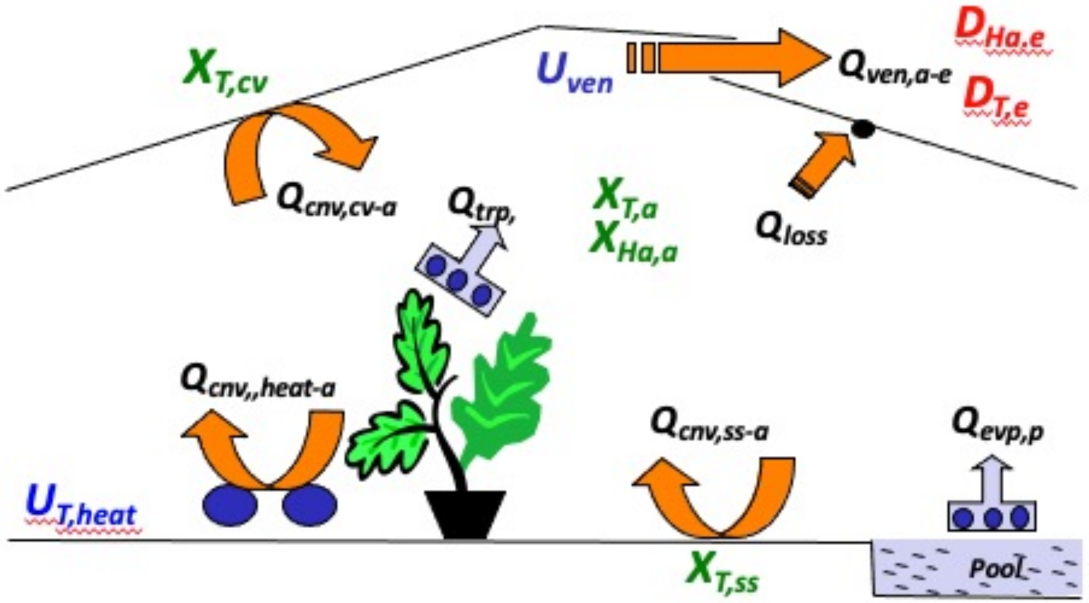
Heat Transfer Fluxes with the Internal Air

The greenhouse air temperature can be modeled using this balance

Air Temperature

Actuators

$$c_{sph,a}\, c_{den,a} \frac{c_{vol,g}}{c_{area,s}} \frac{dX_{t,a}}{d\tau} = Q_{cnv,cv-a} + Q_{cnv,ss-a} + Q_{cnv,heat-a} - Q_{ven} - Q_{trp,cr} - Q_{evp,p}$$



$Q_{cnv,cv-a}$ is the convective flux with the cover

$Q_{cnv,ss-a}$ is the flux with the soil surface

Q_{heat-a} is the heat flux due to the heating system

Q_{ven} is the heat lost by natural ventilation and the heat lost by infiltration losses

$Q_{trp,cr}$ is the latent heat effect of the crop transpiration

$Q_{evp,p}$ is the latent heat effect of evaporation in the pools, humidifiers and dehumidifiers

Heat Transfer Fluxes with the Internal Air

Air Temperature

$$c_{cnv,cb-a1}\left|X_{t,cb}-X_{t,a}\right|^{c_{cnv,cb-a2}}+c_{cnv,cb-a3}\,V_{vv,a}^{c_{cnv,cb-a4}}$$

$$c_{cnv,ss-a1}\left|X_{t,ss}-X_{t,a}\right|^{c_{cnv,ss-a2}}+c_{cnv,ss-a3}\left[V_{vv,a}\exp\left(-c_{cnv,ss-a4}\,P_{LAI}\right)\right]^{c_{cnv,ss-a5}}$$

$$\underbrace{c_{c-esp,a}\,c_{den,a}\frac{c_{vol,inv}}{c_{area,s}}\frac{dX_{t,a}}{dt}}_{\text{accumulated heat in the air}}=\underbrace{V_{cv,cb}\frac{c_{area,cb}}{c_{area,s}}\left(X_{t,cb}-X_{t,a}\right)}_{\text{Cover}}+\underbrace{V_{cv,s}\left(X_{t,s}-X_{t,a}\right)}_{\text{Soil surface}}+\underbrace{V_{cv,cal}\frac{c_{area,cal}}{c_{area,s}}\left(U_{t,cal}-X_{t,a}\right)}_{\text{Heating system}}-$$

$$c_{cnv,cal-a1}\left(\frac{\left|U_{t,cal}-X_{t,a}\right|}{c_{lc,cal}}\right)^{c_{cnv,cal-a2}}$$

$$V_{h,efec}=c_{w,v}\left[\sin(\psi)-\sin(\psi-U_{\alpha})\right]$$

$$\underbrace{-\left\{\frac{c_{largo,vent}\,c_{desc}\,P_{t,e}}{3c_g\left(X_{t,a}-P_{t,e}\right)}\left[\left[V_{h,efec}\,c_g\frac{X_{t,a}-P_{t,e}}{P_{t,e}}+c_{viento}\,P_{v,e}^2\right]^{3/2}-\left(c_{viento}\,P_{v,e}^2\right)^{3/2}\right]\right\}c_{den,a}\,c_{c-esp,a}\cdot\left(X_{t,a}-P_{t,e}\right)}_{\text{Natural vents}}-\underbrace{c_{ren,hora}\frac{c_{vol,inv}}{c_{area,s}}c_{den,a}\left(X_{t.a}-P_{t,e}\right)}_{\text{Infiltration (losses)}}+$$

$$\underbrace{+V_{lt,vap}\frac{V_{r,est}V_{rn,c}\dfrac{V_{pcsv}}{c_{pt}}+2c_{clv}\,V_{LAI}\left(V_{Hsat,a}-X_{H,a}\right)}{\left(1+\dfrac{V_{pcsv}}{c_{pt}}\right)V_{r,est}+V_{r,cl}}}_{\text{Crop}}\;\underbrace{-V_{lt,vap}\left(\frac{V_{pcsat}}{V_{pcsat}+c_{psico}}c_{lt,balsa1}V_{rn,balsa}+\frac{c_{psico}}{V_{pcsat}+c_{psico}}c_{lt,balsa2}V_{dpv,a}\right)}_{\text{Latent heat}}$$

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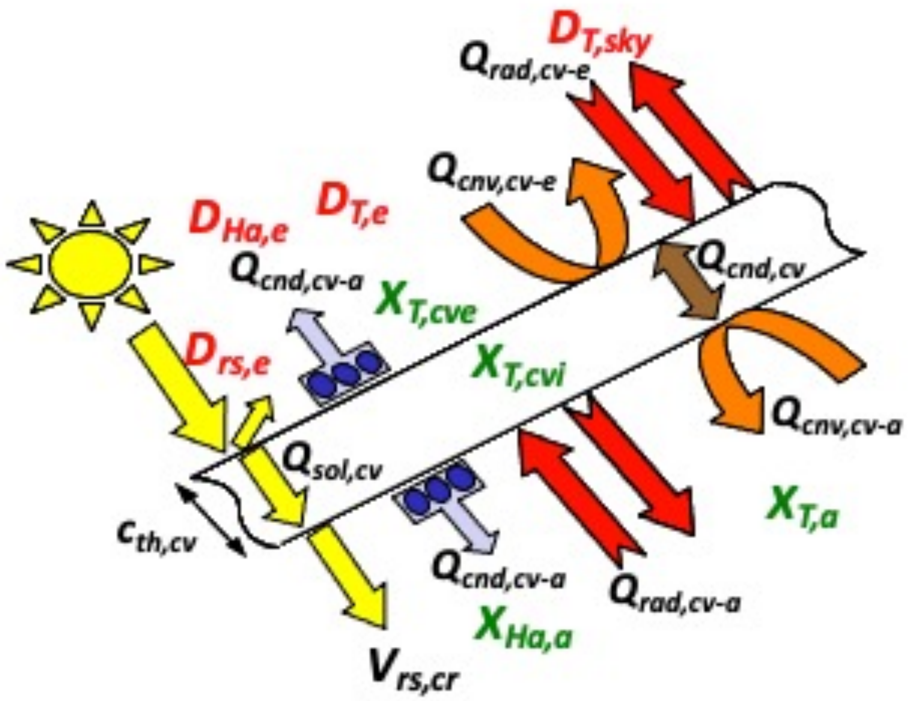
Heat Transfer Through the Cover

The cover temperature can be modeled using the following balance

Cover Temperature

$$c_{\mathrm{sph,cv}} c_{\mathrm{den,cv}} \frac{c_{\mathrm{vol,cv}}}{c_{\mathrm{area,ss}}} \frac{\mathrm{d}X_{\mathrm{T,cv}}}{\mathrm{d}t} = Q_{\mathrm{sol,cv}} - Q_{\mathrm{cnv,cv-a}} - Q_{\mathrm{cnv,cv-e}} - Q_{\mathrm{cd,cv}} + Q_{\mathrm{rad,cv}}$$



$Q_{sol,cv}$ is the solar radiation absorbed by the cover
$Q_{cnv,cv-a}$ is the convective heat transfer with the internal air
$Q_{cnv,cv-e}$ is the convective heat transfer with the external air
$Q_{cd,cv}$ is the latent heat produced by condensation
$Q_{rad,cv}$ is the thermal radiation absorbed by the cover (soil, sky, heating, crop, etc.)

Heat Transfer in the soil layers

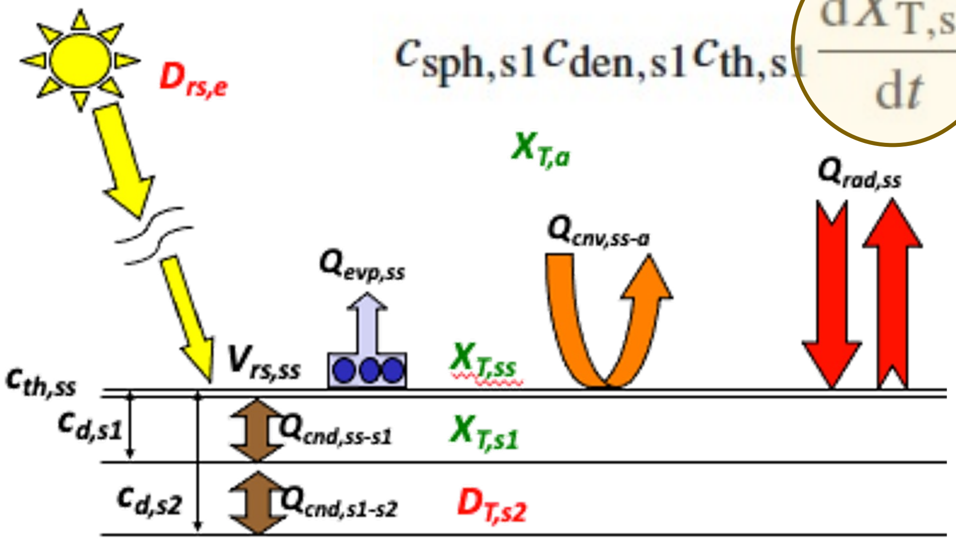
- The model considers the soil divided into three layers:
  - Soils surface.
  - First layer (located at 30cm depth).
  - Deep layer with a constant temperature

- The soil first layer temperature can be modeled using the following balance:

Soil first layer Temperature

$$c_{sph,s1} c_{den,s1} c_{th,s1} \frac{dX_{T,s1}}{dt} = Q_{cnd,ss-s1} - Q_{cnd,s1-s2}$$

$$Q_{cnd.s1-s2} = c_{cnd,s2} \frac{X_{T,s1} - D_{T,s2}}{c_{d,s2} - c_{d,s1}}$$



$Q_{cnd,ss\text{-}s1}$ is the conductive flux between the soil surface, and the first soil layer

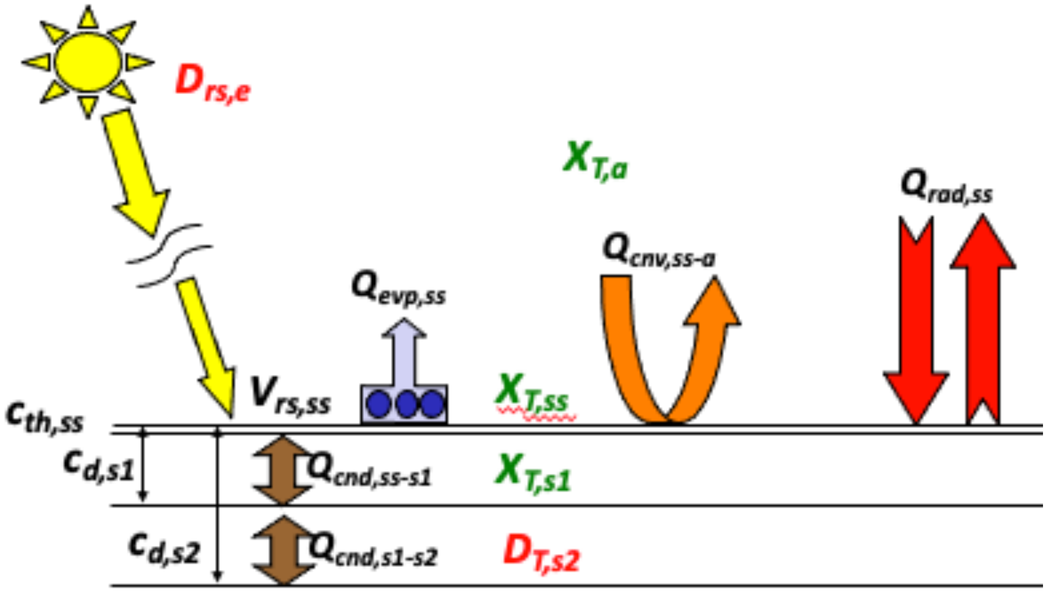
$Q_{cnd,s1\text{-}s2}$ is the conductive flux between the the first soil layer and the deep layer

Heat Transfer in the soil layers

- The soil surface temperature can be modeled using the following balance:

Soil surface Temperature

$$c_{\mathrm{sph,ss}} c_{\mathrm{den,ss}} c_{\mathrm{th,ss}} \frac{\mathrm{d}X_{\mathrm{T,ss}}}{\mathrm{d}t} = Q_{\mathrm{sol,ss}} - Q_{\mathrm{cnv,ss-a}} - Q_{\mathrm{cnd,ss-s1}} - Q_{\mathrm{evp,ss}} + Q_{\mathrm{rad,ss}}$$



$Q_{sol,ss}$ is the solar radiation absorbed by the soil surface

$Q_{cnv,ss-a}$ is the convective heat transfer with the internal air

$Q_{cnd,ss-s1}$ is the conductive flux between the soil surface, and the first soil layer

$Q_{evp,ss}$ is the latent heat produced by evaporation

$Q_{rad,cv}$ is the thermal radiation absorbed by the soil surface (cover, sky, heating, crop, etc.)

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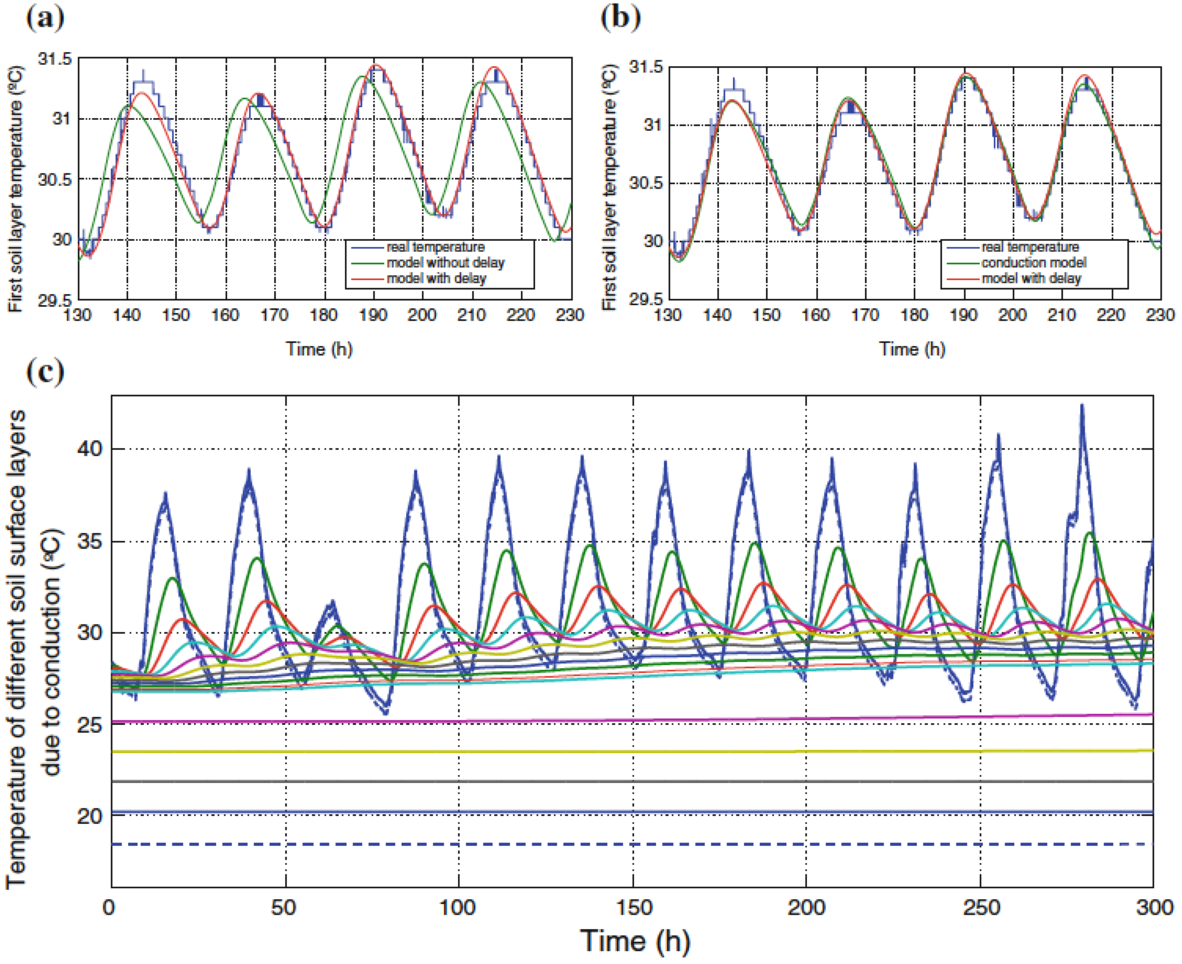
Heat Transfer in the soil layers

This a simple model because the conduction process is modeled solving the Fourier equation considering one-dimensional heat transfer along the deep axis, in steady state, the different soil layers as flat parallel planes, plus a delay in the process.

Really, diffusion equations would be used



¡¡The results are similar!!

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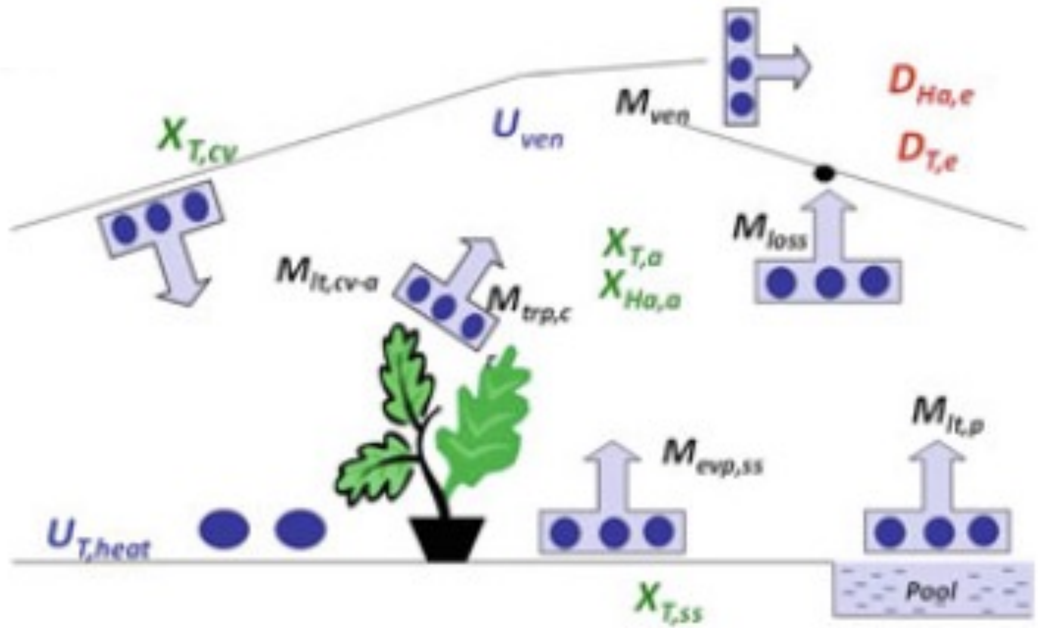
Greenhouse Air humidity model

The greenhouse air absolute humidity can be modeled with a water vapor mass balance equation:

Greenhouse air absolute humidity

Actuators

$$\frac{c_{\mathrm{vol,g}}}{c_{\mathrm{area,s}}} c_{\mathrm{den,a}} \frac{\mathrm{d}X_{\mathrm{H_{a,a}}}}{\mathrm{d}t} = M_{\mathrm{trp,cr}} + M_{\mathrm{evp,p}} + M_{\mathrm{evp,ss}} - M_{\mathrm{cd,cv}} - M_{\mathrm{ven,a-e}} + M_{Hum} - M_{DHum}$$



$M_{trp,cr}$ is the crop transpiration flux
$M_{evp,p}$ is the is the evaporation flux in irrigation reservoirs
$M_{evp,ss}$ is the mass evaporation flux from the soil surface
$M_{cd,cv,}$is condensation flux from the cover
$M_{ven,a\text{-}e}$ is the is the outflow by natural ventilation and infiltration losses
M_{Hum} is the is the water mass provided by humidifiers
M_{DHum} is the is the water mass removed by dehumidifiers

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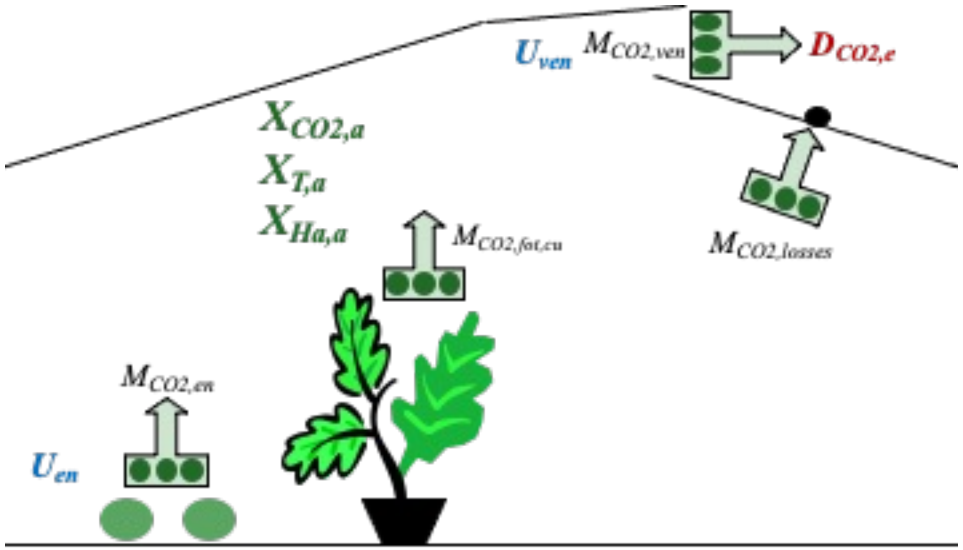
CO_2 Mass Transfer Fluxes with the Internal Air

The CO_2 concentration in greenhouse air can be modeled using a similar to a water mass balance for humidity:

Greenhouse air CO_2 — Actuators

$$\frac{c_{volg}}{c_{area,s}} c_{m,CO2} \frac{dX_{CO2,a}}{dt} = M_{CO2,fot} + M_{CO2,en} - M_{CO2,ven} - M_{CO2,losses}$$



$M_{CO2,fot}$ is the CO_2 mass by crop photosynthesis

$M_{CO2,en}$ is the is the CO_2 mass provided by the enrichment systems

$M_{CO2,ven}$ is the is the CO_2 mass removed by natural vents

$M_{CO2,losses}$ is the is the CO_2 mass removed by infiltration losses

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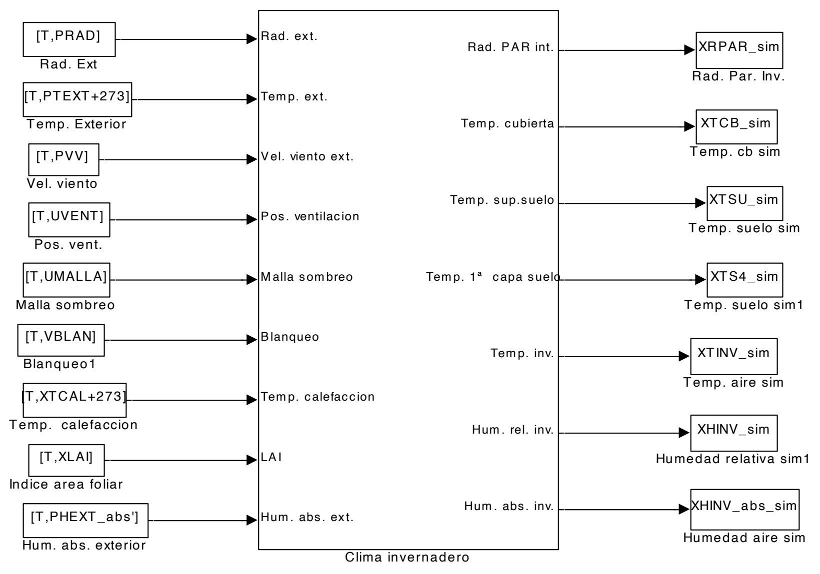
Model implementation

- The designed greenhouse climate model is composed of five ODEs related to the main greenhouse climate variables and 49 algebraic equations

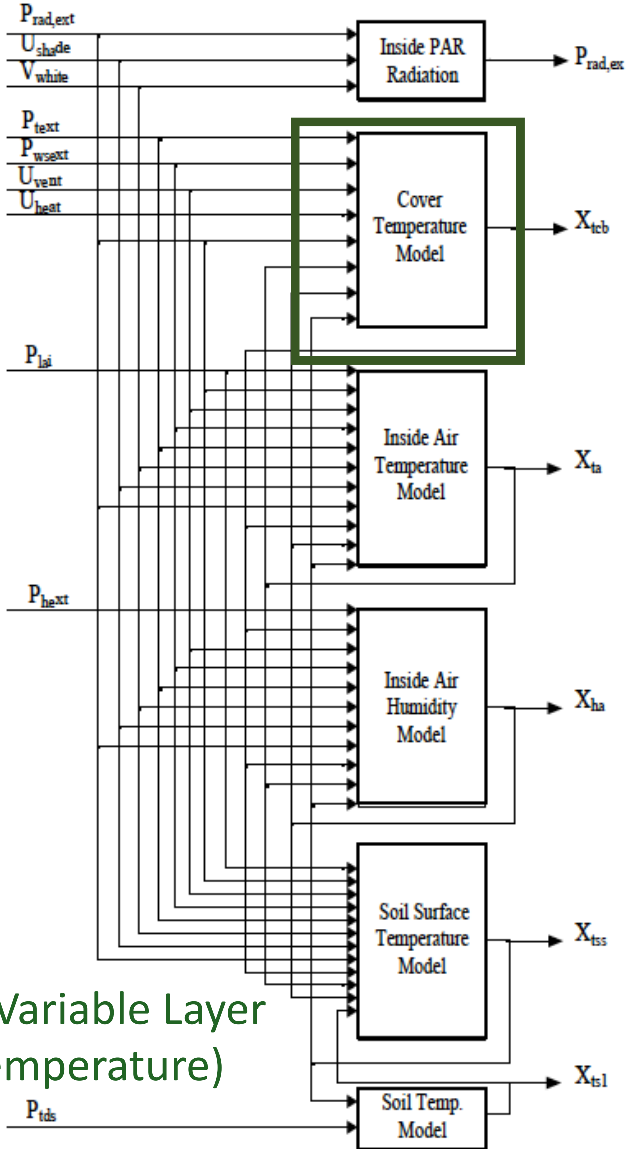
- This model must be divided hierarchically using a top-down approach from a high level that includes all the submodels to the lower level where each physical process is modeled.

- Two paradigms can be used:
  - A Block-based modeling and simulation approach
  - An object-oriented modeling proposal

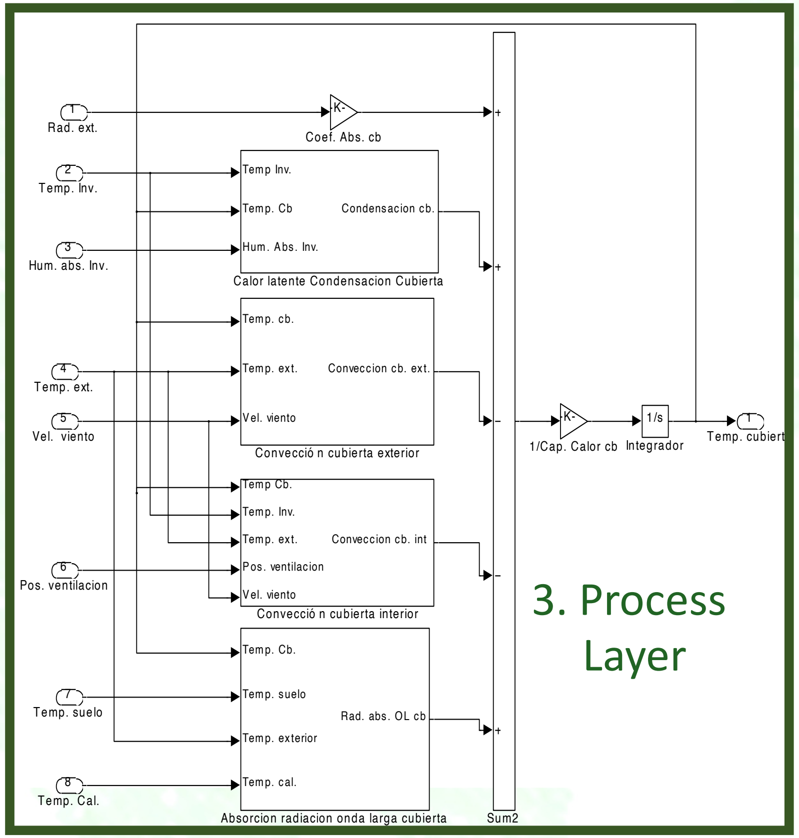
Model implementation. Block based



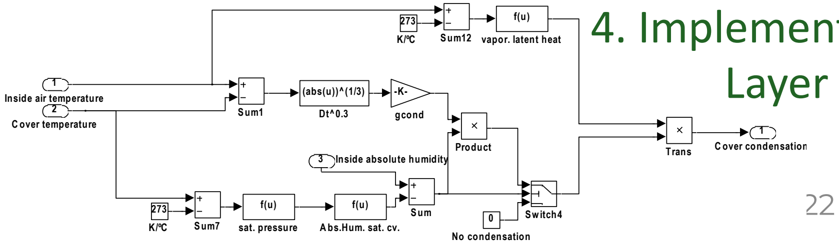
1. Climate Layer



2. Variable Layer (Temperature)



3. Process Layer



4. Implementation Layer

MATLAB SIMULINK

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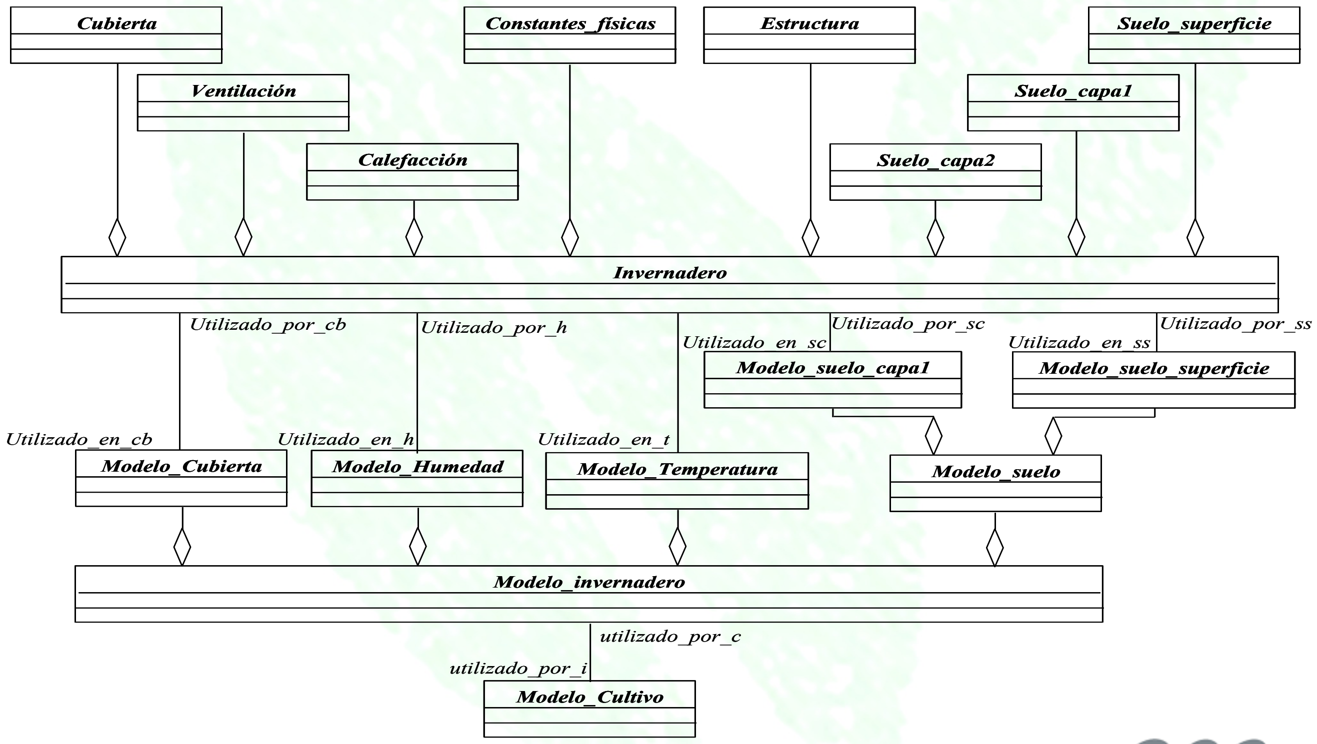
Model implementation. Object based

model class greenhouse_compound
{Submodels}

submodel (greenhouse_humidity) hum
submodel (greenhouse_thermal_cover) cover
submodel (greenhouse_thermal_soil) soil
submodel (greenhouse_thermal_air) air

{Interface}
input Ushad, Prade, Uvent, Pte, Pve, Phabse, Ptds, Pwhite, Plai

{Equations describing the connections between submodels}
{Connection of the greenhouse_humidity model}
hum.Xta = air.Xta-273
hum.Xtcb = cover.Xtcb-273
hum.Xlai = Plai
hum.PHabse = PHabse
hum.Pve = Pve
hum.Pte = Pte
hum.Prade = Prade
hum.Uvent = Uvent
hum.Ushad = Ushad
hum.Pwhite=Pwhite



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Modelica Language

Model Calibration

The main problem is the calibration of the model because it has more than **30 parameters** to estimate, but:

- Data of the different climate variables to model, the disturbances and the actuators status are measured, so the problem has been divided into some submodels calibration processes
- Some of the involved physical processes in the balance equations are not coupled or they have no influence in determined time lapses of a day
- Some of the involved physical processes are modeled in different forms based on determined situations
- In order to estimate the parameters related to the actuation systems, some guided test

A calibration methodology is proposed based on commonly measured data and simple tests.

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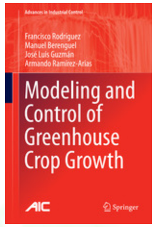
Model Calibration



1. Calibration of the climate variables with an empty greenhouse (without crop)
   a. Climate variables calibration without the effects of the actuation systems (no heating, no ventilation)
      i. Calibration of the first soil layer temperature submodel [4 parameters]
      ii. Calibration during nocturnal time intervals (without solar radiation)
      iii. Calibration of cover temperature submodel
      iv. High wind speed [1 parameter]
      v. Low wind speed [3 parameters]
      vi. Calibration of soil surface submodel [6 parameters]
      vii. Calibration during diurnal time intervals (with solar radiation)
      viii. Calibration of cover temperature submodel [3 parameters]
      ix. Calibration of soil surface temperature submodel [3 parameters]
      x. Calibration of internal air humidity submodel [2 parameters]
   a. Calibration of the parameters related to natural ventilation (without heating) [2 parameters]
   b. Calibration of the parameters related to heating system (without vents) [2 parameters for pipe heating systems or 1 parameter for air heaters]
2. Calibration of the climate variables with crop
   a. Calibration of the long wave parameters in the cover temperature submodel [1 parameter]
   b. Calibration of the long wave parameters in the soil surface temperature submodel [2 parameters]
   c. Calibration of the parameters related with the crop transpiraton process [4 parameters]
3. Calibration of the PAR radiation model [1 parameter]

The largest number of parameters to estimate simultaneously is six in the processes of soil surface calibration in nocturnal time intervals with an empty greenhouse.

The parameters can be obtained obtained by minimizing a least squares criterion:

$$J = \|\mathbf{X}_{\text{real}} - \mathbf{X}_{\text{sim}}\|^2 = \sum_{i=1}^{N} (X_{\text{real}}(i) - X_{\text{sim}}(i))^2$$

X_{real} is a set of N real measurements of the variables to estimate

X_{sim} are the values of the variables calculated by the implemented model

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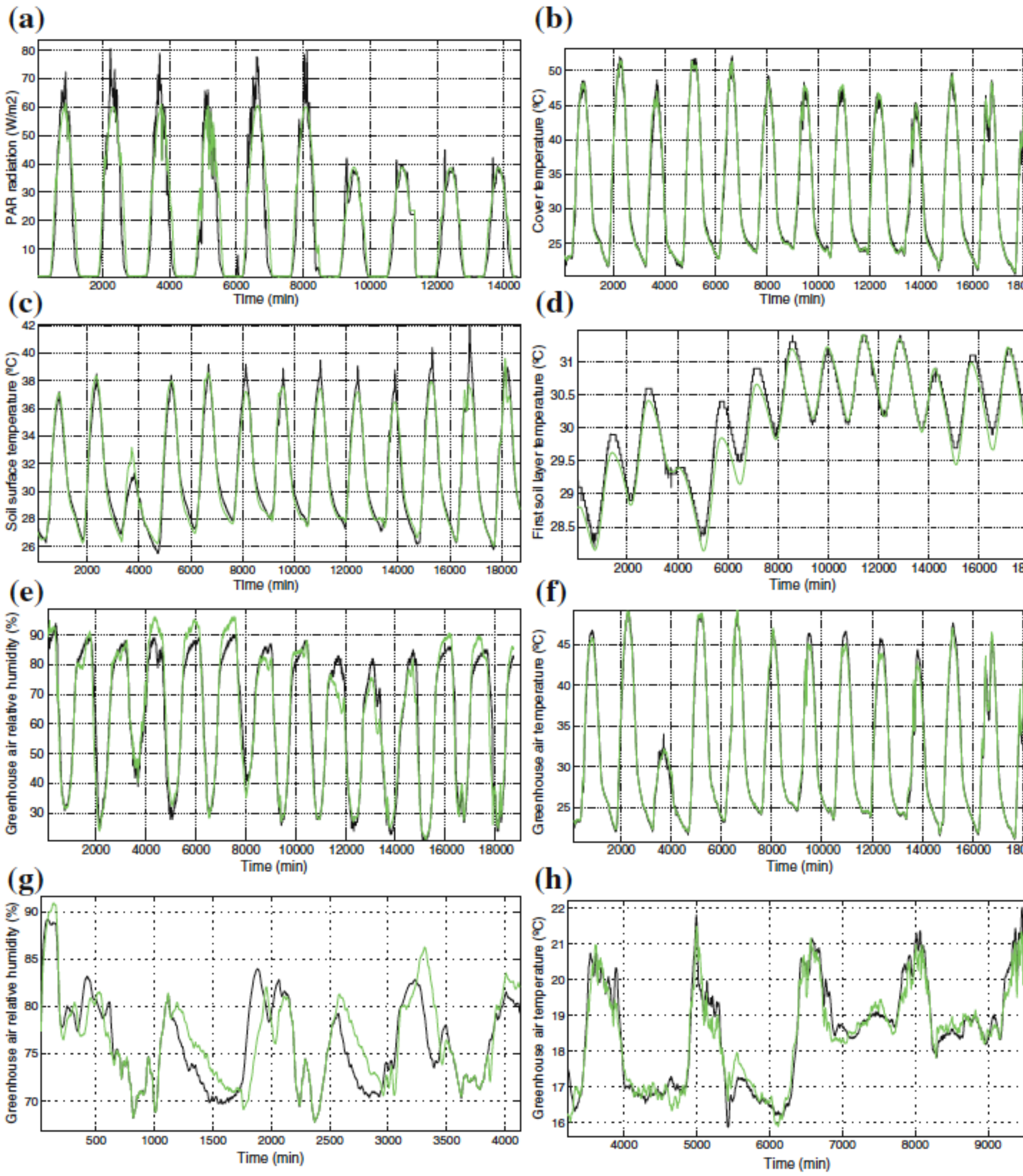
Model Calibration

Araba greenhouse

Almería (Spain)

Summer



Winter

General considerations

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Model Calibration

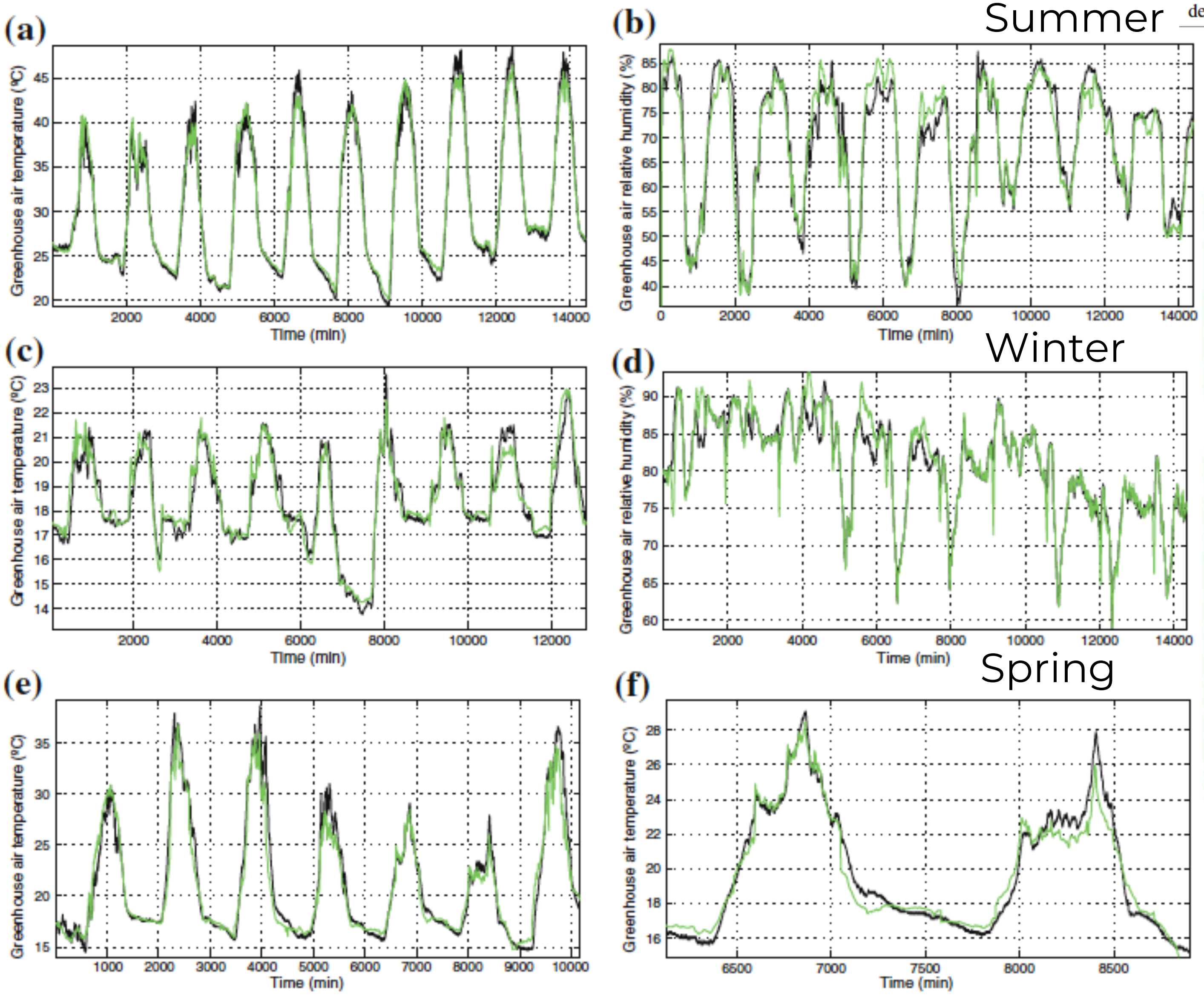
Araba greenhouse

Almería (Spain)

	Summer				Winter		
	Air temp.	Air relative humidity	Cover temp.	Soil surface temp.	First soil layer temp.	Air temp.	Air relative humidity
Variation interval	21.1–49.0 (27.9 °C)	21–94 (73 %)	20.55–52.1 (31.55 °C)	25.5–42 (16.5 °C)	28.19–31.4 (5.9 °C)	11.5–25.5 (14 °C)	47.9–100 (50.3 %)
Mean	0.51	3.96	0.52	0.68	0.25	0.52	2.53
Maximum	2.81	24.32	3.38	4.12	0.79	2.06	17.19
Standard deviation	0.52	3.75	0.53	0.44	0.17	0.48	2.39

Model Validation

	January		April		August	
	Temperature	Humidity	Temperature	Humidity	Temperature	Humidity
Variation interval	11.43–21.67 (10.24 °C)	45.4–99.1 (53.7 %)	11.3–27.3 (16.0 °C)	29.3–58.66 (59.36 %)	18.5–51.1 (32.6 °C)	31.42–92.21 (60.79 %)
Mean	0.56	4.11	0.58	4.54	1.12	3.62
Maximum	4.25	17.85	3.99	20.84	6.05	14.89
Standard deviation	0.52	3.99	0.58	4.09	0.94	3.43



Araba greenhouse

Almería (Spain)

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Model Validation

Araba greenhouse

Almería (Spain)

	January		April		August	
	Temperature	Humidity	Temperature	Humidity	Temperature	Humidity
Variation interval	11.43–21.67 (10.24 °C)	45.4–99.1 (53.7 %)	11.3–27.3 (16.0 °C)	29.3–58.66 (59.36 %)	18.5–51.1 (32.6 °C)	31.42–92.21 (60.79 %)
Mean	0.56	4.11	0.58	4.54	1.12	3.62
Maximum	4.25	17.85	3.99	20.84	6.05	14.89
Standard deviation	0.52	3.99	0.58	4.09	0.94	3.43

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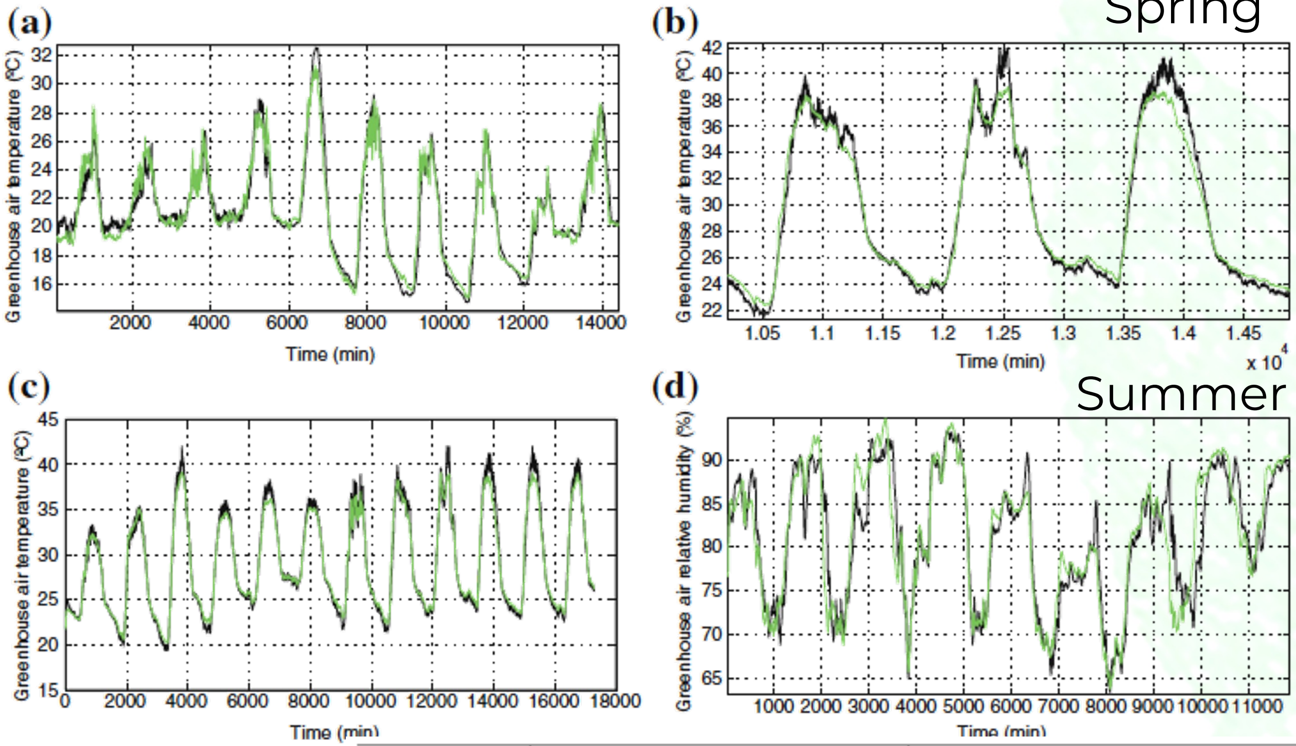
Model Validation



Inamed greenhouse

Almería (Spain)

	January		April		August	
	Temperature	Humidity	Temperature	Humidity	Temperature	Humidity
Variation interval	12.54–23.66 (11.12 °C)	59.4–100 (40.6 %)	14.72–32.53 (17.81 °C)	63.18–93.41 (30.23 %)	18.5–51.1 (32.6 °C)	31.42–92.21 (60.79 %)
Mean	0.48	3.26	0.63	2.11	1.12	4.01
Maximum	3.12	16.01	4.89	12.99	6.05	15.54
Standard deviation	0.43	3.17	0.55	2.19	0.94	3.97

Conclusions

- The internal processes that determine the climate dynamics in a greenhouse are known, so models based on physical principles can be designed and implemented.
- The designed model responds coherently to the dynamics of the external climatic variables and to the state of the installed actuators.
- As all the processes do not occur simultaneously, a theoretical methodology has been proposed to obtain the parameters that characterise them without the need to estimate them all at the same time.
- As the parameters obtained in the calibration process are based on data taken inside a specific greenhouse, the results obtained cannot be extrapolated to other greenhouses, although the fact that the methodology and the model present acceptable results in the independent greenhouses proves their validity.

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Conclusions

- This kind of model is a powerful simulation tool that can be used for the design of controllers, the dimensioning of actuation systems, or to study the effect of different roofing materials on the climate or different growing substrates.
- The formulation and calibration of such models is complex, difficult and tedious:
  - All physical, biological, etc. phenomena have to be taken into account.
  - A large number of variables need to be measured, some of which are difficult to obtain, such as the cover temperature.
  - It is necessary to know the physical parameters of the different elements that make up the greenhouse system.
  - It is necessary to estimate a large number of parameters in the calibration process.

→ It is possible to work with simplified models.

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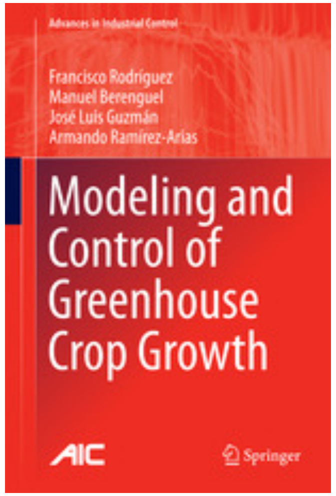
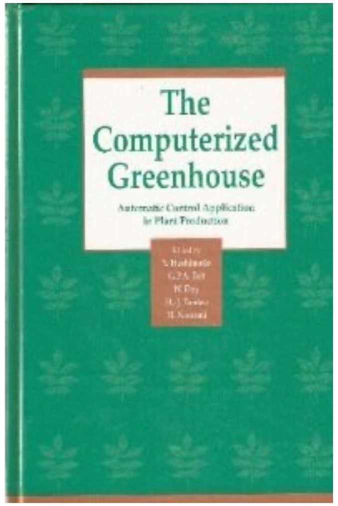
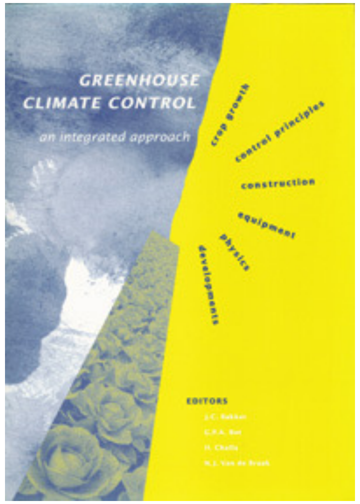
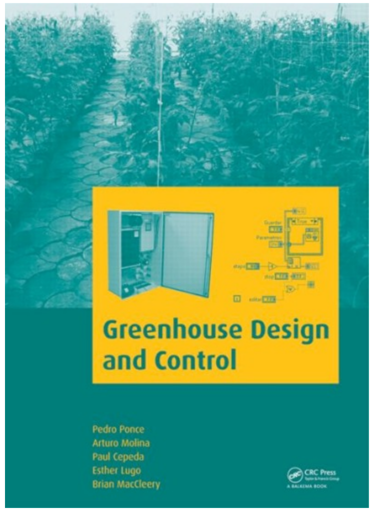
Sources

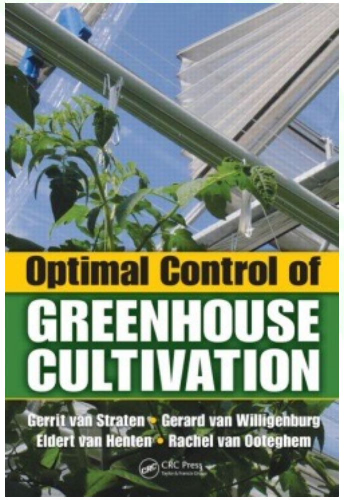


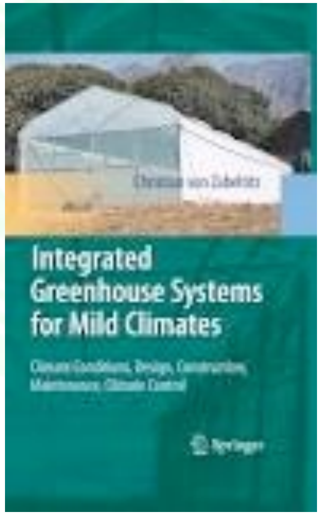
Rodríguez, F., Berenguel, M., Guzman, J.L., Ramírez-Arias, A..; 2015; *Modeling and Control of Greenhouse Crop Growth*; Springer International Publishing; London (UK); 250 pp.

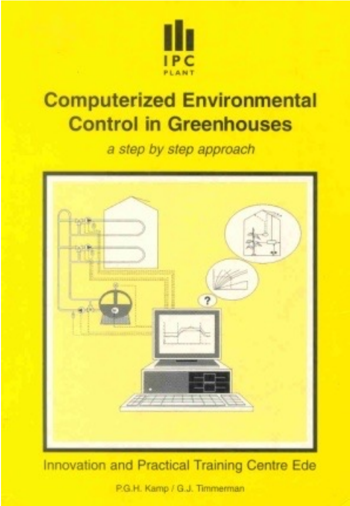












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Co-funded by the Erasmus+ Programme of the European Union

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Module 6: CLIMATE MANAGEMENT

Lesson 6.1: Measurement and Modelling

Theme 6.1.6: Pseudo-physical model

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- General considerations for simplified greenhouse climate modelling
- Climate variables first principles simplified models
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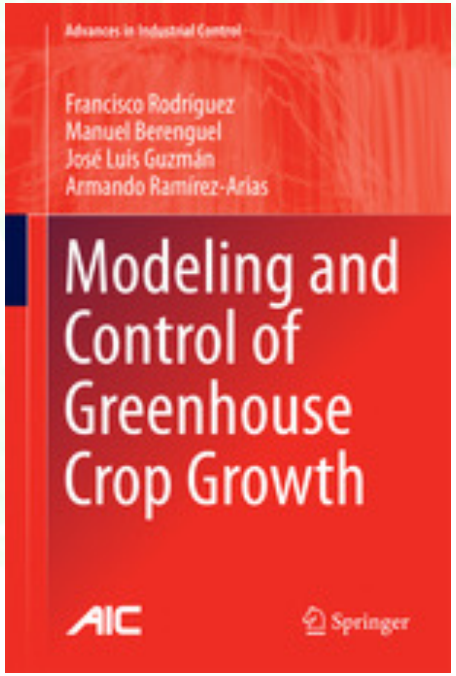
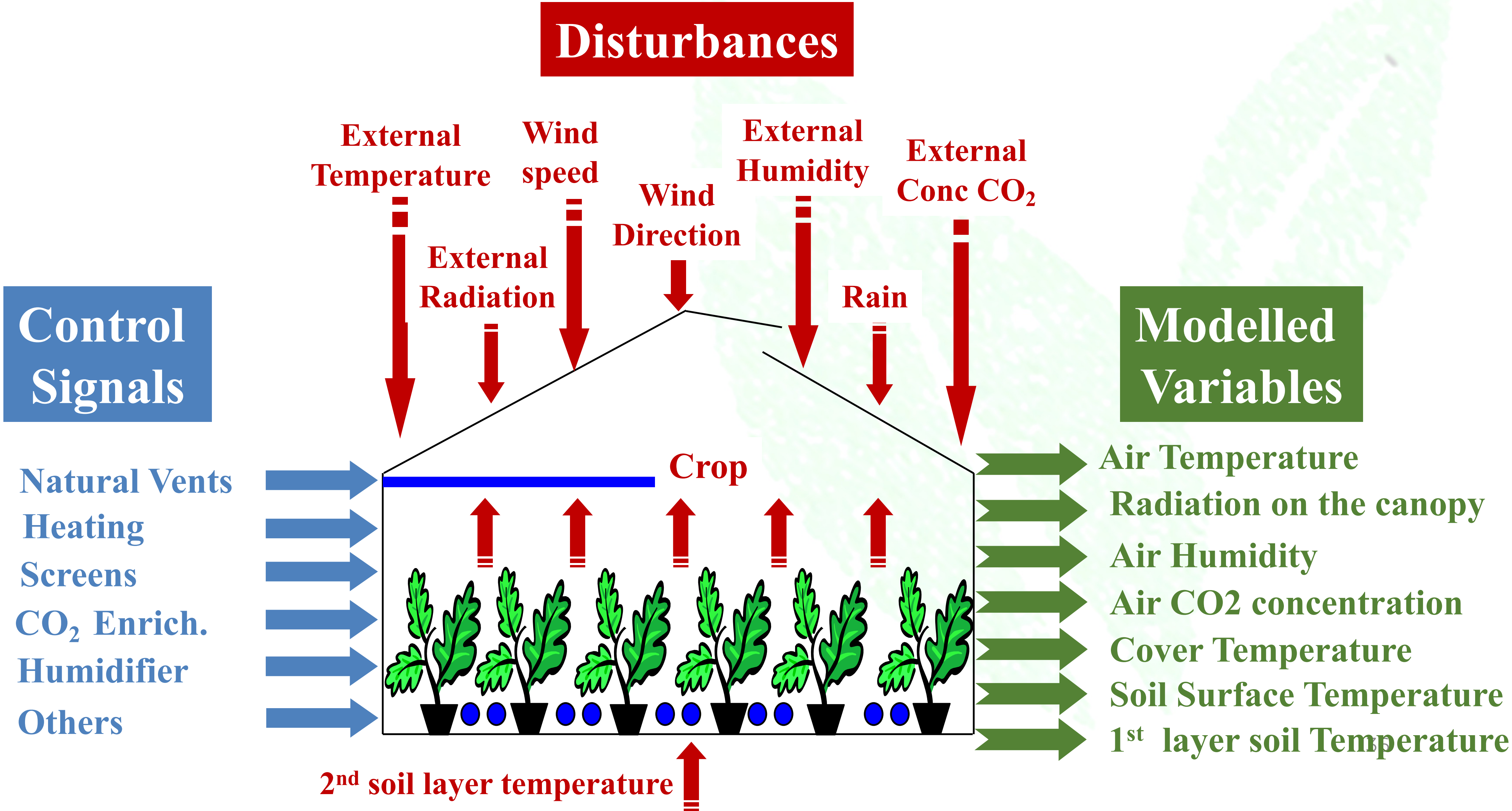
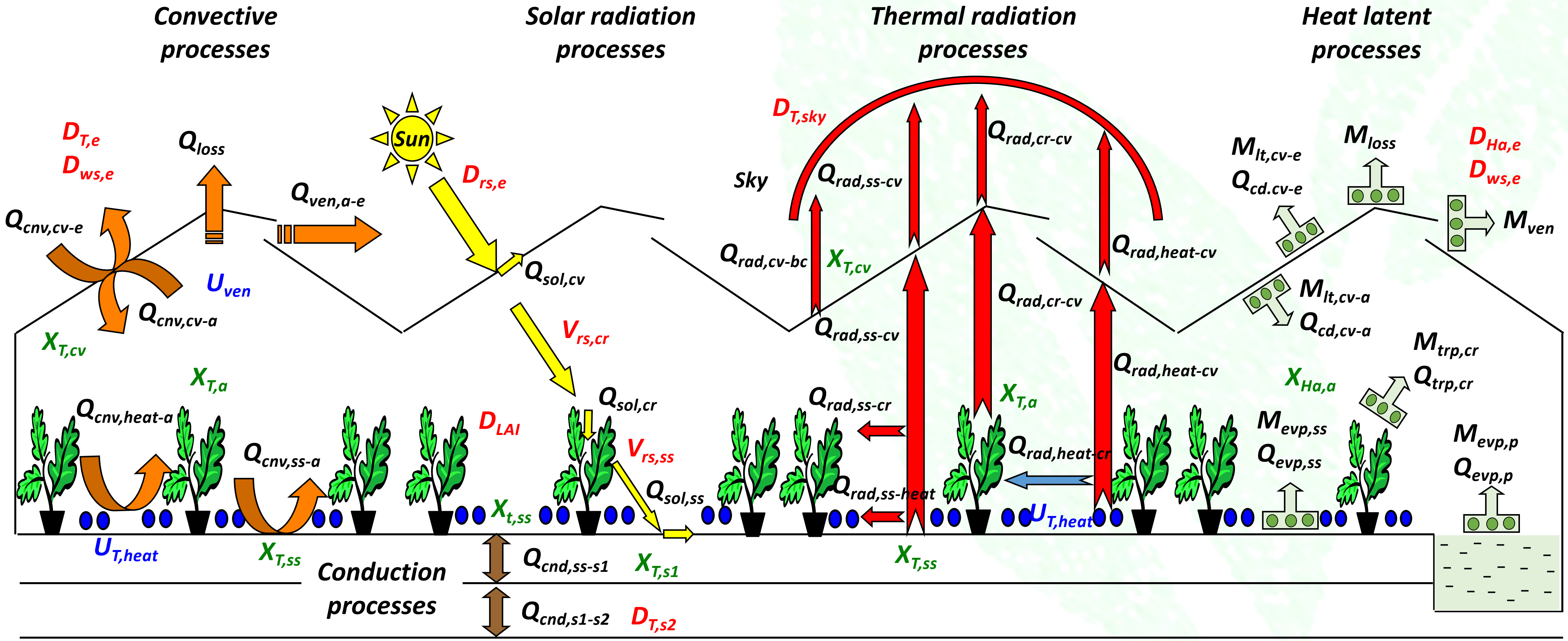
- Conclusions



Complete first principles model



Complete first principles model



Complete first principles model

The greenhouse dynamics are defined by a system of 6 ODEs given as:

$$\frac{\mathrm{d}\mathbf{X}}{\mathrm{d}t} = f\,(\mathbf{X}, \mathbf{U}, \mathbf{D}_m, \mathbf{V}, \mathbf{C}, t) \text{ with } \mathbf{X}(t_i) = \mathbf{X}_i$$

Where:

$X=X(t) \in R^n$	is a n-dimensional vector of state variables (n=6)
$U=U(t) \in R^m$	is a m-dimensional vector of input variables (m= 7)
$P=P(t) \in R^o$	is an o-dimensional vector of measurable disturbances (o= 8)
$V=V(t) \in R^p$	is a p-dimensional vector of system variables
$C \in R^q$	is a q-dimensional vector of system constants
t	is the time
X_{ti}	is the known initial state at the initial time
t_i	is the initial time
$f: R^{n+m+o+p+q} \rightarrow R^n$	is a nonlinear function based on mass and heat transfer balances.

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Complete first principles model

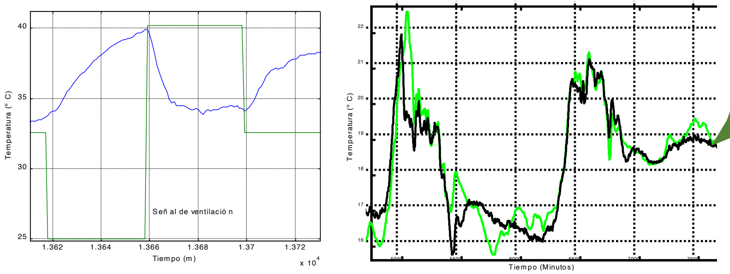
- This kind of model is a powerful simulation tool that can be used for the design of controllers, the dimensioning of actuation systems, or to study the effect of different roofing materials on the climate or different growing substrates.

- The formulation and calibration of such models is complex, difficult and tedious:

It is possible to work with simplified models

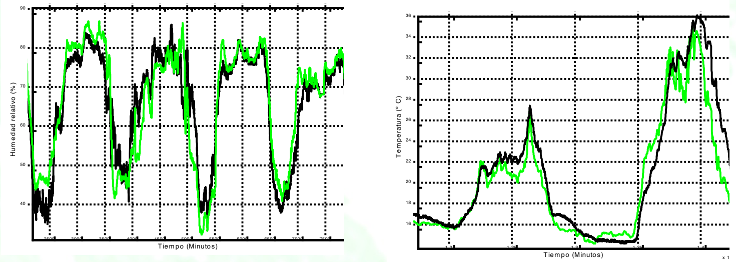
Simplified models

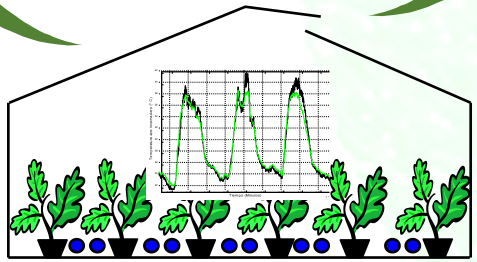
Linear empirical models based on the reaction curve



Simplified first principles models

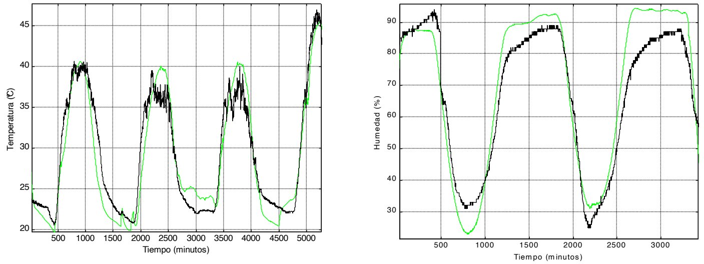
$$c_{ter,a}\frac{dX_{t,a}}{dt} = c_r P_{r,e} + c_h(X_{t,h} - X_{t,a}) - (\varphi_v + \varphi_c)(X_{t,a} - P_{t.e}) + c_s(X_{t,s} - X_{t,a}) + V_\lambda V_{evap}$$



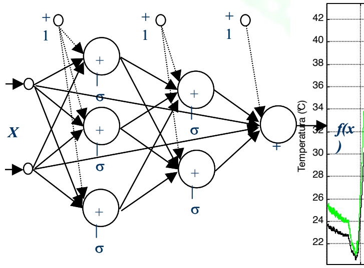


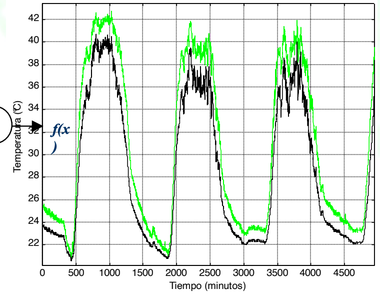
Linear empirical models based on ARX structures

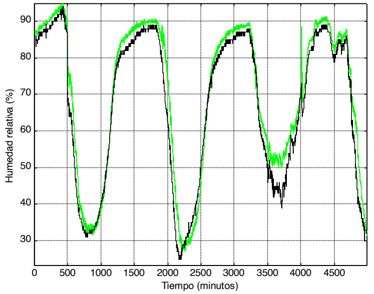
$$A(z^{-1})y(k) = B(z^{-1})u(k) + v(k)$$



Non-linear empirical models based on neural networks







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Simplified models

The main objective of a model for some applications (such as control) is its ability to capture the dominant dynamics of the modelled system

Models based on simplified first principles that are able to capture the dynamics of the main climate variables of a greenhouse can be used.

They are represented by a system of differential equations:

$$\frac{dX}{d\tau} = f(X, U, P, V, C, \tau) \quad \text{with} \quad X(\tau_i) = X_i$$

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General considerations

The main subsystems of a greenhouse are:

- Air. It is a gaseous medium joining the different solid elements in the greenhouse.
- Soil. It is a porous medium responsible for the greenhouse thermal inertia, absorbing energy during the day and emitting it overnight

The following system are not considered:

- Cover. It is only an interface between the inside and outside air where energy is exchanged depending on the inside-outside temperature difference.
- Crop. its effect on climate is modeled by transpiration and CO2 supply or consumption due to photosynthesis and respiration

General considerations

- Although air is inert to radiation, most simplified models of inside air temperature include a term depending on global radiation to model air warming due to the sun.
- The soil surface temperature model only considers the energy fluxes due to convection processes with greenhouse air and conduction ones with the first soil layer are taken into account. The thermal radiation processes among physical elements of the greenhouses are not considered.
- Heat transfer coefficients with the soil or heating pipes are considered constant.
- The model of several physical processes such as ventilation is simplified, often using empirical relationships or considering some energy fluxes in steady state, such as those from the heating system

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General Hypotheses

- If soil surface temperature sensors are available, then the greenhouse model only consider the greenhouse air as elements.
- The external elements that interact with greenhouse are: external air, crop and soil layers.
- The physical properties of air are considered constant with respect to temperature and time.
- The state variables of the model are: greenhouse air temperature ($X_{T,a}$), CO2 concentration ($X_{co2,a}$) and humidity (absolute $X_{Ha,a}$ and relative $X_{Hr\ ,a}$), and first soil layer temperature ($X_{T,sl}$) if it is not measured.

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General Hypotheses

- The exogenous and disturbance inputs acting on the system are the outside air temperature ($D_{T,e}$), CO2 concentration ($D_{CO2,e}$) and absolute humidity ($D_{Ha,e}$), wind speed ($D_{ws,e}$) and direction ($D_{wd,e}$), outside global solar radiation ($D_{rs,e}$), PAR radiation ($D_{rp,e}$), greenhouse whitening (D_{wh}), the transpiration rate inside the greenhouse via the leaf area index (D_{LAI}) and the temperature of the soil layer [soil surface ($D_{T,ss}$) or deepest soil layer ($D_{T,s2}$)].
- The control inputs of the system are: the position of the natural ventilation (U_{ven}), the position of the shade screen (U_{shd}), the heating system (U_{heat}), the humidifier system (U_{hum}), the dehumidifier system (U_{dhum}), and the CO_2 enrichment system(U_{CO2}).
- A uniform homogeneous distribution of variables is considered in the air and soil.

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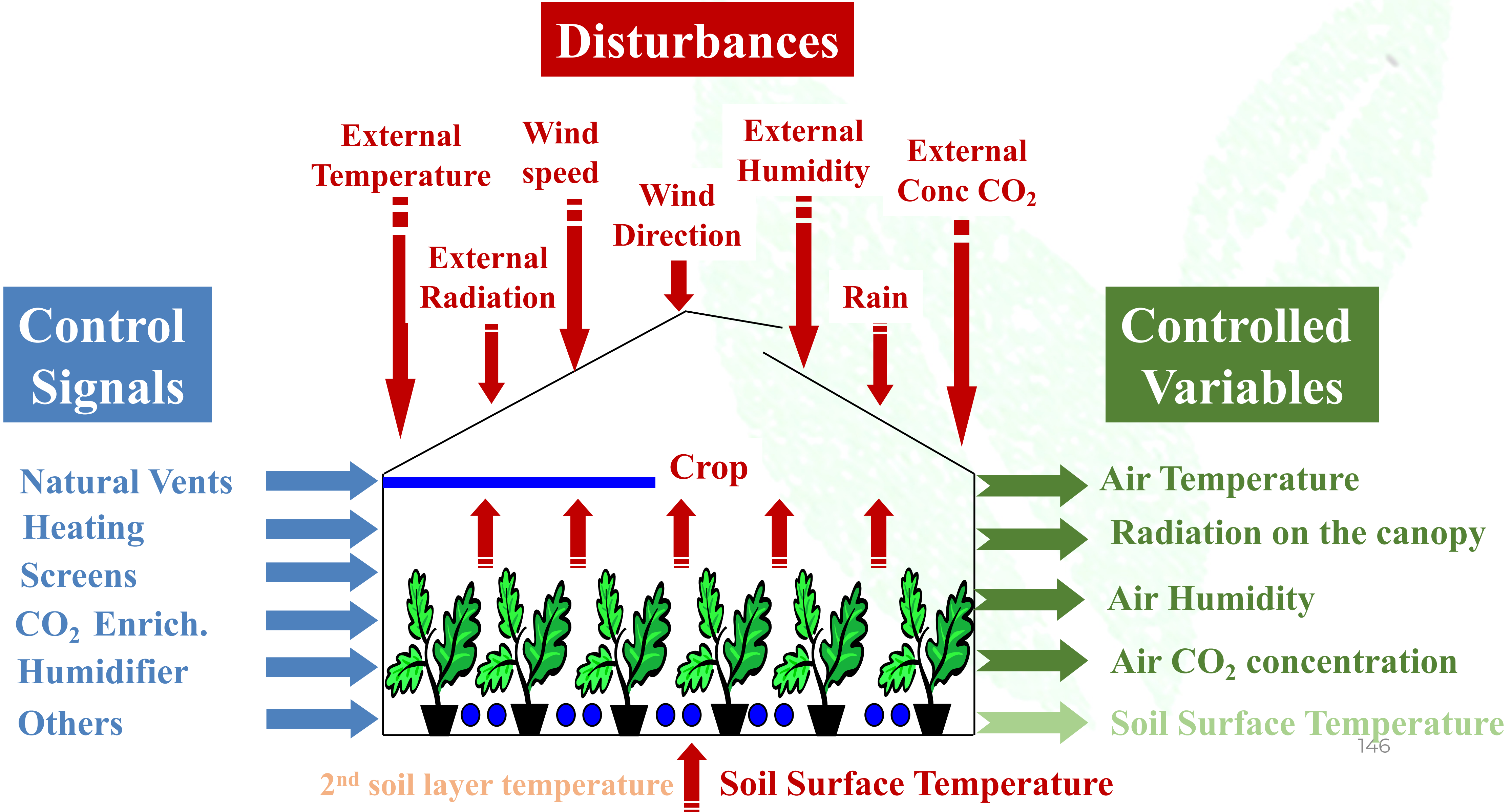
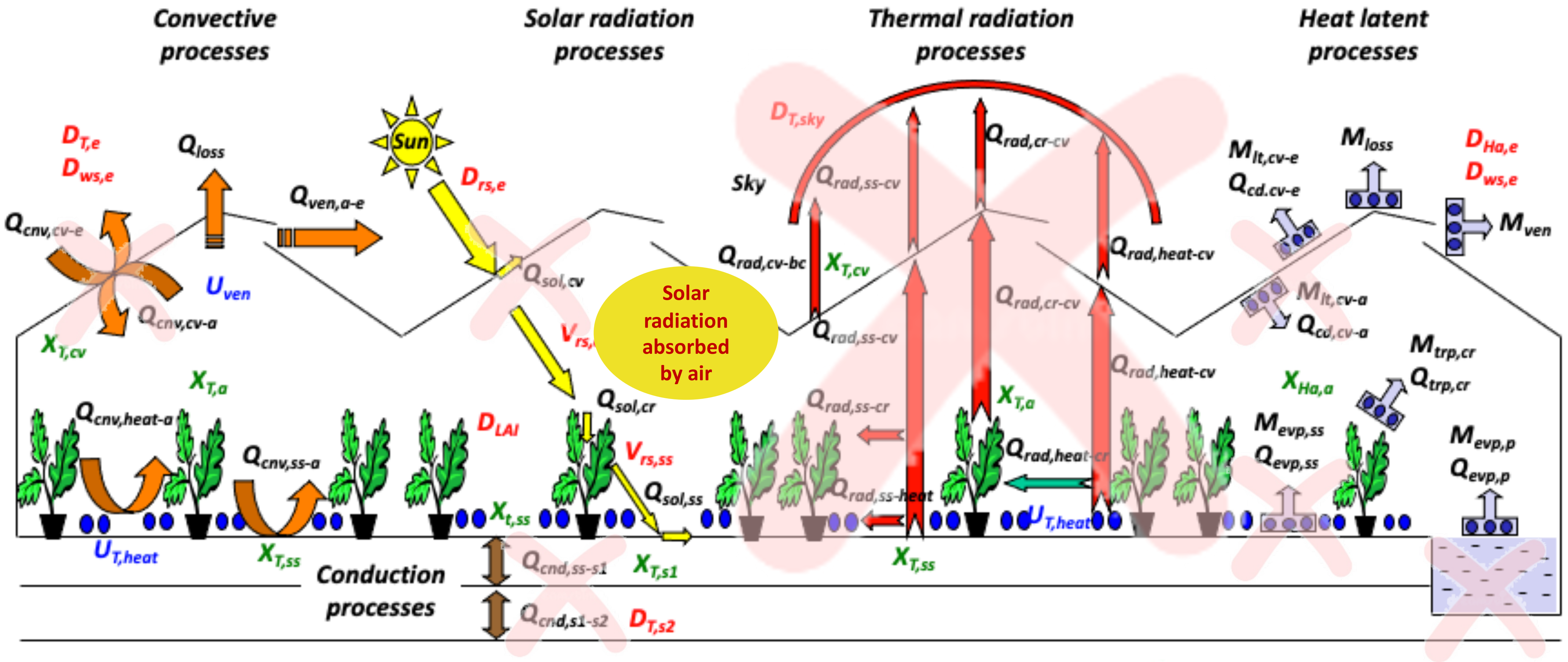
General Hypotheses



General Hypotheses



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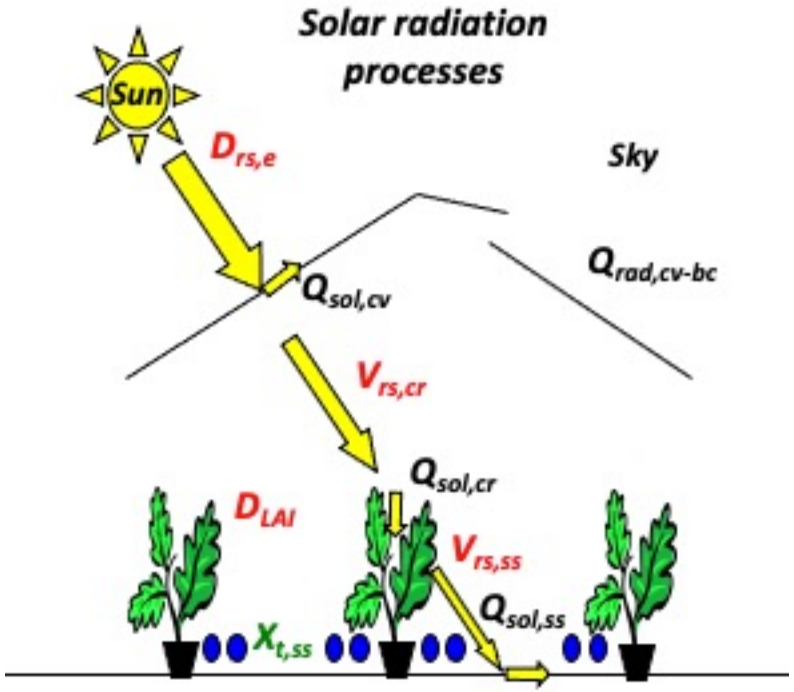
Radiation (Global and PAR) model

The Global and PAR radiation onto the canopy is modeled using an algebraic equation, because it is similar to the external radiation dimmed by the different physical elements that absorb the radiation (mainly cover material, cover whitening and shade screen)



$$X_{\mathrm{rp,a}} = V_{\mathrm{tsw,g}} D_{\mathrm{rp,e}}$$

$$V_{\mathrm{tsw,g}} = \begin{cases} c_{\mathrm{tsw,cv}} & \text{no shade, no whitening} \\ c_{\mathrm{tsw,cv}} c_{\mathrm{tsw,wh}} & \text{no shade, whitening} \\ c_{\mathrm{tsw,cv}} c_{\mathrm{tsw,shd}} & \text{shade, no whitening} \\ c_{\mathrm{tsw,cv}} c_{\mathrm{tsw,wh}} c_{\mathrm{tsw,shd}} & \text{shade, whitening} \end{cases}$$

Greenhouse Air Temperature model

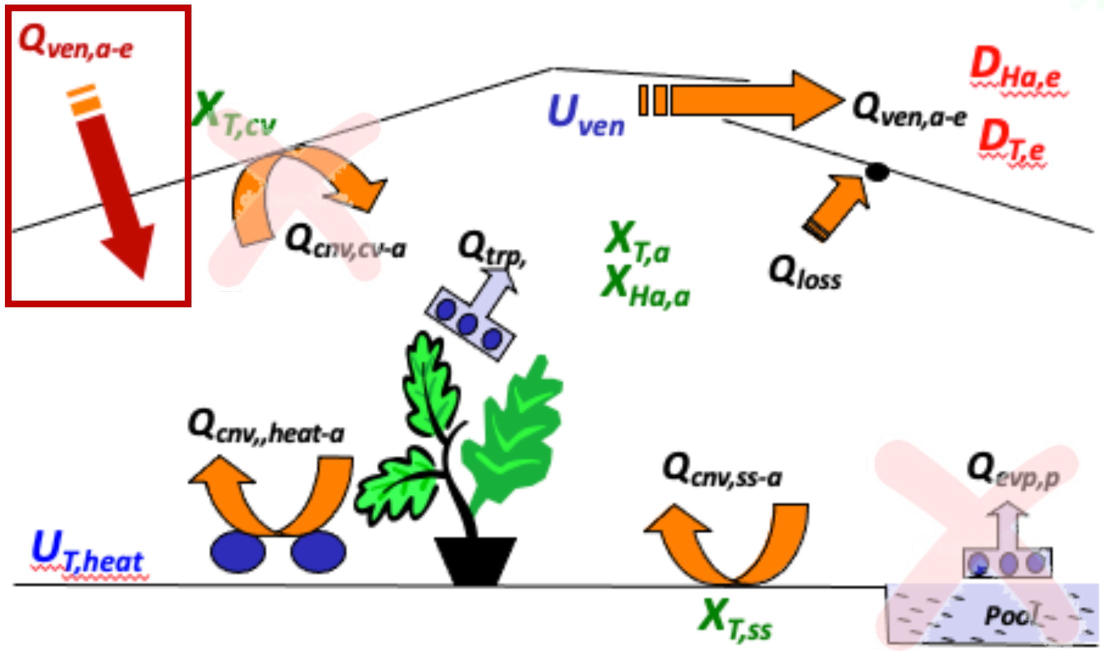
The greenhouse air temperature can be modeled using the following balance

Actuators

Air Temperature

$$c_{sph,a} c_{den,a} \frac{c_{vol,g}}{c_{area,ss}} \frac{dX_{T,a}}{dt} = Q_{sol,a} + Q_{cnv,ss-a} + Q_{heat-a} + Q_{cnv-cnd,a-e} - Q_{ven,a-e} - Q_{loss,a-e} - Q_{trp,cr}$$

Solar radiation absorbed by air



Q_{sol-a} is the solar radiation absorbed by the air

$Q_{cnv-cnd,a-e}$ is the convective-conductive flux with the cover

$Q_{cnv,ss-a}$ is the flux with the soil surface

Q_{heat-a} is the heat flux due to the heating system

Q_{ven} is the heat lost by natural ventilation and the heat lost by infiltration losses

$Q_{loss,a-e}$ is the heat lost by infiltration losses

$Q_{trp,cr}$ is the latent heat effect of the crop transpiration

Greenhouse Air Temperature model

The greenhouse air temperature can be modeled using the following balance

Air Temperature

$$c_{\mathrm{sph,a}} c_{\mathrm{den,a}} \frac{c_{\mathrm{vol,g}}}{c_{\mathrm{area,ss}}} \frac{\mathrm{d}X_{\mathrm{T,a}}}{\mathrm{d}t} = Q_{\mathrm{sol,a}} + Q_{\mathrm{cnv,ss-a}} + Q_{\mathrm{heat-a}} + Q_{\mathrm{cnv-cnd,a-e}} - Q_{\mathrm{ven,a-e}} - Q_{\mathrm{loss,a-e}} - Q_{\mathrm{trp,cr}}$$

$$Q_{\mathrm{sol,a}} = c_{\mathrm{asw,a}} V_{\mathrm{rs,cr}}$$

Constants in this kind of model

$$Q_{\mathrm{cnv,ss-a}} = c_{\mathrm{cnv,ss-a}} (X_{\mathrm{T,ss}} - X_{\mathrm{T,a}})$$

$$Q_{\mathrm{cnd-cnv,a-e}} = c_{\mathrm{cnd-cnv,a-e}} (X_{\mathrm{T,a}} - D_{\mathrm{T,e}})$$

$$Q_{\mathrm{ven,a-e}} + Q_{\mathrm{loss,a-e}} = \frac{c_{\mathrm{den,a}} c_{\mathrm{sph,a}}}{c_{\mathrm{area,ss}}} V_{\mathrm{ven,flux}} (X_{\mathrm{T,a}} - D_{\mathrm{T,e}})$$

$$Q_{\mathrm{trp,cr}} = V_{\mathrm{lt,vap}} M_{\mathrm{trp,cr}}$$

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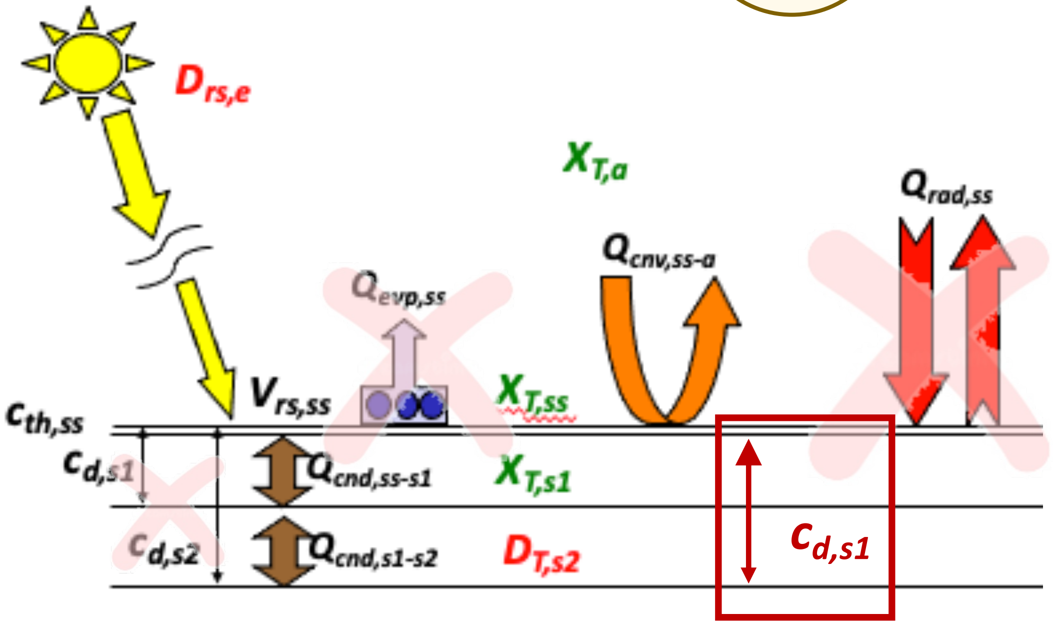
Soil surface temperature model

If necessary, the soil surface temperature can be modeled using the following balance:

Soil surface Temperature

$$c_{\mathrm{sph,ss}} c_{\mathrm{den,ss}} c_{\mathrm{th,ss}} \frac{\mathrm{d}X_{\mathrm{T,ss}}}{\mathrm{d}t} = Q_{\mathrm{sol,ss}} - Q_{\mathrm{cnv,ss-a}} - Q_{\mathrm{cnd,ss-s1}}$$



$Q_{sol,ss}$ is the solar radiation absorbed by the soil surface

$Q_{cnv,ss-a}$ is the convective heat transfer with the internal air

$Q_{cnd,ss-s1}$ is the conductive flux between the soil surface, and the deep soil layer

Soil surface temperature model

If necessary, the soil surface temperature can be modeled using the following balance:

Soil surface Temperature

$$c_{sph,ss} c_{den,ss} c_{th,ss} \frac{dX_{T,ss}}{dt} = Q_{sol,ss} - Q_{cnv,ss-a} - Q_{cnd,ss-s2}$$

$$Q_{sol,ss} = c_{asw,ss} V_{rs,cr} \exp\left(-c_{extsw,cr} D_{LAI}\right)$$

$$V_{rs,cr} = V_{tsw,g} D_{rs,e}$$

Constant in this kind of model

$$Q_{cnv,ss-a} = c_{cnv,ss-a} (X_{T,ss} - X_{T,a})$$

$$Q_{cnd,ss-s1} = c_{cnd,s1} \frac{X_{T,ss} - X_{T,s1}}{c_{d,s1} - c_{d,ss}}$$

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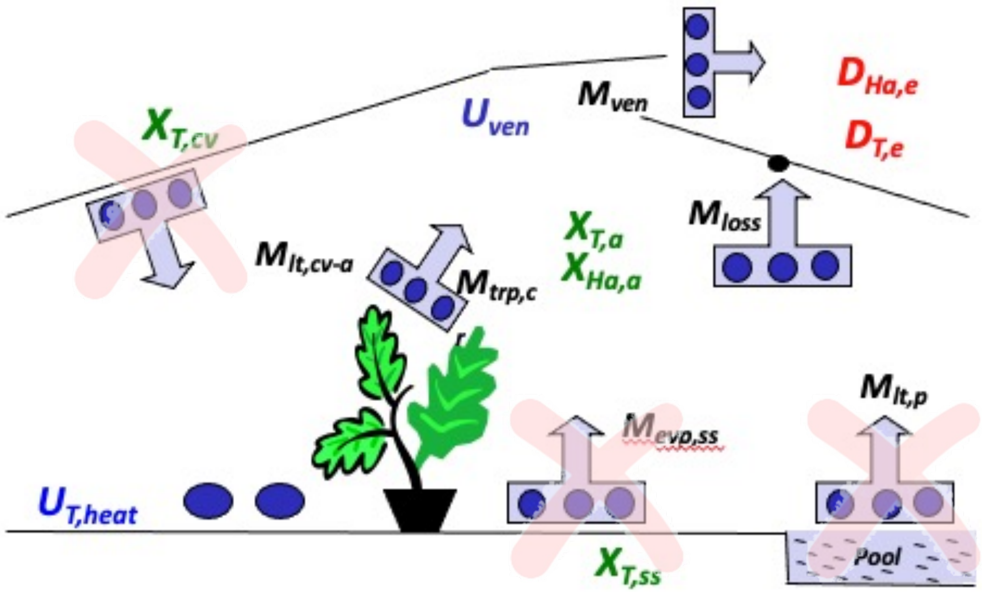
Water Mass Transfer Fluxes with the Internal Air

The greenhouse air absolute humidity can be modeled with a water vapor mass balance equation:

Greenhouse air absolute humidity

Actuators

$$c_{\mathrm{den,a}}(c_{\mathrm{vol,g}}/c_{\mathrm{area,ss}})\frac{dX_{\mathrm{H_{a,a}}}}{dt} = M_{\mathrm{trp,cr}} - M_{\mathrm{ven,a-e}} + M_{Hum} - M_{DHum}$$



$M_{trp,cr}$ is the crop transpiration flux

$M_{ven,a\text{-}e}$ is the is the outflow by natural ventilation and infiltration losses

M_{Hum} is the is the water mass provided by humidifiers

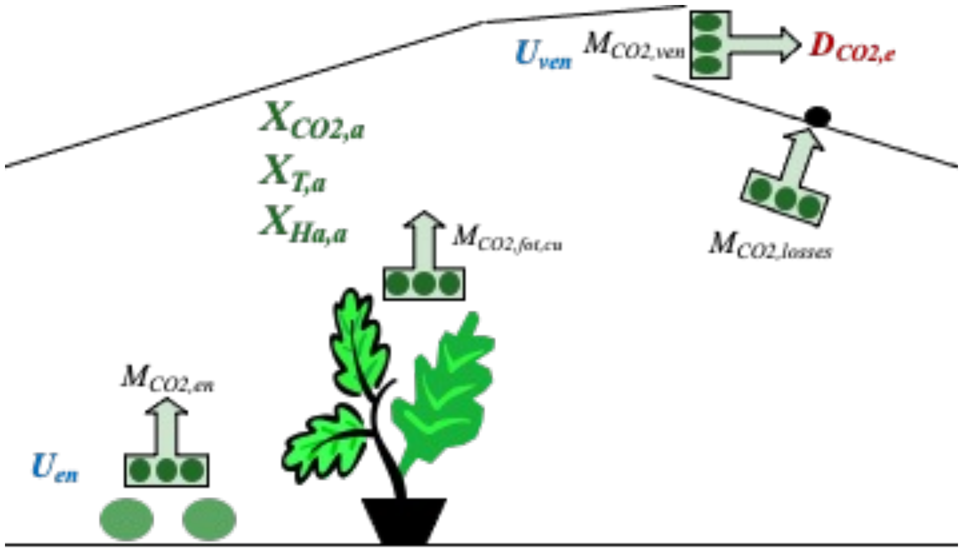
M_{DHum} is the is the water mass removed by dehumidifiers

CO_2 Mass Transfer Fluxes with the Internal Air

The CO_2 concentration in greenhouse air can be modeled with a CO_2 mass balance equation: :

Greenhouse air CO_2 **Actuators**

$$\frac{c_{volg}}{c_{area,s}} c_{m,CO2} \frac{dX_{CO2,a}}{dt} = M_{CO2,fot} + M_{CO2,en} - M_{CO2,ven} - M_{CO2,losses}$$



$M_{CO2,fot}$ is the CO_2 mass by crop photosynthesis
$M_{CO2,en}$ is the is the CO_2 mass provided by the enrichment systems
$M_{CO2,ven}$ is the is the CO_2 mass removed by natural vents
$M_{CO2,losses}$ is the is the CO_2 mass removed by infiltration losses

Model implementation and calibration

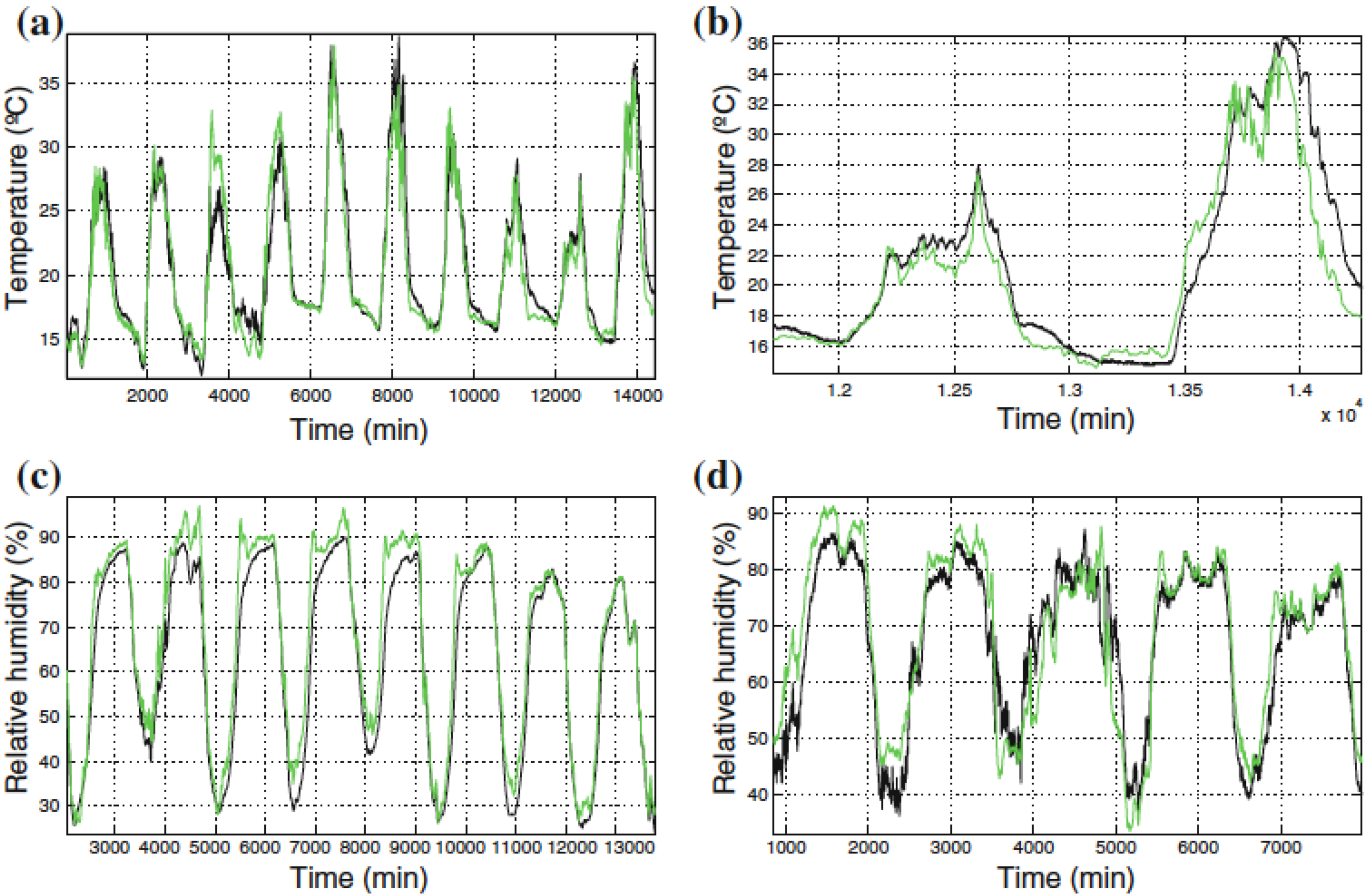
In order to implement, calibrate and validate the model, the same techniques described in complete first principles model section must be used.

Inamed greenhouse

Almería (Spain)

	January		April		August	
	Temperature	Humidity	Temperature	Humidity	Temperature	Humidity
Variation interval	13.76–23.55 (9.79 °C)	55.64–100 (44.36 %)	14.5–38.6 (24.1 °C)	36.2–87.7 (51.5 %)	19.4–48.6 (29.2 °C)	36.36–87.4 (51.11 %)
Mean	0.74	3.64	1.31	4.32	1.14	4.71
Maximum	3.67	17.10	6.71	20.02	5.32	22.01
Standard deviation	0.71	3.23	1.36	3.86	1.09	3.79

Model implementation and calibration



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General considerations

Simplified Climate models

Model calibration and validation

Conclusions

Comparation models

Simplified model

	January		April		August	
	Temperature	Humidity	Temperature	Humidity	Temperature	Humidity
Variation interval	13.76–23.55 (9.79 °C)	55.64–100 (44.36 %)	14.5–38.6 (24.1 °C)	36.2–87.7 (51.5 %)	19.4–48.6 (29.2 °C)	36.36–87.4 (51.11 %)
Mean	0.74	3.64	1.31	4.32	1.14	4.71
Maximum	3.67	17.10	6.71	20.02	5.32	22.01
Standard deviation	0.71	3.23	1.36	3.86	1.09	3.79

First Principles complete model

	January		April		August	
	Temperature	Humidity	Temperature	Humidity	Temperature	Humidity
Variation interval	12.54–23.66 (11.12 °C)	59.4–100 (40.6 %)	14.72–32.53 (17.81 °C)	63.18–93.41 (30.23 %)	18.5–51.1 (32.6 °C)	31.42–92.21 (60.79 %)
Mean	0.48	3.26	0.63	2.11	1.12	4.01
Maximum	3.12	16.01	4.89	12.99	6.05	15.54
Standard deviation	0.43	3.17	0.55	2.19	0.94	3.97

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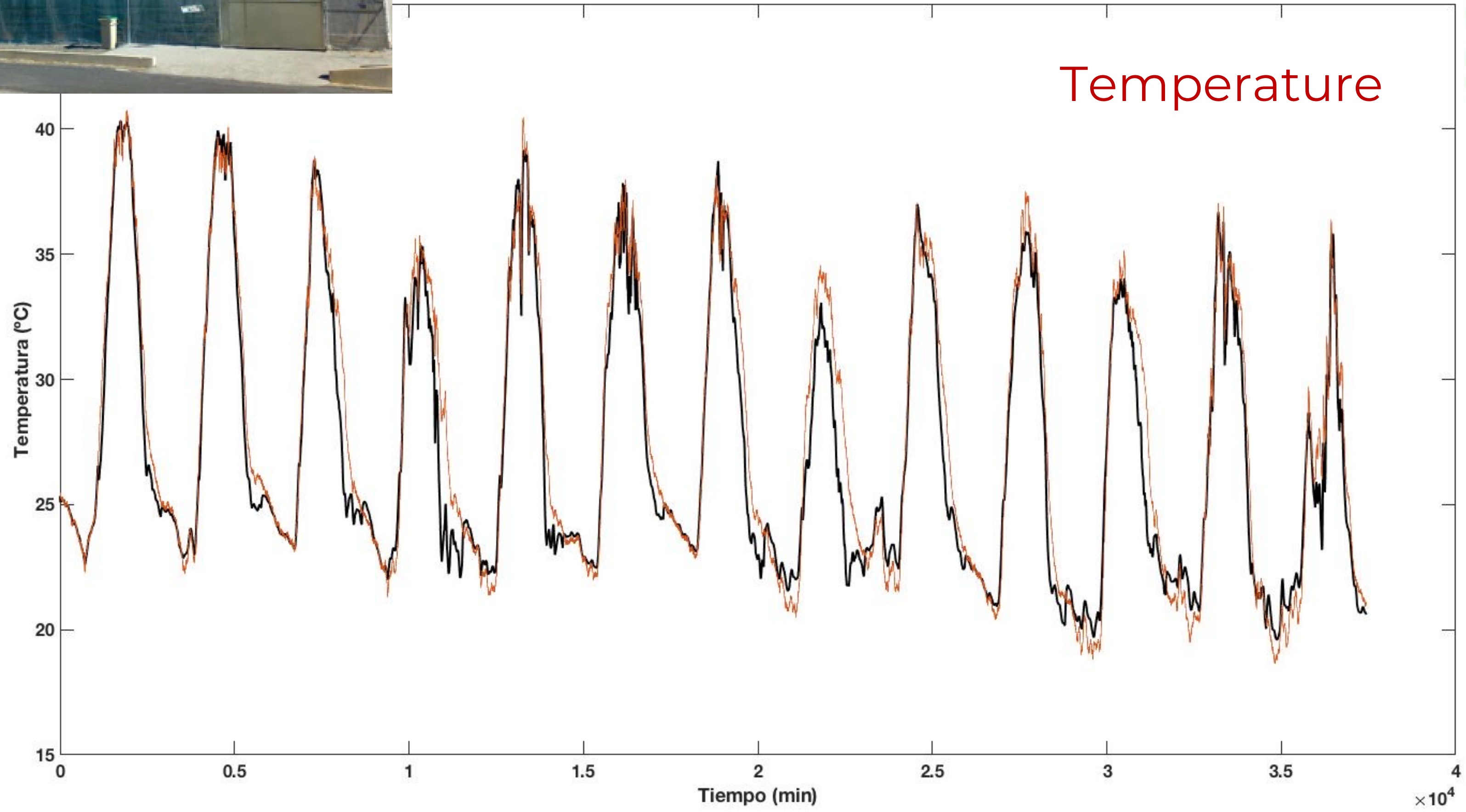
Model Validation

Almeria type greenhouse

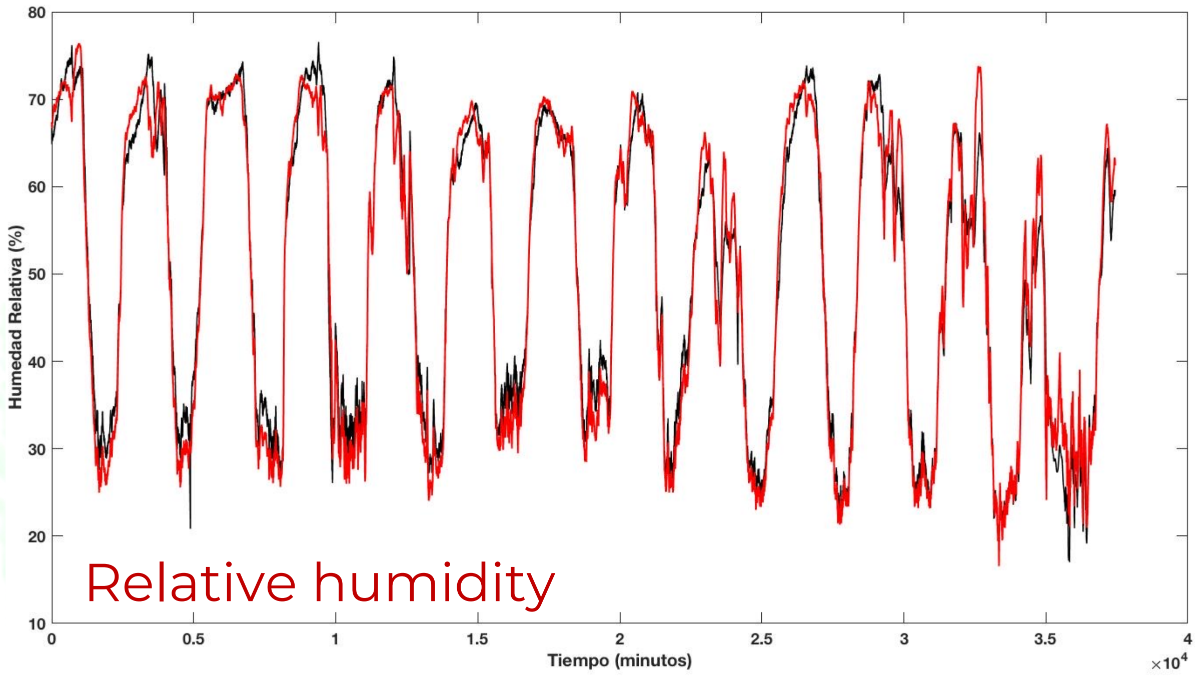
Almería (Spain)

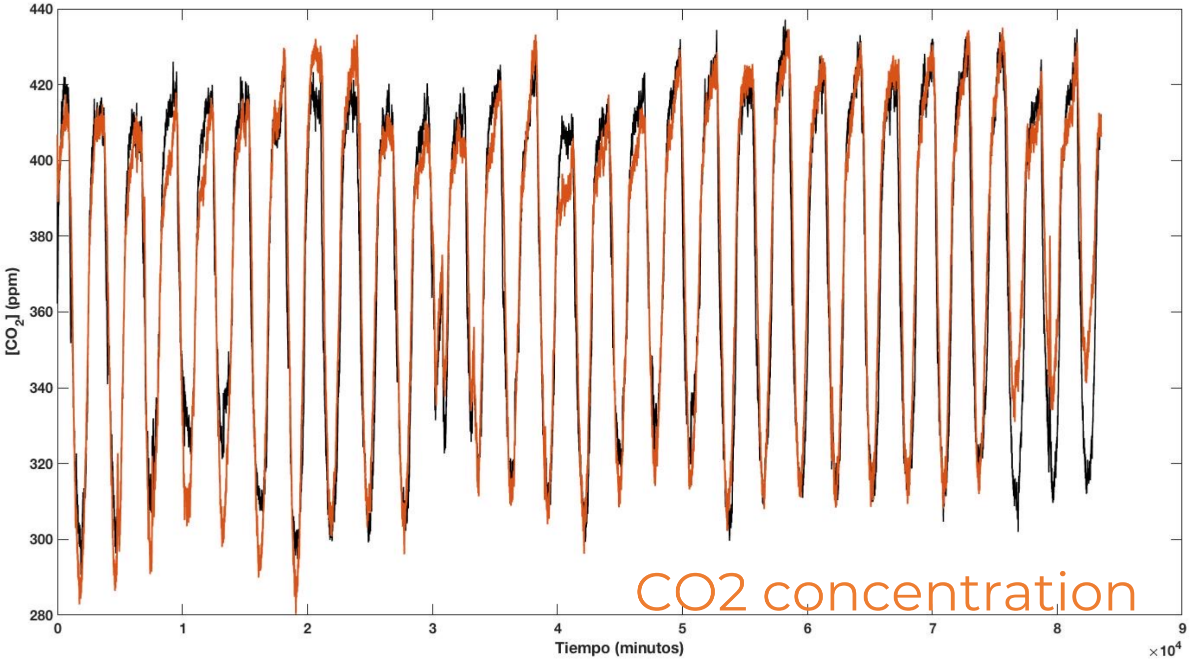


Model Validation

Almeria type greenhouse

Almería (Spain)





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General considerations

Simplified Climate models

Model calibration and validation

Conclusions

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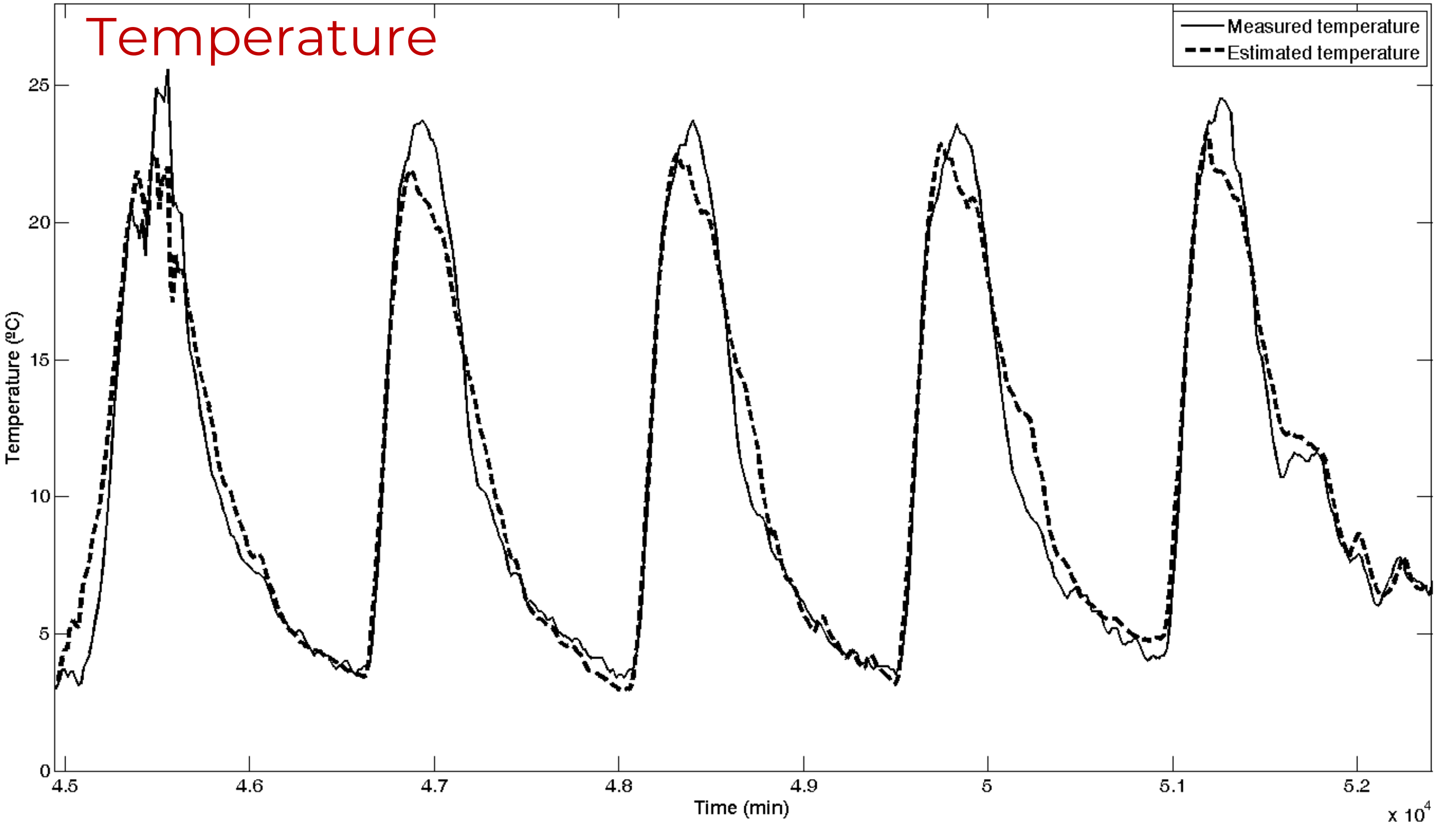
Model Validation

Chinese greenhouse

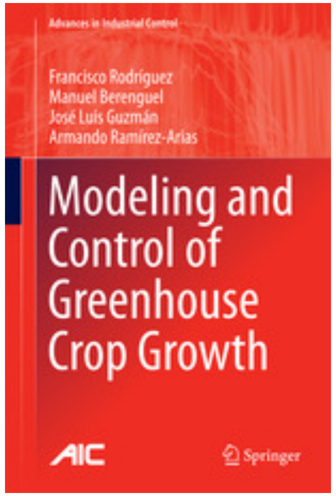
Beijing (China)



Conclusions

- The designed simplified model responds coherently to the dynamics of the external climatic variables and to the state of the installed actuators.
- They are pseudo physical models because use process that really don’t occur in the greenhouse to simulate the effect of other not considered processes . Furthermore, the formulation of other processes are simplified.
- The calibration process is less expensive because the number of parameters to be estimated is much smaller.
- As the parameters obtained in the calibration process are based on data taken inside a specific greenhouse, the results obtained cannot be extrapolated to other greenhouses, although the fact that the methodology and the model present acceptable results in the independent greenhouses proves their validity.

Sources



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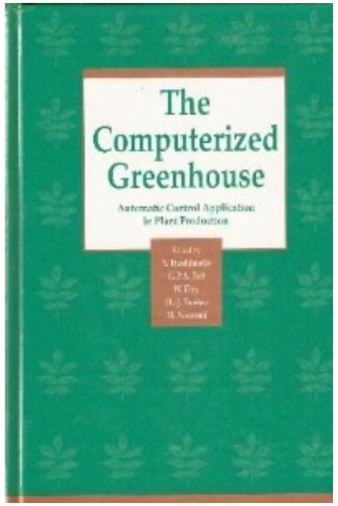

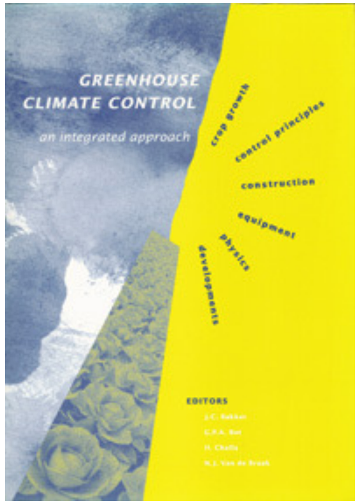

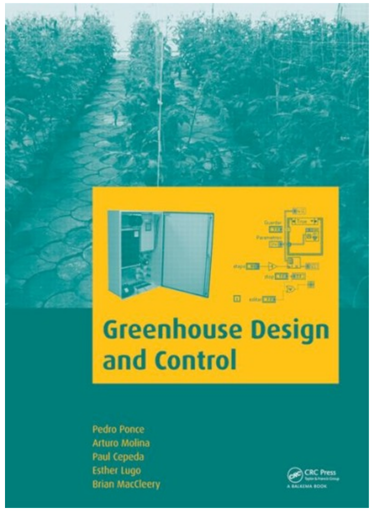

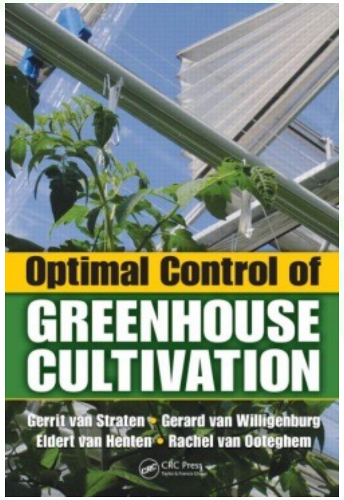

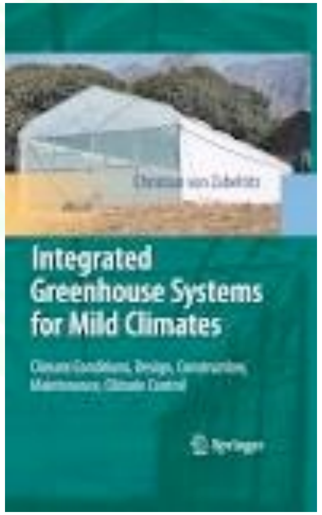

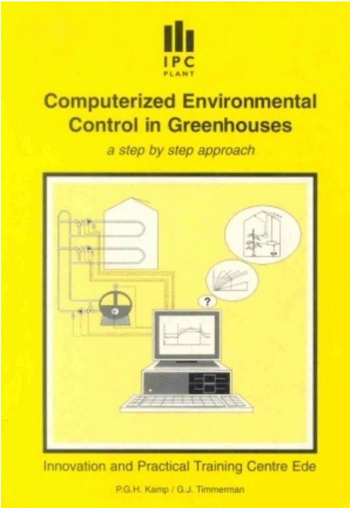

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Module 6: CLIMATE MANAGEMENT

Lesson 6.2: Greenhouse climate variable control

Theme 6.2.1: Greenhouse temperature control with natural vents

Temperature control

Control schema

Control algorithms

Conclusions

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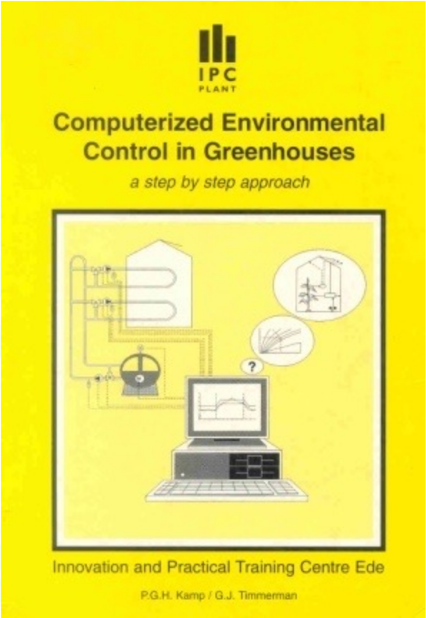
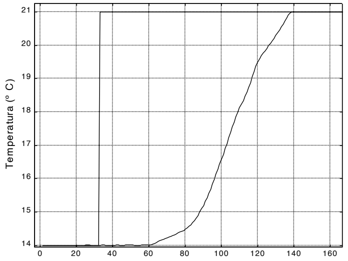
- Temperature control problem
- Control schema
- Control algorithms
- Conclusions

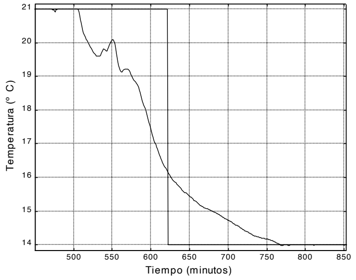


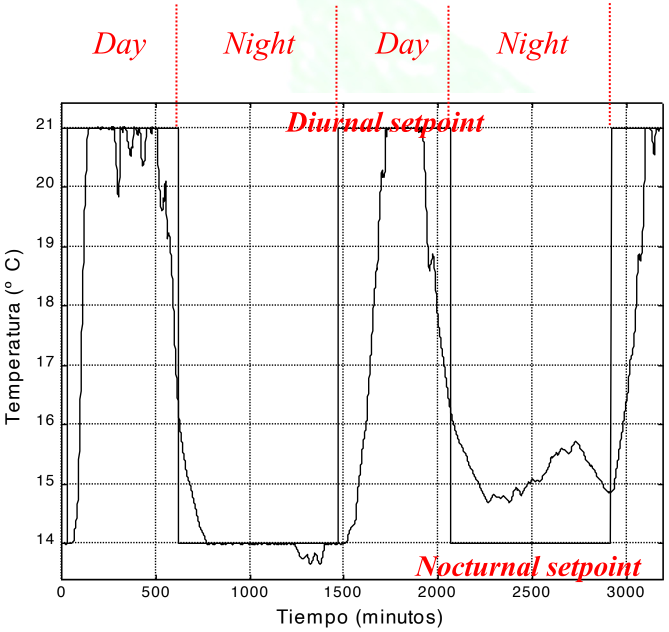
Kamp, P.G.H.; Timmerman, G.J.; 1996; *Computerized environmental control in greenhouses. A step by step approach*; IPC Plant; Ede; 273 pp. .

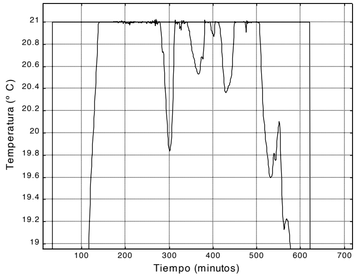
Temperature control problem



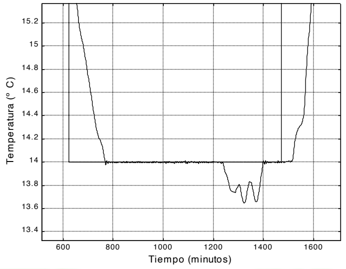
Transition from night to day and vice versa.



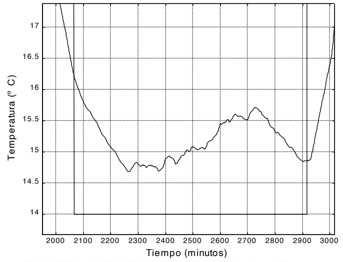




Diurnal time



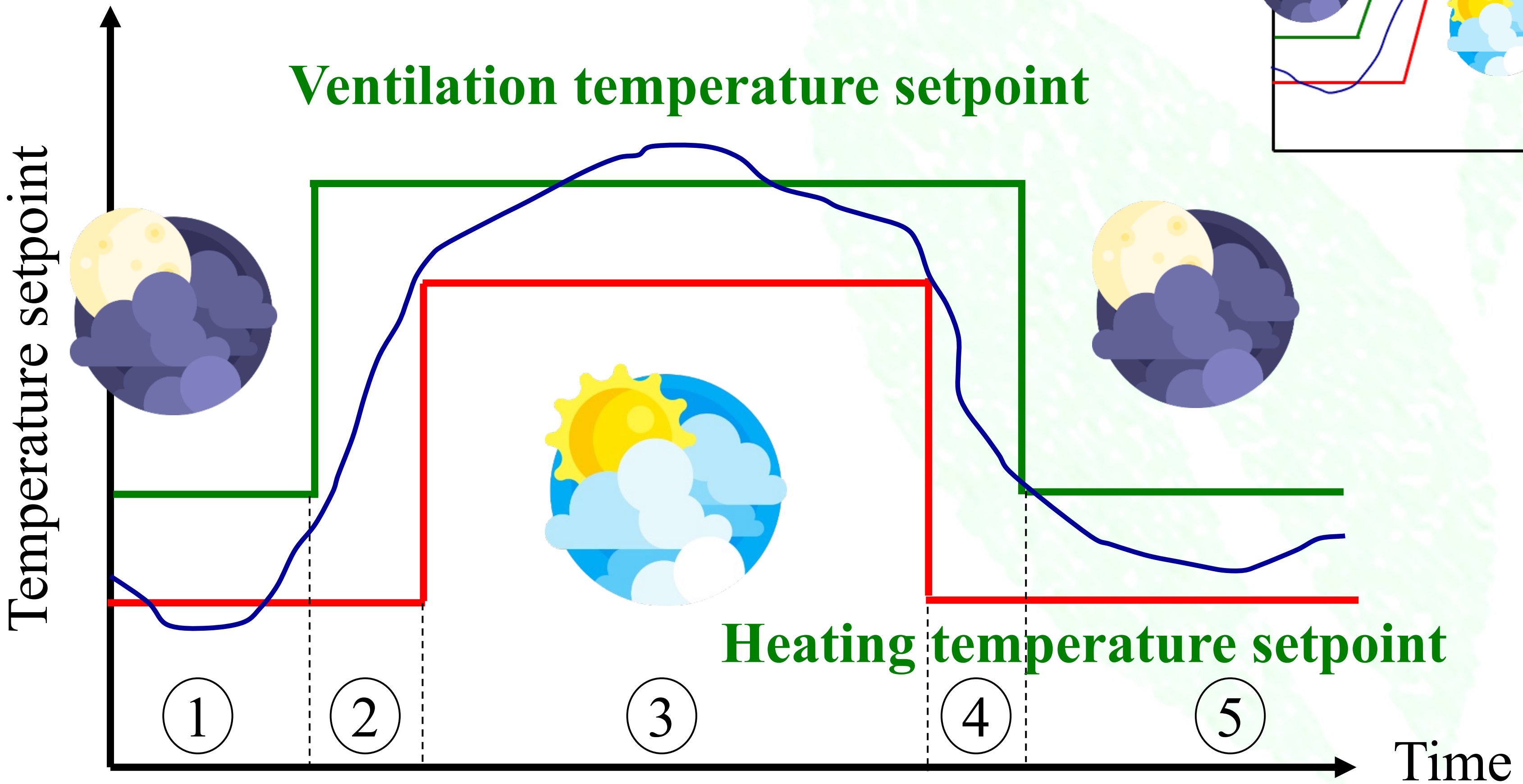
Nocturnal time

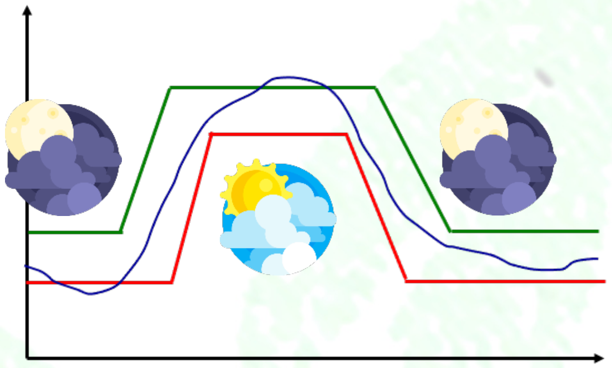


Temperature control problem

Temperature setpoint proposal

Five daily time intervals are considered





Diurnal temperature control

During the day, it is necessary to decrease the greenhouse temperature using natural ventilation.

This consists of a set of windows located around the perimeter of the greenhouse and/or in the roof.

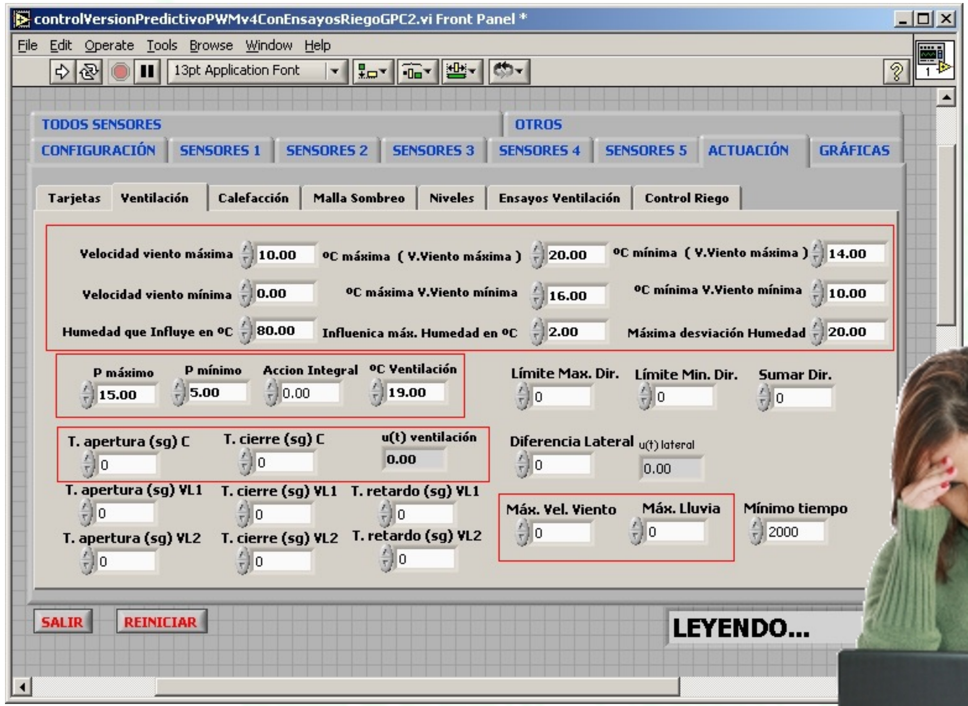
Roof vents

Side vents

When they are open, there is an exchange of air between the interior and exterior of the greenhouse, which depends on:

- The temperature difference between the internal and external air.
- The wind speed.

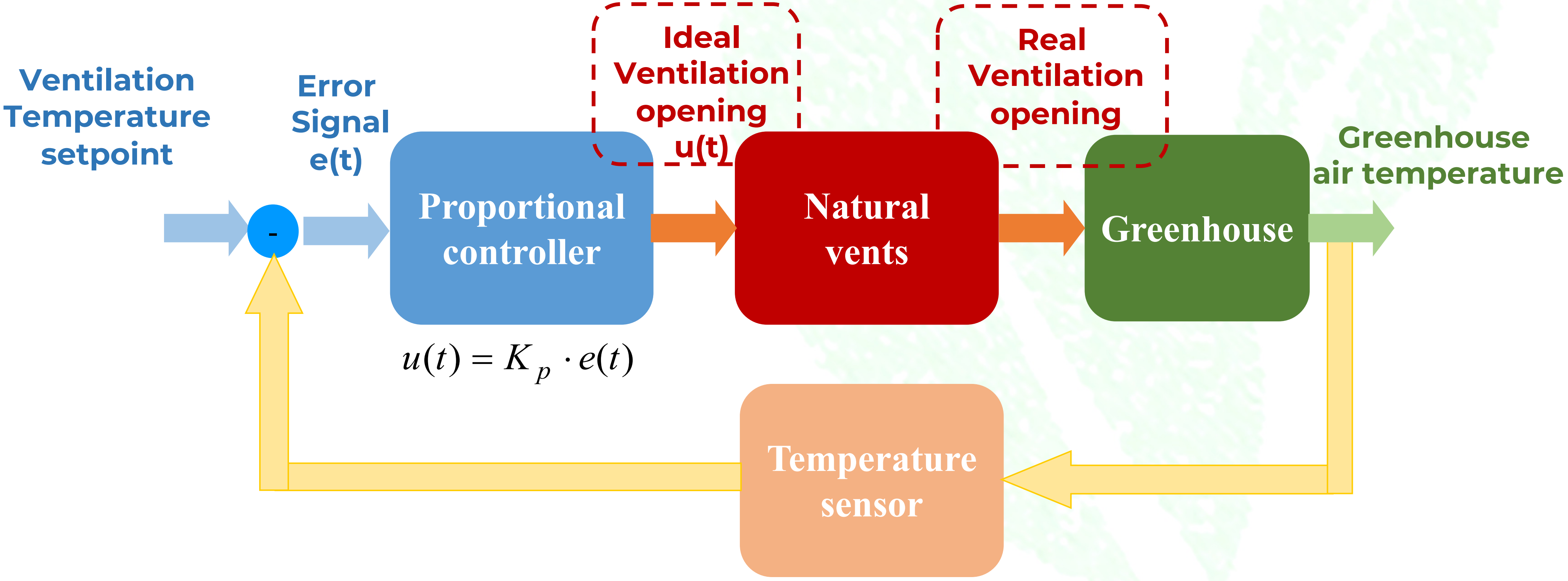
Diurnal temperature control



Control schema

This is a continuous actuator, so a **Proportional controller** is required.

How do you know if the ventilation is in the ideal position?



$$u(t) = K_p \cdot e(t)$$

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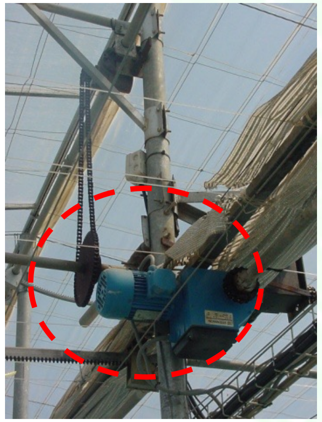
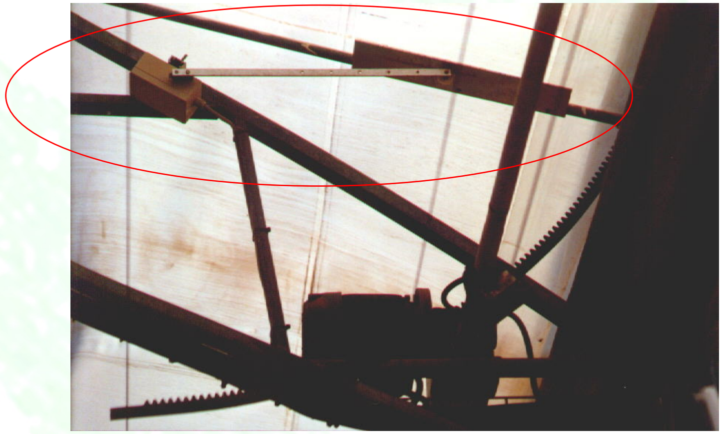
How do you know that ventilation is in the ideal position?

Control schema

To achieve the vent opening calculated by the controller, a motor needs to turn until the vent reaches this position:





- Using a position sensor
- Based on time - the time it takes for the ventilation to open/close is measured and the motor is activated for the necessary period by means of a relay.

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Temperature control

Control schema

Control algorithms

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Control algorithms

This is a continuous actuator, so one needs to use a **Proportional controller**

$$Vent\ opening = K_p(Greenhouse\ Temperature - Vent\ Temperature\ setpoint)$$

Kp= 5 [%/°C] **Setpoint = 22 °C**

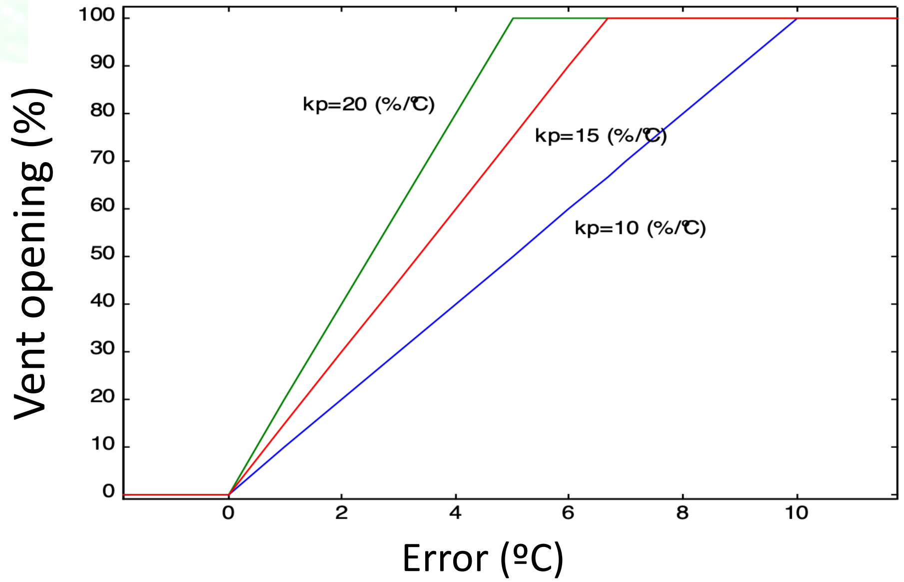
Greenhouse Temperature= 25° C

Error = 3 °C ➔ **Vent opening= 15 [%]**

Greenhouse Temperature= 30° C

Error = 8 °C ➔ **Vent opening= 40 [%]**

It is essential to know the optimal Kp value, which depends on the greenhouse structure and the type of vent.



Control algorithms

This is a continuous actuator, so one needs to use a **Proportional controller**

$$Vent\ opening = K_p(Vent\ Temperature\ setpoint - greenhouse\ Temperature)$$

Kp= 5 [%/°C] **Setpoint = 25°C**

Greenhouse Temperature= 27° C

Error = 2 °C ➡ **Vent opening= 10 [%]**

Does it make sense for the ventilation opening to be the same in these external scenarios?

External Temperature= 20°C
Wind speed= 0 m/s

External Temperature= 10°C
Wind speed= 10 m/s

External Temperature= 20°C
Wind speed= 10 m/s

Control algorithms

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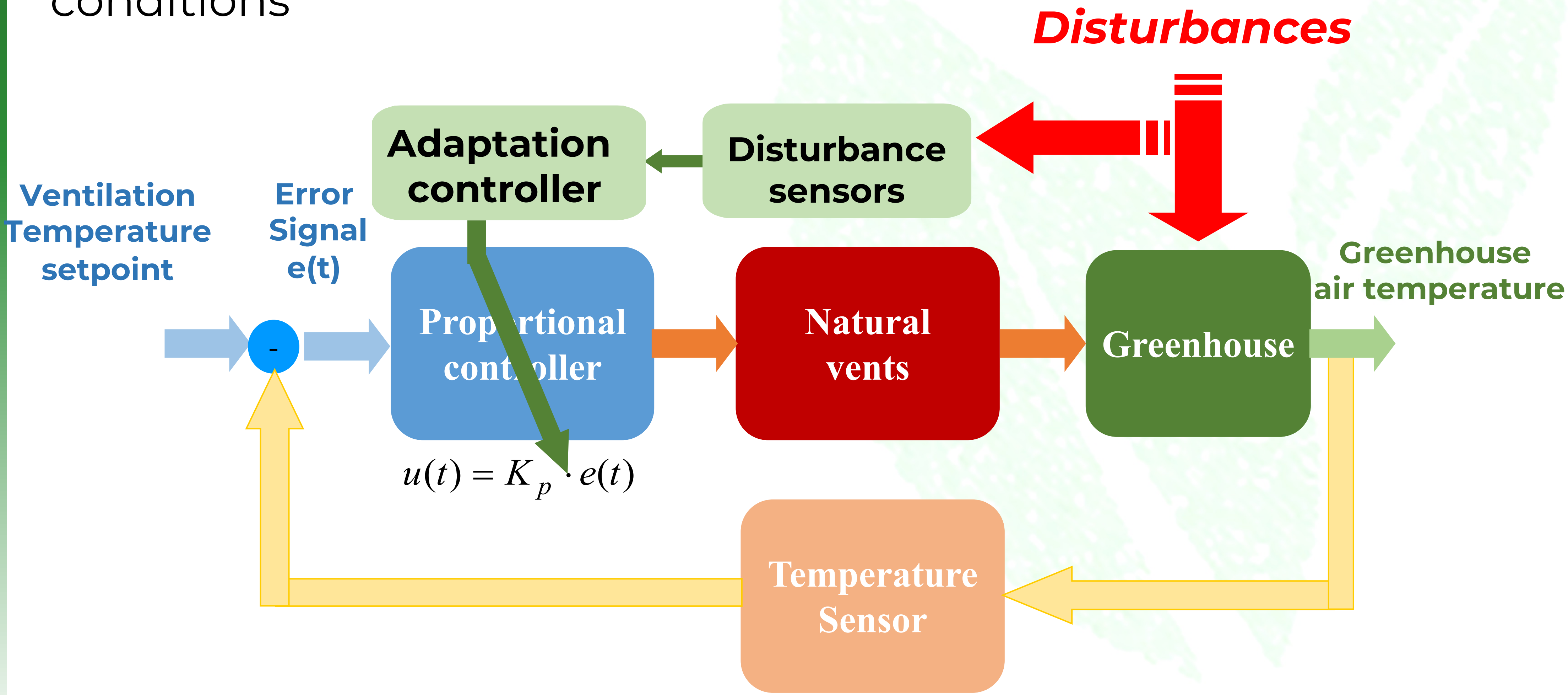
An **adaptive controller** needs to be used to consider the external conditions

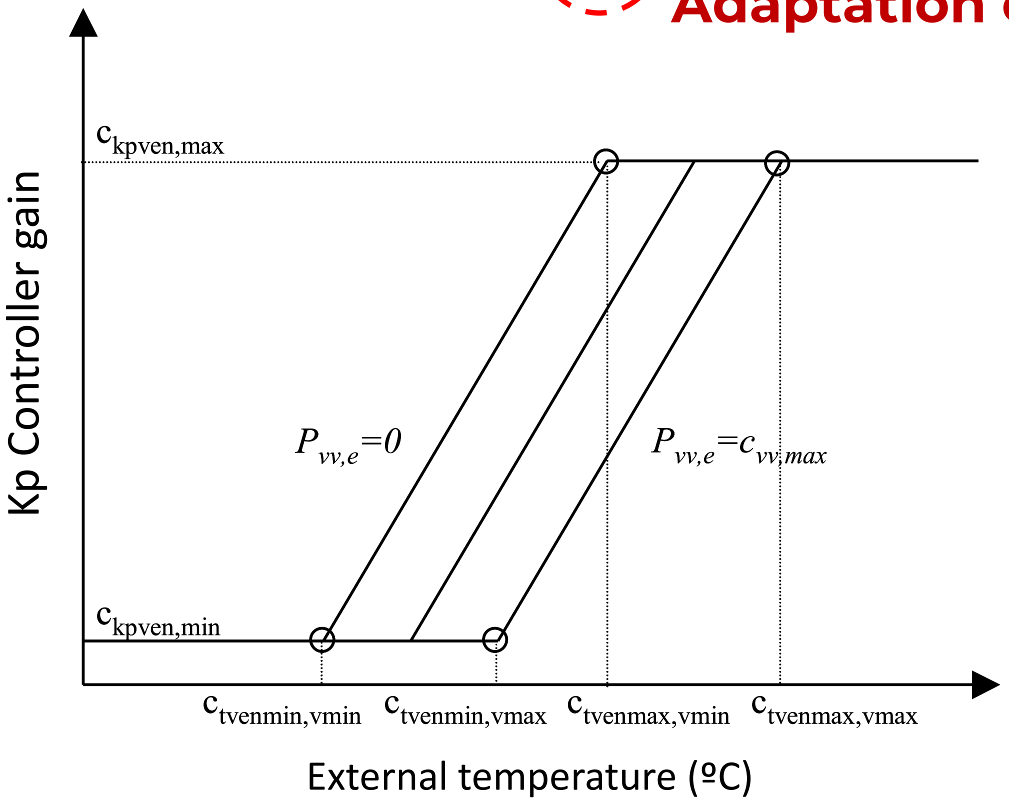


Control algorithms

An **adaptive controller** needs to be used to consider the external temperature and wind speed

$$Vent\ opening = K_p(Greenhouse\ Temperature - Vent\ Temperature\ setpoint)$$

Adaptation of Kp



Setpoint = 22 °C
Greenhouse Temperature= 25° C
Error = 3 °C **Vent opening= ? [%]**

Kp is calculated based on:

- the external temperature
- the wind speed

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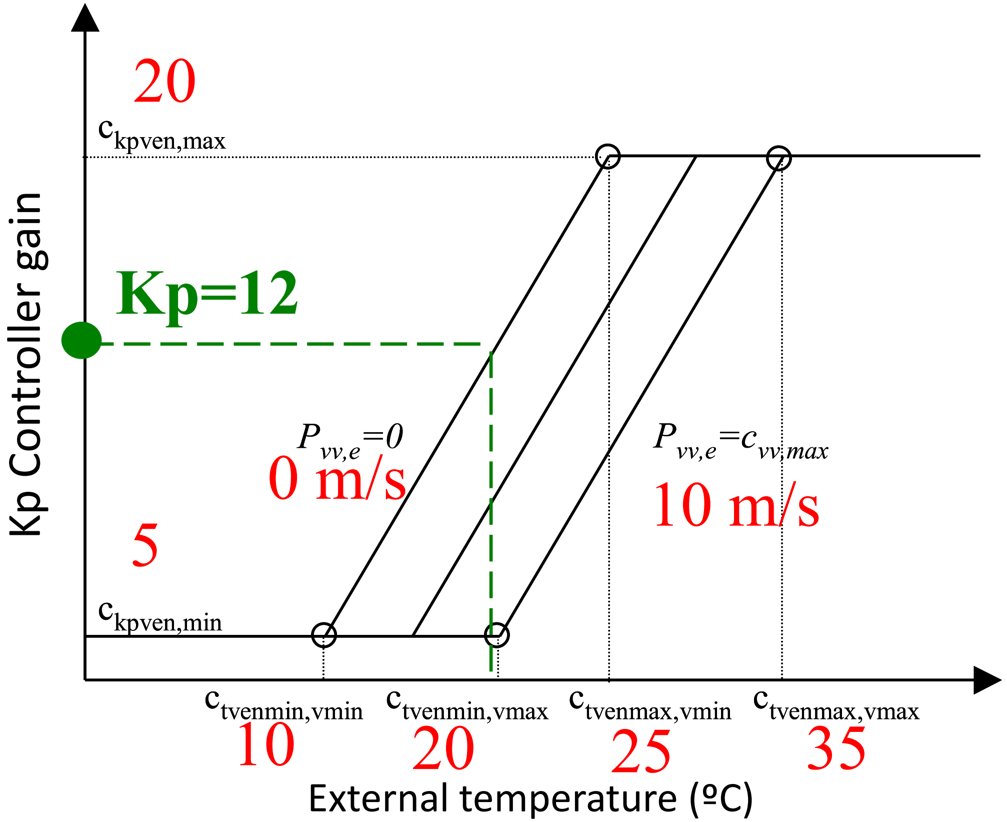
Control algorithms

Setpoint = 22 °C

Greenhouse Temperature= 25° C

Error = 3 °C **Vent opening = ?? [%]**



External Temperature = 20°C
Wind speed = 0 m/s

Kp= 12 %/C

Error = 3 °C **Vent opening= 36 [%]**

External Temperature = 20°C
Wind speed = 10 m/s

Error = 3 °C **Vent opening = ?? [%]**

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Control algorithms

Temperature control

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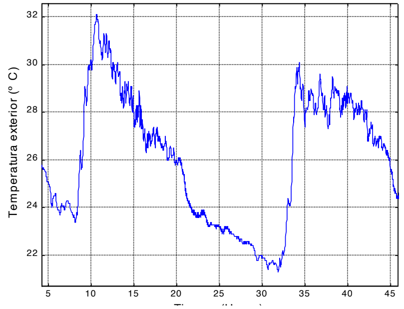
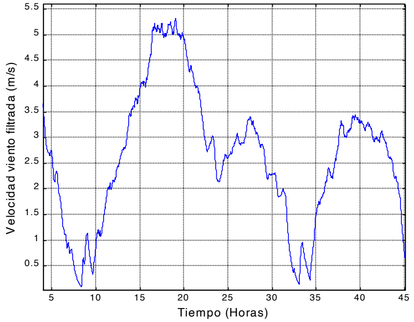
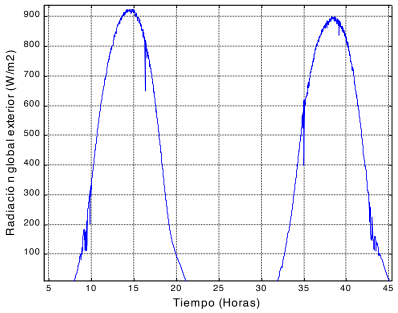
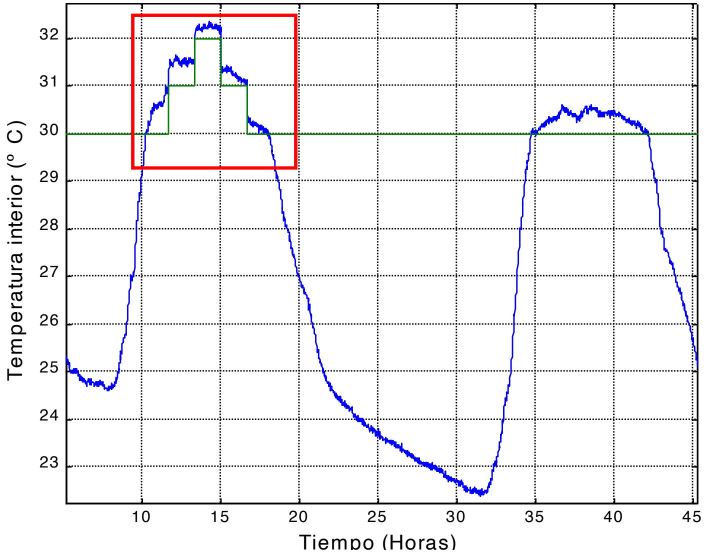
Real results

Disturbances

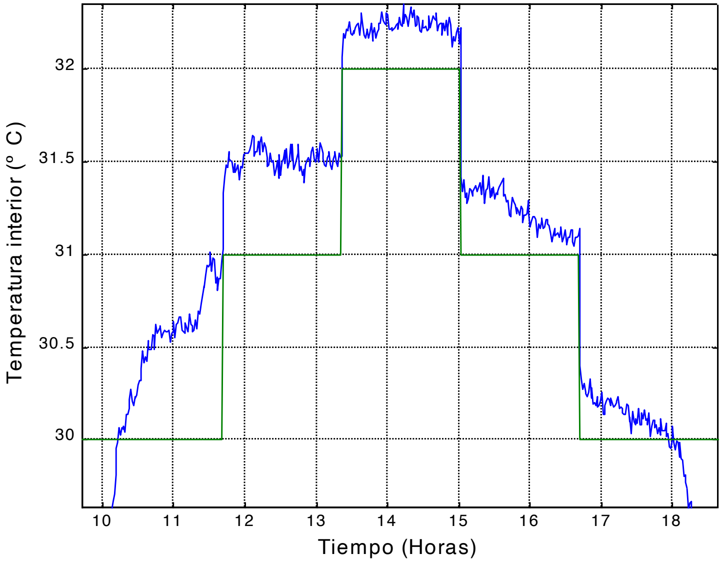


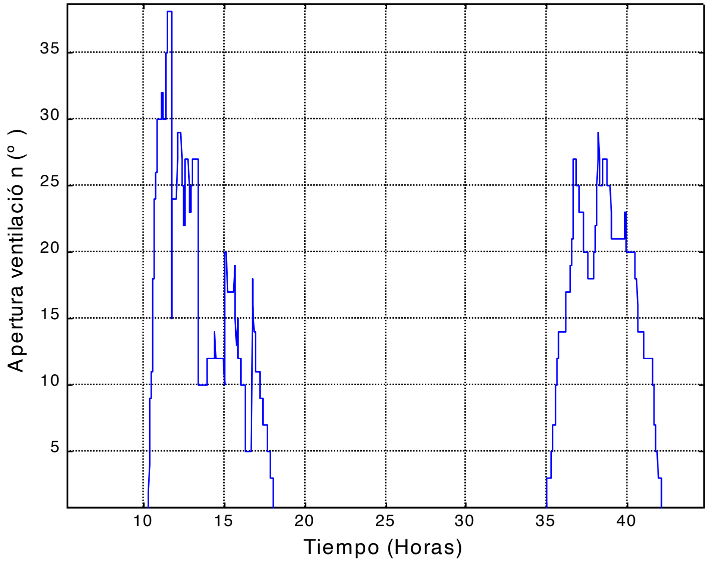






Greenhouse Temperature





Vent openings

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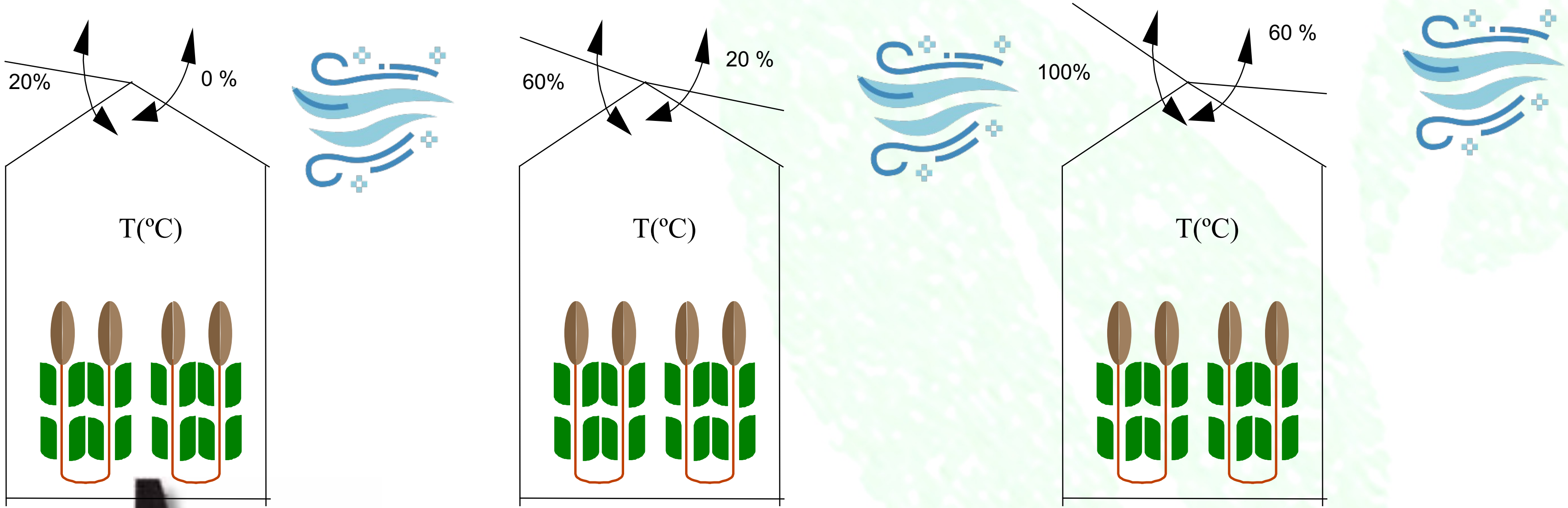
Control algorithms. Adjustment 1

Greenhouses with ventilation installed in different orientations

The leeward ventilation position is normally calculated by the adaptive controller and the windward ventilation is less.



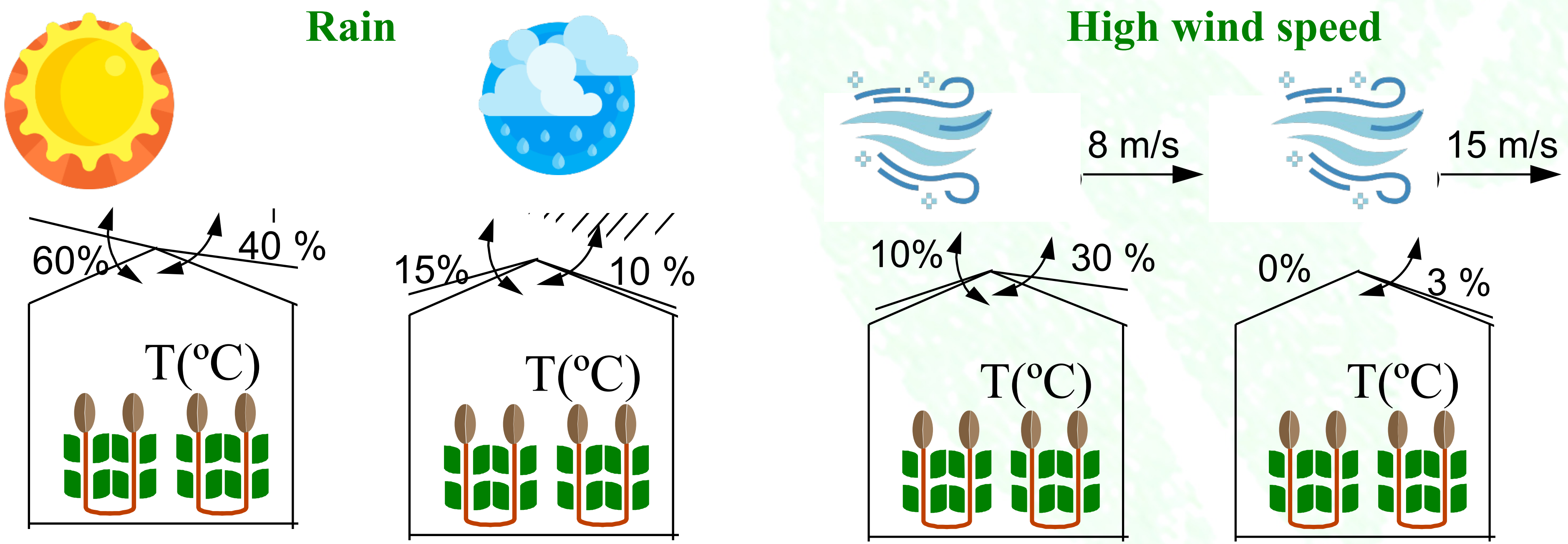
When does the wind direction change?

A weather vane is necessary

Control algorithms. Adjustment 2

Adjusting the algorithm to extreme conditions

A maximum opening is allowed under certain conditions and calculated proportionally to it (as if 100% is achieved with the maximum opening)



Control algorithms. Adjustment 3

Daytime temperature control problem with ventilation

Integral action

When the setpoint is not reached, an integral action is introduced

An integral step is defined that is added to the proportional action if the conditions are not modified.

Example

PI controller
Kp = 10 % /°C
Ki = 5 % /° C
Consigna = 21°C

Constant external temperature and wind speed

Hour	Greenhouse temperature	Error	Ventilation oppening
12:00 (start)	23 ºC	2 ºC	20 % (P action)
12:01	22 ºC	1 ºC	25 % (I action)
12:02	22 ºC	1 ºC	30 % (I action)
12:03	21.5 ºC	0.5 ºC	32.5 % (I action)
12:04	21 ºC	0 ºC	32.5 %

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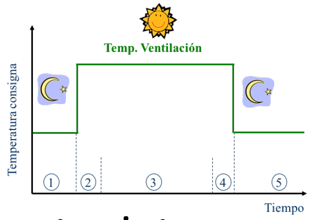
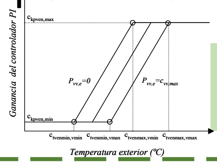
Control algorithm

Parameters



Vent temperature setpoint

Influence of external temperature
Influence of wind speed
Kp intervals



Maximum vent opening for wind direction

Maximum vent opening for rain

Maximum vent opening for high wind speed

Ventilation Temperature setpoint

Error calculation

Kp calculation

Leeward vent opening calculation

Windward vent opening calculation

Adjusting for rain and wind speed

Vent position

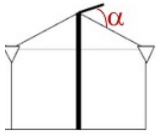
Measurements

Greenhouse temperature

External temperature
Wind speed

Wind direction

Rain
Wind Speed



Temperature control

Control schema

Control algorithms

Conclusions

Conclusions

- Natural ventilation is the main cooling mechanism in greenhouses and it is necessary in mild climate zones.
- The greenhouse diurnal temperature is controlled automatically by a proportional controller.
- Other variables that influence the internal temperature behaviour, such as external conditions, must be taken into account.
- Knowledge of the parameters influencing ventilation is necessary to achieve optimal daytime temperature control.
- Each greenhouse will have its own values for these parameters, which need to be calibrated in each case.

It is very important to understand these parameters and know how to obtain good values for them in order for the diurnal temperature to be well controlled when operating natural vents.

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Temperature control

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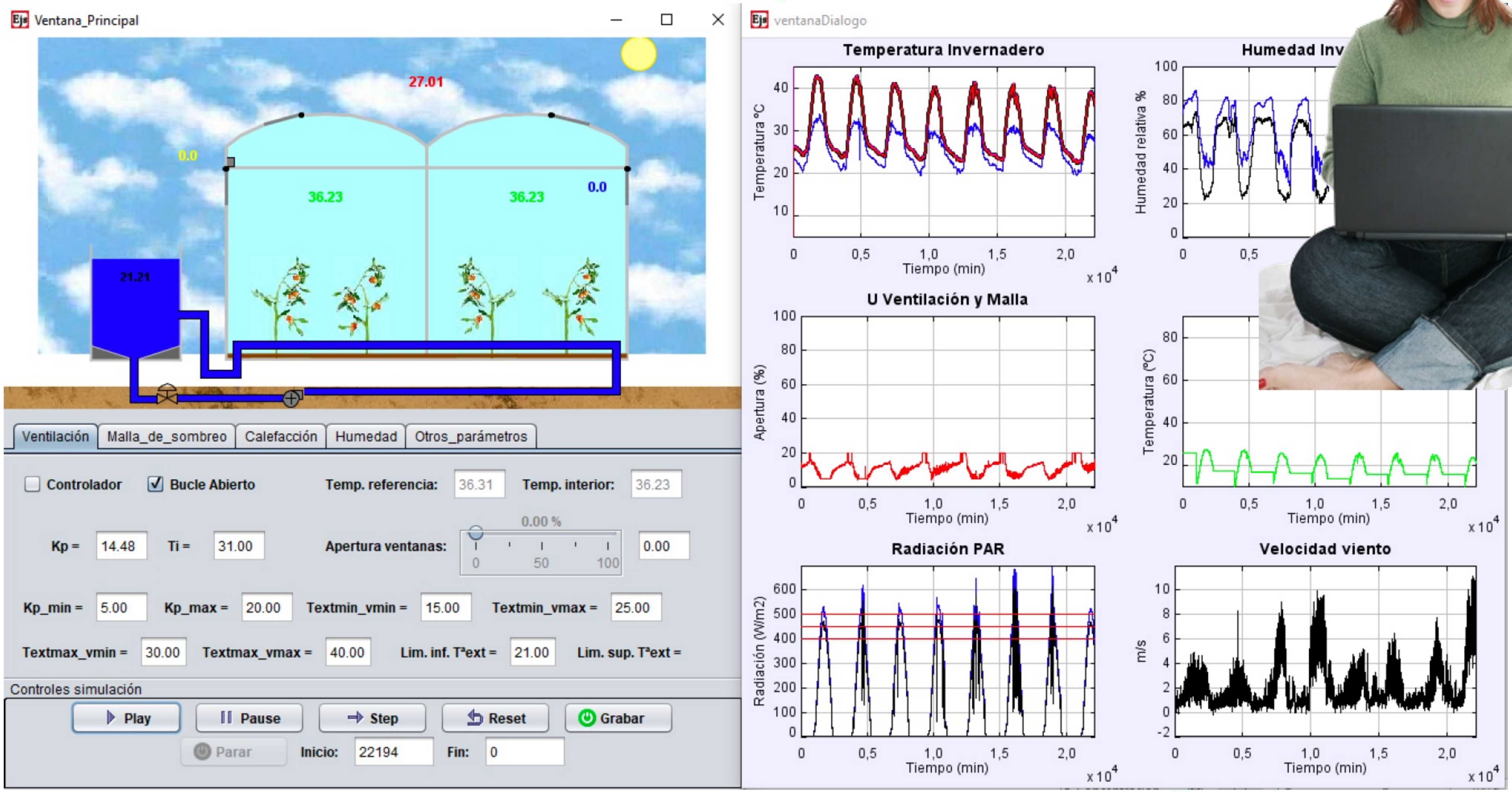
Conclusions



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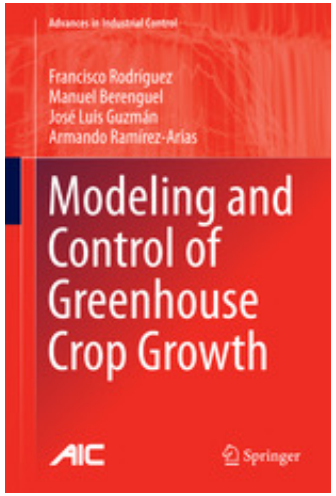

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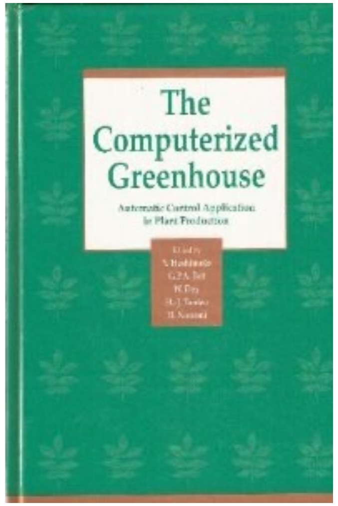

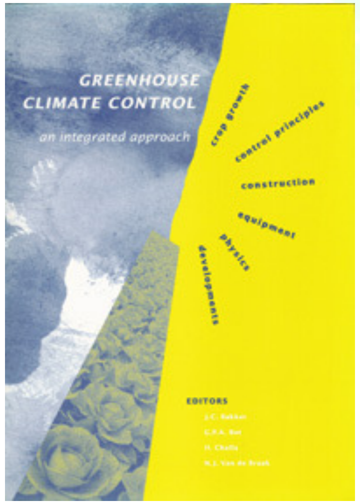

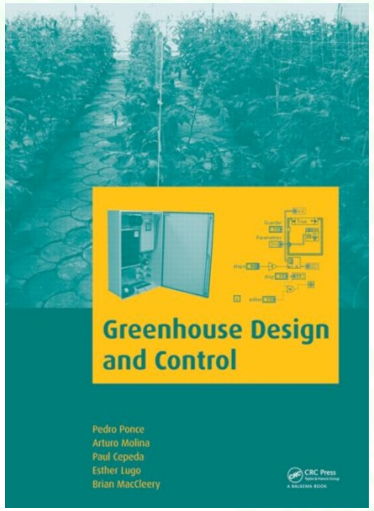

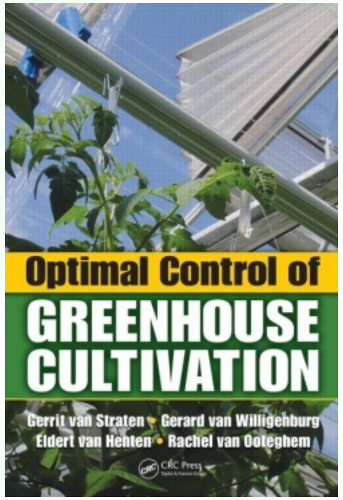

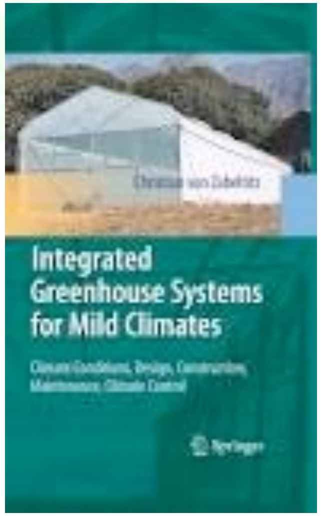

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Module 6: CLIMATE MANAGEMENT

Lesson 6.2: Greenhouse climate variable control

Theme 6.2.2: Greenhouse temperature control with heating systems

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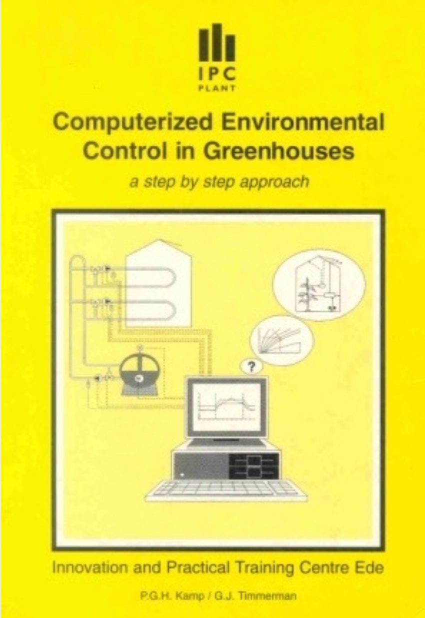
- Nocturnal temperature control problem
- Temperature control using heating from aerial pipes
- Temperature control using heating from forced-air heaters
- Conclusions



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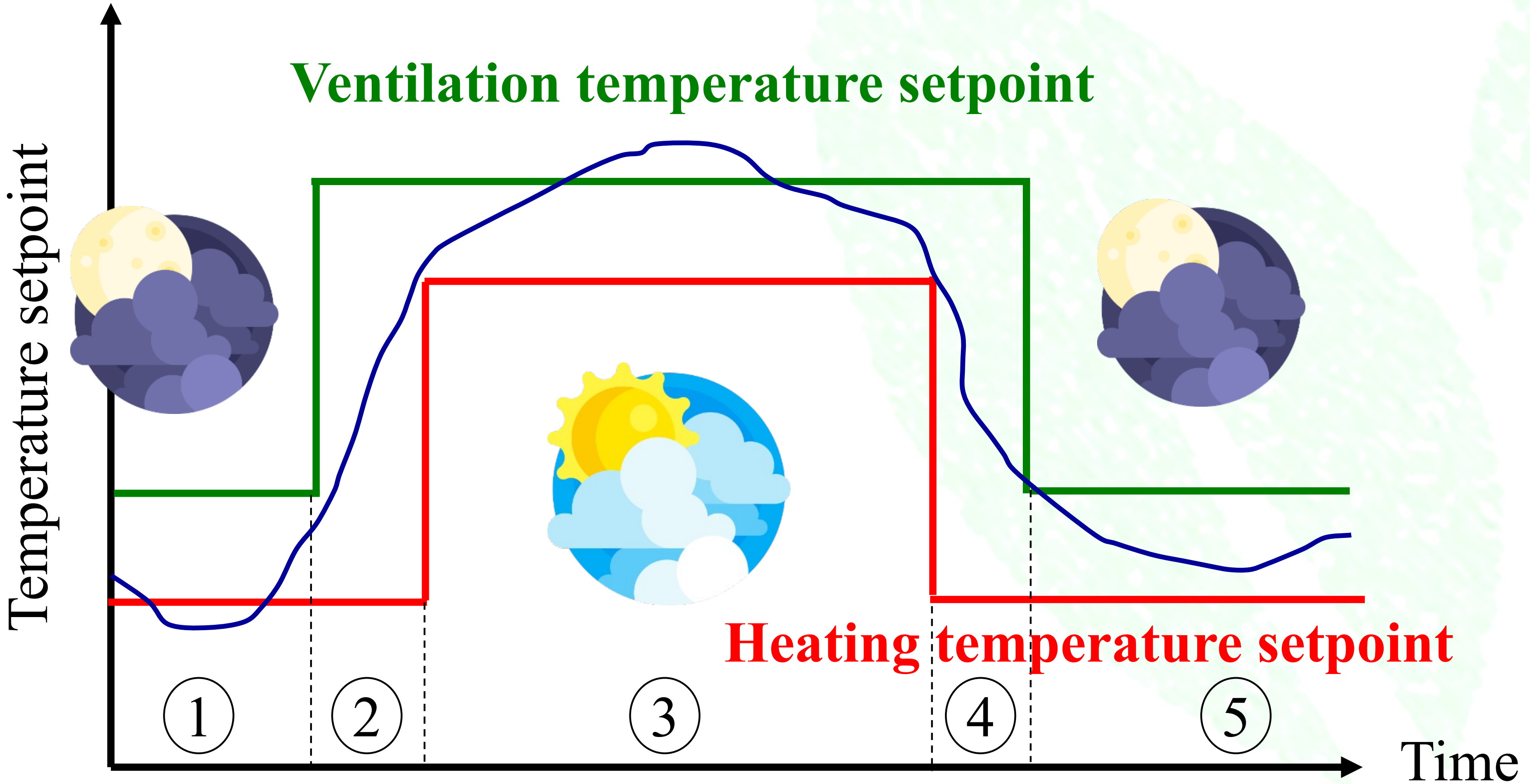
Temperature control problem

Temperature setpoint proposal

Five daily time intervals are considered



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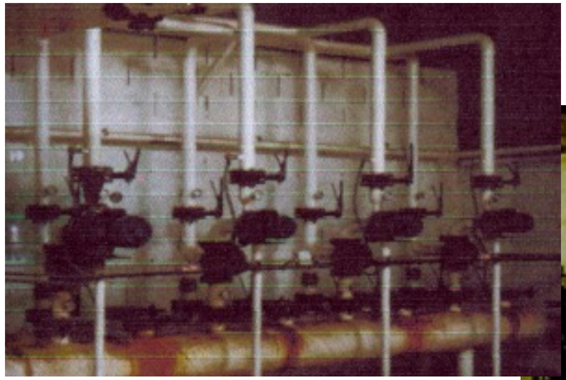
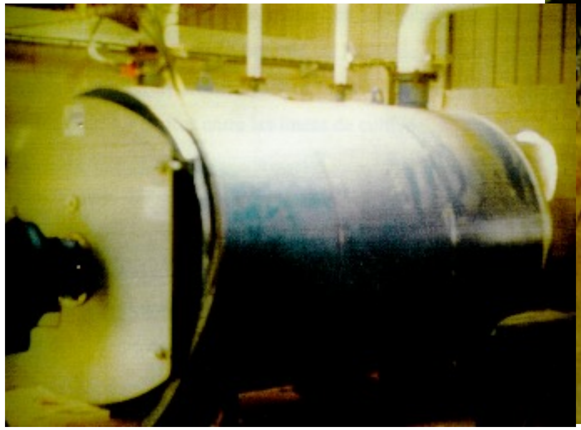
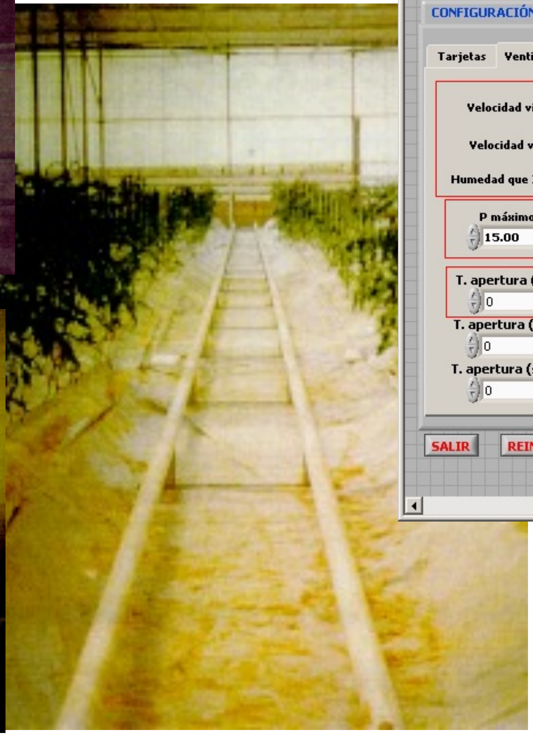
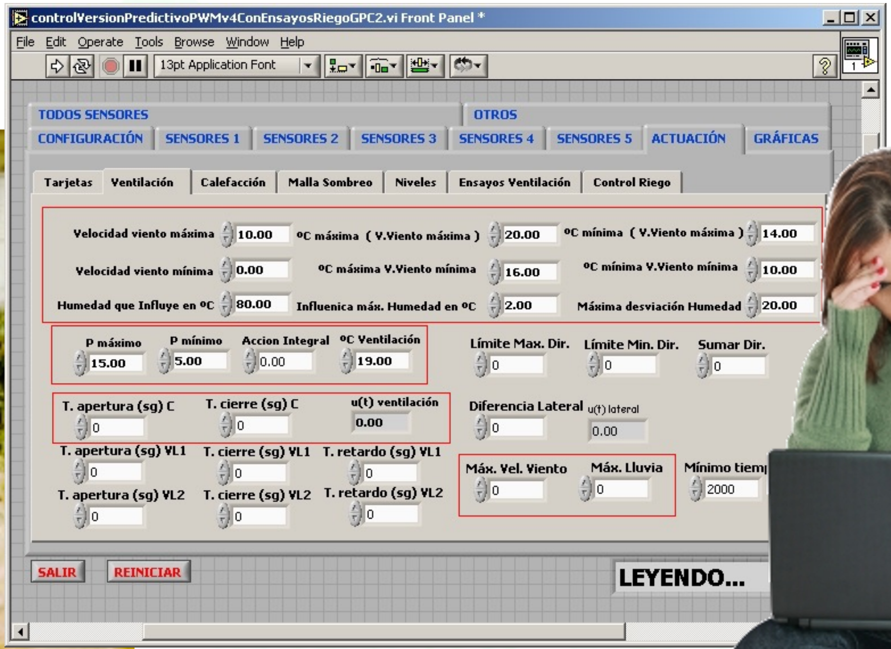






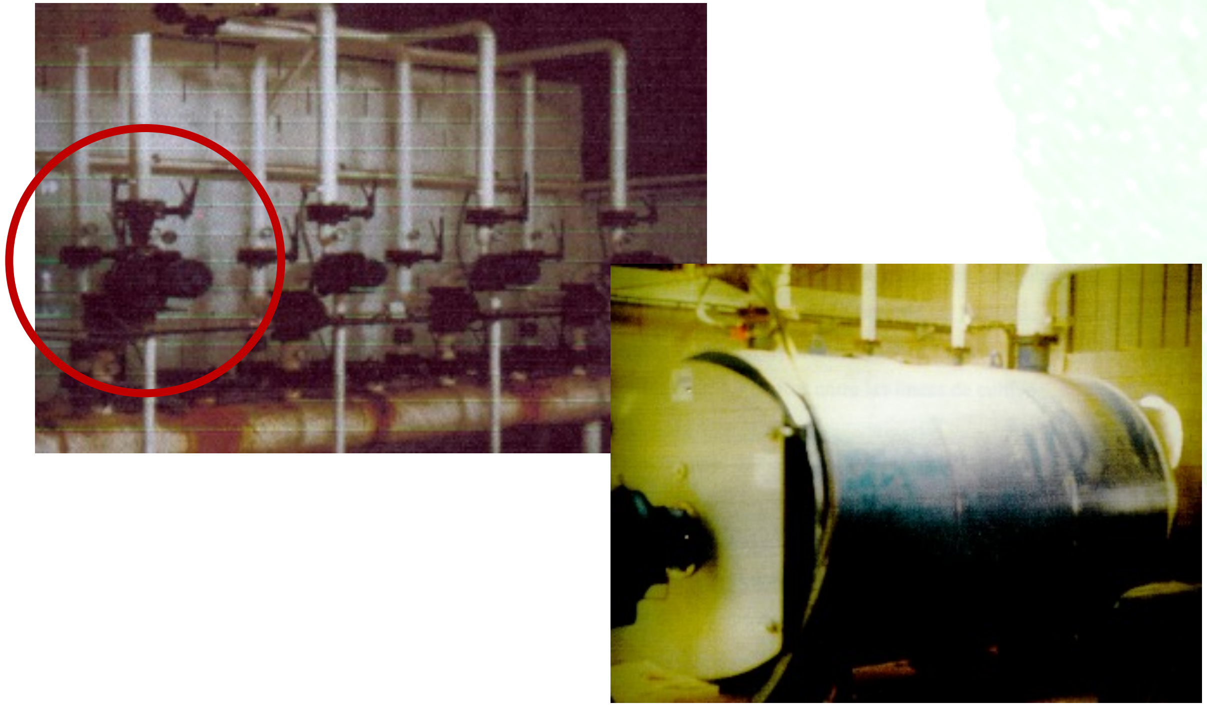


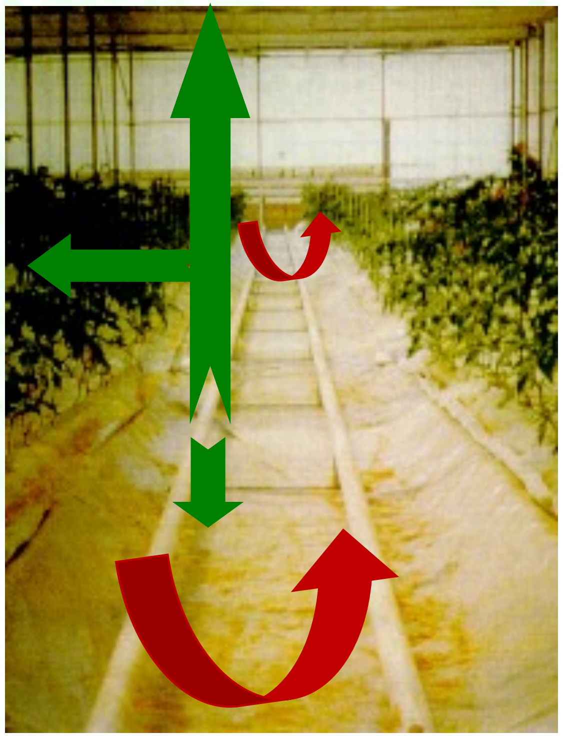
Control of aerial-pipe heating

The water flowing through the pipes is warmer than the air around it, thus increasing the air temperature.

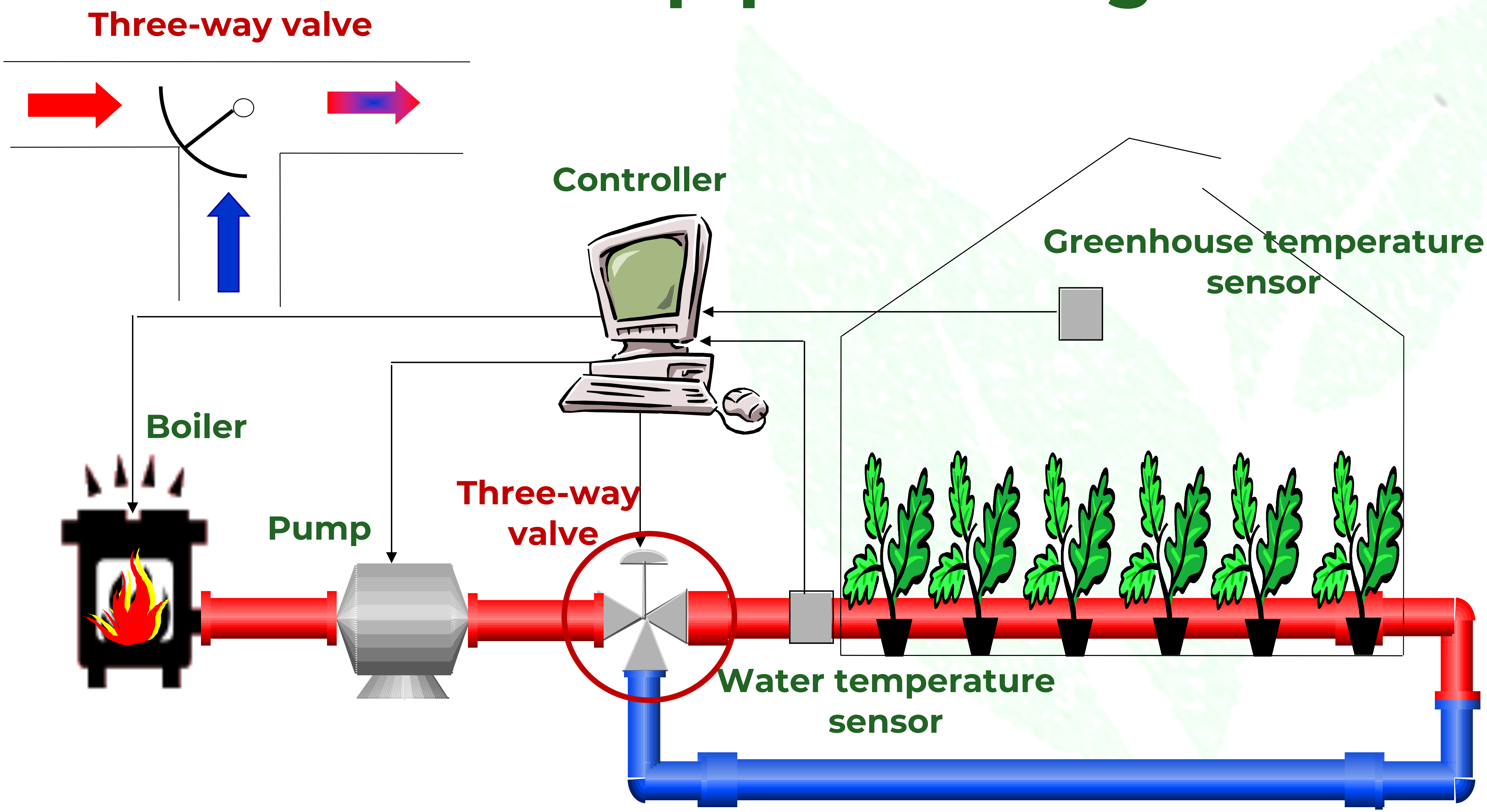
How is the temperature of the water in the pipes controlled?

A three-way valve is used





Control of aerial-pipe heating



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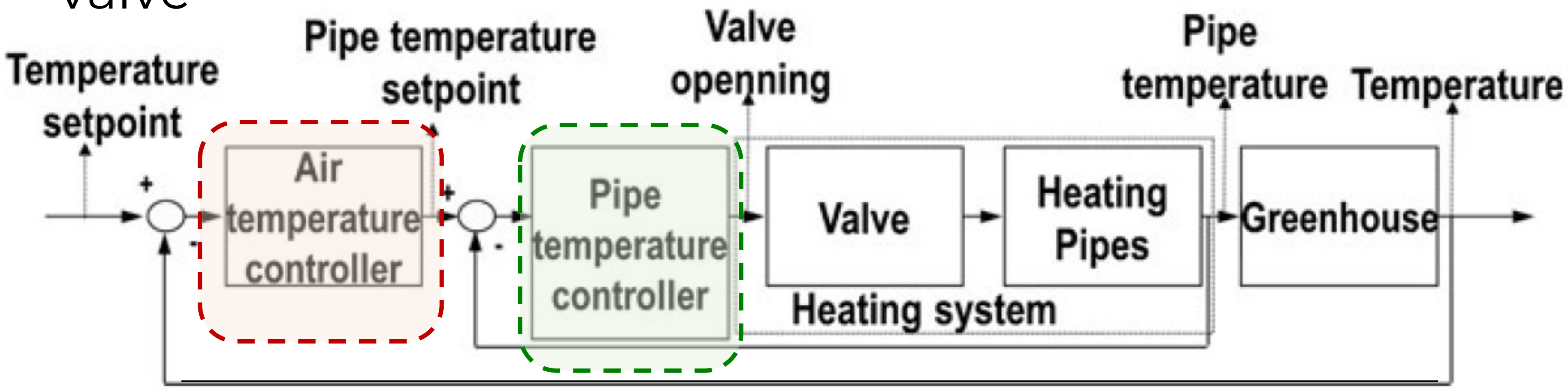
Control of aerial-pipe heating

Control schema

One needs to use a Cascade controller, which consists of two controllers:

- **Master controller**. Air temperature controlled by pipe water temperature
- **Slave controller**. Pipe water temperature controlled via the valve



Control of aerial-pipe heating

Both actuators are continuous, so **proportional controllers** need to be used.

Three steps are performed to control the temperature:

1. If the temperature of the greenhouse (T_g) is lower than the heating temperature setpoint (T_h) , the heating should operate.
2. The temperature of the pipe water (T_w) is calculated by a proportional controller (master controller)

$$T_w = Kp_w(T_g - T_h) + T_{base}$$

3. The valve position (V_p) is calculated by a proportional controller to achieve the desired water temperature (T_w) (slave controller)

$$V_p = V_{p-1} + Kp_v(T_{pw} - T_w)$$

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Control of aerial-pipe heating

Kp_w= 20 [°C_{water}/°C air] **Setpoint = 15°C** **Kp_v= 2 [%/ °C_{water}]**

Base Temperature= 20°C

Water Temperature= 20°C

Greenhouse Temperature= 27° C

Greenhouse temperature	Base temperature	Air temperature Error	Water Proportional steo	Water pipe temperature	initial Valve position	Water temperature error	Valve Proportional step	Valve position
13ºC	20ºC	2ºC	40ºC	**20 + 40 = 60ºC**	15%	40ºC	80%	**15+80=95%**
14ºC	20°C	1ºC	20ºC	**20 + 20 = 40ºC**	95%	-20ºC	-40%	**95-40=55%**
15ºC	20°C	0ºC	0ºC	**20 + 0 = 20ºC**	55%	-20ºC	-40%	**15%**

Does it make sense for the heating system to be the same in these different external scenarios?

External Temperature= 10°C
Wind speed= 0 m/s

External Temperature= 10°C
Wind speed= 10 m/s

External Temperature= -2°C
Wind speed= 0 m/s

Control of aerial-pipe heating

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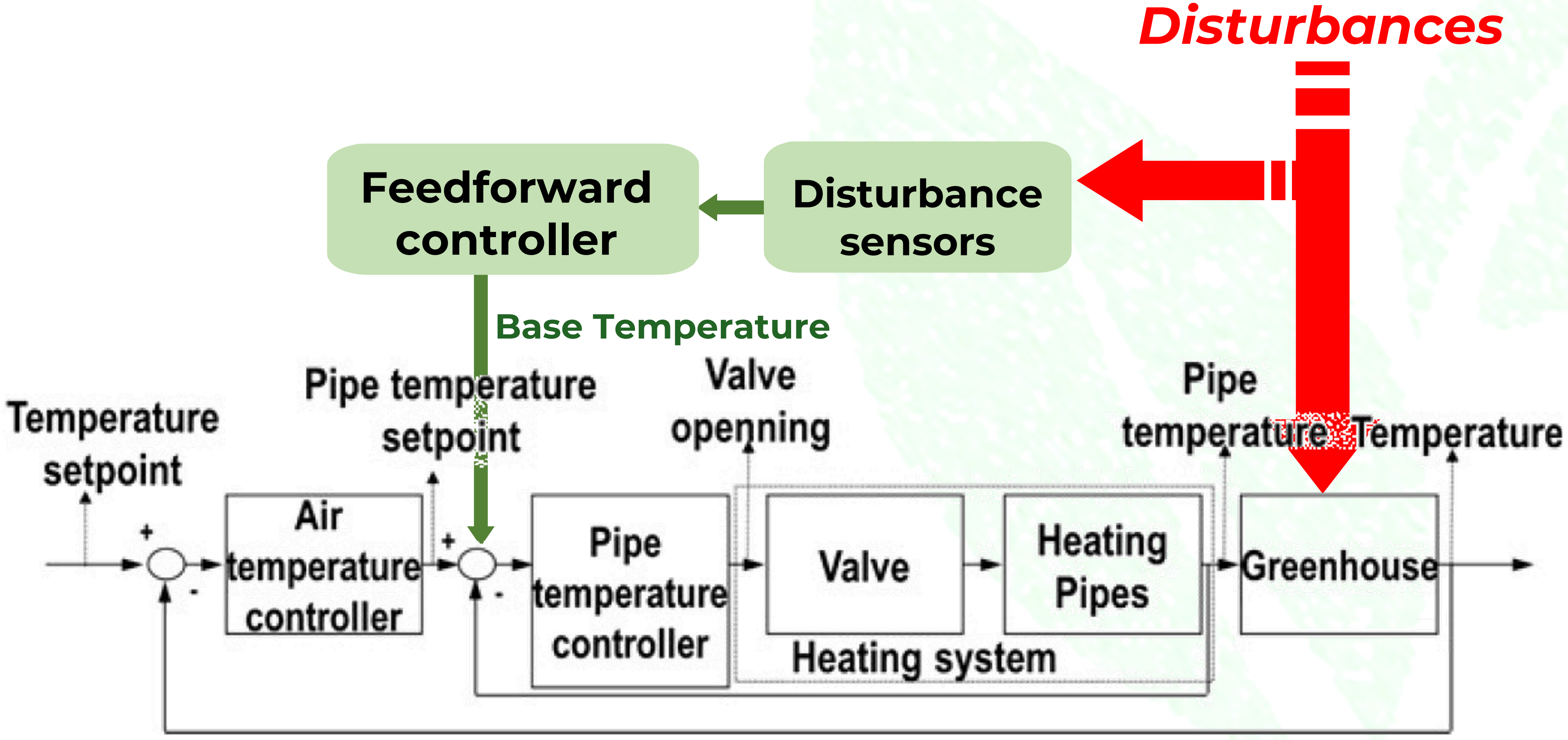
To calculate the **base temperature,** one needs to use a **feedforward controller** to consider the external conditions.



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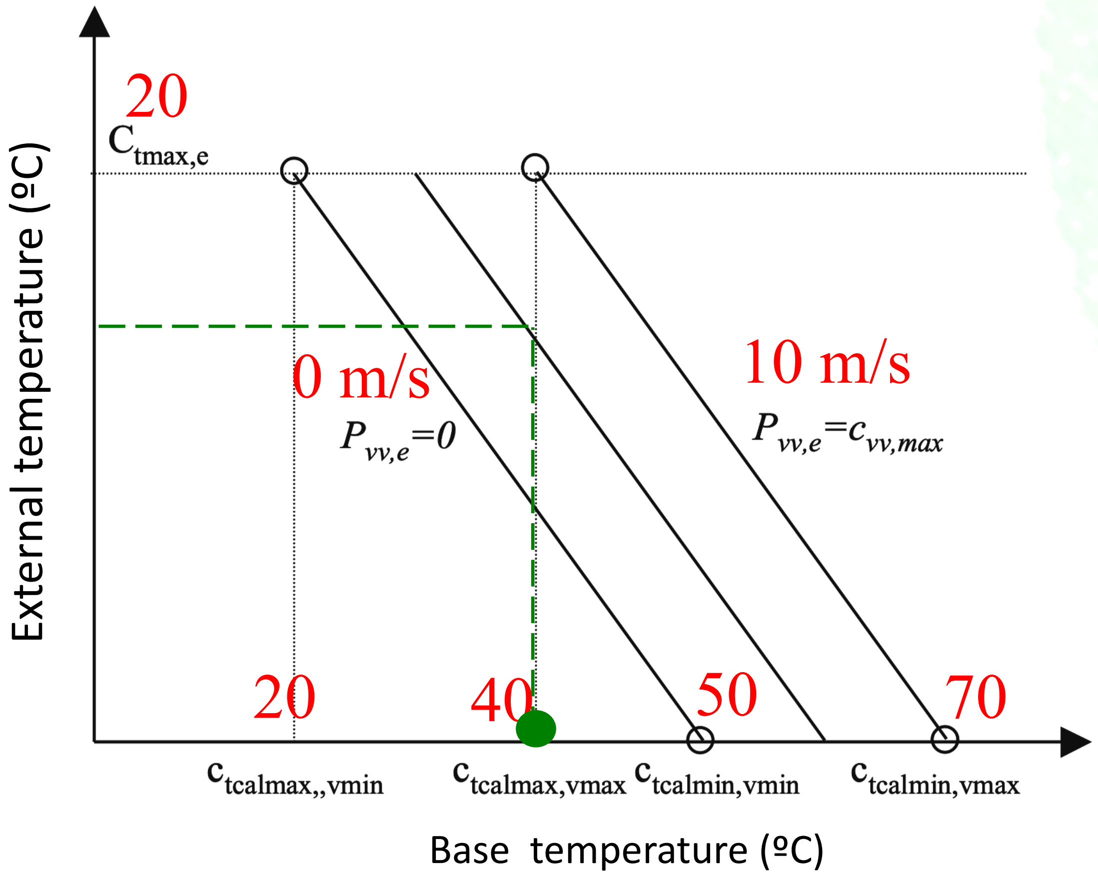
Control of aerial-pipe heating

Increasing the temperature of the pipe water based on the external temperature and wind speed via the Base Temperature

Kp_w= 5 [°C_{water}/°C air] **Heating Setpoint = 16°C**

Greenhouse Temperature= 12° C



External temperature= 15ºC

Wind speed= 5 m/s

Tbase= 40 ºC

$$T_{water}= Kp_w\,(T_{heating}T\text{-}_{greenhouse}\text{-})+T_{base}$$

$$T_{water}= 5\,(16\text{-}12)+40=60\ °C$$

External temperature= 20ºC

Wind speed= 5 m/s

Tbase= 30 ºC

$$T_{water}= 5\,(16\text{-}12)+30=50\ °C$$

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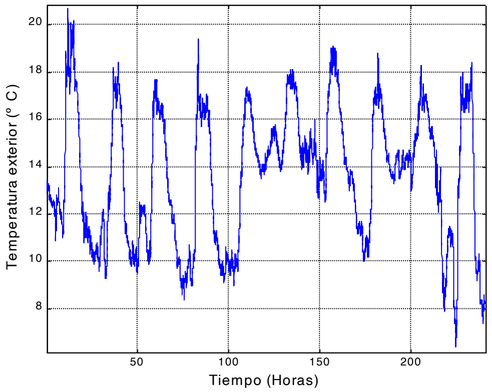
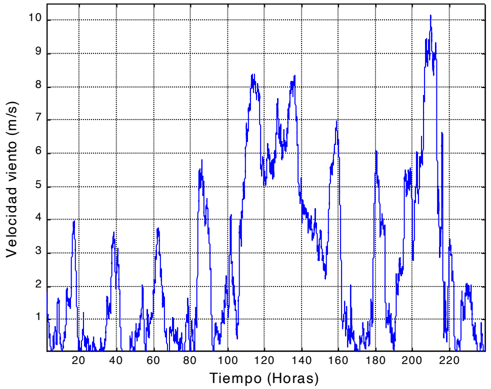
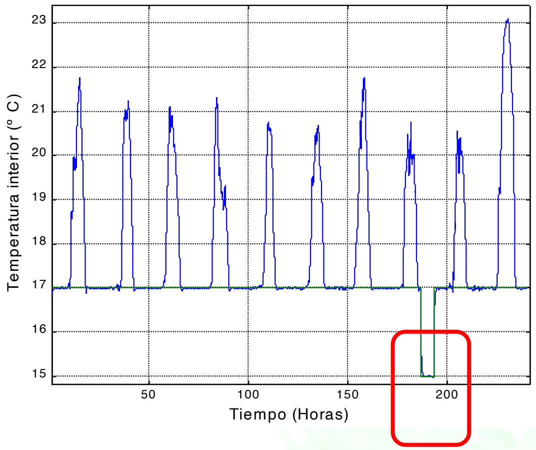
Control of aerial-pipe heating

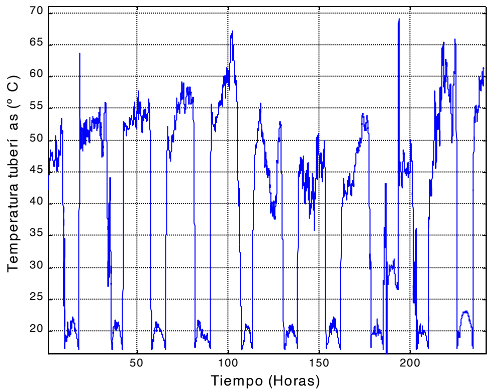
Real results

Disturbances

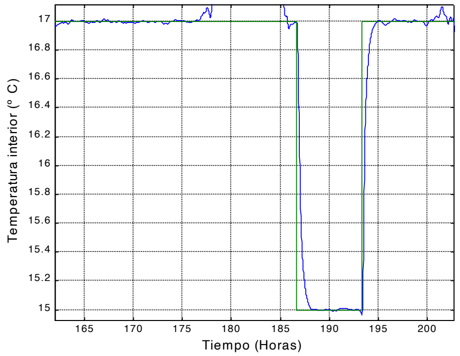


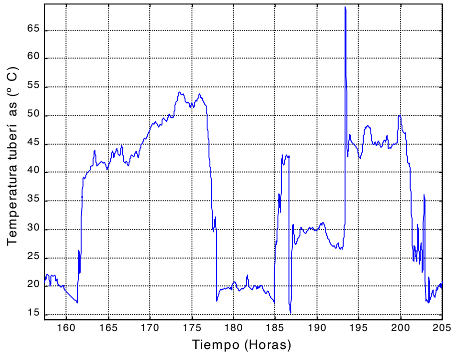






Greenhouse Temperature





Pipe water temperature

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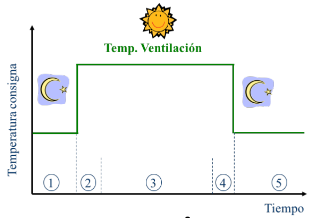
Control algorithm

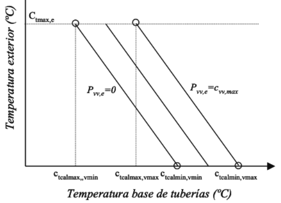
Parameters



Heating temperature setpoint

Kp_w Master controller

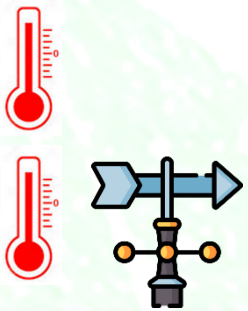
Influence of external temperature
Influence of wind speed



Kp_v slave controller

Heating Temperature setpoint
↓
Error calculation
↓
T_{water} calculation
↓
T_{base} calculation
↓
Pipe water temperature calculation
↓
Valve position calculation
↓
Valve position

Measurements



Greenhouse temperature

External temperature
Wind speed

Pipe water temperature

Nocturnal Temperature control

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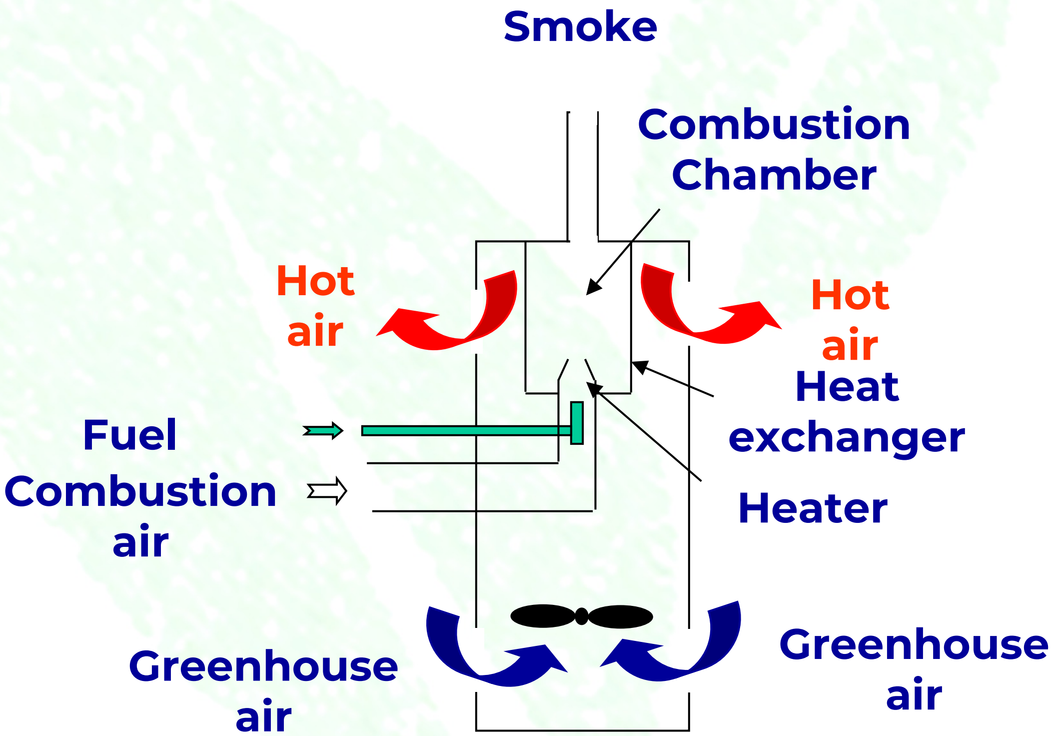
Control of forced-air heating

These heating systems warm the greenhouse air by distributing heated gases throughout the greenhouse via fresh air currents.



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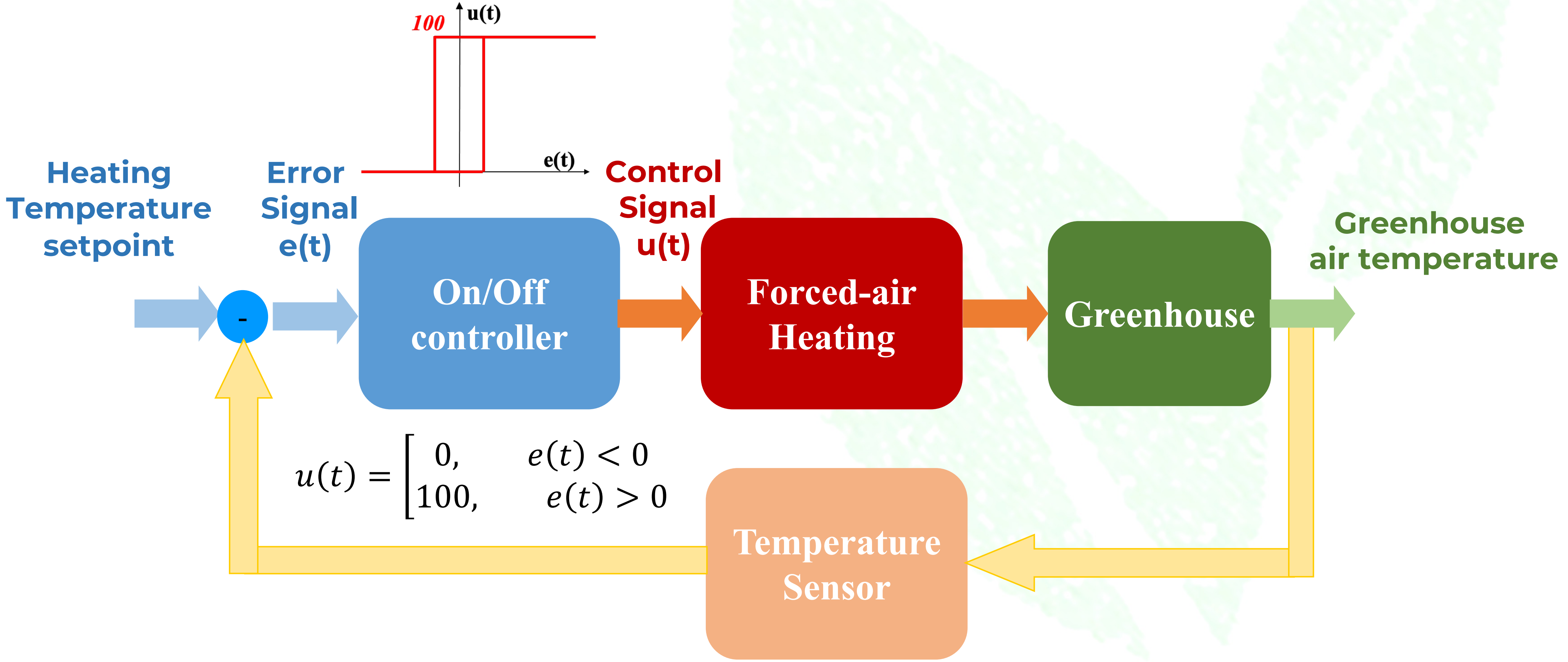
Control of forced-air heating

This is an on/off actuator, so one would need to use an **on/off controller** corrected by a dead zone



$$u(t) = \begin{cases} 0, & e(t) < 0 \\ 100, & e(t) > 0 \end{cases}$$

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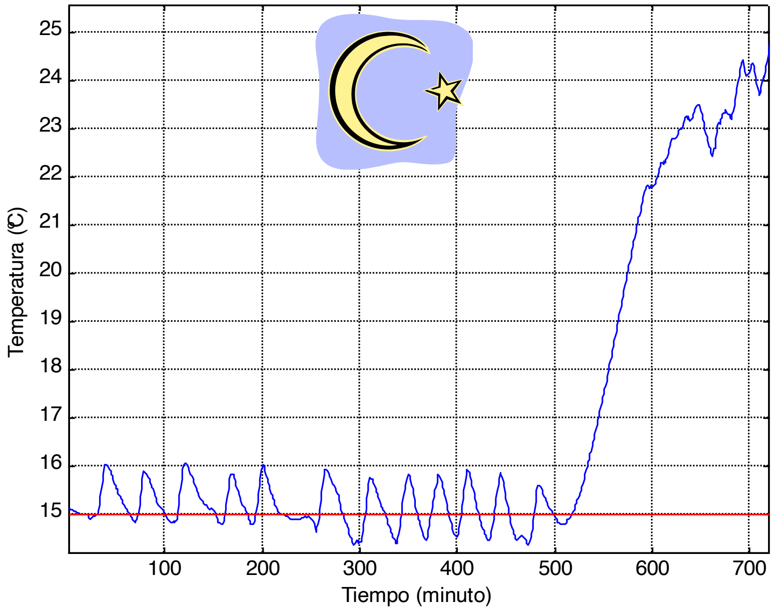
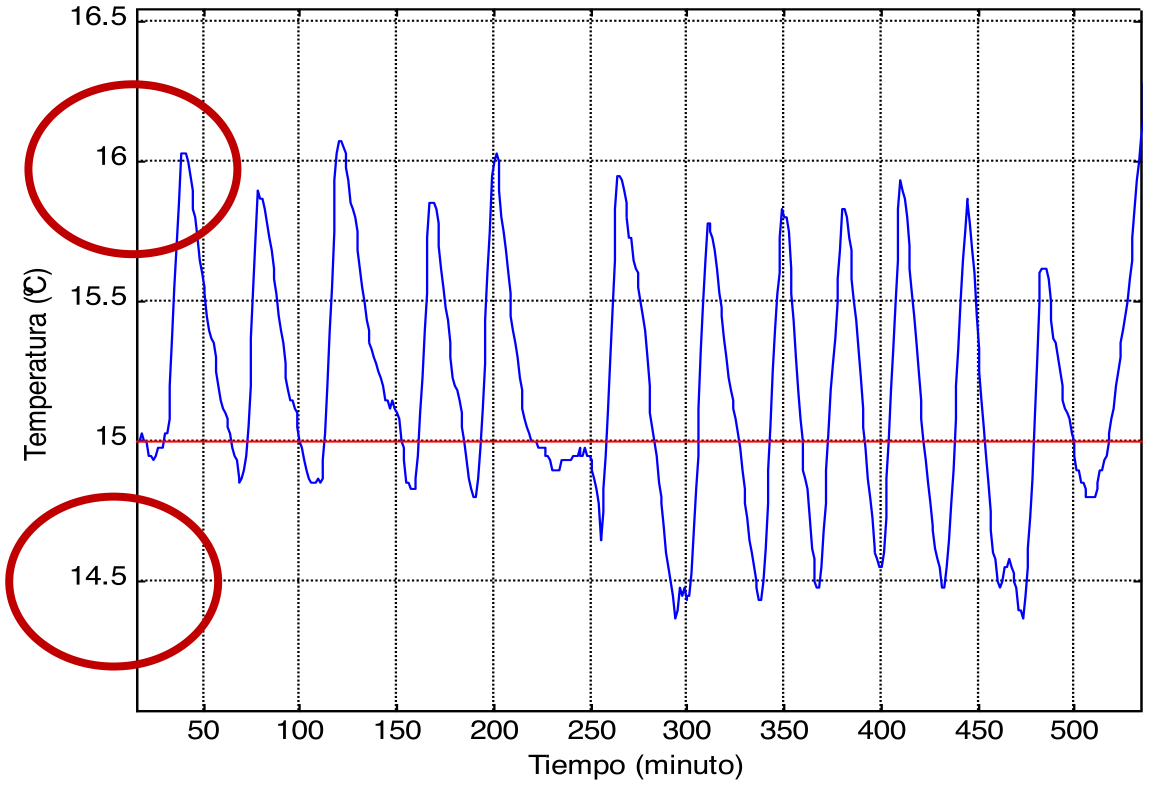
Control of forced-air heating

Typical **sawtooth** behaviour of an on/off controller





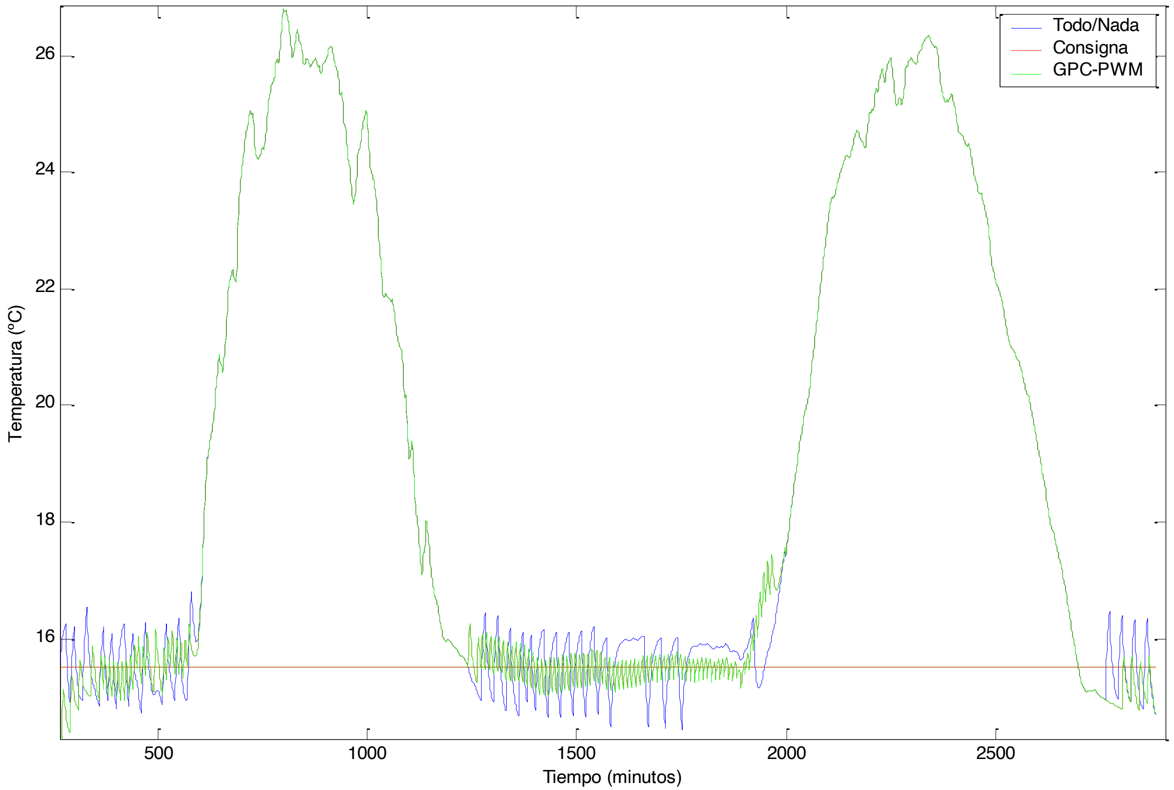
One needs to analyse if the width and duration of the sawteeth are suitable for our greenhouse.

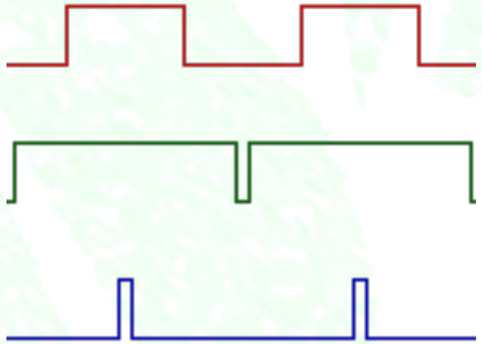
Control with heating by forced air

PWM (Pulse width modulation)

Regulate the power-up time based on the error as if it were a proportional controller

$$Tiempo_{funcionamiento} = k_p \left(Temp_{invernadero} - Temp_{consigna} \right)$$

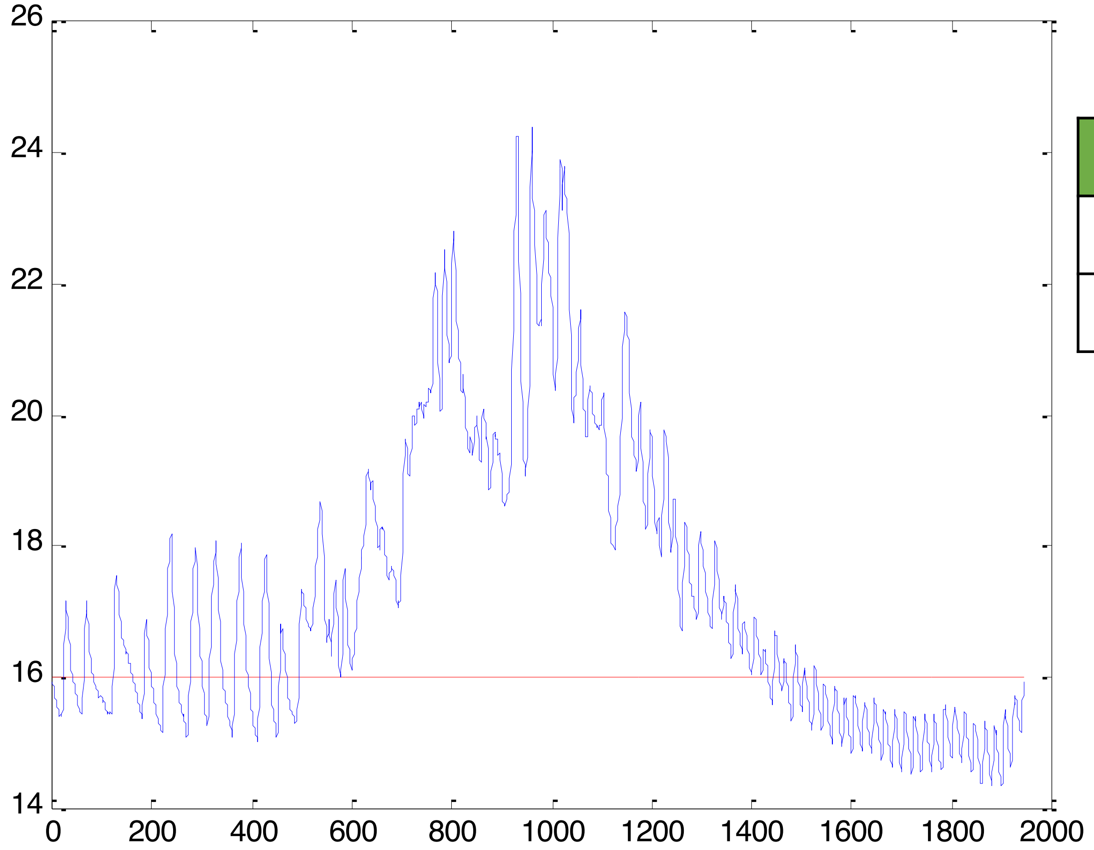




Control with heating by forced air

PWM (Pulse width modulation)

Regulate the power-up time based on the error as if it were a proportional controller



Algorithm	Commutations	Active time
On/Off	13	741
GPC-PWM	39	670

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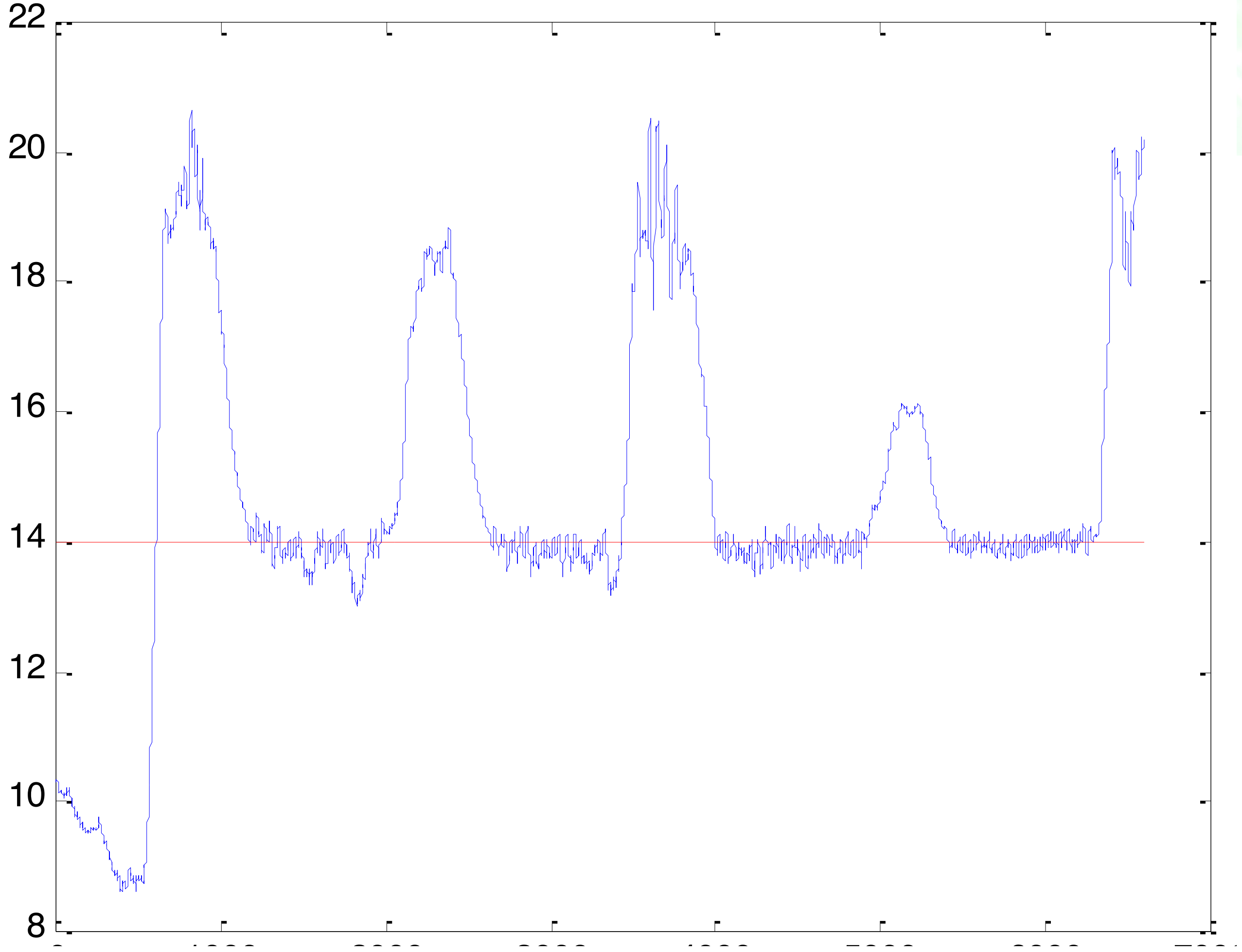
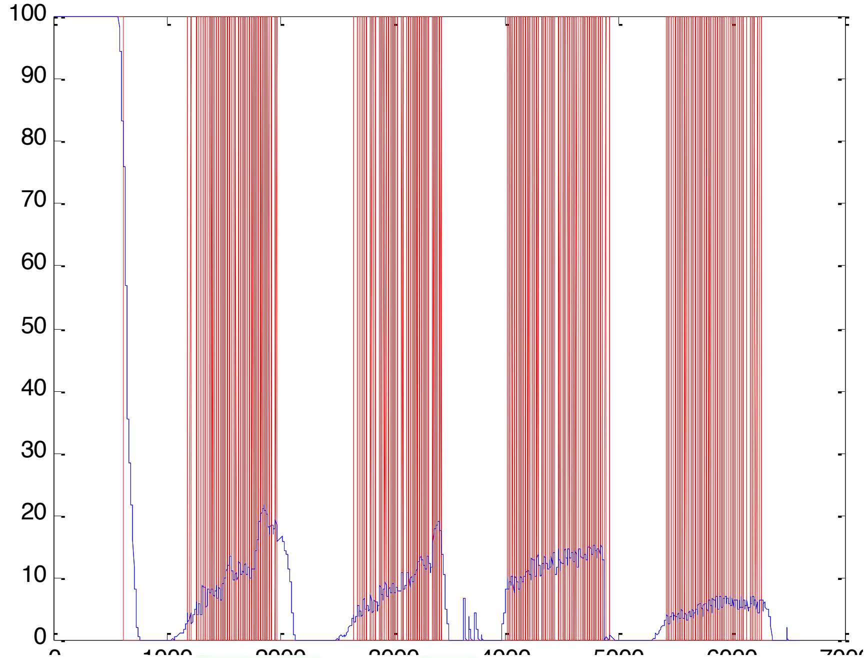
Control with heating by forced air

PWM (Pulse width modulation)

Regulate the power-up time based on the error as if it were a proportional controller





Nocturnal Temperature control

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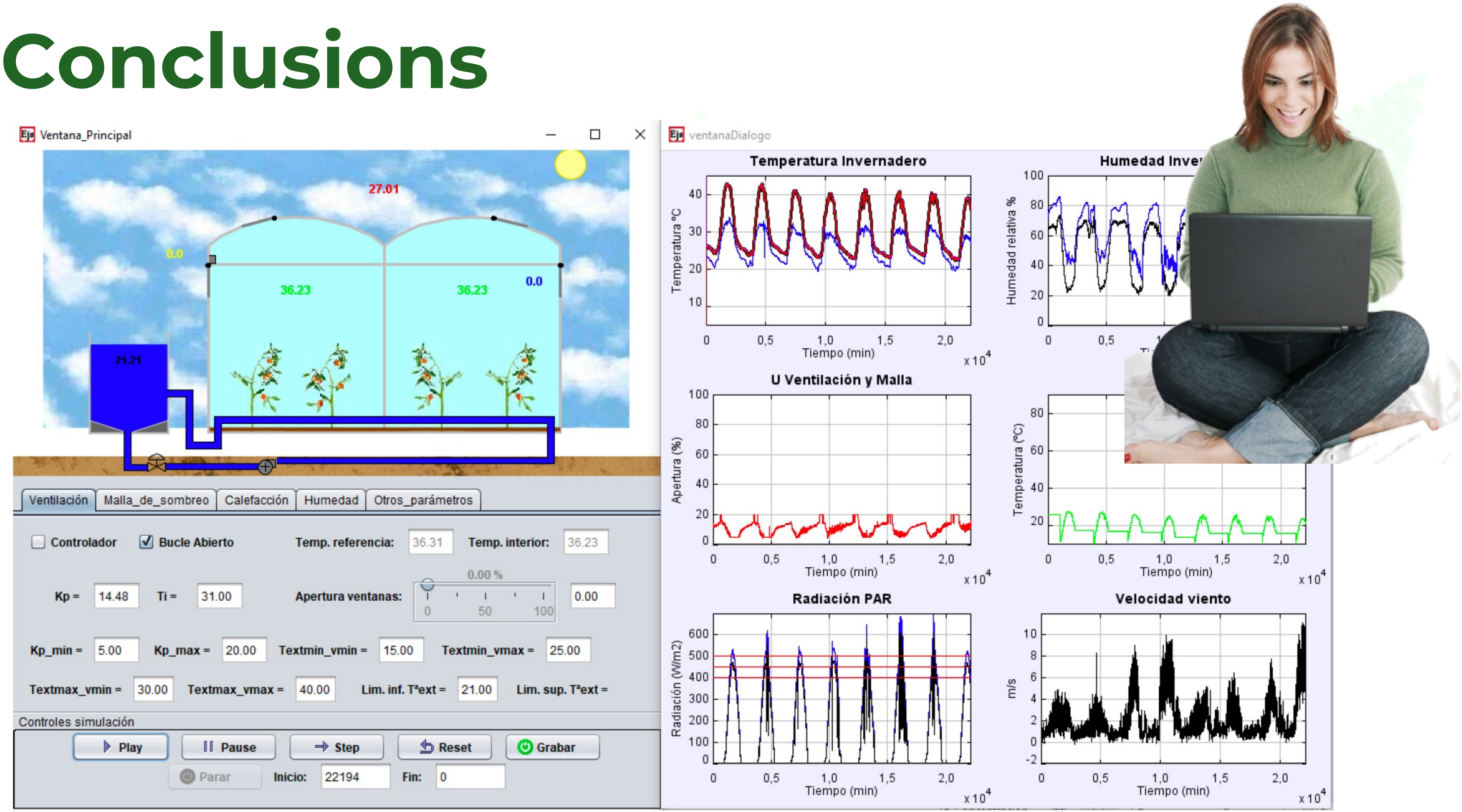
Conclusions

- It is essential to analyse from an economic standpoint whether heating is really necessary in mild climate zones.
- There are different continuous and on/off heating systems which are controlled in different ways.
- The temperature controller used in aerial-pipe heating consists of two proportional control loops, for which all the parameters need to be known and carefully selected.
- The temperature controller used in forced-air heating is easier to tune because it is an on/off controller with few parameters.
- Each greenhouse and heating system will have its own values for these parameters, each of which will need to be calibrated.

It is very important to understand these parameters and know how to obtain good values for them in order for the nocturnal temperature to be well controlled when operating the heating systems.

Conclusions



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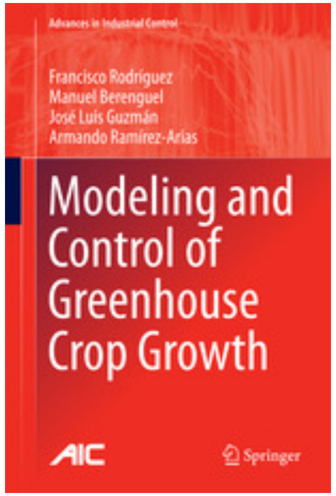

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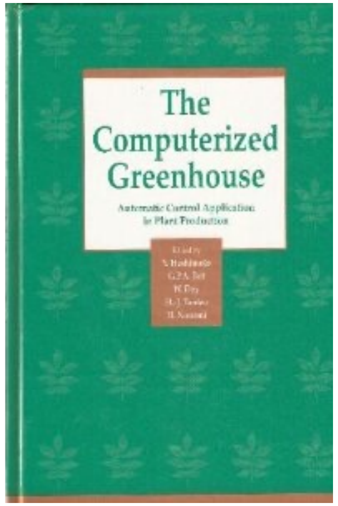

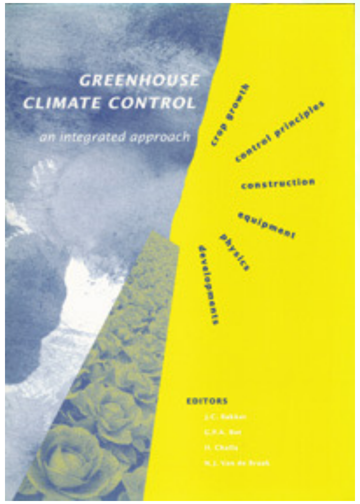

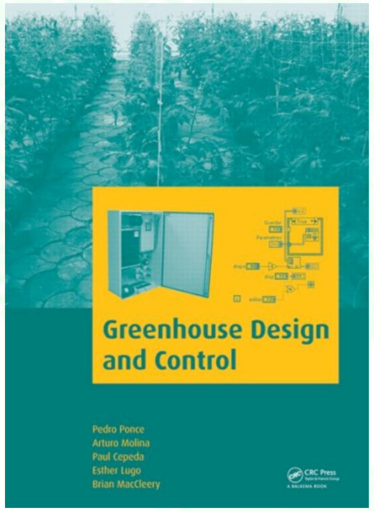

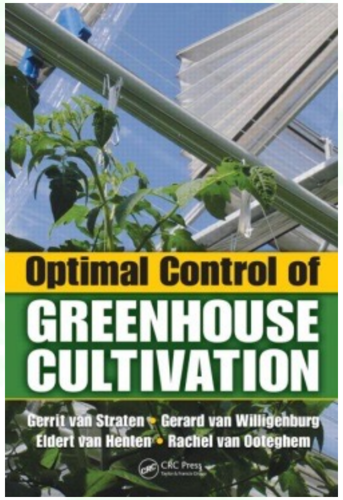

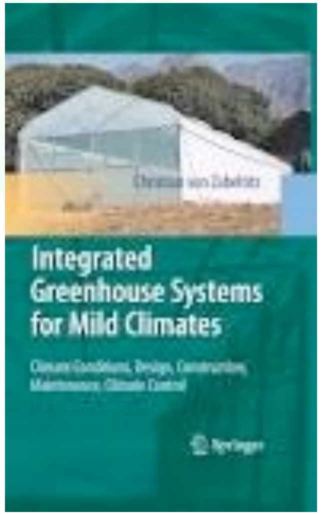

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Module 6: CLIMATE MANAGEMENT

Lesson 6.2: Greenhouse climate variable control

Theme 6.2.3: Greenhouse humidity control

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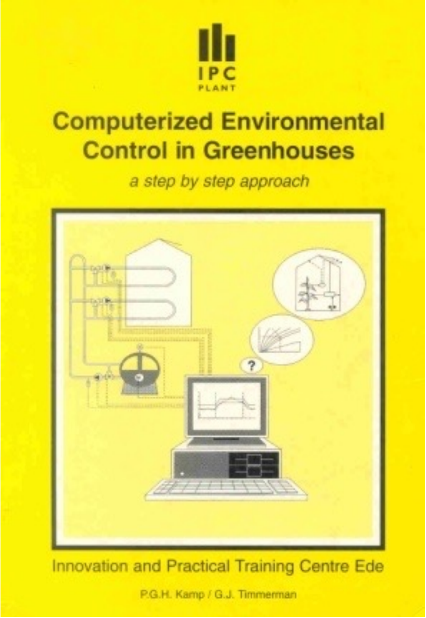
- Humidity control with vents during daytime periods
- Humidity control with heating during night time periods
- Humidity control in night to day transitions
- Control with other actuators
- Conclusions



Kamp, P.G.H.; Timmerman, G.J.; 1996; *Computerized environmental control in greenhouses. A step by step approach*; IPC Plant; Ede; 273 pages.

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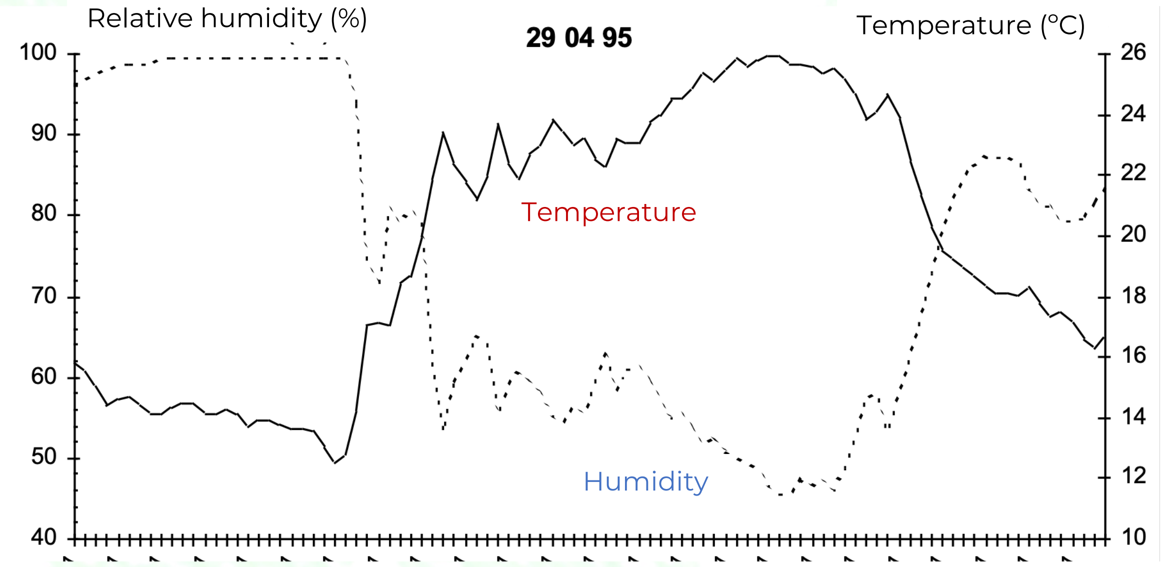
Humidity control problem

- The humidity needs to be kept within a certain interval (60-80%).
- It is strongly correlated with temperature.
- The same temperature actuators must be used to control humidity.



- **Temperature is controlled**
- **Humidity is kept within a certain interval;**
  - Low relative humidity: nebulizers, etc.
  - High relative humidity: vents and heating

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Humidity control

Daytimes with vents

Night times With heating

Night to day

Other actuators

Conclusions

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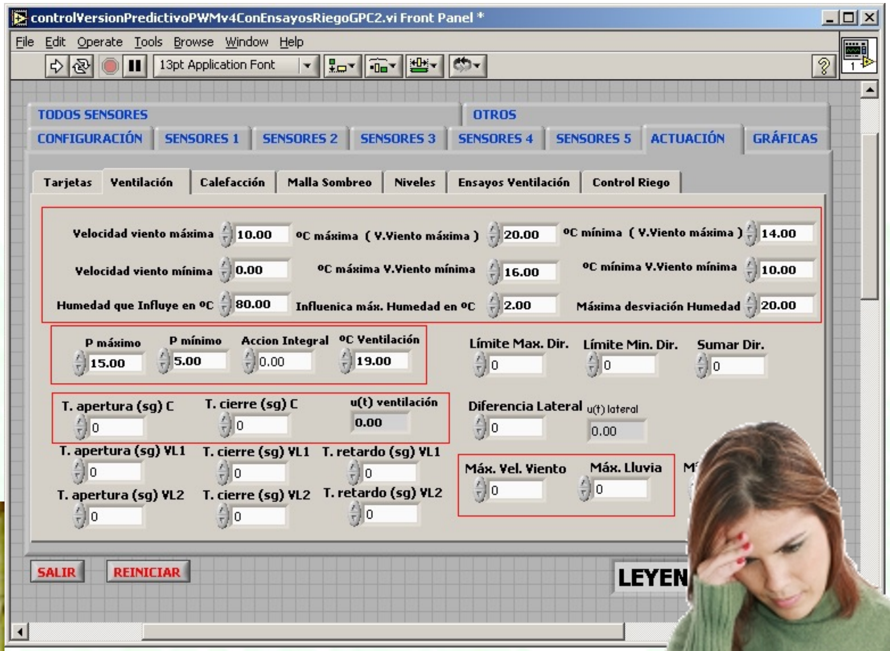
Humidity control



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Humidity control with vents during daytime periods

When the vents open, internal and external air are mixed, producing two effects:

- The internal temperature decreases because the external temperature is usually lower.
- Absolute humidity also decreases because the amount of water vapour inside the greenhouse is generally higher than that contained in the external air.

The relative humidity decreases

Humidity control

Daytimes with vents

Night times With heating

Night to day

Other actuators

Conclusions

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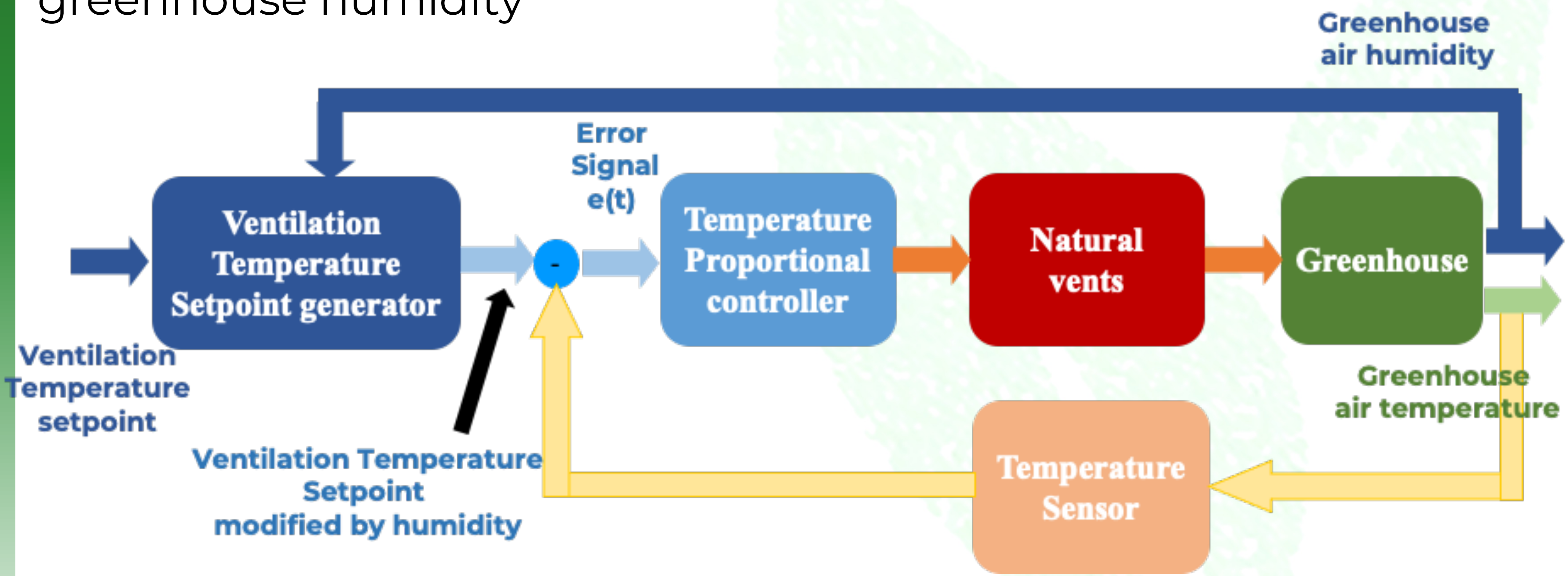
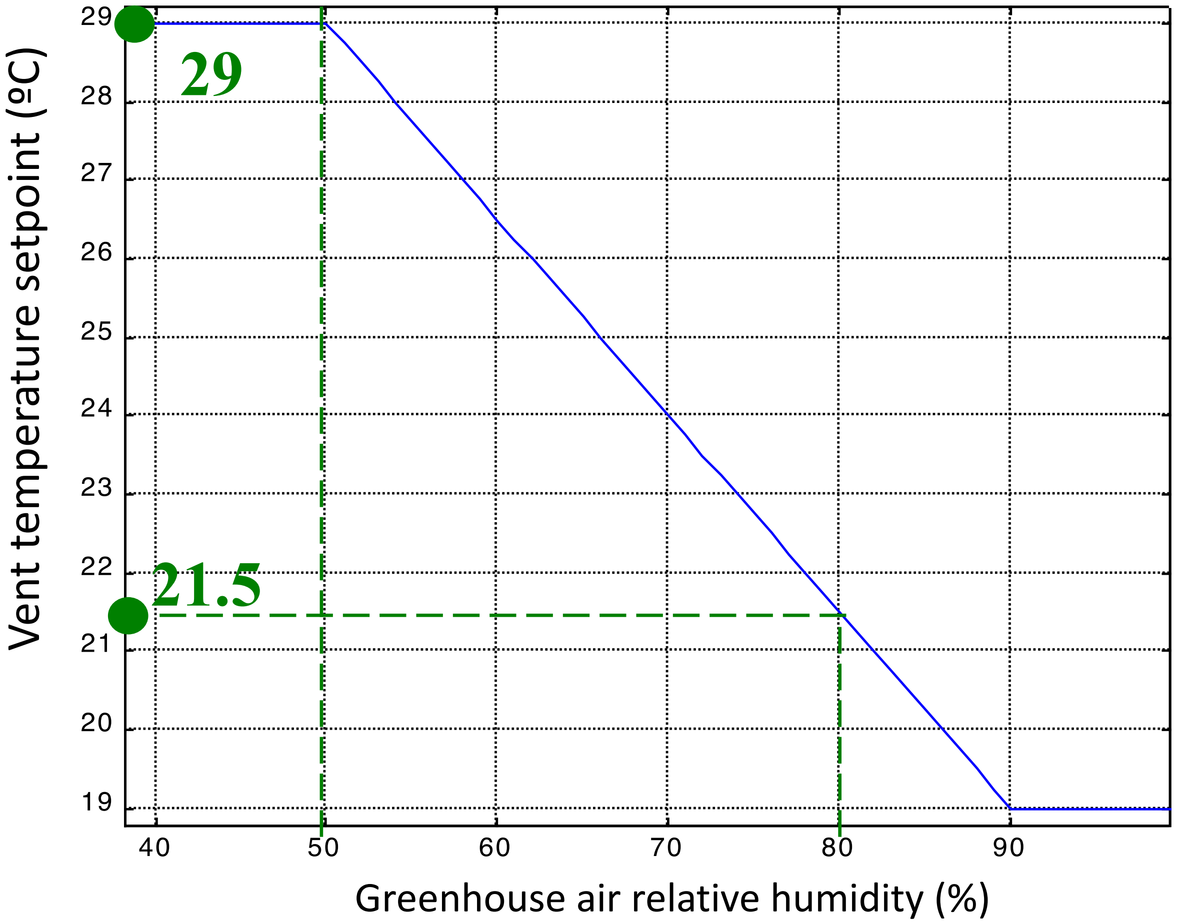
Humidity control with vents

The ventilation temperature setpoint is modified based on the greenhouse humidity



Humidity control with vents

The ventilation temperature setpoint is modified based on the greenhouse humidity

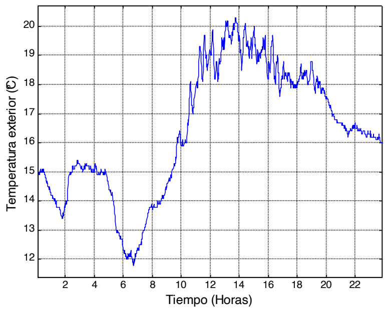


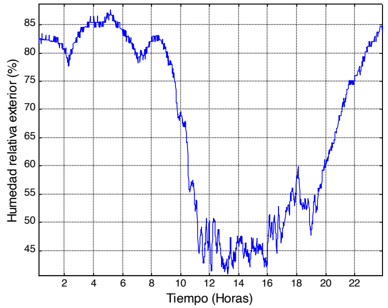
Relative humidity (%)	Greenhouse temperature (ºC)
95	19
90	19
85	20.3
80	**21.5**
75	22.8
70	24
65	25.3
60	26.5
55	27.8
50	**29**
45	29

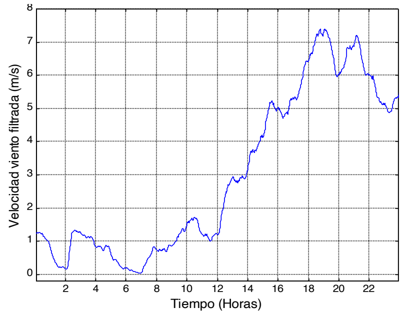
Humidity control with vents

Real results

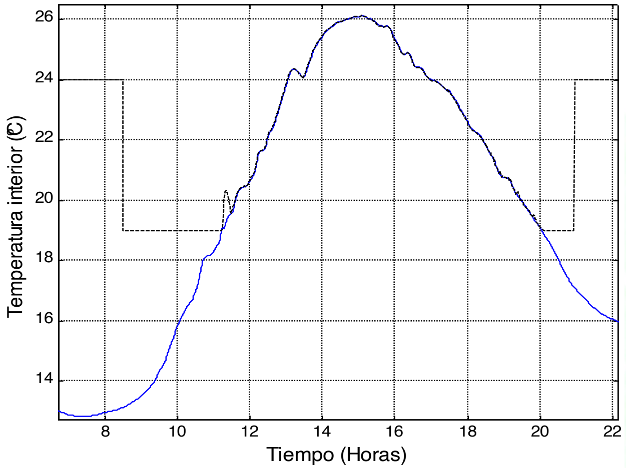
Disturbances



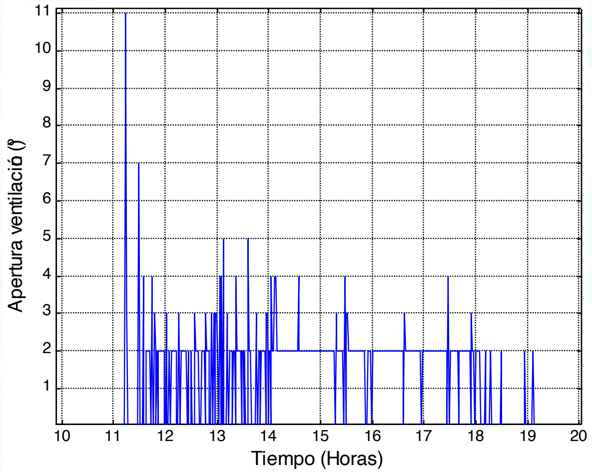


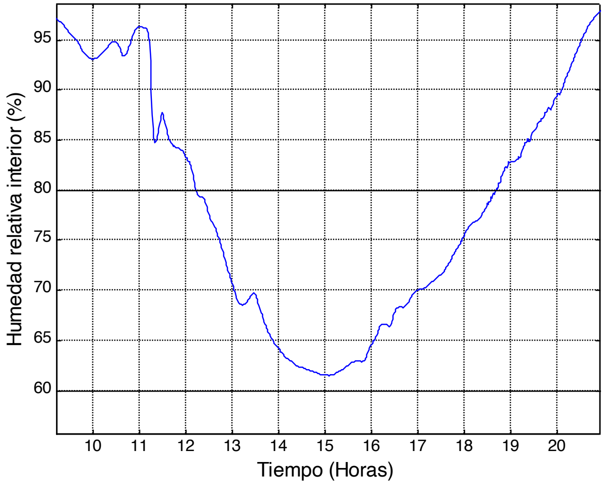


Greenhouse Temperature



Vent opening





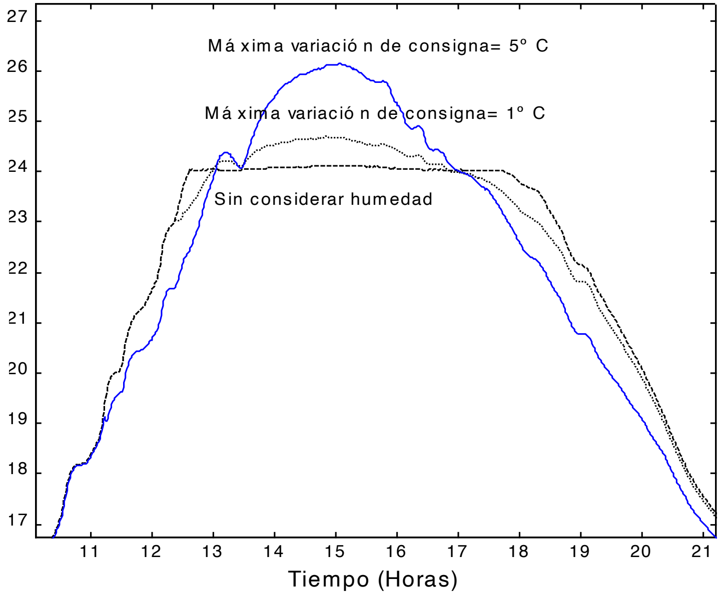
Greenhouse Humidity

Humidity control with vents

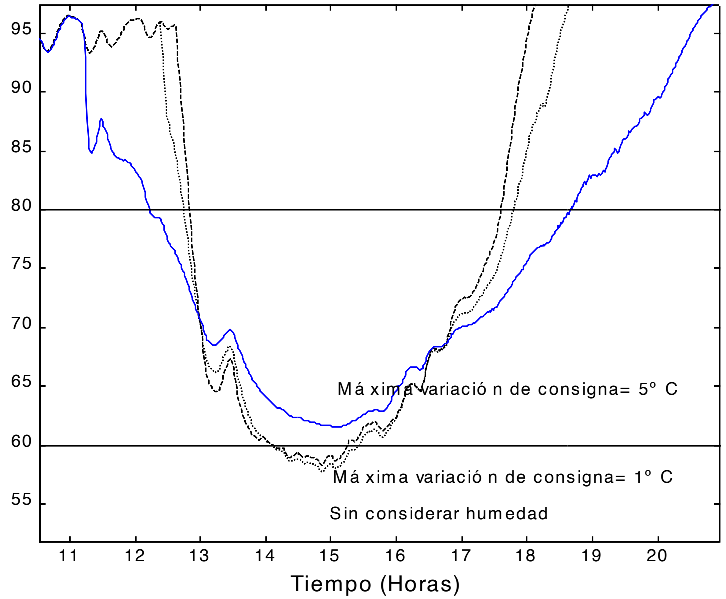
- Humidity control
- **Daytimes with vents**
- Night times With heating
- Night to day
- Other actuators
- Conclusions

Different priorities for temperature and humidity:

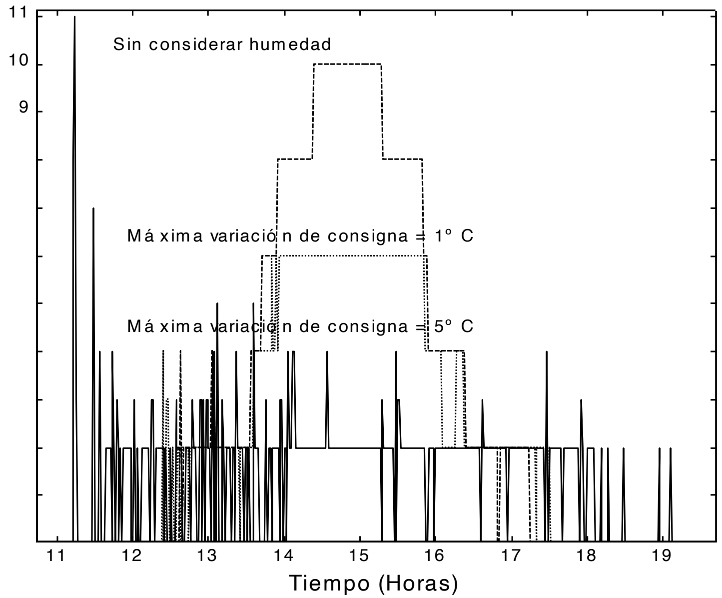
- Priority to temperature only
- High priority to humidity
- High priority to temperature



Greenhouse Temperature



Greenhouse Humidity



Vent opening

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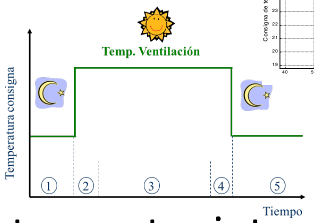
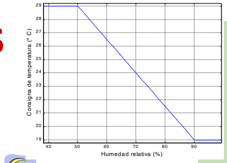
Humidity control with vents

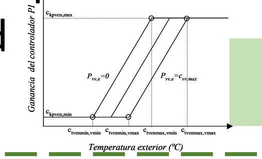
Parameters





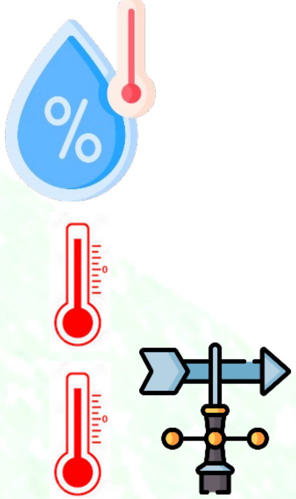
Vent temperature setpoint

Influence of external temperature
Influence of wind speed
Kp intervals



Ventilation Temperature setpoint
↓
Error calculation
↓
Kp calculation
↓
Leeward Vent opening calculation
↓
Windward Vent opening calculation
↓
Adjustment for rain, wind and humidity
↓
Vent position

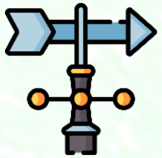
Measurements



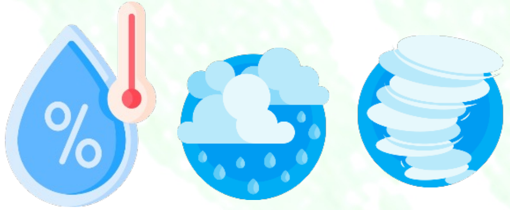
Greenhouse humidity

Greenhouse temperature

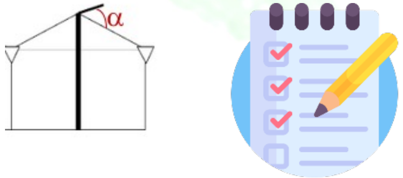
External temperature
External humidity
Wind speed



Wind direction



Rain
Wind Speed
Greenhouse Humidity



Maximum opening vent for wind direction

Maximum opening vent for rain

Maximum opening vent for high wind speed

Humidity control with heating during night time periods

During night time periods, the greenhouse is usually closed, so when the heating systems is in operation:

- The temperature rises,
- **The relative humidity decreases** (although it is usually compensated for by an increase in crop transpiration)

Generally there are no problems with humidity

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Humidity control in night to day transitions

High humidity and low temperature control with ventilation

- A minimum ventilation position is defined as long as the relative humidity is above the limits.
- This is calculated based on the outside temperature and wind speed, which influence the air exchange between the greenhouse interior and exterior.

Humidity control

Daytimes with vents

Night times With heating

Night to day

Other actuators

Conclusions

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Humidity control in night to day transitions

High humidity and low temperature control with ventilation

Greenhouse humidity= 90 %

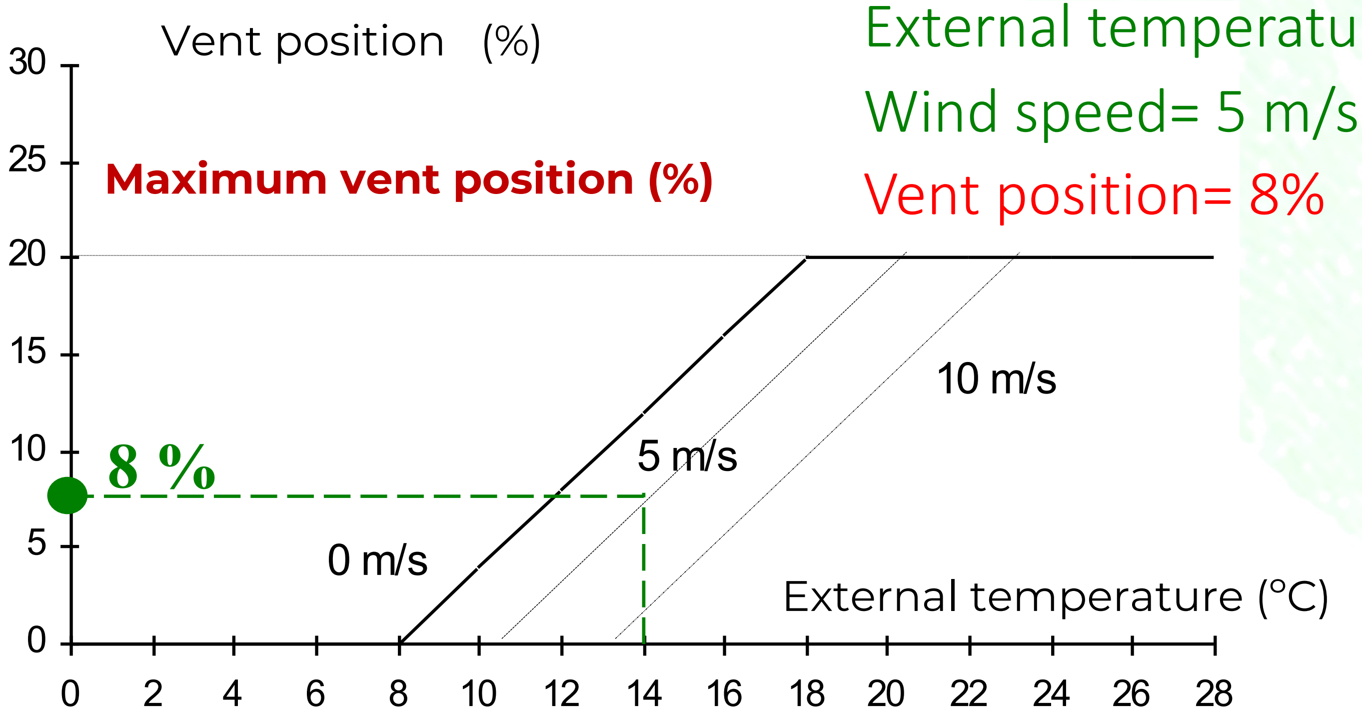
Vent setpoint= 25 ºC

Greenhouse temperature= 20 ºC

External temperature= 14ºC

Wind speed= 5 m/s

Vent position= 8%



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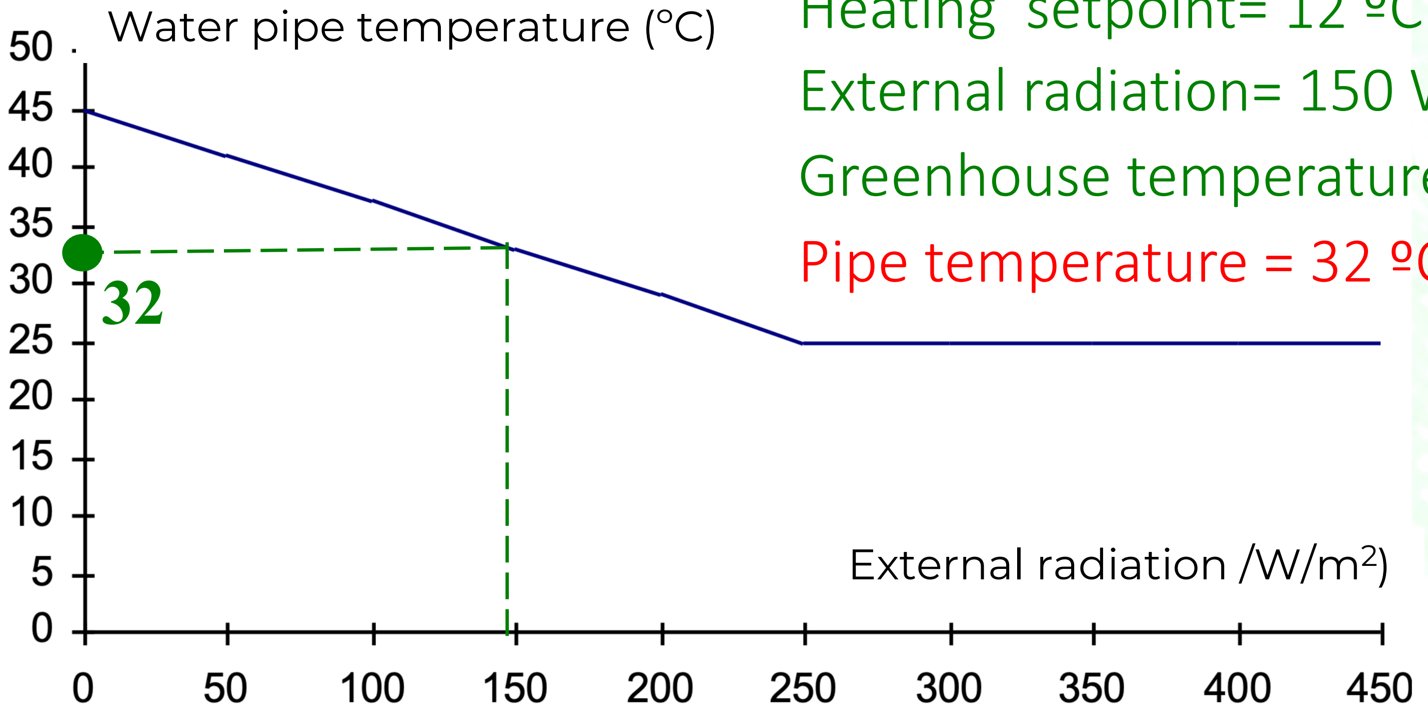
Humidity control in night to day transitions

Control of high humidity at low temperature (but higher than the heating setpoint) **in daytime periods with low radiation and heating.**

A minimum base temperature for the pipes is set as long as the relative humidity is above the limits. It is calculated based on the external radiation.

Humidity control in night to day transitions

Control of high humidity at low temperature (but higher than the heating setpoint) **in daytime periods with low radiation and heating.**



Heating setpoint= 12 ºC

External radiation= 150 W/m^2

Greenhouse temperature= 14 ºC

Pipe temperature = 32 ºC

Control with other actuators

Other actuators used to control the humidity are:

- Fog systems
- Cooling systems
- Dehumidifying machines

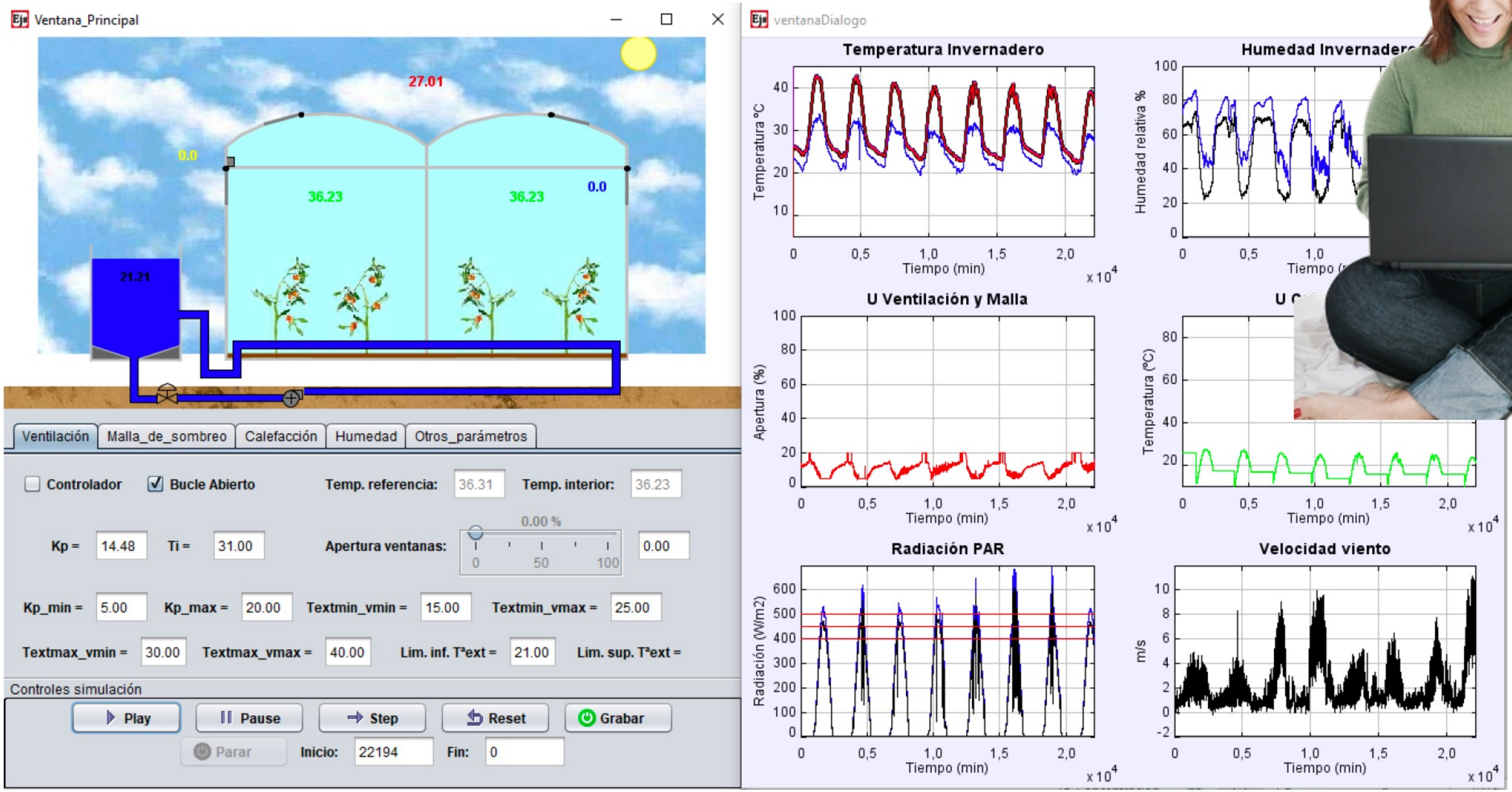
This is an on/off actuator, so one would need to use an on/off controller corrected by a dead zone.

Conclusions

- Relative humidity is not one of the climatic variables that directly affects crop growth, although its control is of particular interest.
- It is essential to analyse from an economic standpoint whether it is really necessary to use actuators in mild climate zones to control the humidity.
- It is essential to modify the greenhouse temperature control with vents and heating systems to account for the humidity.
- In order to modify this, controllers are needed to tune the new parameters.
- Each greenhouse and actuator will have its own values for these parameters, which will need to be calibrated in each case.

It is very important to understand these parameters and know how to obtain good values for them in order for the relative humidity to be well controlled.

Conclusions



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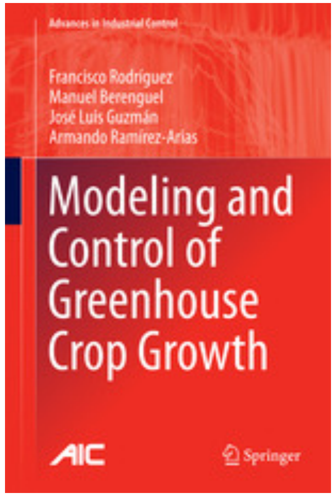
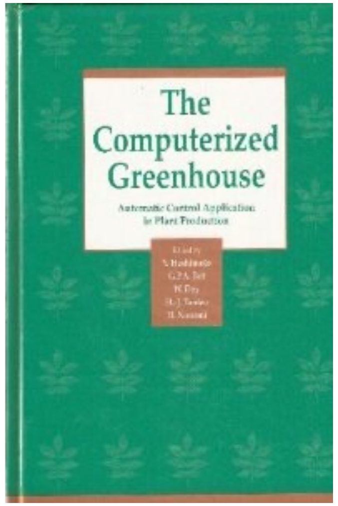
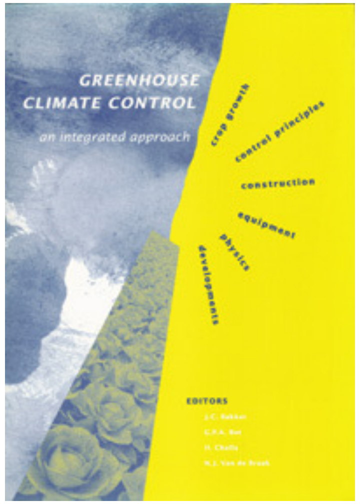
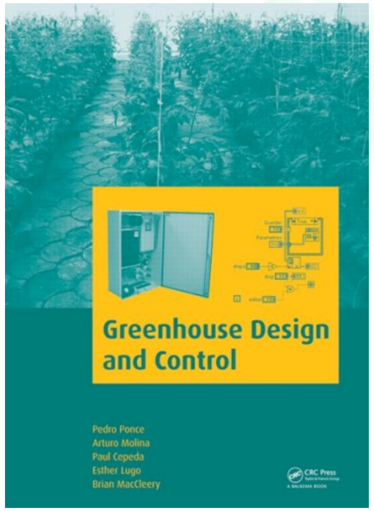
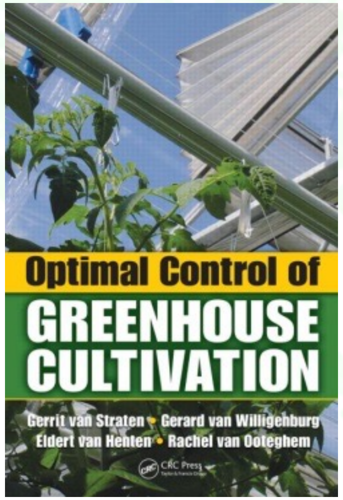


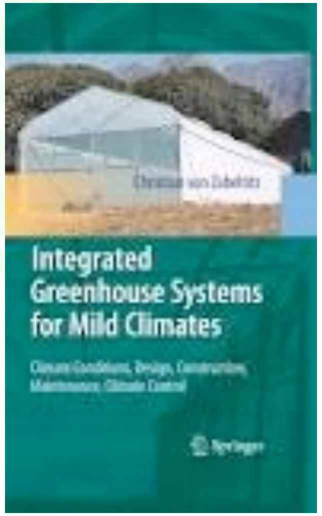
Rodríguez, F., Berenguel, M., Guzman, J.L., Ramírez-Arias, A..; 2015; *Modeling and Control of Greenhouse Crop Growth*; Springer International Publishing; London (UK); 250 pages.











Co-funded by the Erasmus+ Programme of the European Union

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Module 6:
CLIMATE MANAGEMENT

Lesson 6.2:
Greenhouse climate variable control

Theme 6.2.4:
Radiation and CO_2 control

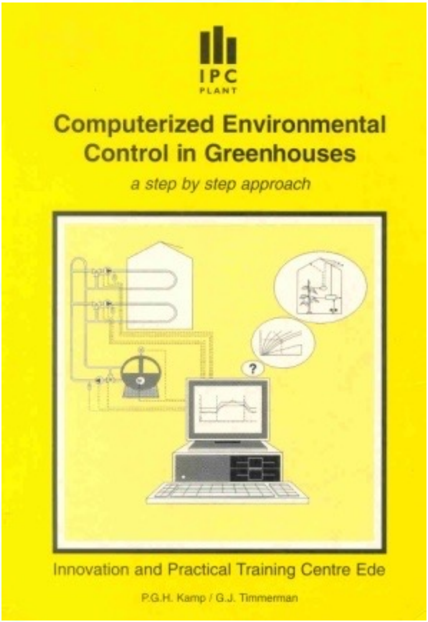
Radiation control

CO_2 control

Conclusions

Index

- Radiation control problem
- CO_2 control problem
- Conclusions



Kamp, P.G.H.; Timmerman, G.J.; 1996; *Computerized environmental control in greenhouses. A step by step approach*; IPC Plant; Ede; 273 pages.

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Radiation control

CO_2 control

Conclusions

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Radiation control problem

It is important to control the radiation because:

- It provides the energy for the physiological processes of plants (photosynthesis).
- It heats the solid elements of the greenhouse, affecting the heat transfer processes.

Excess radiation

- The more radiation, the more photosynthesis.
- The crop and air temperature increase, and this can damage the crop.

Radiation decreases using shade screens

Radiation control

CO_2 control

Conclusions

Radiation control problem

It is important to control the radiation because:

- It provides the energy for the physiological processes of plants (photosynthesis).
- It heats the solid elements of the greenhouse, affecting the heat transfer processes

Lack of radiation

It is necessary for crop growth.

Radiation can be increased using artificial lighting

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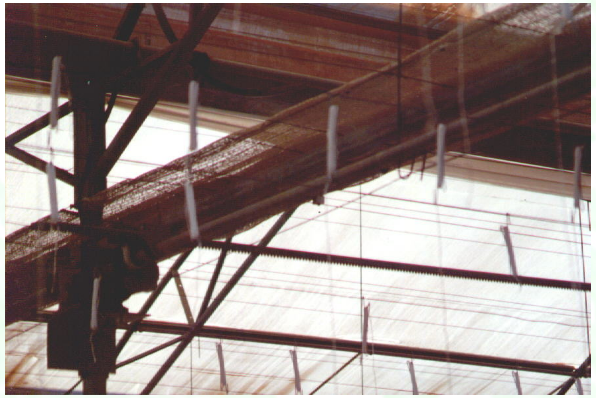
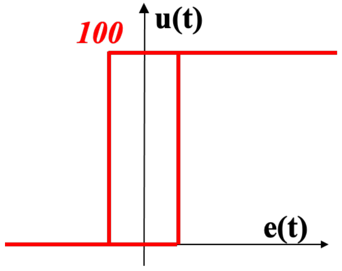
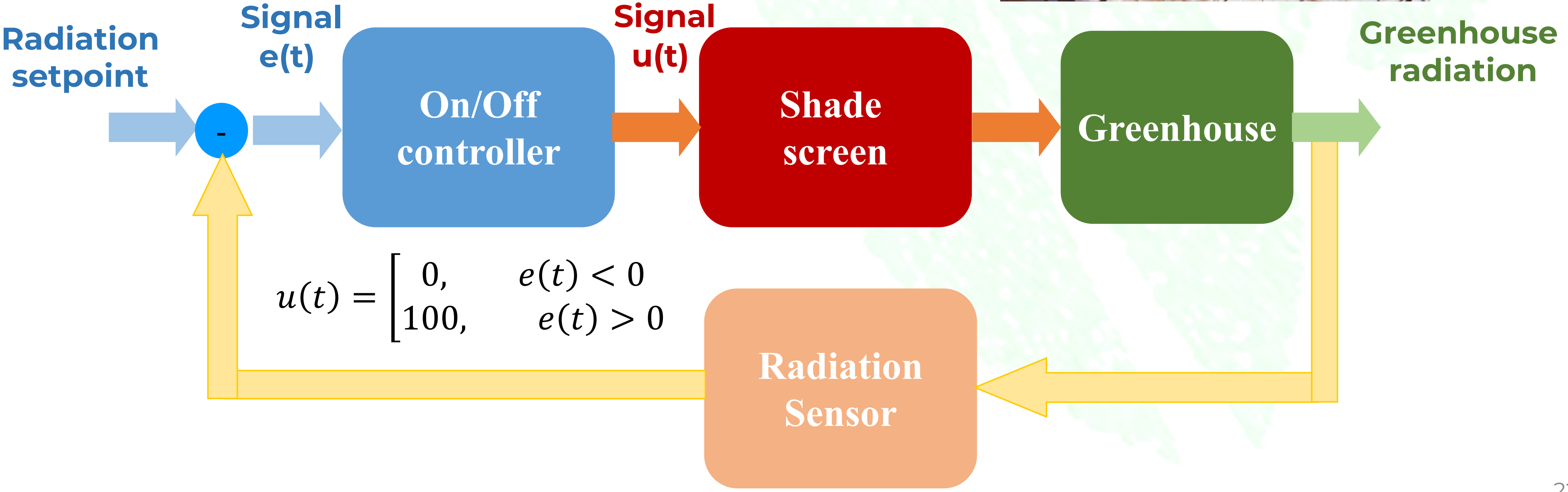
Radiation control with shade screens

This is an on/off actuator, so one would need to use an **on/off controller** corrected by a dead zone.







$$u(t) = \begin{cases} 0, & e(t) < 0 \\ 100, & e(t) > 0 \end{cases}$$

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Radiation control

CO_2 control

Conclusions

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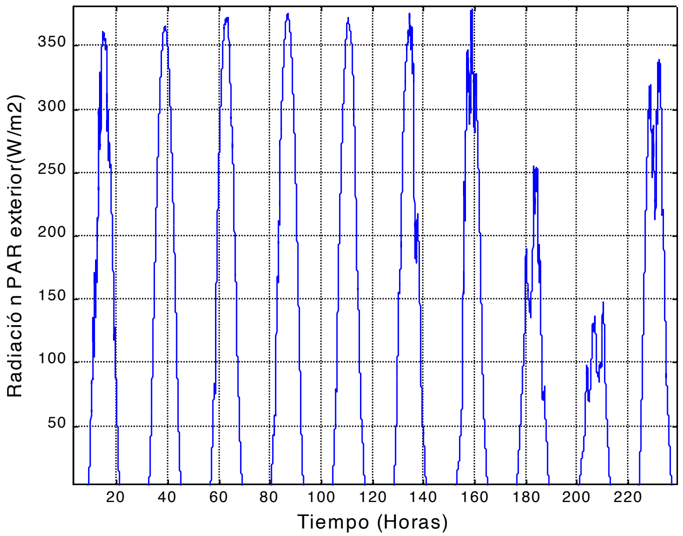
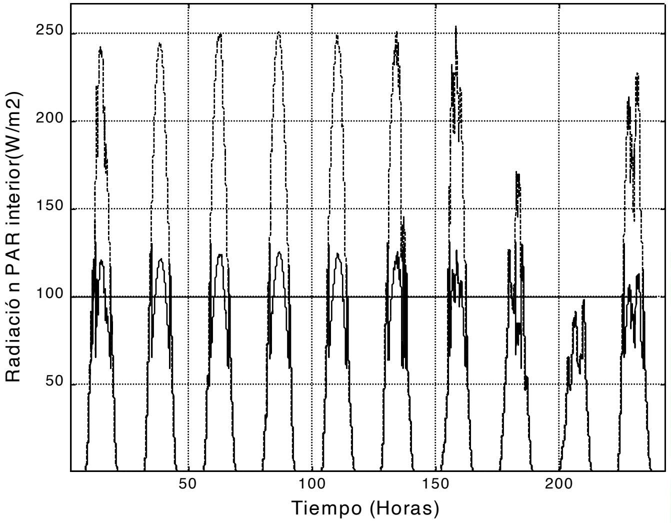
Radiation control with shade screens

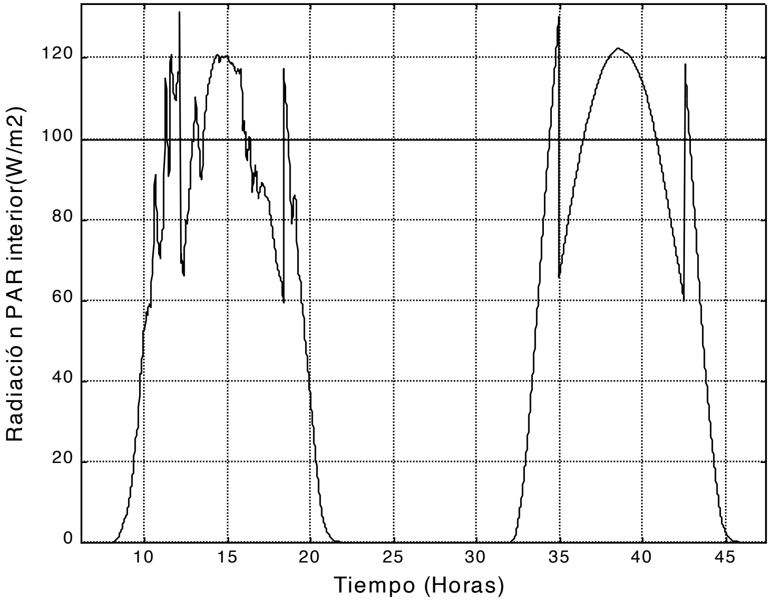
Real results

Disturbances

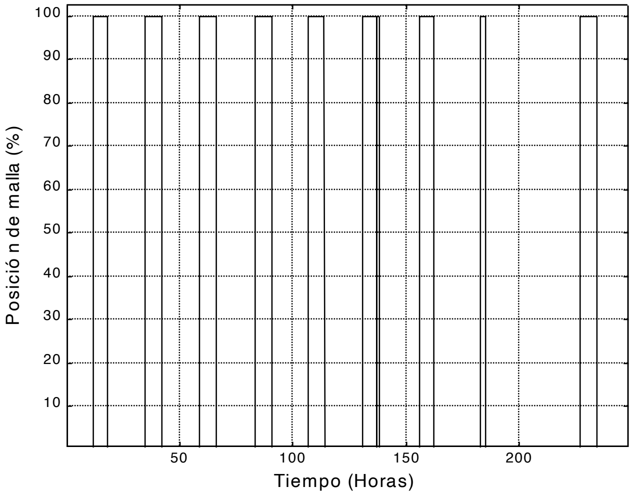


Greenhouse Radiation





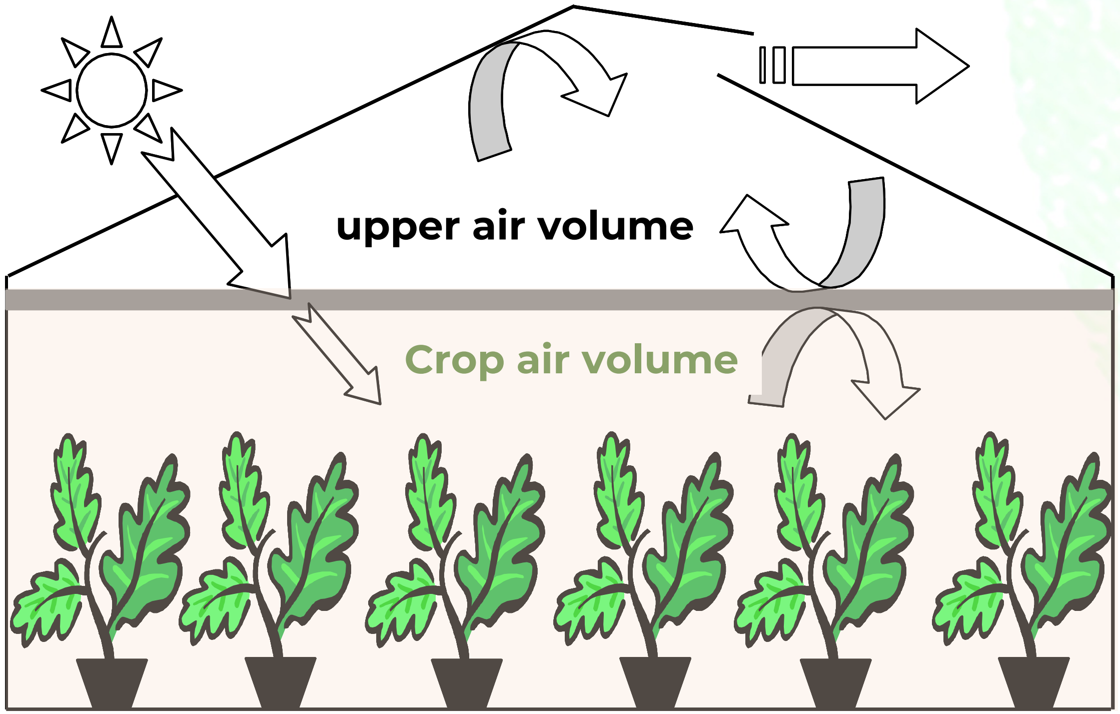
Shade screen



Radiation control with shade screens

Correcting for high humidity and/or high temperature

By extending the shading screens, the volume of air around the crop is reduced as is the exchange of external air.



Under certain conditions, the temperature and/or humidity may increase.

Radiation control

CO_2 control

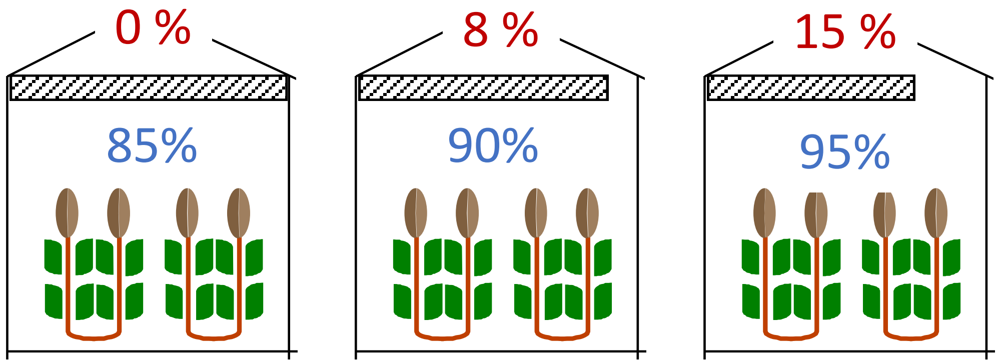
Conclusions

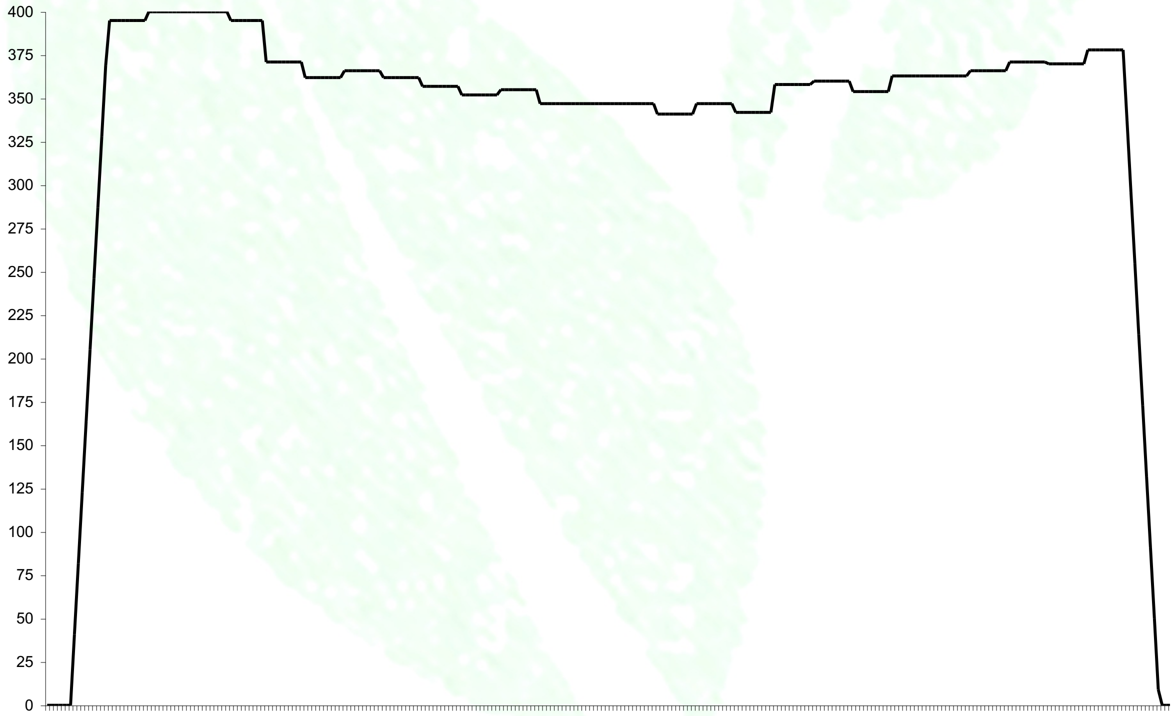
Radiation control with shade screens

Correcting for high humidity

Maximum shade screen opening is allowed to improve the air exchange with the external air.

- Shade screen opening starts when humidity = 85 %
- Maximum position of shade screen when influencing humidity = 15 %.
- Shade screen opening stops when humidity = 95 %





Radiation control with lighting

In this case, a closed-loop controller is not used.

The user only programs the lighting systems by indicating:

- Duration

  When each artificial lighting period begins and its duration.

- Intensity

  It is necessary to indicate the setpoint for the light intensity in each lighting period.

- Type of light

  It is necessary to indicate the type of light (colour, etc.) in each lighting period.

Radiation control

CO_2 control

Conclusions

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CO_2 control problem

CO_2 must be controlled because it is essential for the photosynthesis process.

There is an optimal CO_2 concentration for each crop state.

Objective	Date	CO2 concentration [ppm]
Vegetative growth before flowers appear	Nov-Dec	700-1000
Development of strong clusters and flowers	Jan-Feb	500-700
Maintaining the balance of the plant	Feb-Apr	900-1500
Maintaining the quality of the flowers	May-Jul	>400
Maintaining the fruit quality	Aug-Nov	1000-1250

CO_2 control problem

At night, the plant does photosynthesise so it does not consume CO_2 and the CO_2 concentration is maximum.

During the day, the plant needs CO_2 for photosynthesis, so it consumes it, leading to a deficit.

There is a lack of CO_2

CO2 enrichment is required

Radiation control

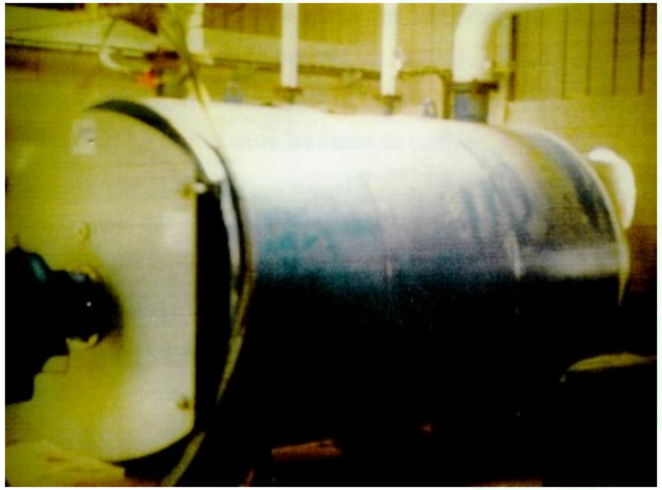
CO_2 control

Conclusions

CO_2 control problem

There are three types of CO_2 actuators

- Pure CO2 cylinders
- Gas combustion
- Gas flow from boilers for water heating



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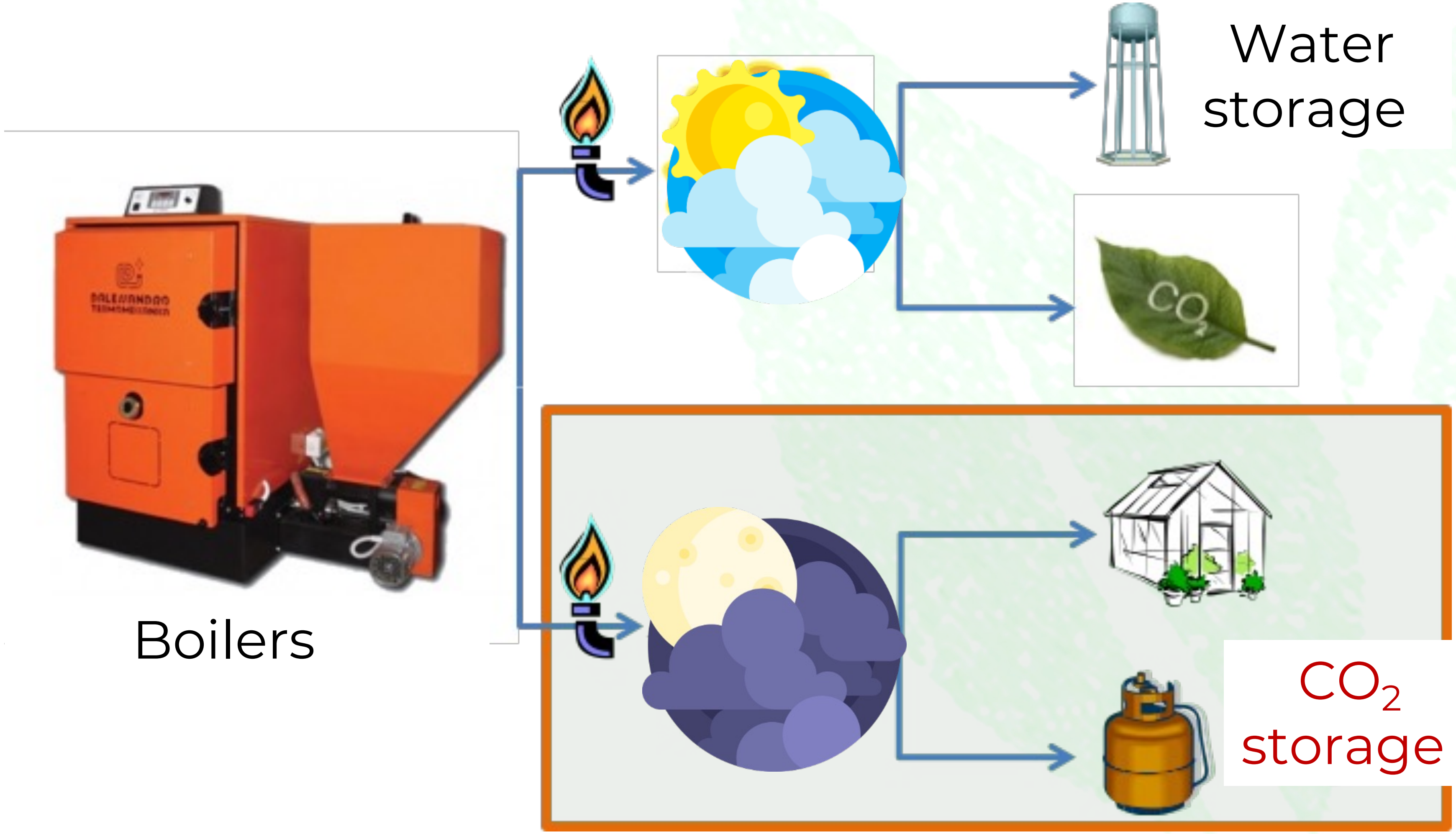
CO_2 control problem

What happens in warm areas?



Radiation control

CO_2 control

Conclusions

CO_2 control problem

Control algorithm for CO2 enrichment systems

Remove CO_2

- Open ventilation
- Turn off enrichment if it was in operation

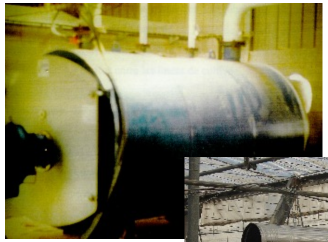
Maximum CO_2 level

CO_2

Permitted concentration

Operate the same

Minimum CO_2 level



Need to enrich

- Turn on enricher if it wasn't in operation
- Store heat if the heating is operating during the daytime

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Radiation control

CO_2 control

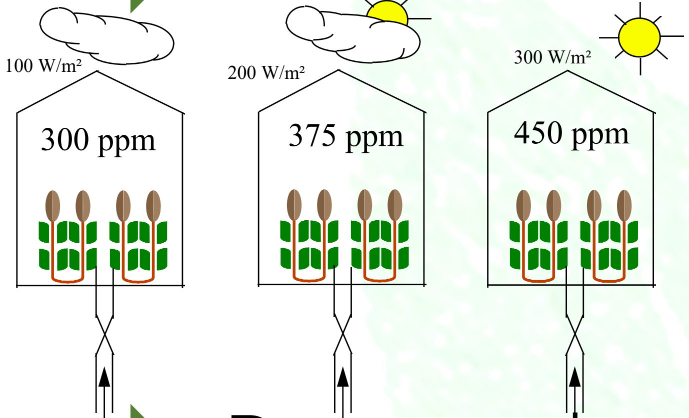
Conclusions

CO_2 control problem

Correcting the control algorithm for CO2 enrichment systems

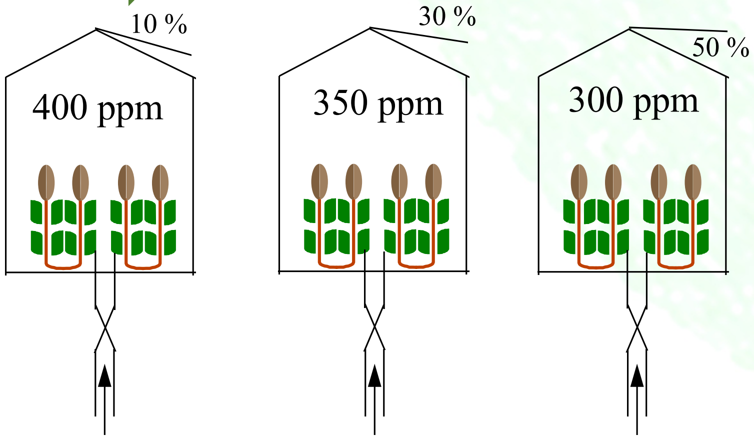
Effect of radiation → Increase the minimum level allowed

Biological criteria



Effect of ventilation → Decrease the minimum level allowed

Economical criteria



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Radiation control

CO_2 control

Conclusions

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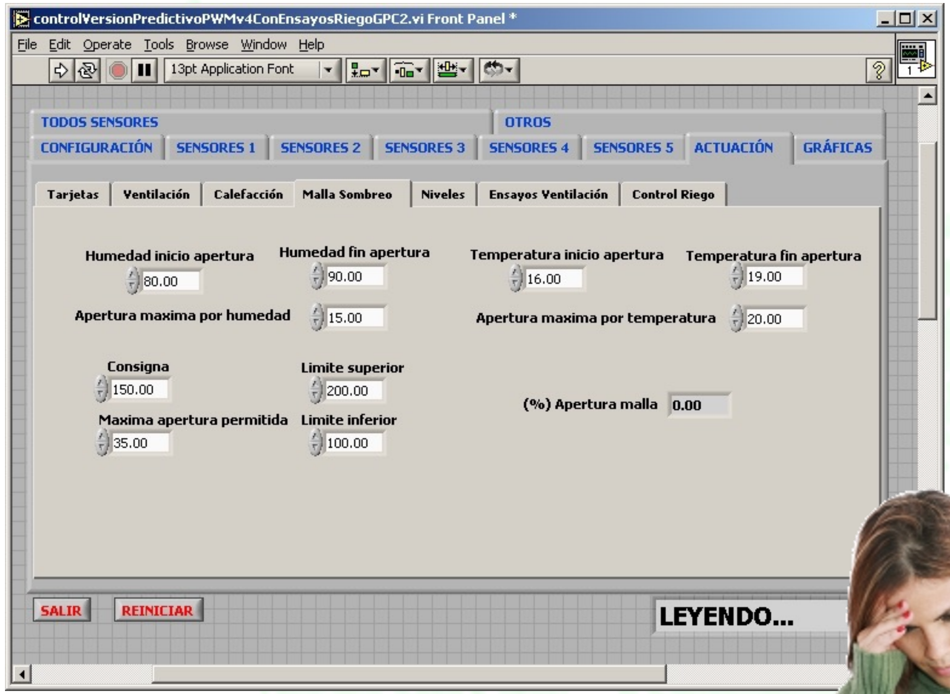
Radiation and CO_2 control



Radiation control

CO_2 control

Conclusions

Conclusions

- Radiation and CO_2 are two variables that directly affect crop growth, so their control is of particular interest.
- It is essential to analyse from an economic standpoint whether these kinds of actuators are really necessary in mild climate zones.
- The control of radiation and CO_2 are easy because the algorithms used only need a few parameters to work.
- Each greenhouse and actuator will have its own values for these parameters, which will need to be calibrated in each case.

It is very important to understand these parameters and know how to obtain good values for them in order for radiation and CO2 to be well controlled.

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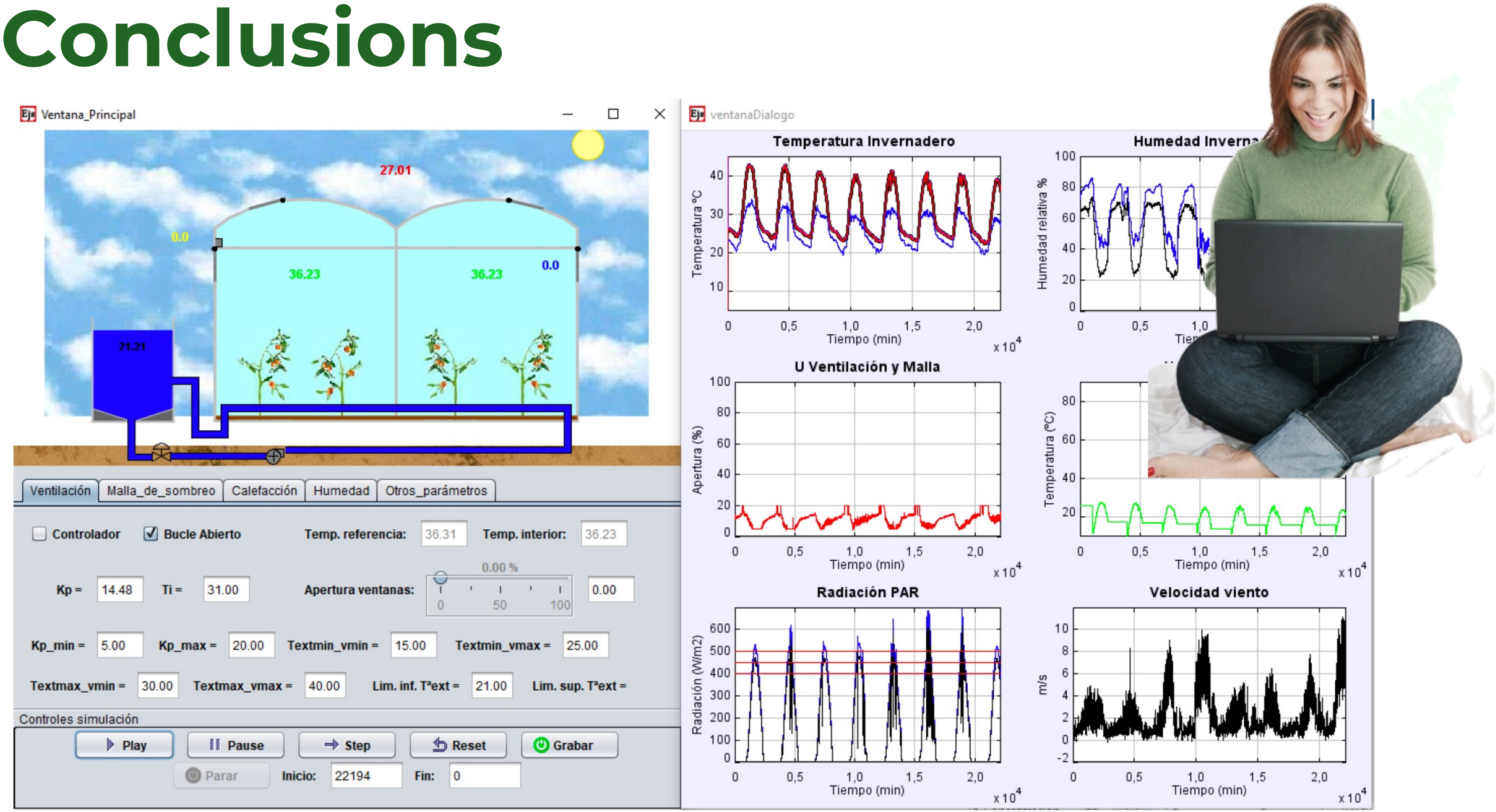
Conclusions



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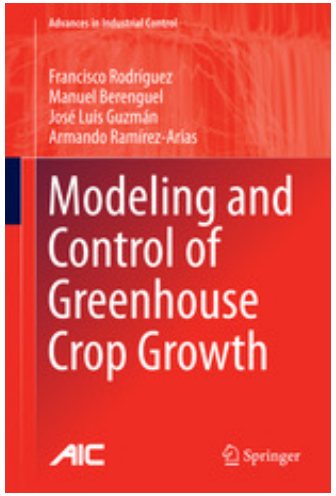

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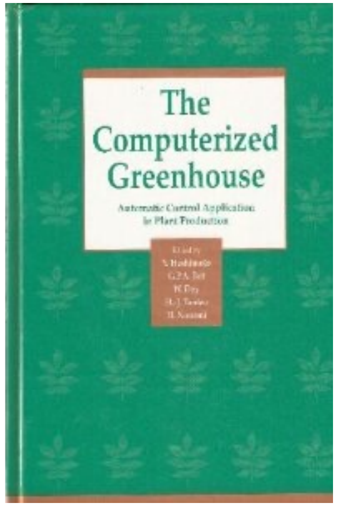

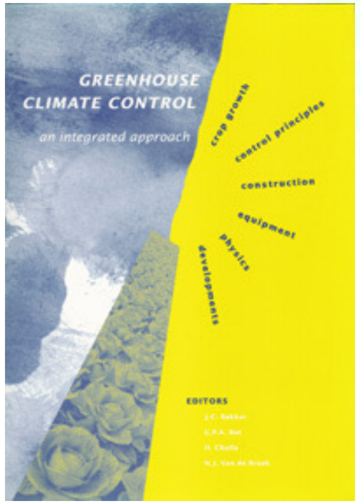

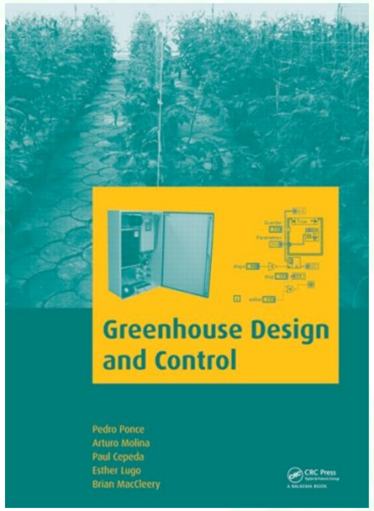

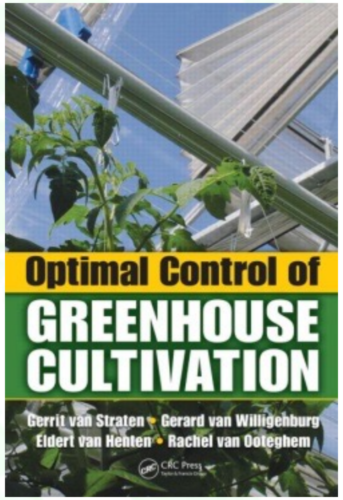

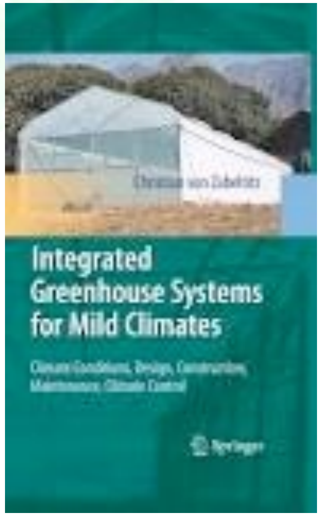

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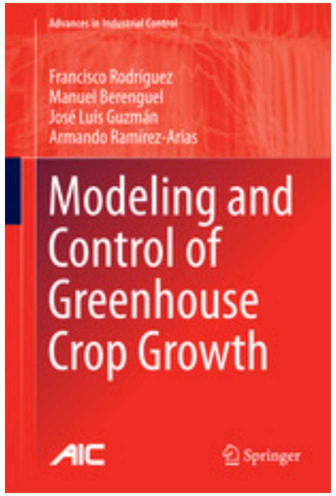
Module 6: CLIMATE MANAGEMENT

Lesson 6.3.1: Crop growth control fundamentals

Index

- Crop growth control
- Hierarchical control approach
- Multiobjective control approach
- Conclusions



Rodríguez, F., Berenguel, M., Guzman, J.L., Ramírez-Arias, A..; 2015; *Modeling and Control of Greenhouse Crop Growth*; Springer International Publishing; London (UK); 250 pages.

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Crop Growth

Climate control strategies

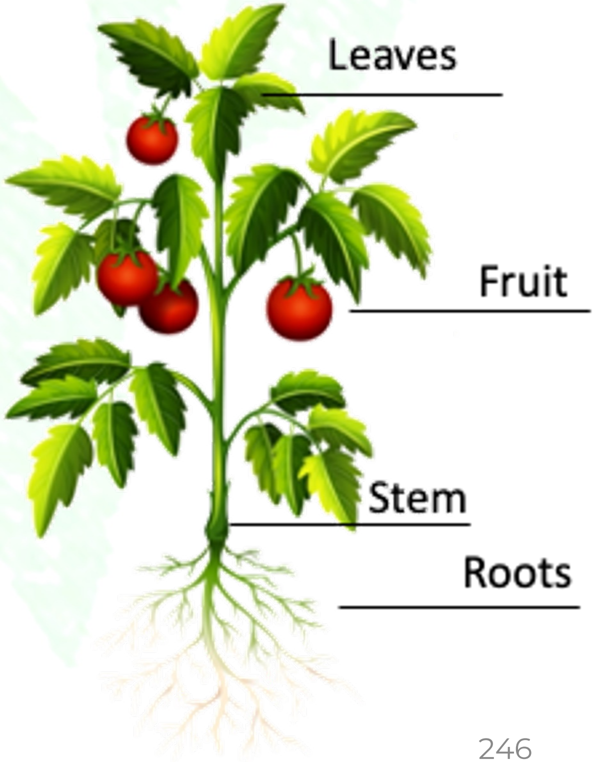
Conclusions

Crop growth

Crop growth can be defined as an increment in the biomass or the physical dimensions of the plants [Bidwell, 1974]

How can it be measured?

- Number and size of leaves
- Dry matter (matter resulting from drying the plants)
- Fresh weight (weight of the plant comprising the dry matter and water)



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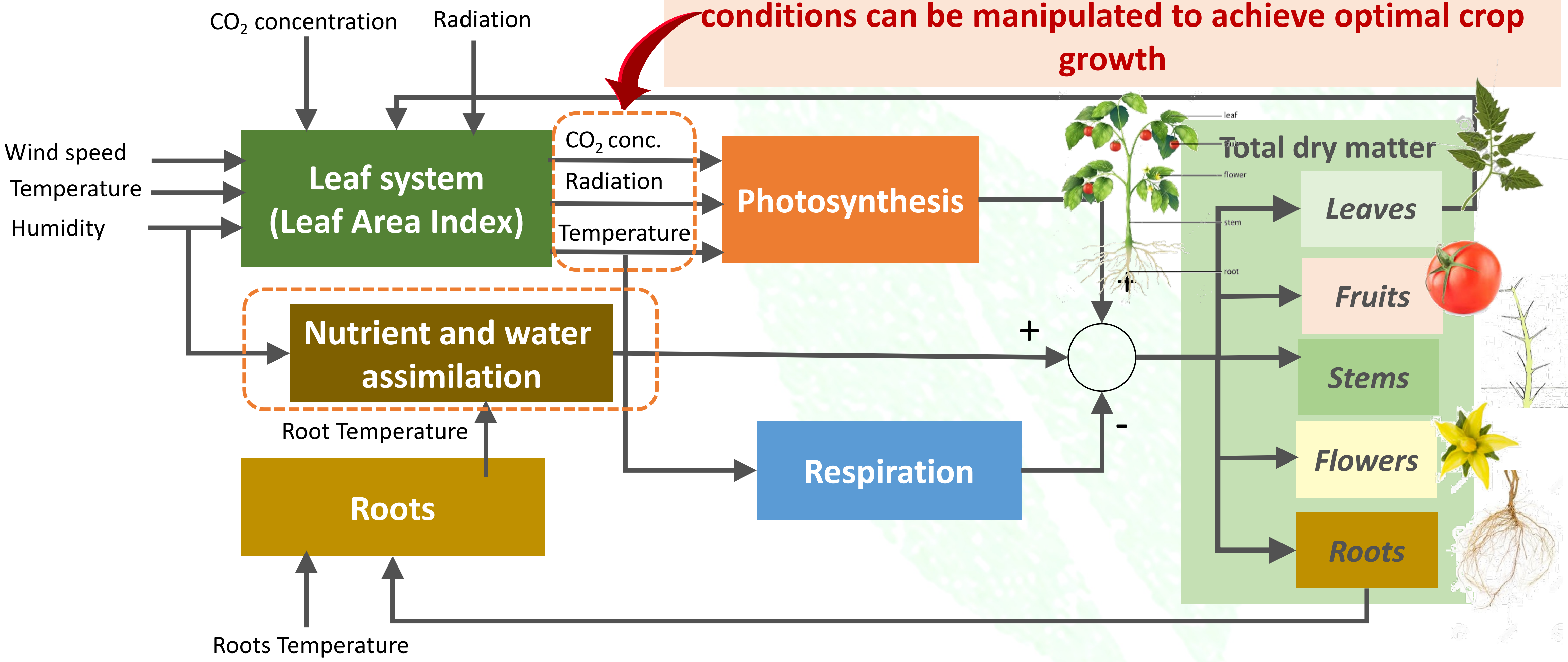
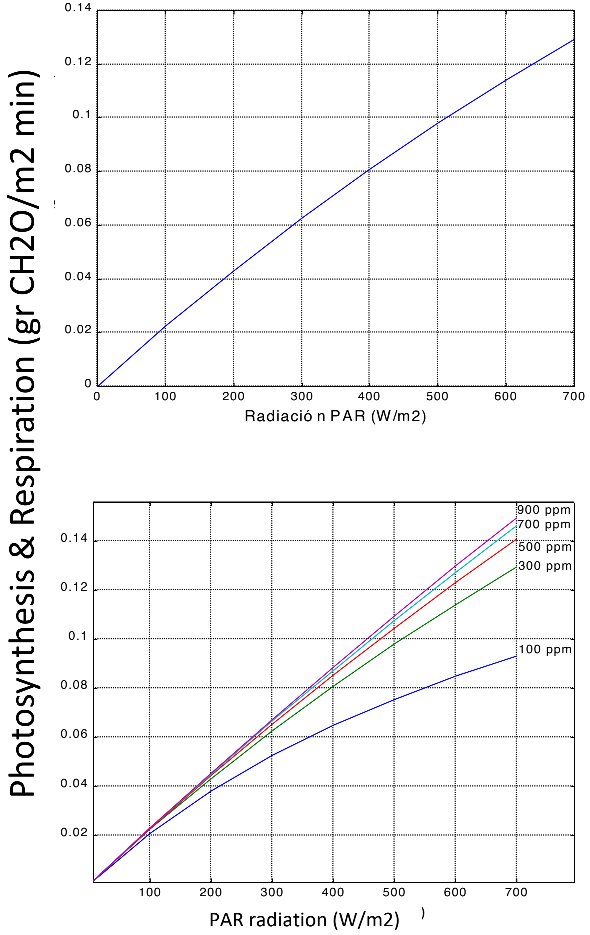
Crop growth

A greenhouse is a sealed enclosure where weather conditions can be manipulated to achieve optimal crop growth



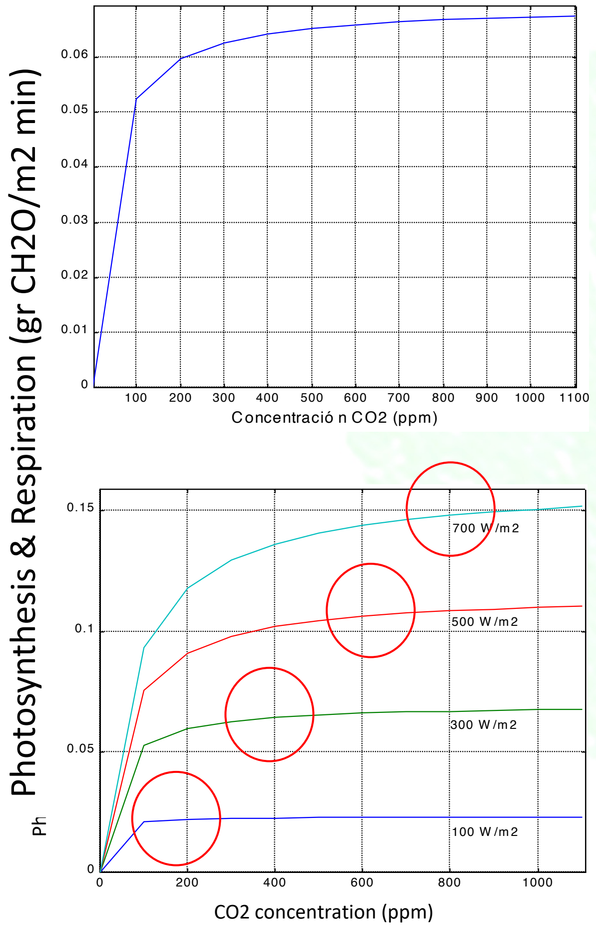
Crop growth

RADIATION



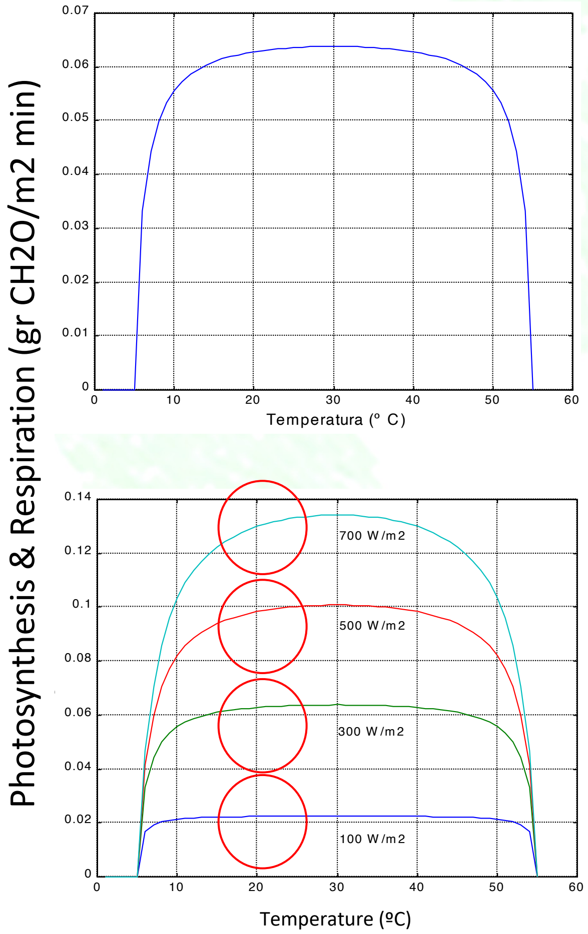
CO_2 concentration RADIATION

CO_2 concentration



RADIATION CO_2 concentration

Temperature



RADIATION Temperature

Crop growth

Climate control strategies

Conclusions

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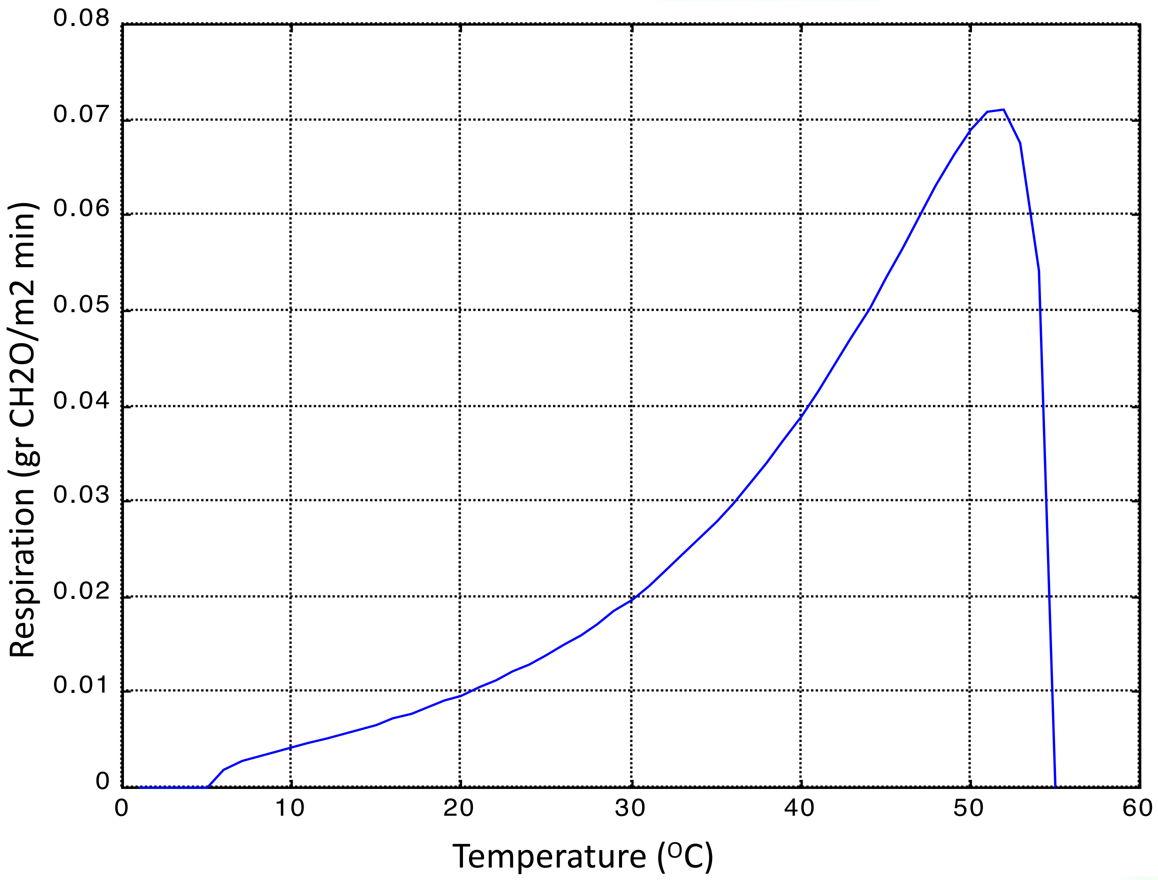
Crop growth

Temperature



Crop growth

Climate control strategies

Conclusions

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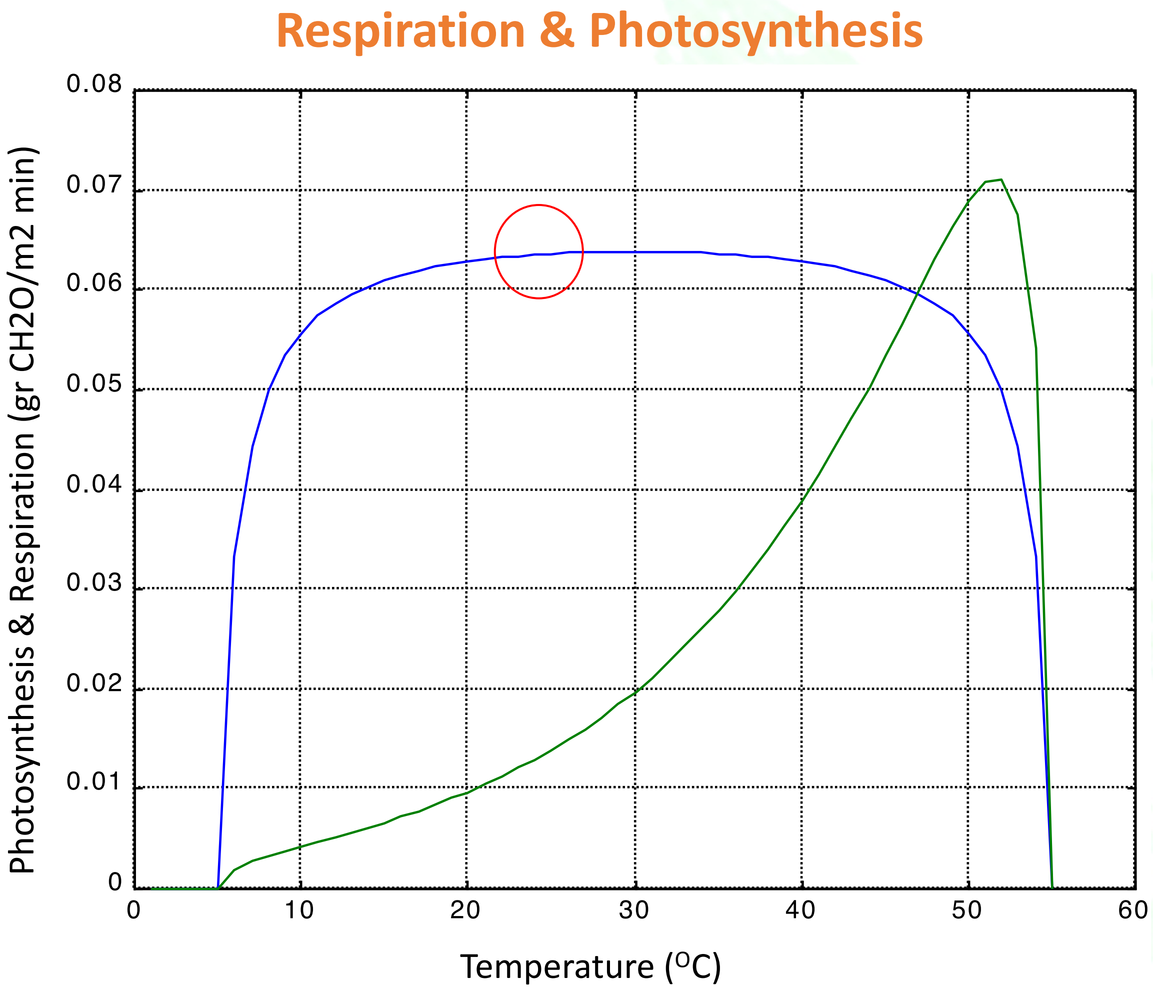
Crop growth

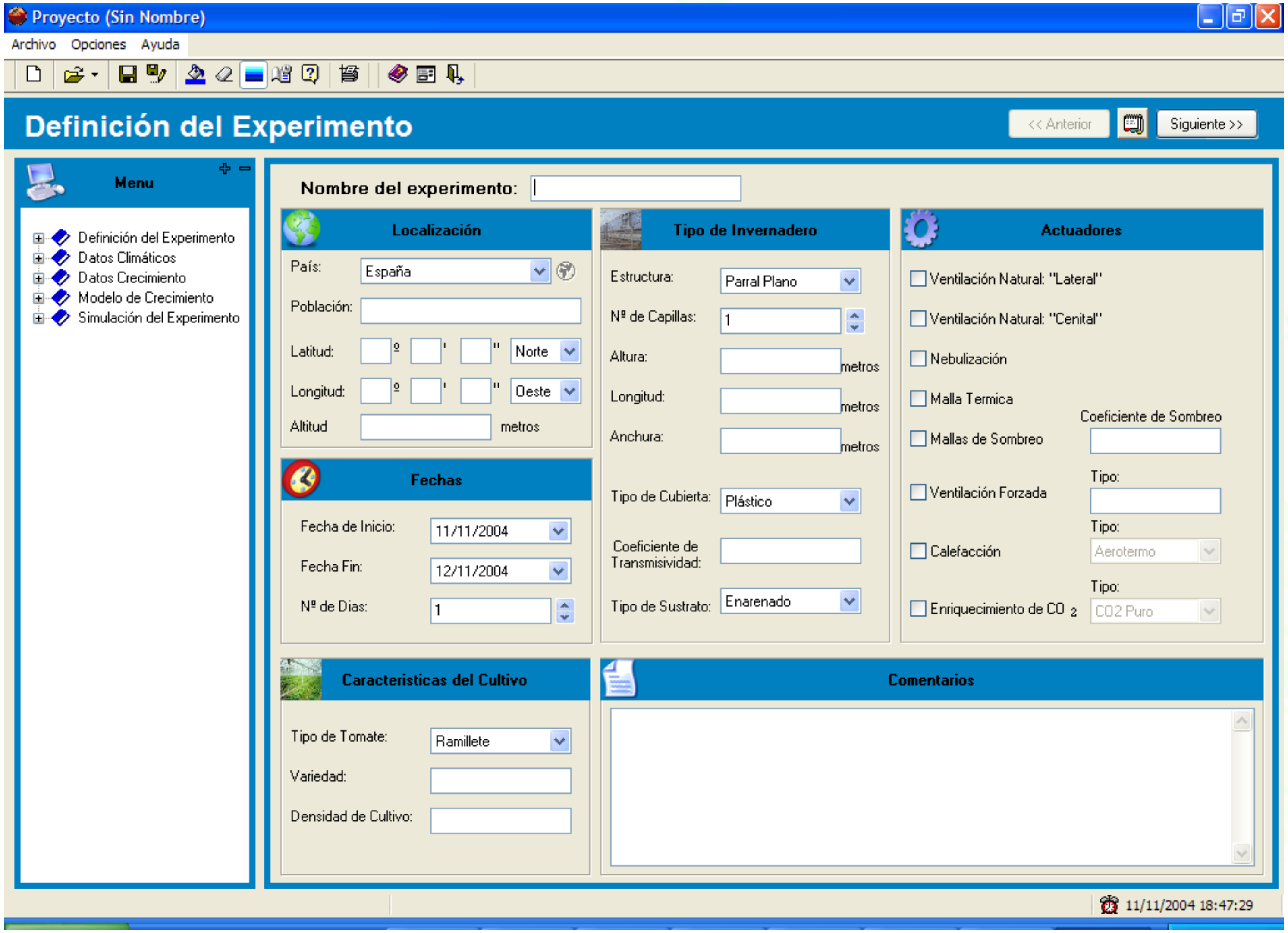


Climate control strategies

Crop growth control

Climate control strategies

Conclusions



Climate control estrategies

Tomato crop in greenhouse

Main features of the experiment:

- Crop density of 3.04 plants/m2
- Latitude: 37º 23" North
- Longitude: 2º 45" West
- Altitude above sea level: 150 meters
- Transmissivity coefficient of the greenhouse: 0.9.
- 98 days of simulation, from 1/2/2021 to 9/5/2021
- Tomsim growth model, default parameters
- Initial conditions, nodes: 10.8, LAI: 0.39, total biomass: 60gr

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Climate control strategies

Crop growth control

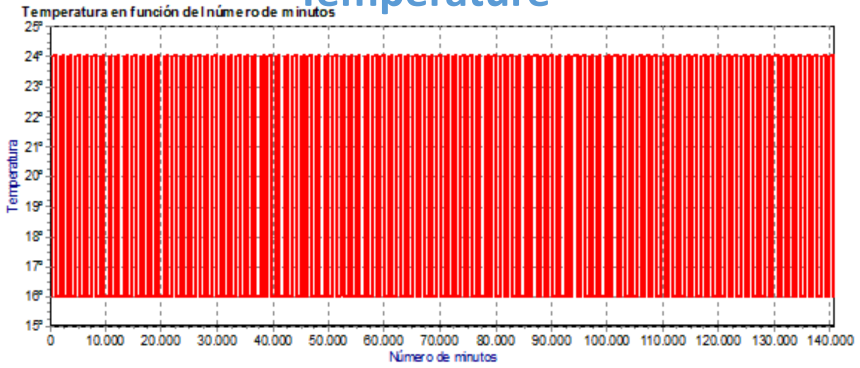
Climate control strategies

Conclusions

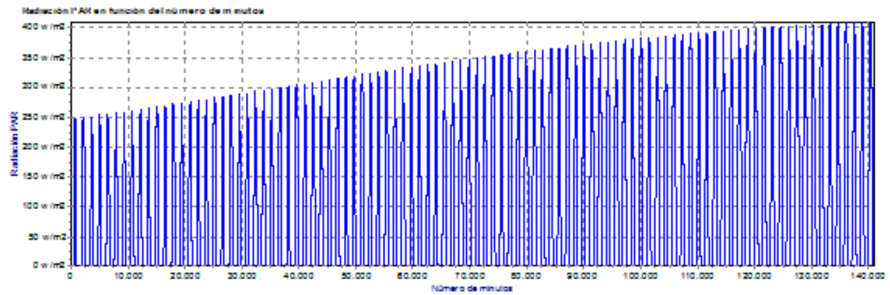
Tomato crop in greenhouse

Climate Strategy 1: Values of climatic variables:

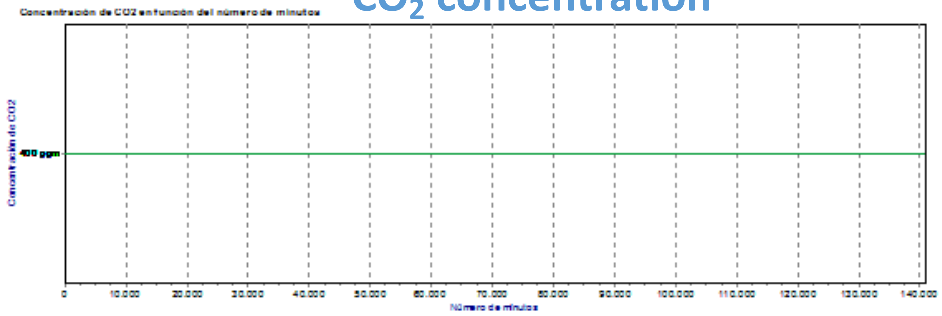
Temperature



Global radiation



CO_2 concentration



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Crop growth control

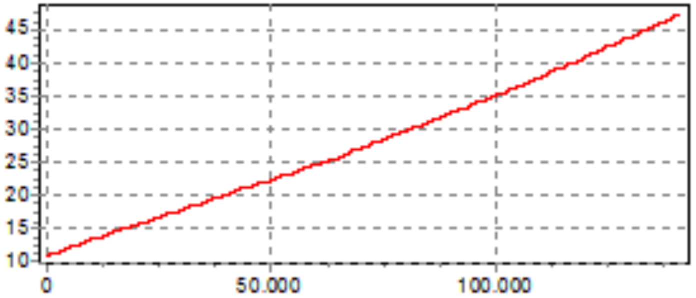
Climate control strategies

Conclusions

Climate control strategies

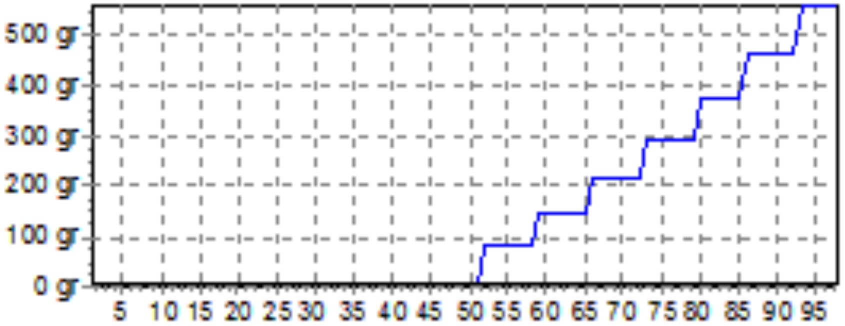
Climate Strategy 1

Nodes



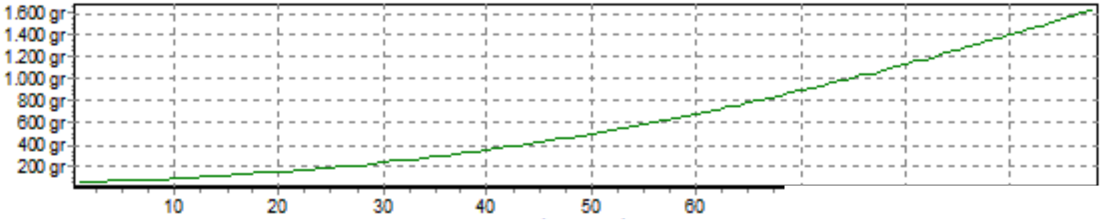
Minutes

Mature fruits



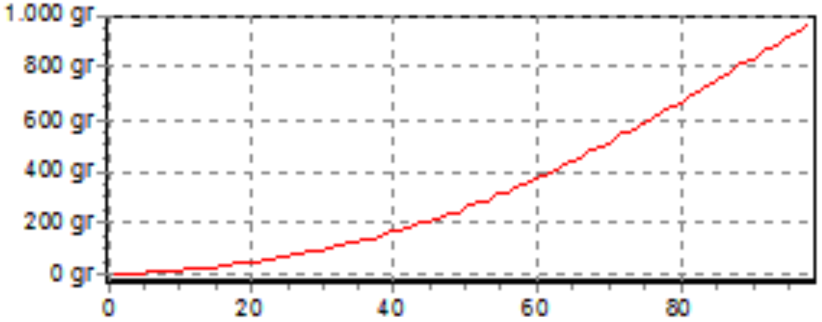
Days

Gross biomass



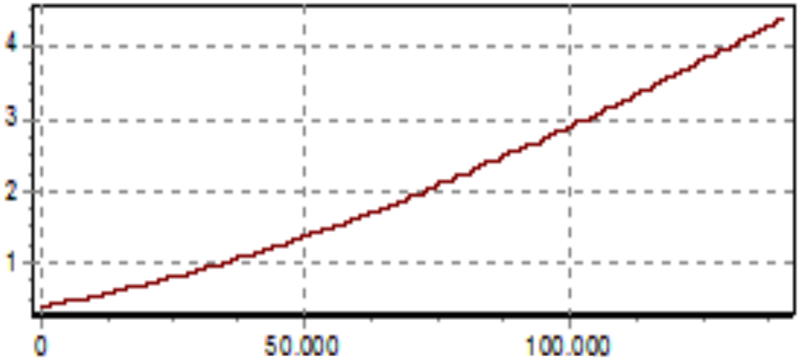
Days

Fruits biomass



Days

LAI



Minutes

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Crop growth control

Climate control strategies

Conclusions

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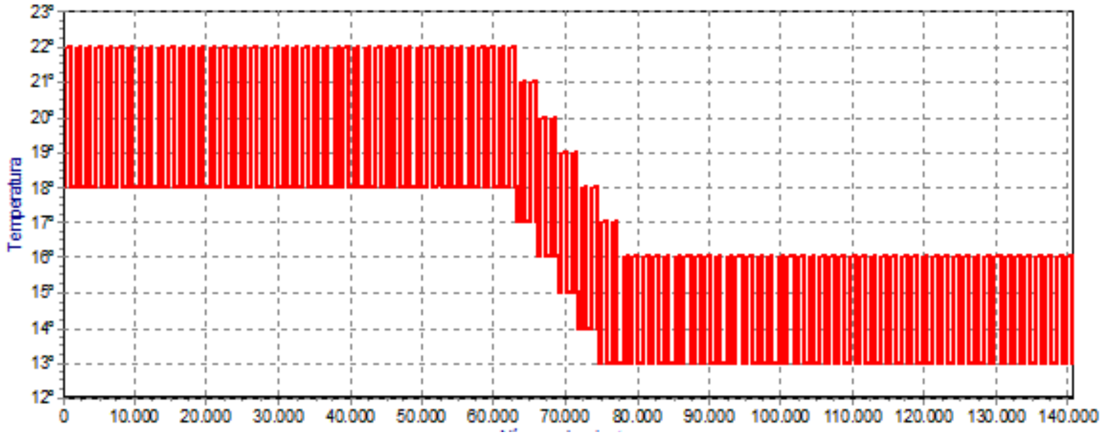
Climate control strategies

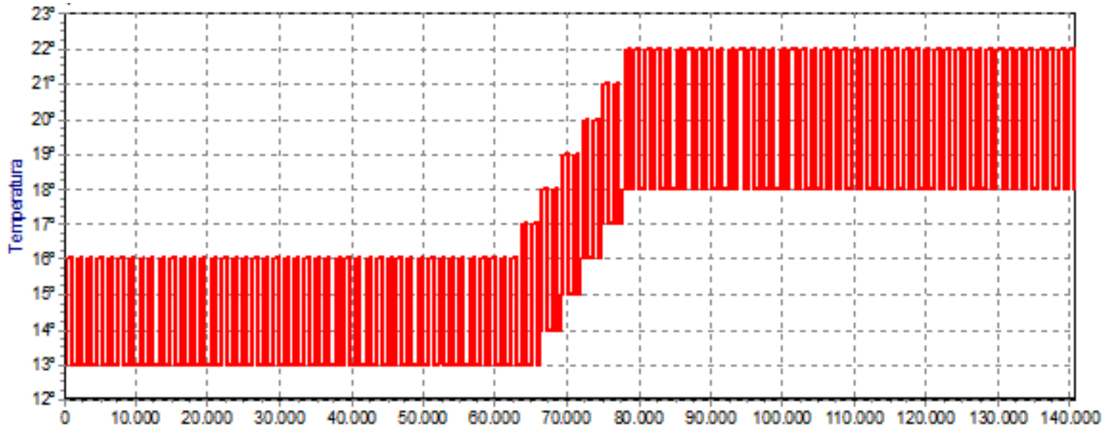
Tomato crop in greenhouse

Climate Strategy 2



Days

Climate Strategy 3

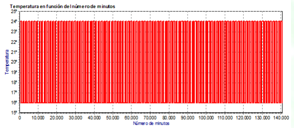


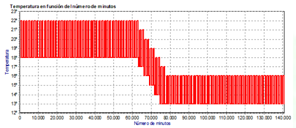
Days

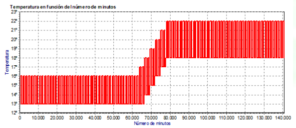
Climate control strategies

Tomato crop in greenhouse

Results of simulation experiments:







	Strategy 1	Strategy 2	Strategy 3
	47,41	43,97	43.68
Leaf area index	4,41	3,98	3,95
Total biomass	1,621 Kg/m^2	1,689 Kg/m^2	1,538 Kg/m^2
Biomass fruits	0,967 Kg/m^2	0,783 Kg/m^2	0,836 Kg/m^2
Biomass mature fruits	0,559 Kg/m^2	0,443 Kg/m^2	0,261 Kg/m^2

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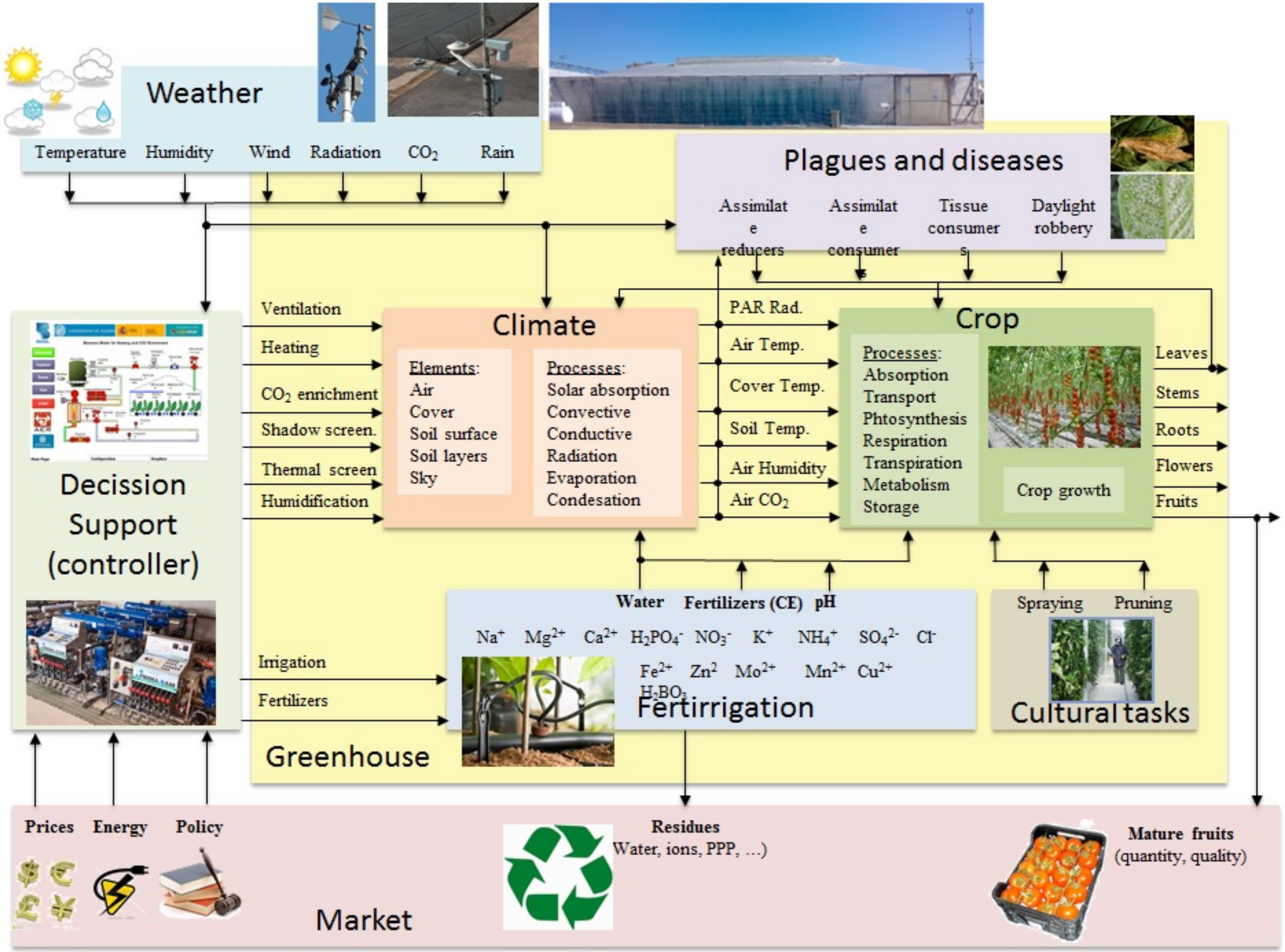
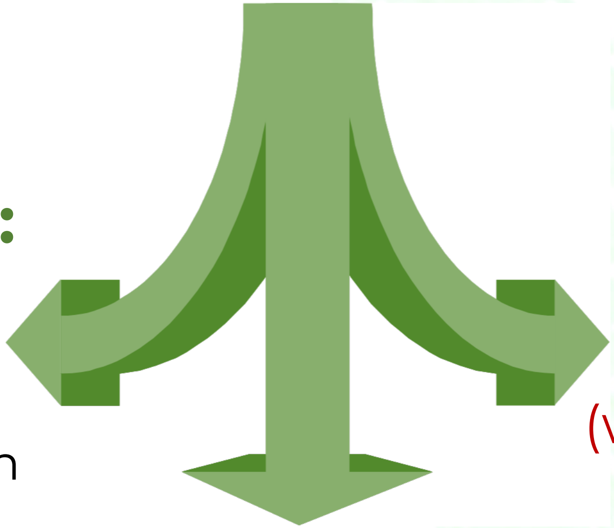
Climate control strategies



Climate control strategies

The greenhouse production process consists of three interacting systems:



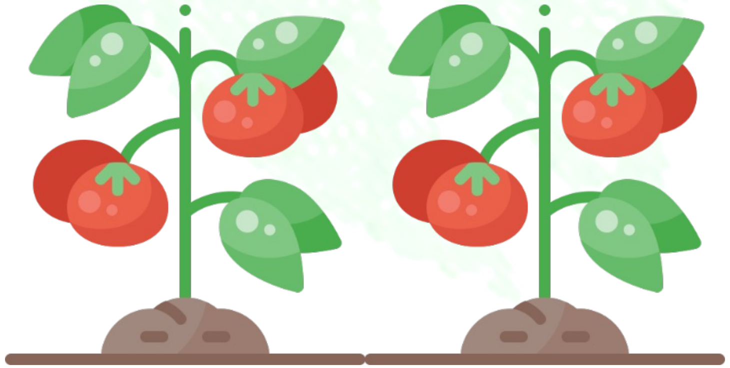
Greenhouse:

- Climate
- Irrigation
- Fertilization

(minutes, seconds)

Market

(weeks, months)

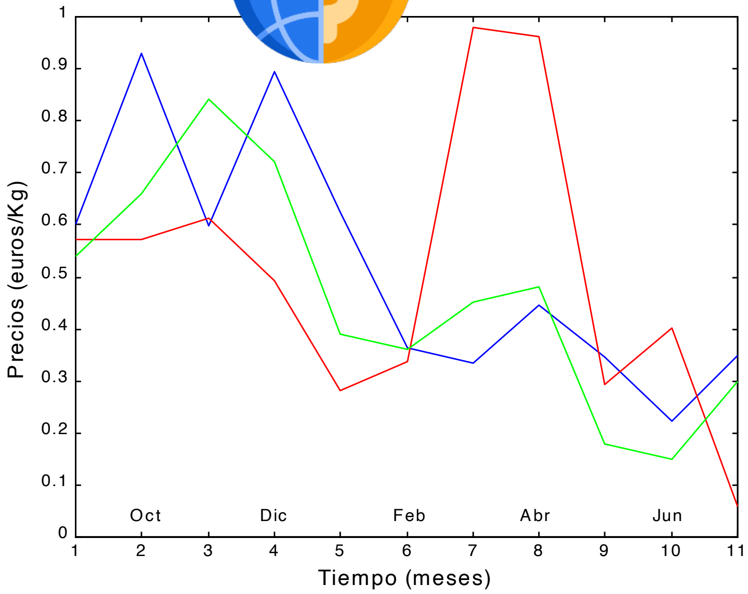


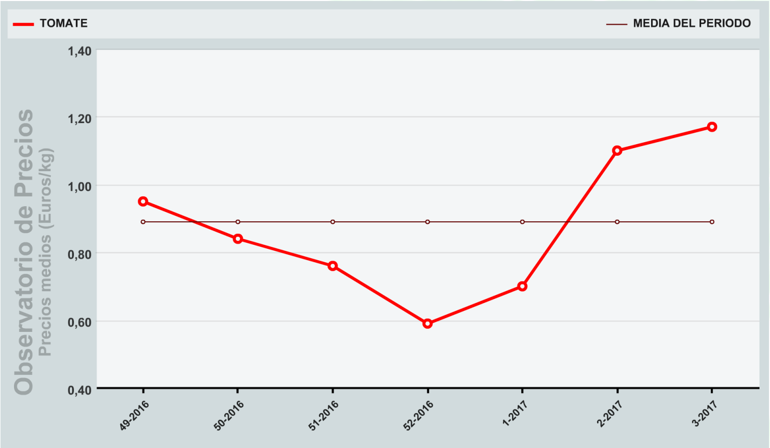
Crop

(days)

Climate control strategies

To obtain and sell the crop production when the prices are highest, one needs to include the economic criteria.





Fecha del intervalo	Producto	Precio Medio (Euros/kg)
Semana 49: (5/12/16 - 11/12/16)	TOMATE	0,95
Semana 50: (12/12/16 - 18/12/16)	TOMATE	0,84
Semana 51: (19/12/16 - 25/12/16)	TOMATE	0,76
Semana 52: (26/12/16 - 1/01/17)	TOMATE	0,59
Semana 1: (2/01/17 - 8/01/17)	TOMATE	0,70
Semana 2: (9/01/17 - 15/01/17)	TOMATE	1,10
Semana 3: (16/01/17 - 22/01/17)	TOMATE	1,17

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Crop growth control

Climate control strategies

Conclusions

Conclusions

- Crop growth control in greenhouses is a complex system, so a hierarchical multilayer controller is a good solution.
- It is necessary to use different models (market, crop, climate, ….)
- The system must be flexible, allowing for manual modifications of the control decisions proposed by the control algorithm.
- These decisions will influence on the final production results and on profits.

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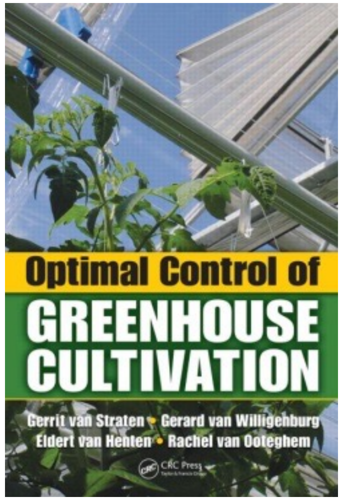
Sources



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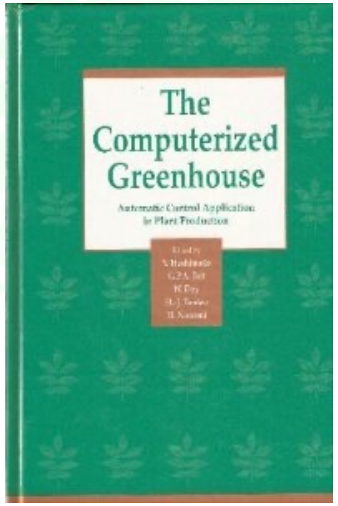
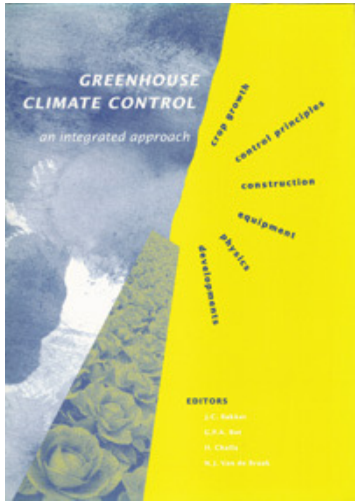
Hashimoto et al.; 1993; The computerized greenhouse. Automatic Control Application in Plant Production; Ed. Academic Press; USA; 340 pages.





Bakker et al; 1995; Greenhouse climate control: an integrated approach; Wageningen Pers; The Netherland; 279 pages.

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Module 6: CLIMATE MANAGEMENT

Lesson 6.3.1: Crop growth control

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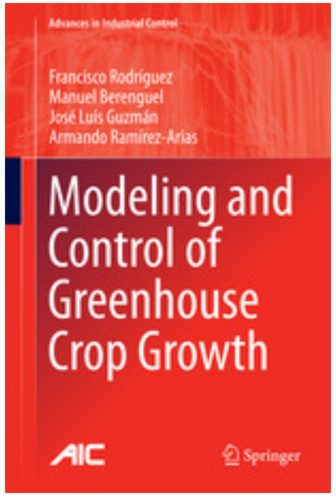
- Hierarchical control approach
- Multiobjective control approach
- Conclusions



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Hierarchical control approach

- Climate
- Water
- Nutrients
- Pests & diseases
- Agricultural practice

Hierarchical control approach

Our first approach was to maximize profit

$$Profit = Sales\ income - Production\ costs$$

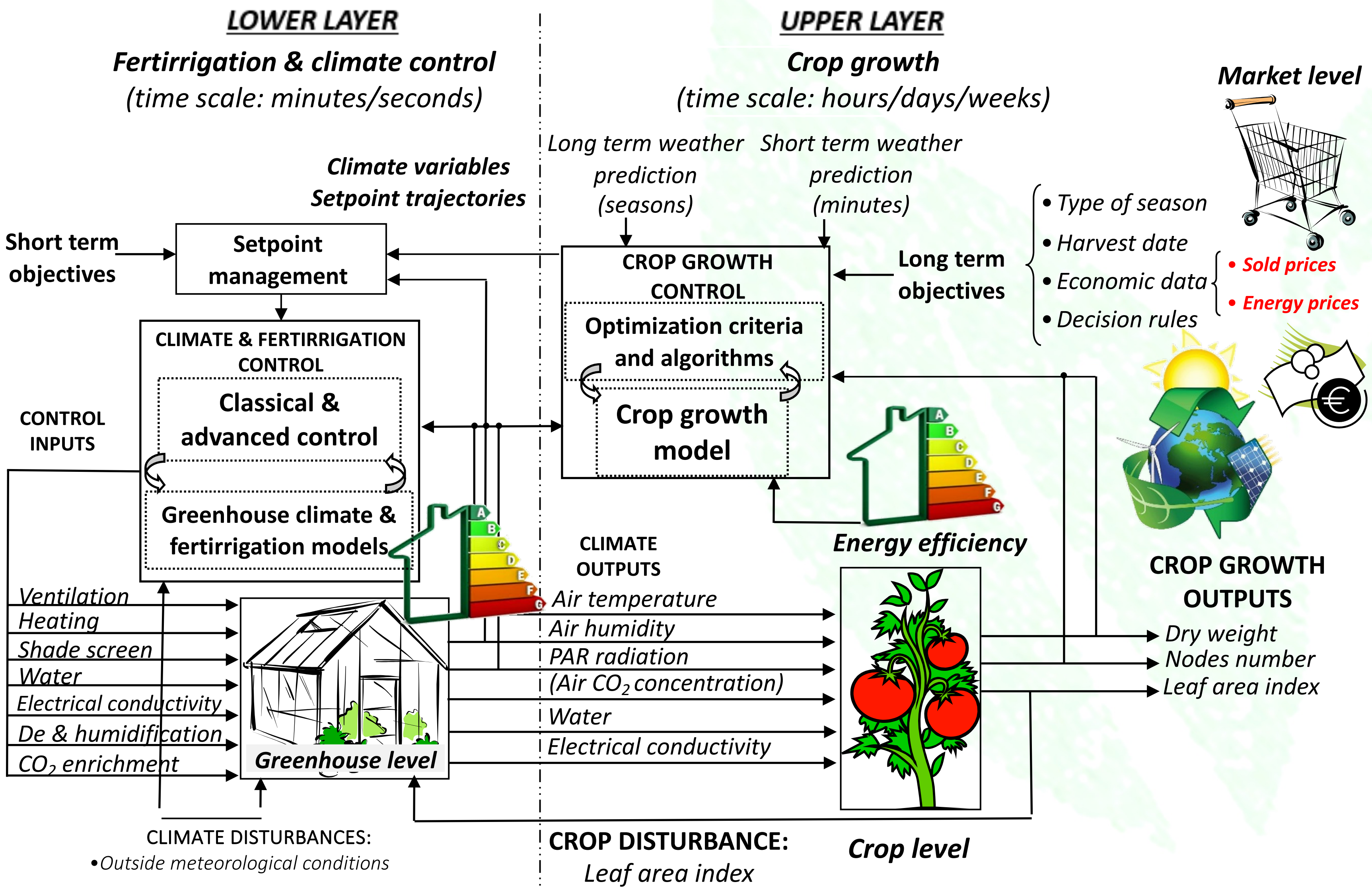
Based on climate variables

Hierarchical control approach

Hierarchical control approach

Multiobjective control approach

Conclusions



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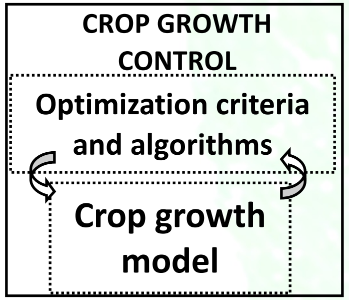
Hierarchical control approach

Hierarchical control approach

Multiobjective control approach

Conclusions



Optimization methodologies based on modeling

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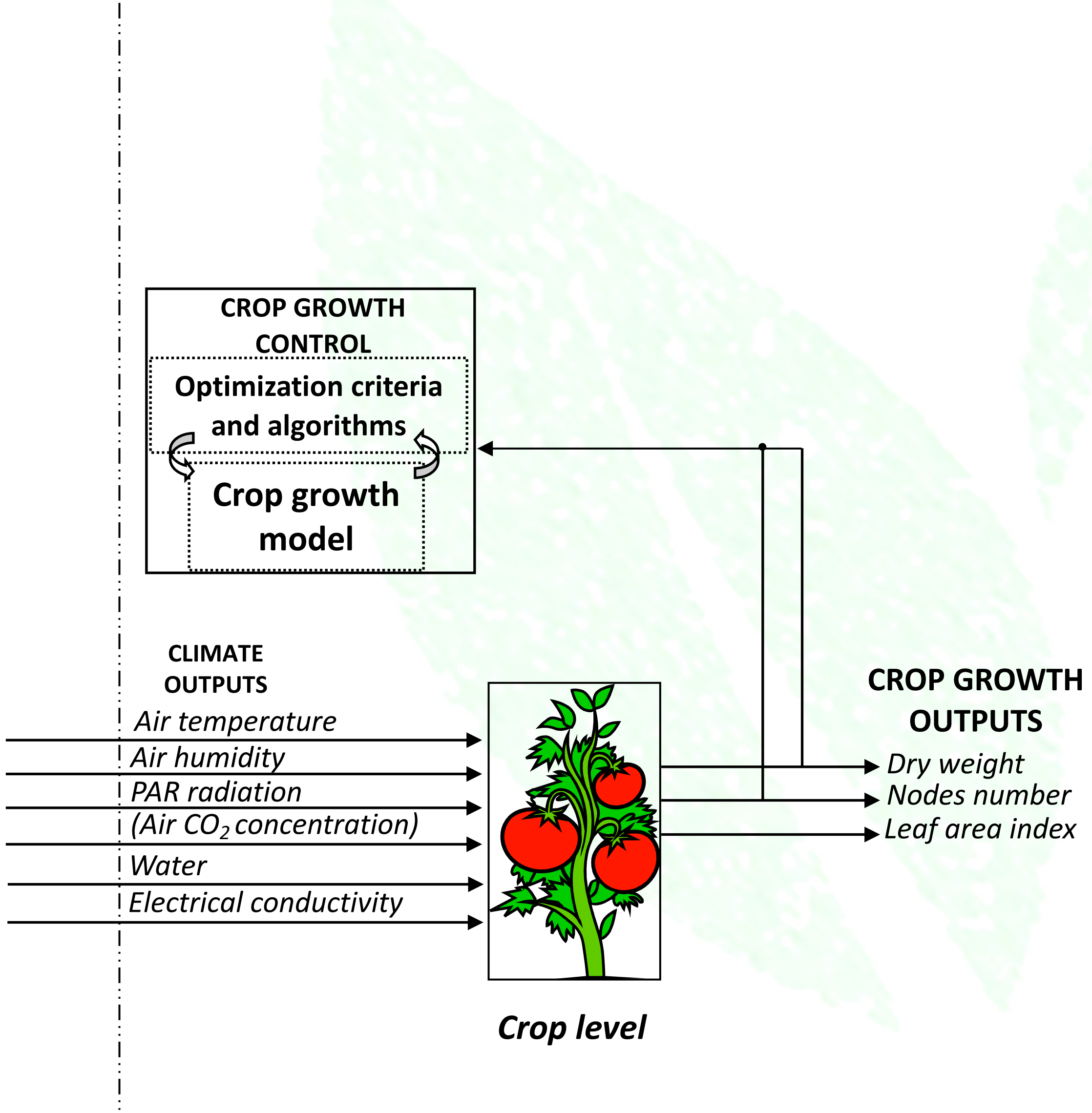
Hierarchical control approach

Hierarchical control approach

Multiobjective control approach

Conclusions



Hierarchical control approach

Hierarchical control approach

Multiobjective control approach

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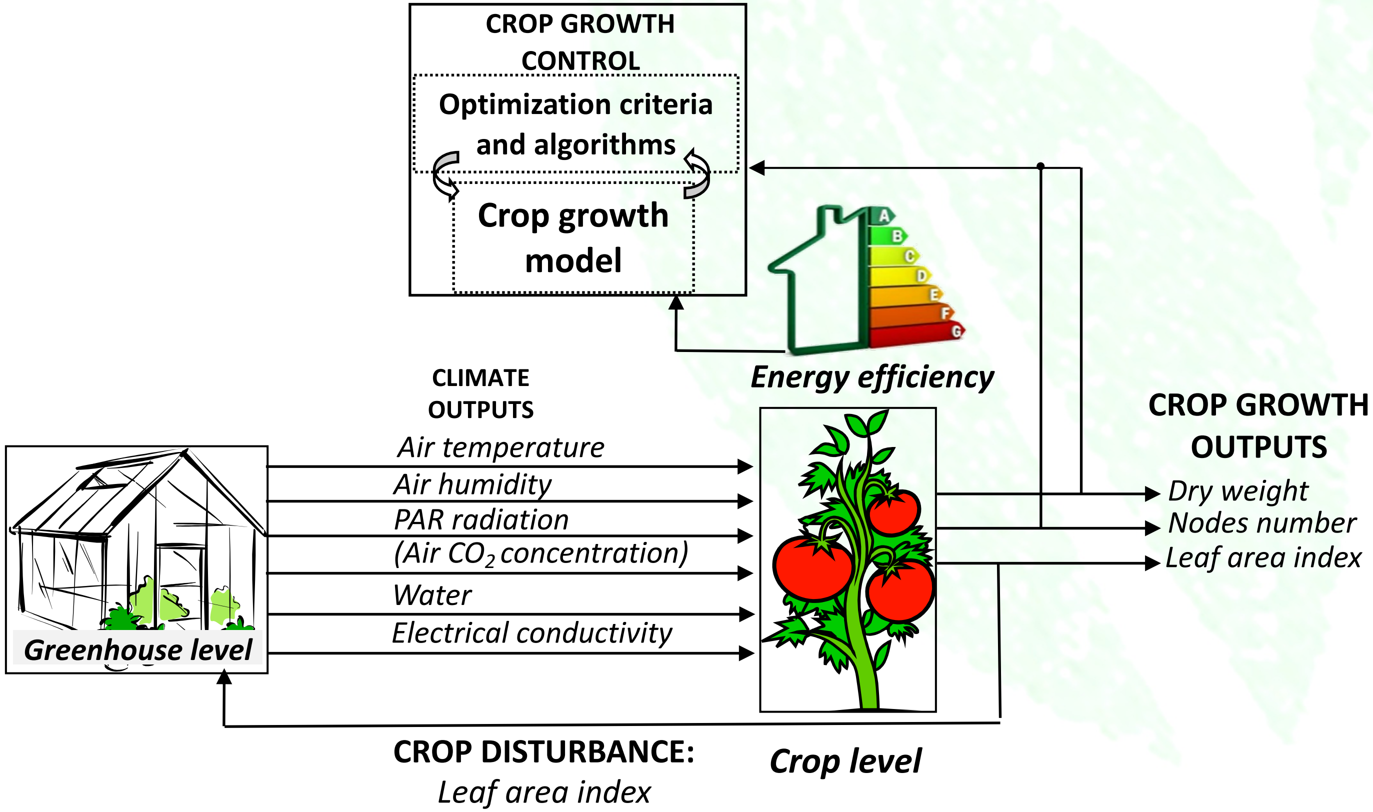
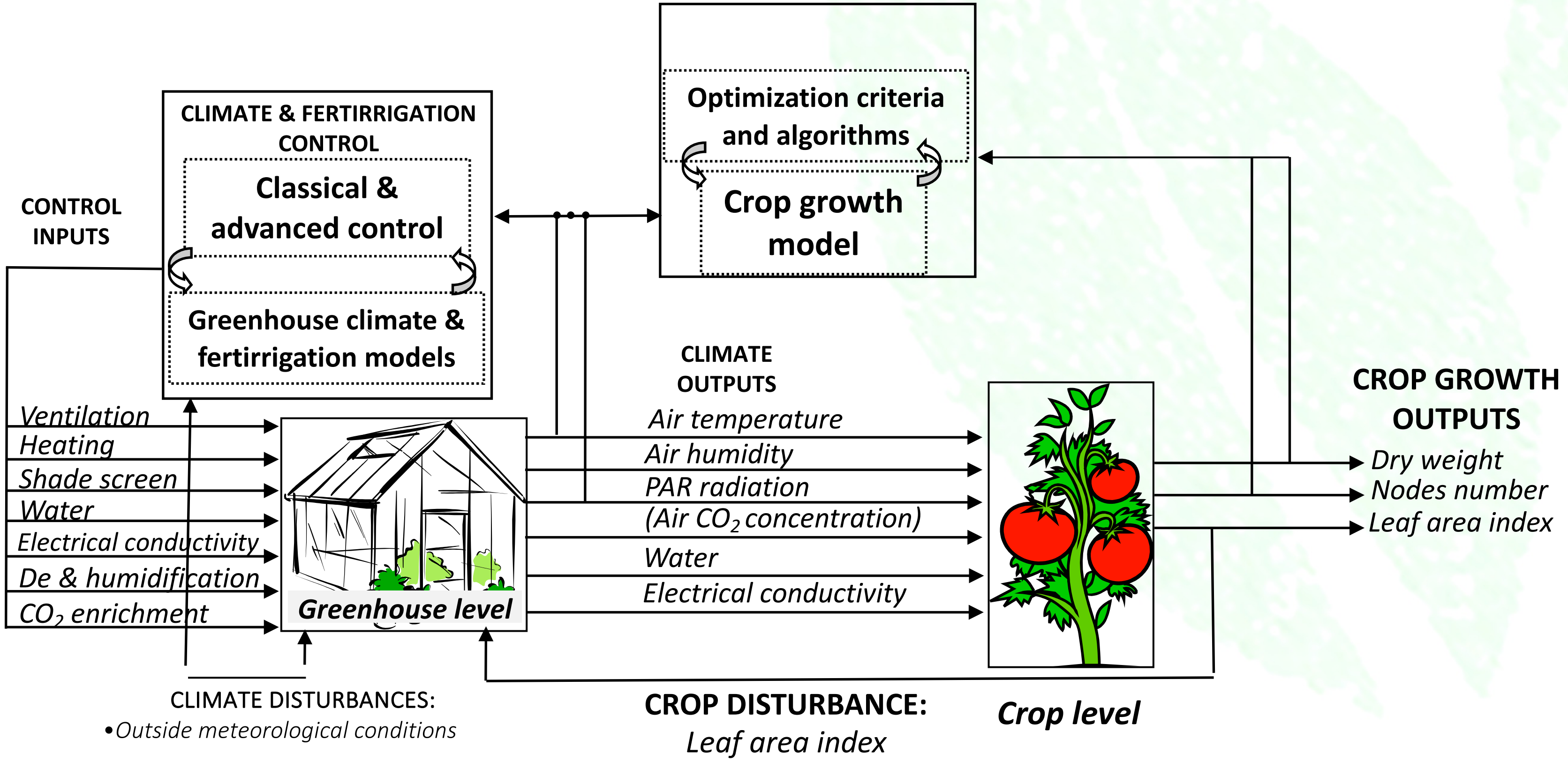


Hierarchical control approach



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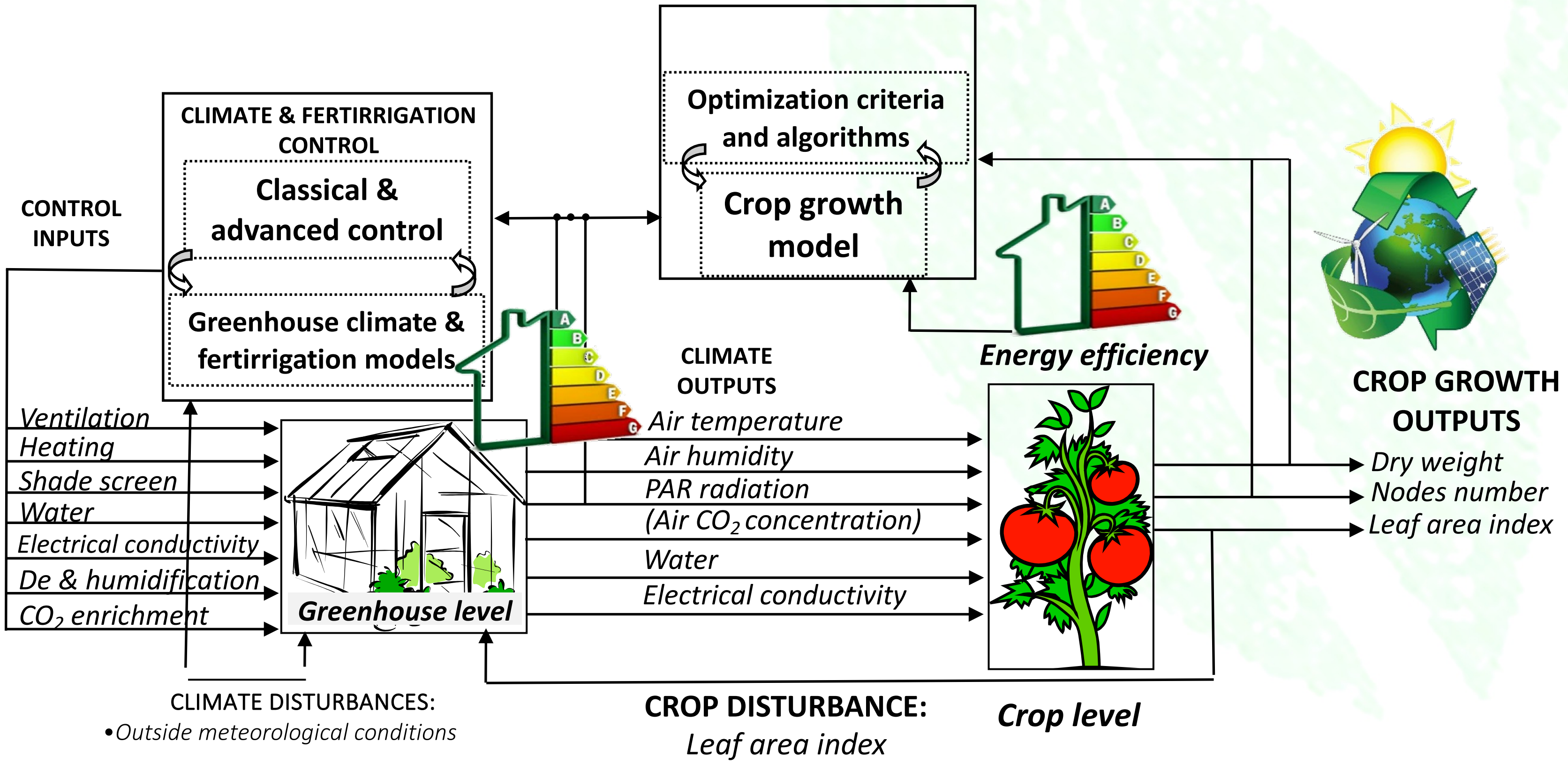

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Hierarchical control approach

Hierarchical control approach

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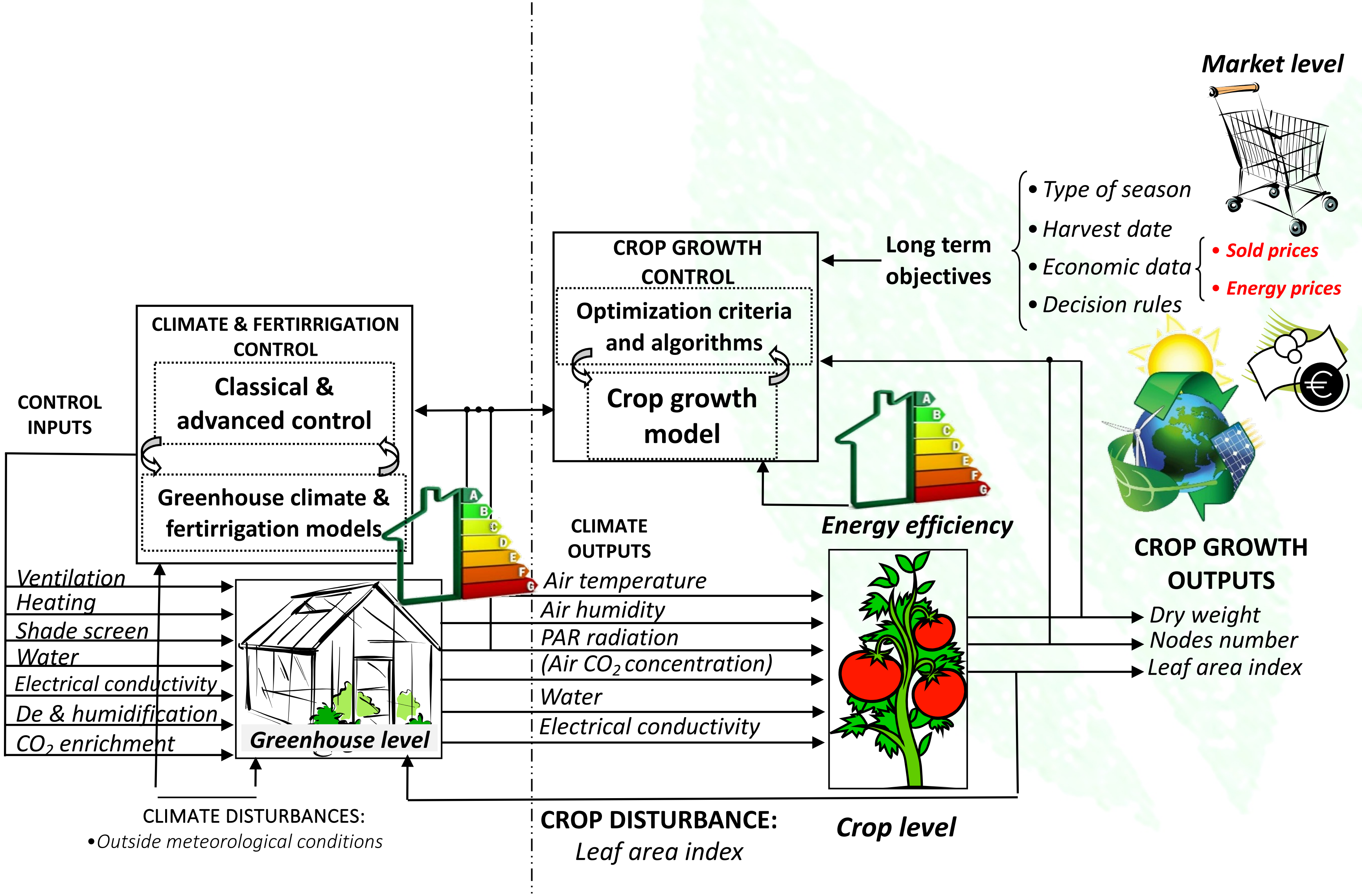

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Hierarchical control approach

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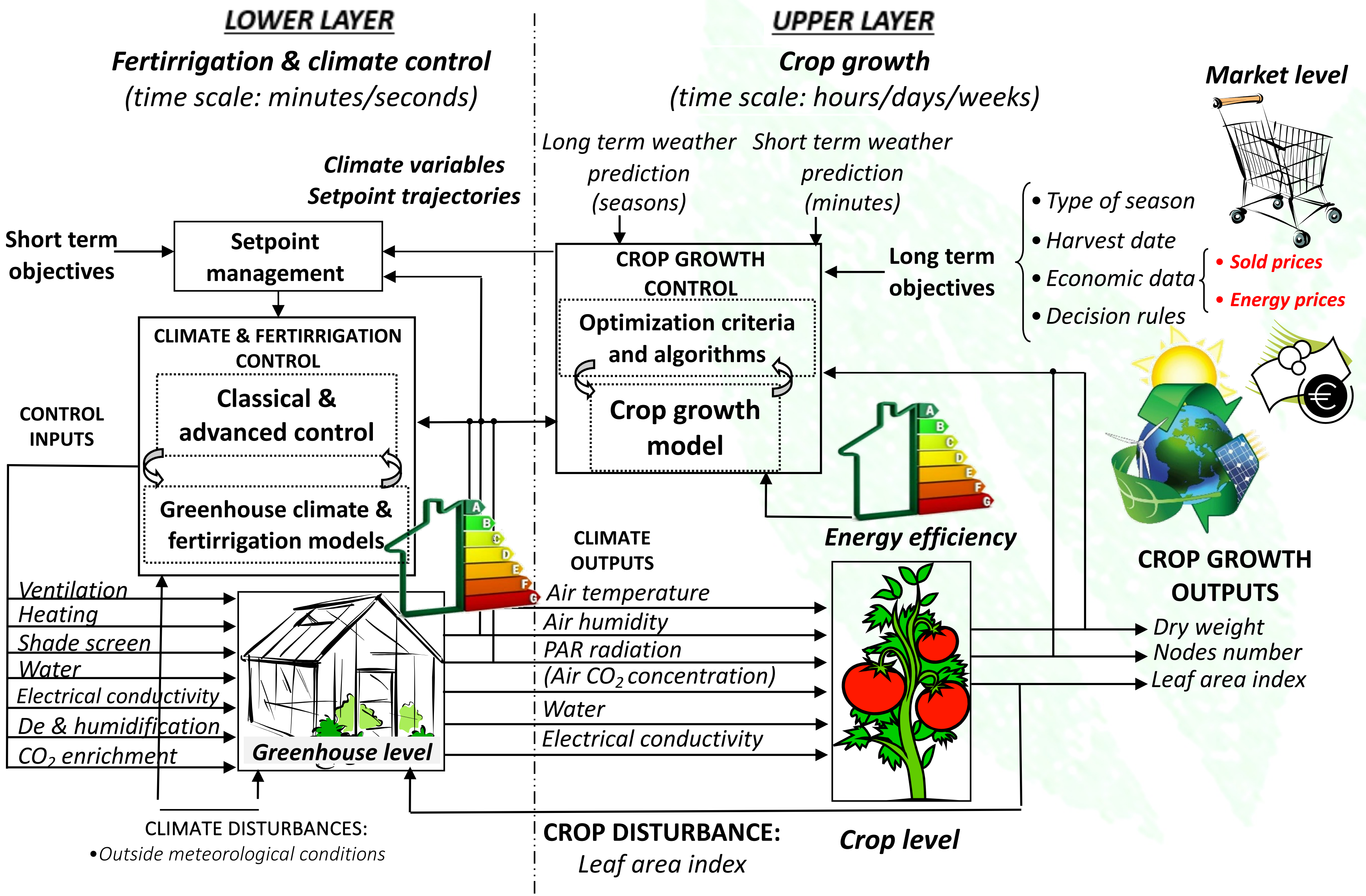
Hierarchical control approach



Hierarchical control approach

Hierarchical control approach

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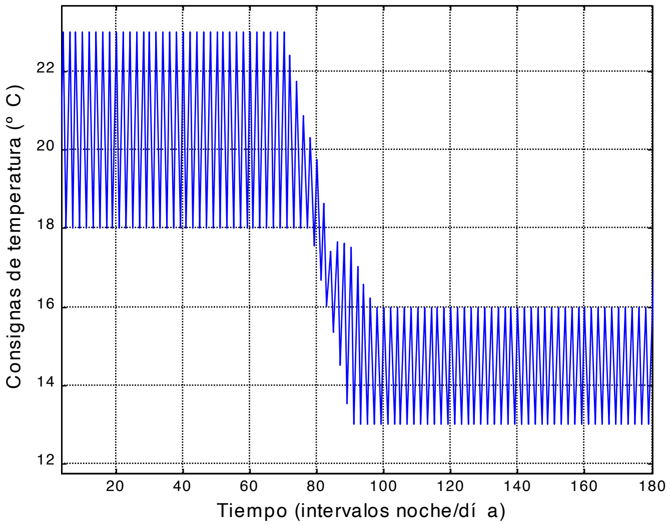
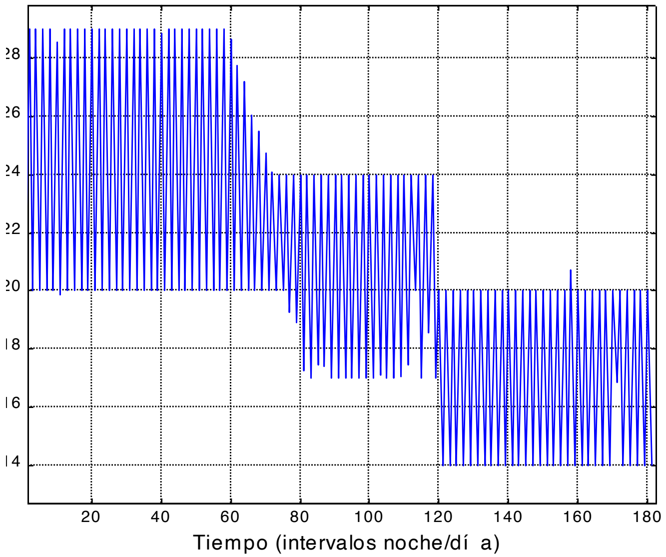
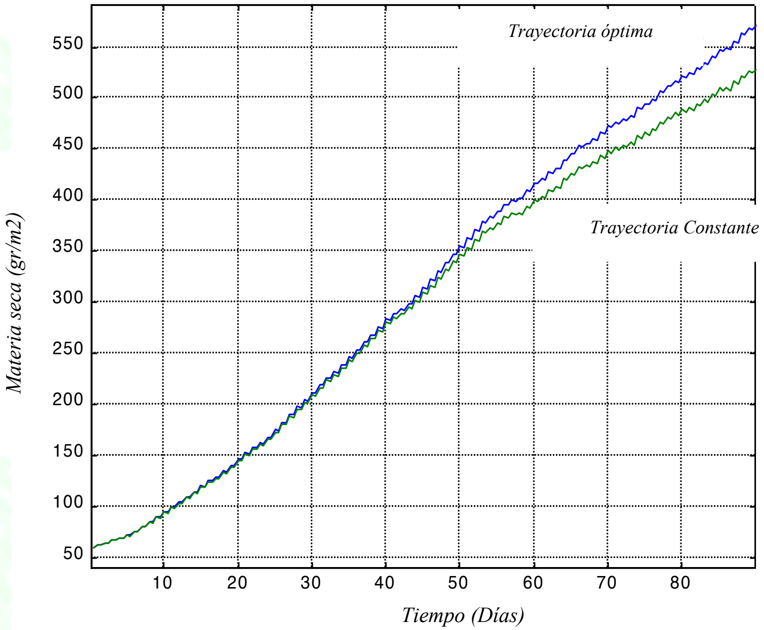
Real results







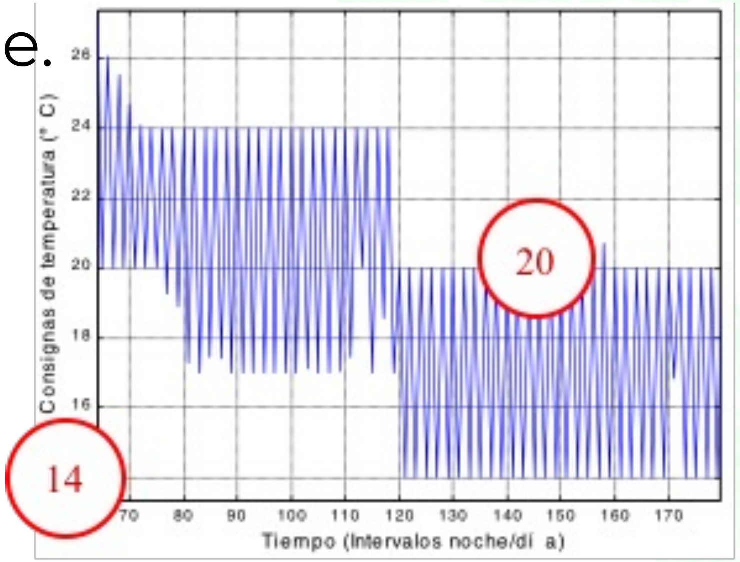
The profit is increased by 18%!!

Hierarchical control approach

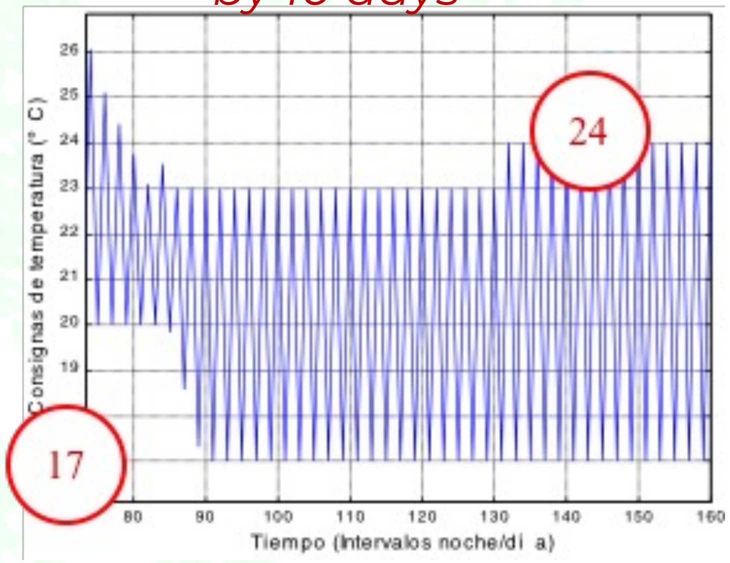
Real results

Response to changes in the harvesting date

- Bringing forward the date.
- Postponing the date.



Bringing forward the 60 interval by 10 days



Multiobjective control approach

- Maximize profits
- Maximize quality
- Reduce contaminants
- Maximize water efficiency
- Maximize the use of renewable energies
- Minimize energy consumption

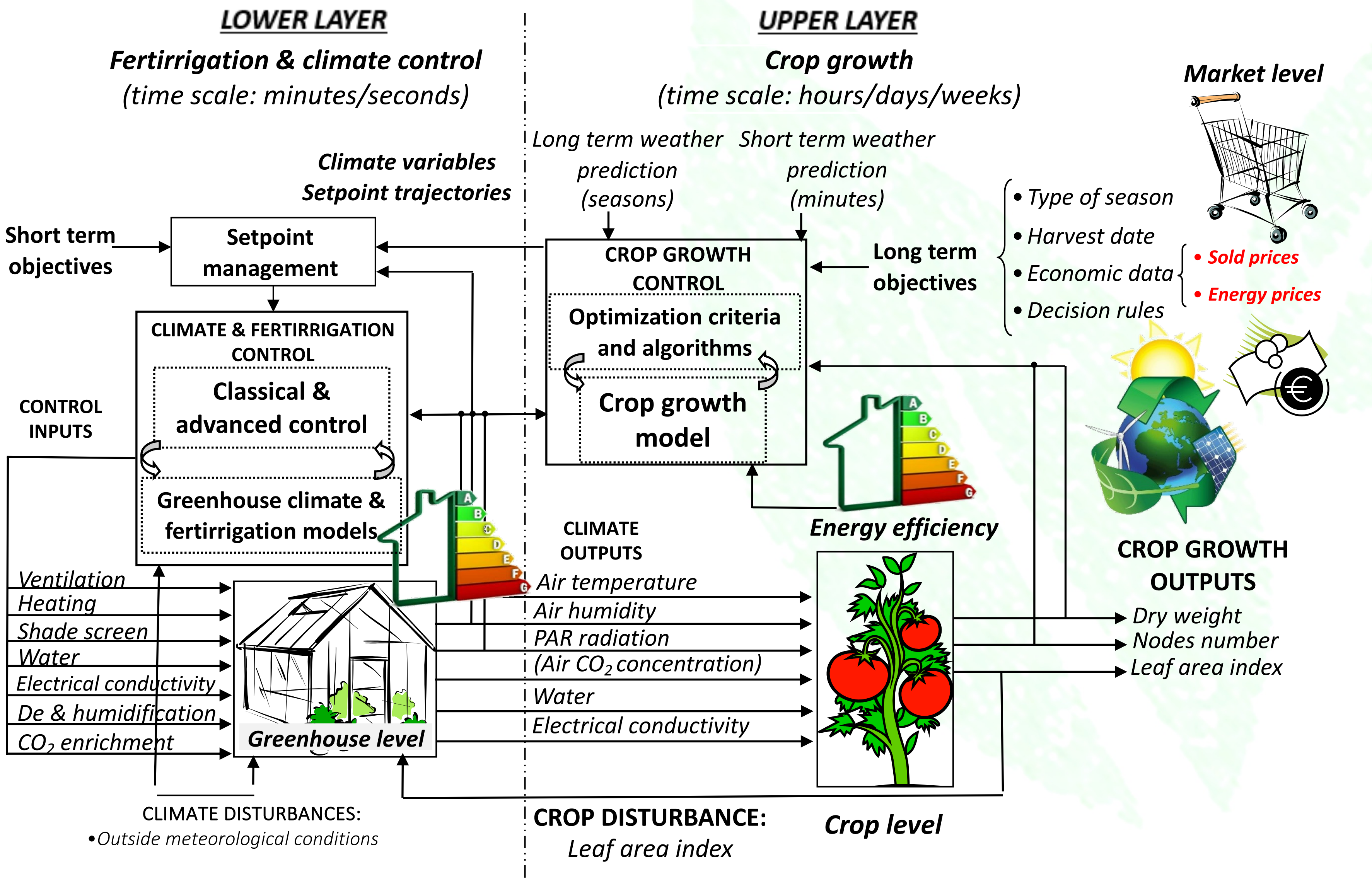
Conflicting objectives

Multiobjective control approach

Hierarchical control approach

Multiobjective control approach

Conclusions



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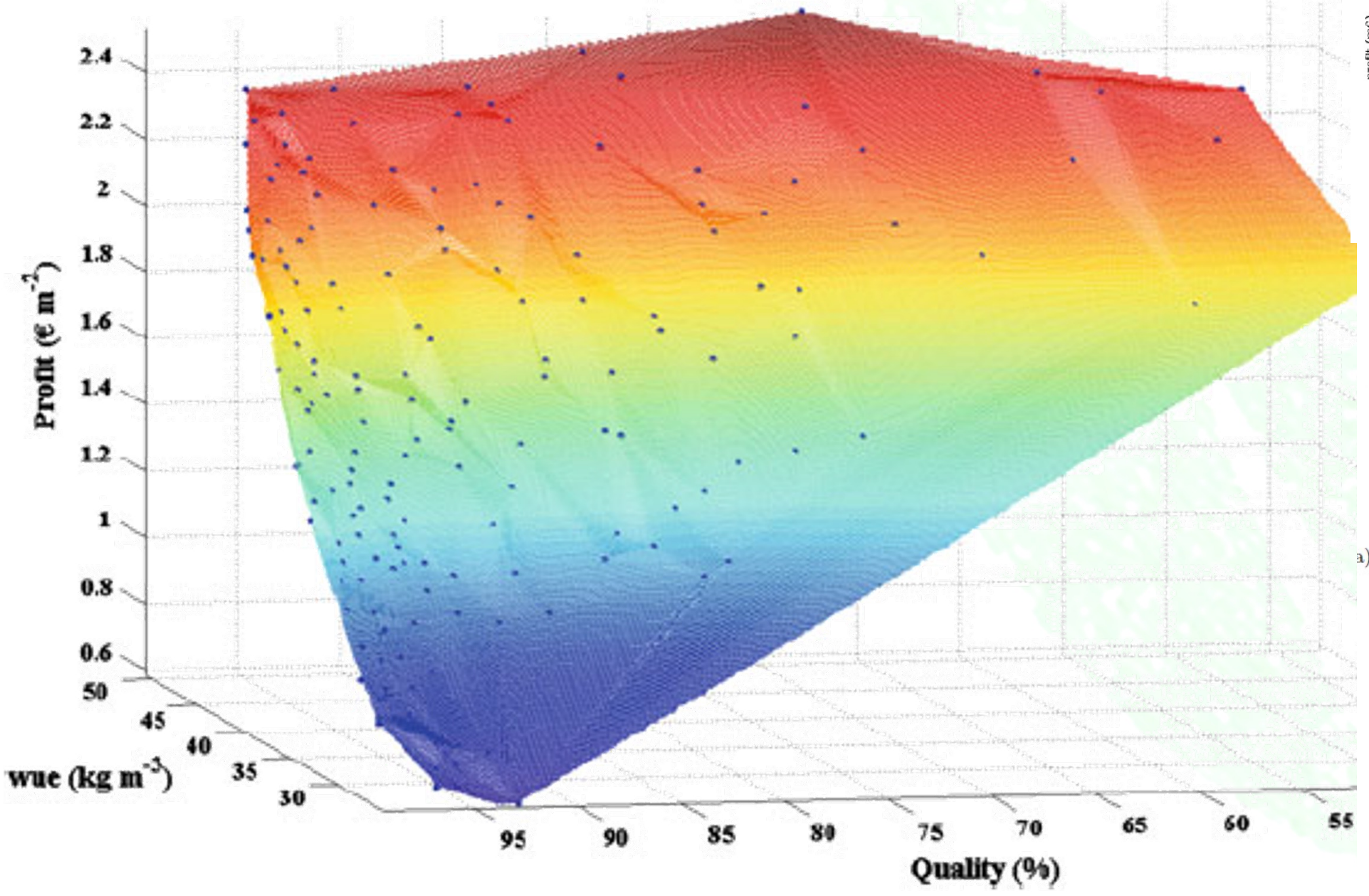
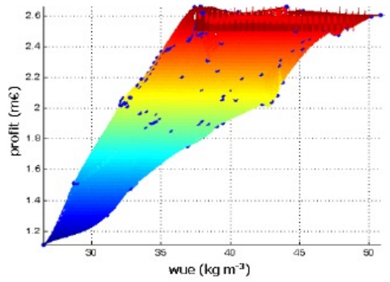
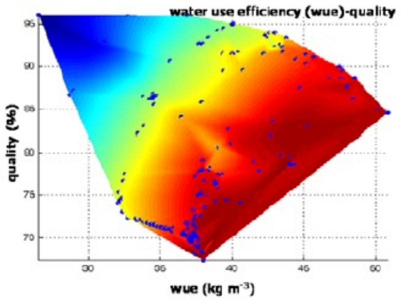
Multiobjective control approach

Real results

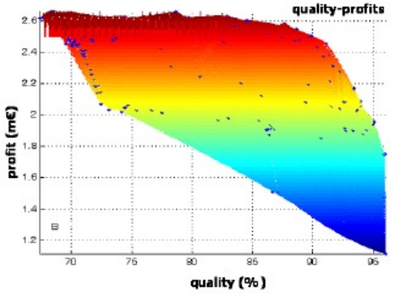




(b) profits - water-use efficiency (wue).



a) water-use efficiency (wue) - quality.



(c) quality-profits.

Multiobjective control approach

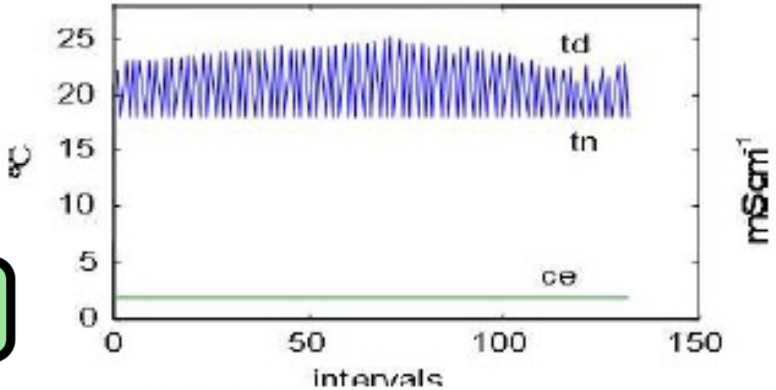
Hierarchical control approach

Multiobjective control approach

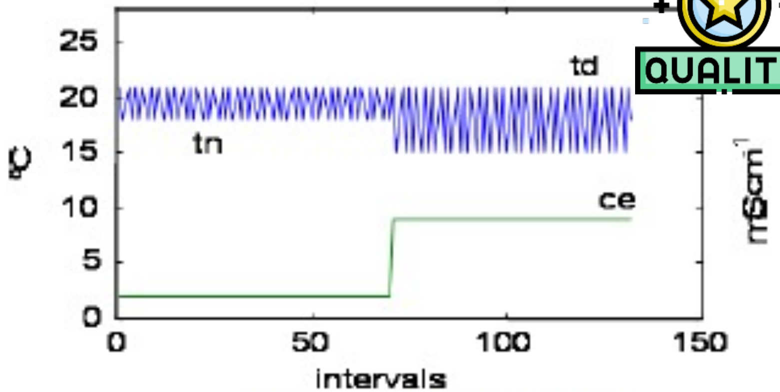
Conclusions

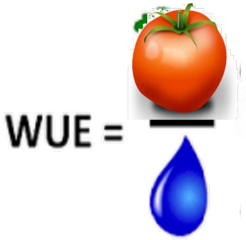
Real results

Profits

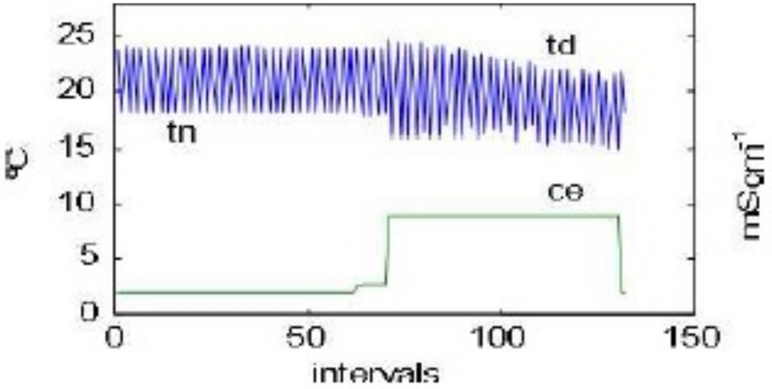


Quality

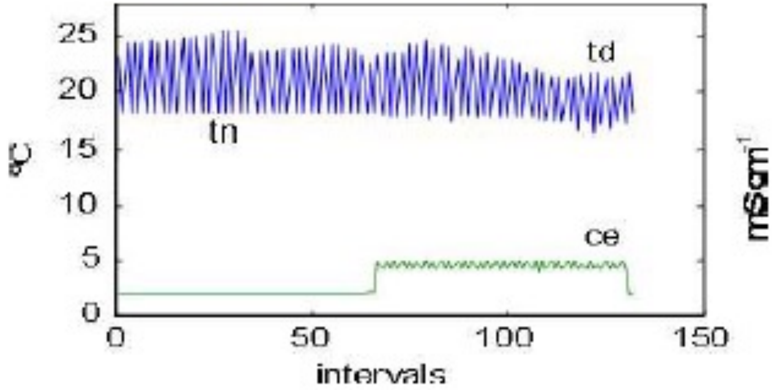




Water-use efficiency



Compromise solution



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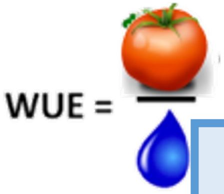
Multiobjective control approach

Real results

profits (€ m^{-2})	WUE (kg m^{-3})	quality index (%)
1.113	26.539	96.062
1.752	36.926	95.963
...	...	...
2.606	50.837	84.563
...	...	...
2.657	44.051	78.641
2.659	37.864	68.435



Hierarchical control approach

Multiobjective control approach

Conclusions

Conclusions

- It is necessary to use different models (market, crop, climate, ...)
- The system must be flexible, allowing for manual modifications of the control decisions proposed by the control algorithm.
- The weather forecast is very important, so the optimization problem must be repeated daily to reduce errors.
- The main goal in greenhouse production is to obtain the maximum profit, although it would be useful to consider other objectives.
- The main drawback of hierarchical architecture is the need to have a good model of market behaviour to predict the selling prices and costs.

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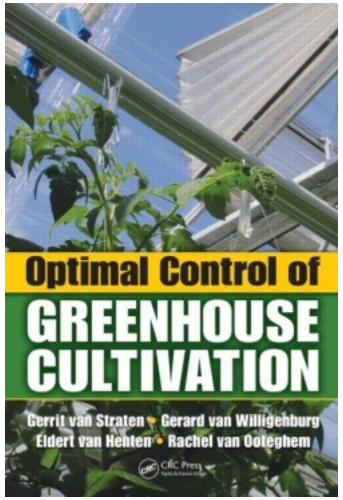
Sources



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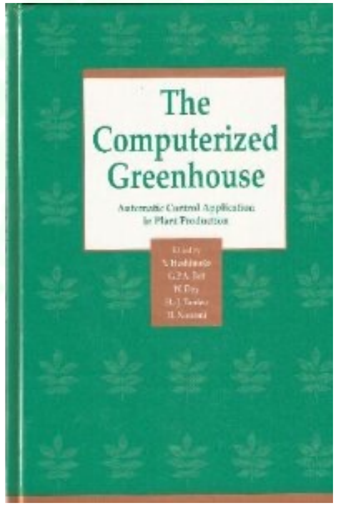

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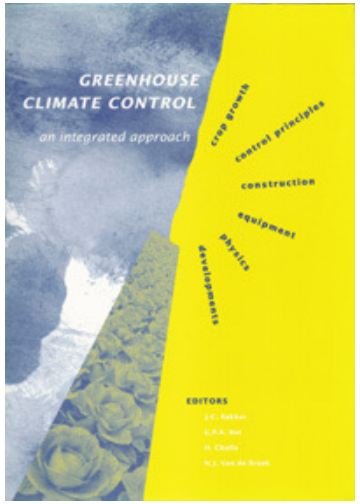

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THANK YOU

CLIMATE MANAGEMENT

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