École polytechnique de Louvain

Micro-climate modelling inside a greenhouse

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Abstract

Greenhouses offer an intensive method of plant production, guaranteeing high yields independently of external climate conditions. The control technologies used in greenhouses have evolved considerably to develop sustainable plant production with higher yields using limited resources. In Louvain-la-Neuve, it is possible to find an automated greenhouse, which is part of the EPPN2020 project that aims to study plant phenotyping. It has been observed that the growth of the plants was very variable even though the greenhouse environment is controlled. As a result, it was decided to establish a simple model that would predict the temperature within the greenhouse based on the physical phenomena that influence it.

This master thesis presents first the main physical phenomena influencing the microclimate of a greenhouse through a literature review. Then, an analysis of the experimental data collected in 2019 and 2020 was performed to identify the key phenomena that influence the temperature of the studied automated greenhouse. The physical phenomena identified as key in this work are the intensity of solar radiation, the heating system, the natural ventilation, and the conduction losses. The time-dependent physical model was then developed and implemented to predict the temperature in the greenhouse. The model is based on the principle of energy conservation within the greenhouse, i.e. it considers the heat gained and lost by the greenhouse at each moment and considers that the temperature within the greenhouse is homogeneous. The implementation of the model was carried out using MATLAB and consists of solving a differential equation. The predicted temperatures from the model were compared to the recorded values. It was observed that the model correctly predicts the temperature inside the greenhouse for different periods of the year.

A proposal is also made on how to model and study the spatial temperature difference within the greenhouse.

Acknowledgements

First of all, I would like to sincerely thank Pr. Denis Dochain for always being available to share with me comments and advice throughout this work, as well as for having given me the possibility to work on a subject that I had not yet had the opportunity to discover during my university studies, thus pushing me to broaden my horizons and to put forward my critical mind. Secondly, I would like to thank Pr. Xavier Draye for having proposed this subject to me and for his availability and his various advice during the year. Then I would like to thank Mr. Marc Migon for having always been available to guide me in the greenhouses and help me to understand their functioning. I would like to express my gratitude to Mr. Robert David who accepted to be my assessor for this master thesis.

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Contents

Glossary

A_d Discharged coefficient of the opening with insect-proof nets [-]

C_a Heat capacity of air inside the greenhouse $[Jm^{-3}K^{-1}]$

C_w Wind effect coefficient [-]

$C_{p,d}$ Heat capacity of dry air $[Jkg^{-1}K^{-1}]$

$C_{p,wv}$ Heat capacity of water vapor inside GH $[Jkg^{-1}K^{-1}]$

G Volume flow rate exchanged between the inside and outside of the greenhouse $[m^3s^{-1}]$

H_c The height of the opening of the window [m]

I Intensity of incoming solar radiation $[Wm^{-2}]$

Q_F Heat exchange with the floor $[W]$

Q_V Heat loss from ventilation $[W]$

Q_c Heat loss from condensation $[W]$

Q_H Amount of heat provided by heating system $[W]$

Q_{cond_cover} Heat loss from conduction through the cover $[W]$

Q_{evap} Heat loss from evaporation $[W]$

Q_{gain} Amount of energy entering the greenhouse $[W]$

Q_{inf} Heat loss from infiltration $[W]$

Q_{loss} Amount of energy leaving the greenhouse $[W]$

Q_{sol} Heat gain from solar radiaion $[W]$

Q_{total} Total heat transfer of the structure $[W]$

S_c Surface area of the cover of the greenhouse $[m^2]$

S_p Surface area of one heating pipe [m^2]

S_v Surface area of the open vent [m^2]

S_w Surface area of the window [m^2]

S_{GH} Greenhouse surface [m^2]

T_c Cover temperature[K]]

T_i Inside air temperature of the greenhouse [K]

T_p Water temperature inside the pipe [K]

V_{GH} Greenhouse volume [m^3]

ΔT Temperature difference between two locations [K]

γ Constant of the proportion of solar radiation entering the greenhouse, useful to increase internal temperature[-]

λ Thermal conductivity [$Wm^{-1}K^{-1}$]

ρ Air density [kgm^{-3}]

τ Light transmission coefficient of the greenhouse cover [-]

a_p Heat transfer coefficient [$Wm^{-2}K^{-1}$]

g Gravitational constant [ms^{-2}]

k_c Heat transfer coefficient of the cover material [$Wm^{-2}K^{-1}$]

n_p Number of heating pipes [-]

q specific humidity [$kgkg^{-1}$]

v Velocity of the air inside the greenhouse [ms^{-1}]

w Outside wind speed [ms^{-1}]

CFD Computational Fluid Dynamics

EPPN European Plant Phenotyping Network

PE Polypropylene

UV Ultraviolet

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Chapter 1

Introduction

1.1 Context

Plant-based products are at the center of many challenges arising from the growing need for food, and raw materials. For example, there has been a 49% increase in the consumption of plant-based products in the last two years [1]. Many questions are therefore being asked about the different ways of growing all these plant-based products.
Crop production is becoming increasingly difficult. Variable weather conditions can be either favorable or unfavorable to some crops and play an important role in their production rate. Living in a period where we cannot afford to have these kinds of limitations, the focus has been put on solutions that allow agricultural production in controlled environments, i.e. greenhouse agriculture.[2]

Agricultural greenhouses are therefore of primary importance because they offer an intensive production method, guaranteeing high yields independently of the weather. These greenhouses contribute to the creation of a microclimate, in terms of humidity and temperatures of the plant canopy and indoor air, favorable to the plant's requirements. They are generally designed to control solar radiation, temperature, humidity and CO_2 content. [2]

In recent years the control technologies used in greenhouses have evolved significantly to develop sustainable plant production with higher yields using limited resources. Particular attention is given to molecular and genetic plant approaches. Many experimental greenhouses are looking at plant phenotyping, which is an emerging science that links genomics to plant ecophysiology. Ecophysiology is the quantitative analysis of plant growth. Plant phenotyping works by combining automation, data acquisition using sensors and cameras, data management and analysis, and plant growth modeling. A series of universities and research centers have joined a European project EPPN (European Plant Phenotyping Network) to develop a plant phenotyping community in Europe. [3, 4, 5, 6]

In the research center of Louvain-la-Neuve, there is one of these modern greenhouses that accommodates a root phenotyping platform that is part of the EPPN2020 project [7]. This greenhouse is used for a large number of experiments. What has been observed is that even though it is a controlled environment, the plants seem to grow in different ways depending on the season of the year. Furthermore, it was observed that even during the same experiment, the growth of the plants within the greenhouse can vary depending on their position in the greenhouse. This is why it will be necessary here to study this greenhouse further.

1.2 Aim of the paper

The first objective of this work is to identify the physical phenomena that influence the microclimate of the greenhouse that is used for studies in Louvain-la-Neuve. From the identified physical phenomena, it is then required to realize a first simple time dependent model which will enable the researchers to estimate the temperature within the greenhouse at different periods of the year. This model will be used to determine the optimal period of the year to perform various experiments but also to eventually help in the programming of the control system. A first version of the spatial model will also be proposed to study in future work the spatial variation of the temperature within the greenhouse.

1.3 Outline of the paper

To reach the objectives of this master thesis, the paper is structured in the following way:

Chapter 2 presents through a literature review the information necessary to provide sufficient background knowledge on greenhouses. This chapter focuses more specifically on the explanation of the main elements that constitute a greenhouse as well as the main physical phenomena that influence the microclimate within the greenhouse.

Chapter 3 focuses on the identification of the physical phenomena that influence the temperature in the greenhouse of Louvain-la-Neuve that is studied in this work.

The environment of the experimental greenhouse will first be presented. Then, the results obtained during different experiments carried out in this greenhouse are analyzed. This analysis is used to identify the physical phenomena that directly influence the temperature in this greenhouse but also to identify aspects that could be improved in the future series of experiments.

Chapter 4 presents the simple model developed to predict the temperature in the greenhouse and its implementation. In this chapter, each phenomenon identified as important in Chapter 3 is translated into mathematical form.

In Chapter 5, the results obtained from the model of Chapter 4 will be presented and discussed. The validity of the developed model will thus be studied. Some parameters will also be further discussed here.

Finally, Chapter 6 presents the first version of a spatial model. An implementation idea will also be discussed in this chapter.

Chapter 2

Greenhouse basics

2.1 Overview

The objective of this first part is to explain how greenhouses function. The different types of agricultural greenhouses will be defined and the processes that affect the microclimate of the greenhouse and more specifically the interior temperature are reviewed.

The climate factors that influence the greenhouse climate are air temperature and humidity, solar radiation, outside wind, and all the different components related to the greenhouse as a whole, such as its cover. Each of these factors leads to different effects that may or may not be favorable to the operation of the greenhouse depending on the prevailing local conditions. Temperature plays a major role in the growth and development of vegetation, CO_2 and water vapor concentrations play a major role in plant transpiration and photosynthesis, and solar radiation also plays a role in photosynthesis. [8]

Since temperature is one of the most influential climate factors after humidity for the growth and development of vegetation, we are here interested in the study of temperature in greenhouses.

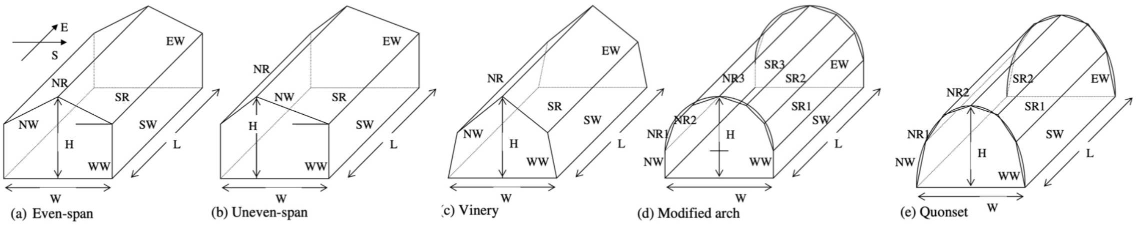
2.2 Greenhouse description

Let us first look at the general functioning of a greenhouse. The greenhouse was originally conceived as a simple shelter or an enclosure intended for the cultivation or protection of plants by exploiting the sun rays. Later on, the greenhouse became an industrial plant production facility that modifies the immediate environment of the plant, in order to improve its productivity and quality, by separating it from the external climate, the local soil and even the seasons.[8, 9]

Greenhouses are generally represented as a system made up of four distinct and homogeneous environments: the soil, the plants, the indoor air and the wall separating the interior from the exterior of the greenhouse. Within these different environments, many biological and physical mechanisms take place governed by mass, air movement and thermal exchanges. There exist various types of greenhouses.[10]

2.2.1 Types of greenhouses

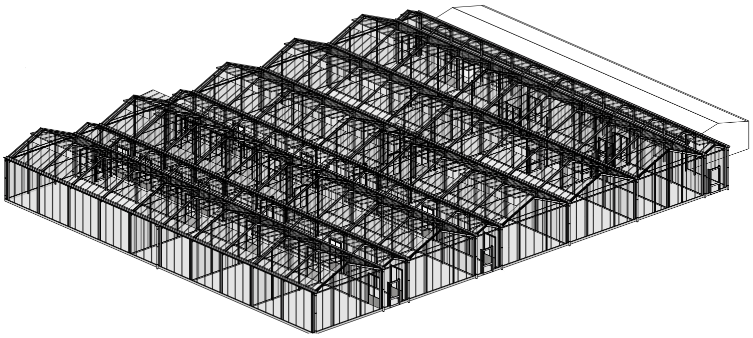
The classification of greenhouses is very complex. It is often done according to the shapes given by the supporting frames that constitute the structure. While each type has benefits for a particular application, there is generally no one type of greenhouse that can be considered as the best. Different types of greenhouses are designed to meet specific needs.[11]
Three classes of greenhouses can be identified: attached greenhouses, free-standing greenhouses and gutter-connected greenhouses [12]. It is therefore possible to have both small free-standing structures and large greenhouses connected by gutters. Free-standing greenhouses are completely free-standing structures that come in a variety of different designs. Gutter-connected greenhouses are connected to the roof by a common gutter.[13]



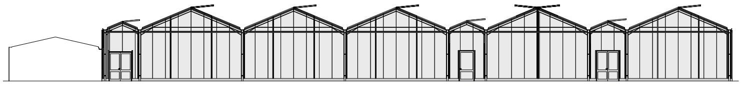
(a) Even-span
(b) Uneven-span
(c) Vinery
(d) Modified arch
(e) Quonset

Figure 2.1 Different types of Free-standing greenhouses [12]

A Free-standing greenhouse can have a Quonset, an Even-span, an Uneven-span, a Vinery or a modified arch as it can be seen on Figure 2.1. This type of structure is what one usually thinks of when the word greenhouse is mentioned. The Free-standing design is generally the best choice for the small grower who plans



(a) Overall view of the greenhouses.



(b) Side view of the greenhouses separated by gutters.

Figure 2.2 Plans of the greenhouse complex showing attached greenhouses separated by gutters. [16]

on a growing space of less than 10 000 m^2. Attached greenhouses are simply a series of free-standing greenhouses connected with each other. It is also possible however to refer to greenhouses connected by a gutter as it can be seen on Figure 2.2. These consist of a number of greenhouses of even span connected by a common gutter. The production area can either be completely open between the spans of the greenhouse or it can have inner walls that allow dividing the greenhouse into different compartments.[14, 15]

It is important to know here that the solar radiation obtained by the greenhouse at a certain time and on a certain site depends on its shape and orientation. This has an important impact on indoor air temperature. A large part of the direct solar radiation passes through the greenhouse and increases the temperature of the air inside it. Radiation diffused through the roof and reflected from the ground, from the roof, and each wall also heats the air, so the shape and orientation of the greenhouse have a crucial influence on the air temperature inside it. The orientation of a greenhouse is typically either along the East-West or the North-South axis. Orientation can have an impact on the total solar radiation received by the greenhouse and can also reduce the heating loads of the installed systems. Such factors may affect the greenhouse microclimate.[15, 17]

Numerous studies have been conducted to determine the advantages and disadvantages of different shapes and orientations of greenhouses. However, as explained previously, there is no one best shape or orientation. Rather, it all depends on its intended purpose as well as its geographical location.[12, 17, 18]

2.2.2 Structure of the greenhouse

One important thing to consider here is that depending on the type of greenhouse, different materials for the structure and the roof are used. For example, in the case where the span is large, the material needs to be more sturdy, and therefore more structural components are used to make strong lattice-type frames. Simpler designs like hoops can be used for smaller spans [19]. The choice of materials used for the greenhouse cover will have a great influence on the light radiation received by the plants, on light diffusion, shade levels, and temperature or humidity, all of which are important factors for crop growth. The durability of the material and its cost must be taken into account. [15, 19]

Three materials are commonly used to build greenhouse frames: aluminum, steel and wood. Wooden frames are much less common because these materials deteriorate quickly after installation. If wood is used, it is typically advisable to get pressure-treated wood that can resist decomposition. Between aluminum and steel, aluminum is considered the most durable and economical. It is therefore often used for roof rafters, side frames, and other structural elements of the greenhouse.[15, 19, 20]

When it comes to greenhouse covering materials they generally need to meet three criteria: to be clear enough to allow for optimal light transmission, to be durable, and to be inexpensive. There are a large number of materials that meet these criteria and that have been made commercially available to meet these needs. There are two categories of covers, flexible plastic films, such as polyethylene, and rigid covering materials such as polycarbonate sheets or glass. [15, 20]
Polyethylene (PE) is one of the most popular covering materials. It is a non-rigid material and therefore easy to install compared to other materials. Another advantage of this material is its lower price compared to other materials available. While the maintenance of these roofing materials is expensive, the initial investment is lower. The need for structural components to support these covering materials is also lower. PE is therefore considered more economical for consumers and producers. [15, 20]
Glass as a covering material for greenhouses allows an optimal transmission of light for the production of greenhouse crops and offers greater insulation than simple plastic. Glass however has certain disadvantages such as its price, which is higher than other materials, the higher cost needed for stronger structural components to

be used to support it, as it is a heavy material, and the fact that it is fragile to impacts. [15, 20]
Fiberglass is another covering material that is more durable and does not require large structural components like those required for glass greenhouses. It is frequently used for commercial purposes. While fiberglass is generally a good alternative to glass, one of its major disadvantages is that it is more sensitive to ultraviolet (UV) light and allows less light transmission in the longer term as the fibers swell. [15, 19, 21]

One other parameter that characterises a greenhouse is the floor area. It is possible to identify three types of ground surfaces that are used depending on the type of production as well as the price one is willing to invest in their ground: soil, gravel, and concrete floors. The floor will have an important influence on the insulation of the greenhouse and can in some cases reduce heat loss from the greenhouse and even provide heat. [22, 23]

2.3 Physical processes influencing the greenhouse climate

As previously stated, the climate of the greenhouse has an important impact on the growth and development of the different components of the plants. The climate is therefore an important factor that we must try to quantify in order to have optimal production, ensuring the climate conditions that the plants need. It is therefore important to understand the different processes that influence this climate. [8, 13]

Here are the definitions of climate and microclimate:

- Climate is the combination of temperature, humidity, sunshine, wind, and other characteristic weather conditions that prevail over large areas of space for long periods of time [24].
- Microclimate refers to the climate that prevails over a relatively small surface area. Microclimates are generally minor changes in the main background climate, altered by landscape characteristics [24].

Thus, it is possible on the one hand to study the overall climate of the greenhouse, in order to have an overview of what is happening, and on the other hand to be interested in what is happening locally on small surfaces, i.e. to be interested in the microclimate. The overall climate inside a greenhouse depends essentially on the outdoor climate, the physical characteristics of the indoor air, the shape of the greenhouse, the volume of the greenhouse, its orientation, and the physical and chemical properties of the covering materials used as seen in the previous section. The main factors of the internal environment of a greenhouse that are modified with respect to the outside, are: temperature, light, humidity and concentrations of gases such as CO_2 and O_2.[13, 25]

There are two mechanisms that explain the difference between the climate inside the greenhouse and the one outside:

- The first mechanism is related to the fact that the greenhouse is isolated from the outside by its enclosure, which causes a decrease in the exchange of air between the inside and outside of the greenhouse. Consequently, the air inside the greenhouse is considered stagnant, its local speed is indeed very low compared to that of the outside. In this mechanism, the decrease of the air renewal has a direct influence on the energy and mass balances of the air of the greenhouse whereas the lower local air velocities have an impact on the transfer processes between the air of the greenhouse and its inventory.[26, 27]
- The second mechanism is related to light radiation. Incoming shortwave radiation, whether directly from the sun or scattered from the sky and clouds, is reduced due to the interception of light by the opaque and transparent components of the greenhouse. The exchange of long-wave radiation between the interior and exterior of the greenhouse is altered due to the radiative properties of the covering materials. When glass is used as the greenhouse cover material, it is possible to observe what is known as the mousetrap theory. This theory is explained by the fact that glass is transparent to incoming shortwave radiation and opaque to long-wave radiation emitted from within, thus trapping energy. Radiative effects are essential in describing the greenhouse climate because they directly affect all energy balances and, hence, the indoor temperature.[26, 27]

While these two mechanisms may seem simple, their impact on the greenhouse climate is quite complex. We will hence now focus on the different processes that influence the climate of the greenhouse and more precisely on temperature, which is the factor that interests us most here. Each process will be reviewed to understand its influence and impact on the temperature.

2.3.1 Heating system

Greenhouses often require a heating system to provide heat to the greenhouse area due to the extreme winter temperatures. There are two main types of heating systems: surface heating and floor heating. In some cases, it is possible to have a combination of both systems [27]. These heating systems work in the following way: a central boiler supplies heat through heating water that circulates in a system of pipes located in the greenhouse. [26, 28]

The purpose of the ground surface heating system is to heat both the air and the floor of the greenhouse. The pipe system is usually located 5-10 cm above the ground. It is possible in some cases to see a second series of pipes located higher, at the height of the plants. This is done when the climate is colder, and the plants are not directly protected from the cold. It should be noted that the pipes can either be located around the greenhouse, or they can be located between the rows of plants. The advantages of this heating system are numerous. First it reacts well and quickly to short-term outside temperature changes. Secondly it allows for well-directed indoor air movement and the air also has a suitable velocity for most crops. Finally it is a heating system that has a positive influence on most known plant crops with better yields and good quality products. [26, 27, 28]

A floor heating system consists of pipes that are located under the floor. Such pipes are in general located 50 cm below the surface of the floor and at intervals of 40 cm from each other. This type of heating system allows to maintain a constant temperature around the root system of the plant. It offers many advantages for a list of bulbous vegetable and flower crops, and can allow for earlier harvest and lower heat consumption.[21, 27]

The size of the required pipes strongly depends on the size of both greenhouse and the heating system used. For example in a greenhouse with a floor and a surface heating system, the floor heating system provides approximately 60% of the needed heat. [21, 27].

2.3.2 Ventilation

There are two terms often used in the literature to describe the exchange of air between the greenhouse and the outside: "aeration" and "ventilation". The term ventilation is the one used in this work.

Ventilation is a process that allows to evacuate excess heat and decrease the temperature of the ambient air. Moreover, it has a significant effect on humidity since it allows to modify the humidity by evacuating more or less quickly the indoor air that is enriched in water from the transpiration of the plants. Ventilation therefore strongly affects the distribution of the climate in the greenhouse. This is a very

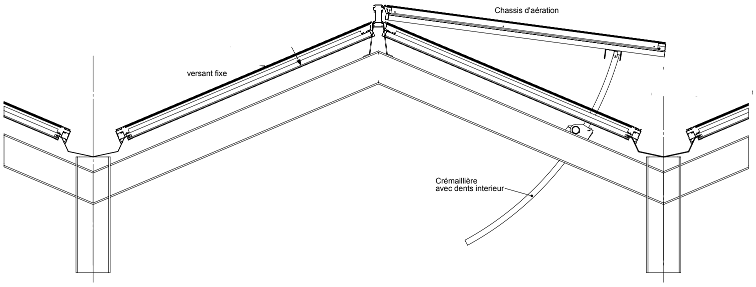


Figure 2.3 Roof window on a greenhouse [16]

important phenomenon which is quantified by the airflow rate, i.e. the volume of air entering or leaving the room during a given period of time. It is necessary to distinguish here two types of ventilation, the so-called forced ventilation and natural ventilation.[21, 27, 29, 30]

Forced or mechanical ventilation refers to two different principles. The first one is exhaust ventilation, which is done with a fan that extracts air to the outside, while the outside air enters through shutters installed on the greenhouse. The second one is positive pressure ventilation, which draws fresh air from outside into the greenhouse. These two mechanisms are used in very specific cases. For example, positive ventilation is generally cheaper for a free-standing greenhouse and gives the same results as exhaust ventilation. On the other hand, it is not recommended for multi-room greenhouses, because it requires a very complex system, thus much more expensive. For this type of greenhouses, an extraction system is recommended. The forced ventilation allows having good ventilation of the greenhouse even when there is not enough wind outside. Its main disadvantage is that it requires a lot of energy. The efficiency of the system depends mainly on the power of the installed system and can be quantified by the difference in temperature between the indoor and outdoor air, but also by the air renewal rate. [31, 32, 33]

An example of natural ventilation is when a window in the greenhouse is opened. It is called natural ventilation because it draws its source only from the wind. In the case of a greenhouse, this ventilation is achieved by means of side vents and/or roof vents. In general, natural ventilation is sufficient for the efficient operation of a greenhouse. Its efficiency depends on the one hand on the external meteorological conditions (outside temperature, wind speed and direction) and on the other hand on the structure of the greenhouse in general [34]. Indeed the arrangement of the openings can vary from one greenhouse to another but their relative surface is generally related to the surface of the greenhouse floor. The surface area of the openings is generally on average 16% of the floor area for optimal ventilation [27]. Their arrangement depends on the size of the greenhouse, its orientation, and its structure. For example, it is possible to have a greenhouse with a single window on the roof (see Figure 2.3), a double window on the roof or even to have side and roof windows.

The basic principle of this exchanged air flow is related to the pressure differences that exist at the ventilation openings. The warm air rises and the chimney effect caused by the roof window pushes the warm air outside. The cool air from outside enters through the roof and slowly goes down. [35, 36, 37]

2.3.3 Solar radiation

Solar radiation is an important natural source of energy for heating the greenhouse. It is in fact one of the most important environmental factors for plant growth. Solar radiation received at the surface of the earth varies greatly depending on the geographical location, but also depending on the season. The energy collected from the sun at a specific location on the earth can vary greatly from one place to another. When the solar radiation passes through the atmosphere around the earth, part of the solar radiation is absorbed, and the other part is reflected. Therefore, the solar radiation received on the earth's surface is composed of direct and diffused radiation. Direct radiation directly comes from the sun while diffused radiation is reflected in the atmosphere and comes from all directions in the sky [27]. It is difficult to quantify the diffused radiation, so when we analyze the energy received by the greenhouse due to the solar radiation, the focus is on the direct radiation. [9, 18, 27, 38, 39, 40]

Radiation can also be differentiated based on the light frequency: long wavelength radiation (low frequency, infrared radiation) and short wavelength radiation (high frequency, radiation close to the ultraviolet and the visible light spectrum). The radiation that reaches the earth is in a spectral band roughly between 0.3 and 2.5µm in wavelength. It can be divided into three parts, the ultraviolet, the visible and the infrared. The ultraviolet is characterized by a wavelength between 0.3 and 0.4µm. The visible is characterized by a wavelength range from 0.4 to 0.8µm and represents about 45% of the total energy. The infrared is characterized by a wavelength limited between 0.8 and 2.5µm.[8, 9, 18]

When the light radiation arrives on a surface, e.g. on the glass roof, the incident radiation is divided into three parts. These are the transmitted, the absorbed and the reflected radiation, as can be seen in Figure 2.4. This separation will depend on the one hand on the material of the greenhouse cover, but also on the wavelength.

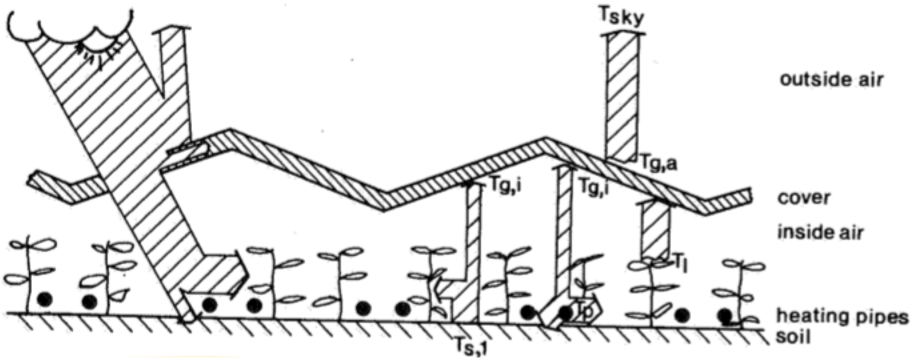


Figure 2.4 Interaction between the shortwave and longwave radiation [26]

It is known that the solar radiation useful for photosynthesis is between 0.4 and 0.7 µm [41]. It is desirable to have an efficient transmission of short wavelengths in the greenhouse and that is why glass is sometimes chosen as the material for the structure. In fact, the material used for the greenhouse structure should be as transparent as possible for short wavelengths and as opaque as possible for long wavelengths. The long wavelengths have no real impact on plant growth. [9, 26]

2.3.4 Convective exchanges

Convection is also one of the most important heat transfer mechanisms that occur in a greenhouse. It involves the physical movement of a warm gas or liquid to a cooler area. In the case of the greenhouse, when air is heated inside the greenhouse, it rises toward the roof and loses some of its heat in the covering materials. Then the colder, heavier air moves down to the ground until it is warmed by the heating or by the ground. Three different types of convection can be observed: free, forced or mixed convection. The type of convection observed will depend mainly on the type of greenhouses, the ventilation as well as the outdoor climate conditions. In situations of good ventilation, forced convection due to the outside wind is dominant, but if the greenhouse is completely closed, free convection due to buoyancy forces is dominant. [26, 27, 42],

Natural convection is the flow regime obtained when a fluid is heated without any external flow being imposed. Natural convection occurs when the movement of the fluid is due to the simultaneous action of temperature differences in the medium and a mass force field. In the case of a greenhouse, during the day, the ground surface heats up because its radiative balance is positive. The air temperature increases and its density decreases. A particle of warm air receives a buoyancy force from the colder surrounding air. This air particle rises and is replaced by colder air which in turn heats up and the process continues. This example involves only gravity forces and free convection is then called natural convection. [43, 37, 44]

In the case of forced convection, the fluid/air moves due to an external cause, e.g. a fan in the case of a greenhouse. In forced convection, the buoyancy is negligible compared to the forces used to set the fluid in motion. Under natural conditions, forced convection is due to the wind which is itself the result of the local gradient of atmospheric pressure. [9, 43]

In the case of mixed convection, there is an external cause for the fluid motion, but it is not sufficient for buoyancy to be neglected. This convection is often considered as a transition regime between free and forced convection. This case is often encountered in natural conditions when the wind speed is low. The air movements are then produced both by the factors which maintain the wind and by the vertical gradients of temperature. The heat and mass transfers are then partly due to natural convection and partly to forced convection.[9, 43]

2.3.5 Conductive exchanges

The majority of the heat lost in the greenhouse is lost by conduction, i.e. the transfer or flow of heat through a material such as the glass or the floor of the greenhouse. This is because the different materials that make up the greenhouse vary in the rate at which each one conducts heat from the warm interior to the cooler exterior. [42, 45]

The most important heat exchanges by conduction are mainly within the soil and through the greenhouse walls. In the case of the walls, we can consider that these exchanges are stationary because of their small thickness and thus integrate them in a global transfer coefficient. It should be noted here that the heat losses related to conduction that will take place, will strongly depend on the materials constituting the greenhouse. [9]

2.3.6 Other Processes

There are a large series of additional parameters/processes that influence the climate within the greenhouse, but which have not been analyzed here. These processes either have a smaller impact on the climate or the link between the process, and the description and study of the climate is more complex, and therefore considered beyond this work.

These other processes include the following [21, 46]:

- Plant transpiration: After the evapotranspiration of the plants comes their transpiration. This phenomenon has an impact on the temperature in the greenhouse, but it is very complicated to quantify it because it varies from plant to plant and during their growth.
- Infiltration, i.e. the loss of heat: This regards to the loss of heat within the greenhouse due to the imperfections of the structure.
- Fogging system: In some cases, a misting system is added within a greenhouse to drive a decrease in the temperature when it cannot be regulated with the ventilation system.
- Shading system: Some greenhouses have a cover over the plants that opens and closes. This cover has two effects, the first one is to limit the solar radiation that enters the greenhouse while the second one is to keep the heat in the greenhouse at night.
- Thermal mass: This phenomenon is mainly related to the floor of the greenhouse when it is made of concrete for example. Thermal mass is the capacity of a material to store heat during a temperature change [47]. Heat can be stored in the floor of the greenhouse during the day and released during the night.

Chapter 3

Analysis of the available results

3.1 Overview

We have seen in the previous chapter the main concepts allowing to understand the functioning of a greenhouse. The different structures and orientations of the greenhouses have been presented. In addition, their impact on the greenhouse climate has been explained. The different processes influencing the climate and more precisely the temperature in the greenhouse have been introduced. All this has given a general overall view of the climate in a greenhouse. Nevertheless these are only general principles, and we shall now see how to apply them to the specific greenhouse we are interested in.

In this chapter, we shall focus on the analysis of the climate of the greenhouse on the basis of the concepts explained in the previous chapter. The main objective of this chapter is therefore to explain how the climate and the microclimate vary in the specific greenhouse that we are interested in order to identify the physical phenomena that have a great influence on it. This step will subsequently allow us to develop our first physical model which will be based on the physical phenomena that have been identified as dominant in this greenhouse.

The data that will be analyzed in this chapter come from experiments that were carried out by different researchers in previous studies. These data were not gathered with the objective to be used in this work; they were obtained in the context of other research.

This chapter will be structured as follows: First the experimental set-up that allowed the data to be collected will be explained. The environment in which they were collected will be described, i.e. the greenhouse on which we focus here. Then the relevant data will be pointed out. In a third step, the different measurement errors will be highlighted in order for us to be able to present the results afterwards. Finally opportunities or suggestions for future improvement experiments based on the collected data will be discussed.

3.2 Experimental set-up

3.2.1 Environment and equipment

The experiment took place in a greenhouse in Louvain-la-Neuve. In Louvain-la-Neuve, there is a whole complex in which research greenhouses are located. It is possible to speak of a large greenhouse which consists of many smaller greenhouses, or in other words, many small greenhouses are located next to each other. Figure 3.1, which represents the plans of the greenhouses of Louvain-la-Neuve, shows their arrangement. These greenhouses are separated in several sections. There is for example a section dedicated to tropical greenhouses, another section dedicated to temperate greenhouses and a third section being an isolated part from the others in which plants carrying diseases are studied. The greenhouses are either built one against the other and are therefore separated only by a glass "wall" or some are separated by corridors.

The greenhouse in which the experiments took place is circled in red in Figure 3.1. It is a greenhouse that shares two of its walls with two other greenhouses and two walls with the corridors. This greenhouse is 8m x 8 m (S_{GH}= 64 m^2) and has a volume of V_{GH}=263.2 m^3. It is an even-span greenhouse oriented in the North-South direction, that is to say that the inclination of the inclined parts of the roof face either East or West. In terms of windows, it has a single window on the west side of the roof that has a surface of S_w=12 m^2 , which represents 18.8% of the greenhouse surface. This window also has a 300-micrometer mesh screen to protect from insects. The structure of the greenhouse is made of steel and its roof and walls are made of glass. The roof is double glazed (4 mm and 6mm glass) for better insulation while the walls are single glazed. The floor of the greenhouse is made of concrete and consists of three layers for better insulation, there is a layer of concrete on the surface on a layer of polypropylene which is on another layer of concrete.
As far as heating is concerned, the greenhouse has a surface heating system using two series of parallel pipes that are placed around the greenhouse. One is at 5

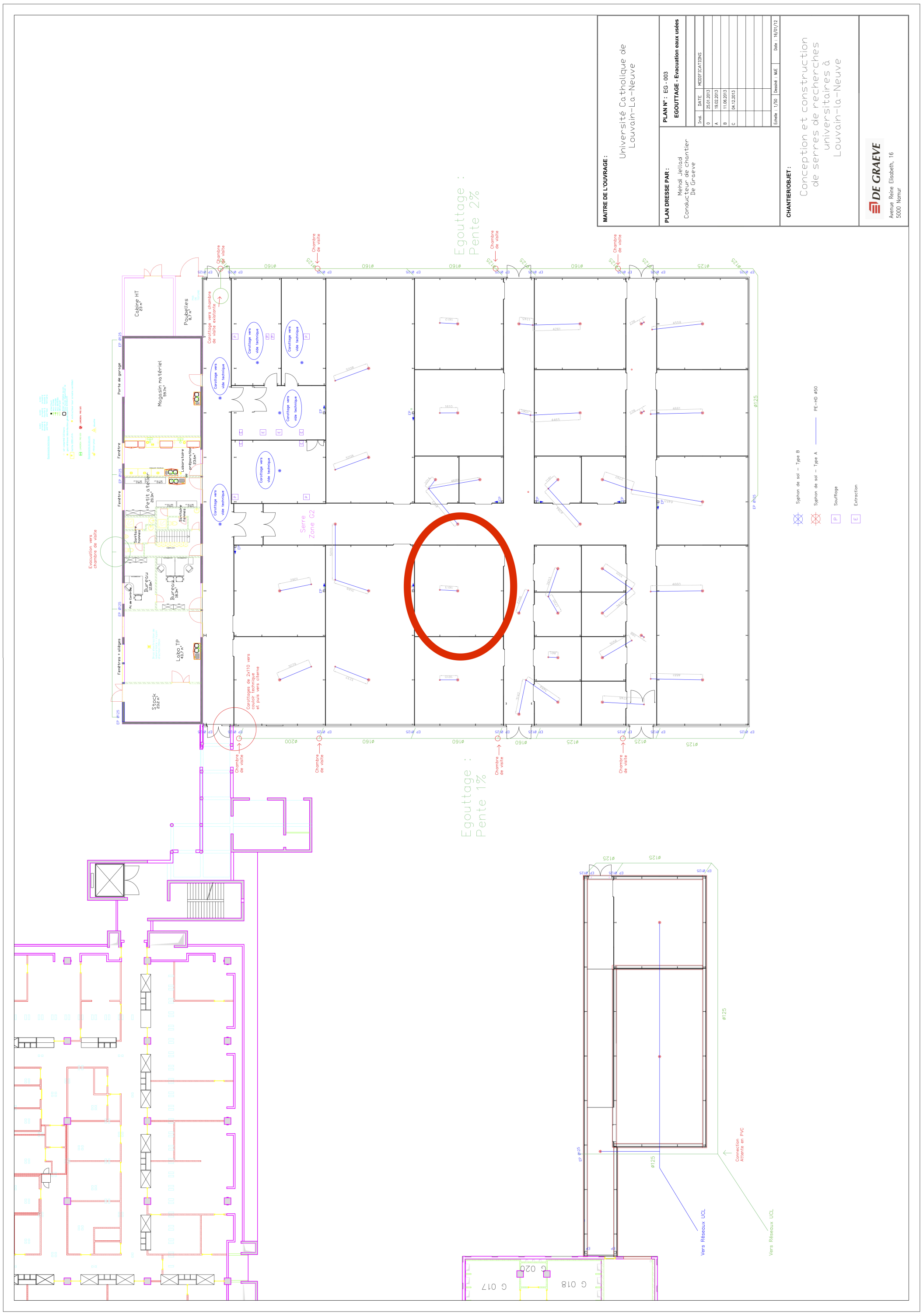


Figure 3.1 Plans of the compound containing the greenhouses in Louvain-la-Neuve [16]. The greenhouse in which the experiment took place is circled in red.

centimeters from the ground while the second is at the height of the plants, that is to say at 1.5 meters from the ground. In addition, the greenhouse has a shading system by having a cover that folds and unfolds according to what has been programmed. A misting system is available in the greenhouse, but it is not often used because of the different sensors that are installed in the greenhouse. Lamps that give three colors (blue, white and red) are also installed to help photosynthesis.[16]

Now let us take a closer look at the equipment used for the experiments as well as the way the data are collected. As it can be seen in Figure 3.2, there are two closed Styrofoam boxes in which the plants are placed. The dimensions of the boxes are 1.5 m x 1.6 m x 3.2 m. The plants are placed in these boxes leaving only their stems sticking out. These boxes have an automatic system that allows the plants to be changed place during the day. Each box has 6 sensors that are placed at the ends and in the middle. These sensors collect the temperature and humidity of the place where they are located. In addition to these 12 sensors, there is a sensor in the center of the greenhouse that allows the system to adjust the temperature of the heaters, the opening of the windows, etc.

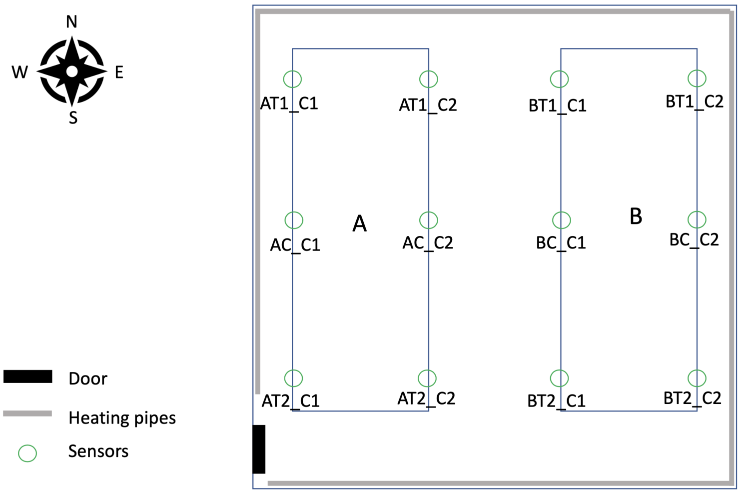


Figure 3.2 Inside arrangement of the greenhouse.

The climate parameters outside the greenhouse were recorded by a weather station located at a height of 5.8 m. The weather station is not located directly above the greenhouse but is central to the compound. It provided us with the following information on the outdoor conditions: temperature, humidity, solar radiation, wind speed and direction.

3.2.2 Control system

The greenhouses in Louvain-la-Neuve use a system where most of the variables of the greenhouse are controlled. During the time of the experiments, a certain set of instructions are introduced to the greenhouse control system.

A theoretical temperature will be imposed in the greenhouse and a margin of two degrees will be allowed. For example, in general, the desired temperature in the experiment is around 20 °C. In that case, as long as the central sensor of the greenhouse indicates a temperature between 18 and 24 °C, the conditions will be satisfied. If the temperature is below the acceptable threshold, the system will automatically increase the temperature of the greenhouse, by increasing the temperature of the heating and by closing the windows. In the opposite case, if the temperature is above the indicated threshold, the system will open the windows for natural ventilation. In this second case the misting system could also be active. However, this is often avoided in order not to damage the different sensors in the greenhouse. With respect to the window opening, it is important to know that they are neither completely open nor completely closed. Depending on the external conditions, the windows open to a certain degree or close. They can be opened up to 90 degrees. Here the wind and its direction are of great importance.

Depending on the different experiments taking place in the greenhouse, the conditions imposed may slightly vary. The greenhouse manager would therefore introduce the desired temperature into the system and the control system will maintain the required temperature. The control system will also respect the time slots imposed by the greenhouse manager. The automatic system does not use a system of anticipation of the climate data, it adapts according to the data that it receives on the one hand by the central sensor of the greenhouse and on the other hand by the weather station.

3.3 Data available

Data from 8 different experiments were obtained. All these experiments were performed in 2019 and 2020. The periods of these experiments are as follows:

- January 2019
- May 2019
- September 2019

- October 2019
- November 2019
- February 2020
- June 2020
- December 2020

For each period, between 20 and 50 days of data are available. While each experiment lasts in general between 20 and 25 days, the sensors are however placed a few days before the experiment to be calibrated, and they are removed a few days after the end of the experiment. For each experiment, the 12 sensors were positioned on the boxes in the greenhouse as can be seen in Figure 3.2. These sensors took measurements of temperature and humidity every 10 minutes. In Table 3.1 it is possible to observe an example of the information provided by the sensors. For each set of experiments, there were between 3600 and 8640 data available depending on the number of days that the sensors were turned on in the greenhouse.

Table 3.1 Example of the first 10 data received by the sensor "AC_C1" for the experiment performed in December 2020

	Date	Time	Temperature [°C]	Humidity [%]
1	11/30/20	10:00:00 AM	19.888	50.946
2	11/30/20	10:10:00 AM	19.817	51.686
3	11/30/20	10:20:00 AM	19.770	52.428
4	11/30/20	10:30:00 AM	19.746	53.232
5	11/30/20	10:40:00 AM	19.722	53.725
6	11/30/20	10:50:00 AM	19.722	54.158
7	11/30/20	11:00:00 AM	19.722	54.158
8	11/30/20	11:10:00 AM	19.722	53.632
9	11/30/20	11:20:00 AM	19.722	53.973
10	11/30/20	11:30:00 AM	19.746	54.502

3.4 Known errors of measurement

By analyzing the data collected, it could be observed that, as a general rule, despite having 12 temperature and light sensors, there was always one or two that did not work as expected during the experiments. Thus, there were typically only 10 sensors that were working during each experiment. Apart from this problem of one or two sensors not working properly, the experiments seem to have been carried out under suitable conditions and the sensors seem to have been well positioned in the greenhouse.

3.5 Insights from existing analysis of data

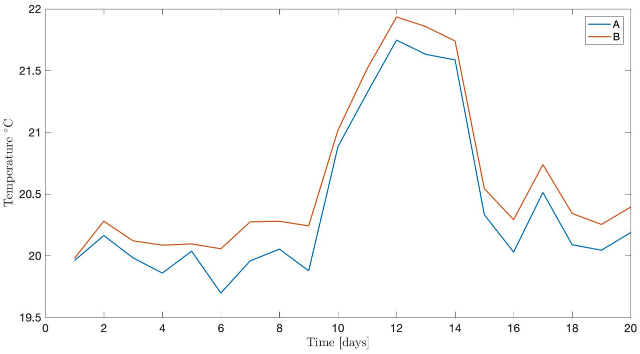
Now that the experimental setup has been explained and the environment of the experiment has been analyzed, we focus on the analysis of the data received in order to be able to identify the key elements of the climate of the greenhouse of interest to us in order to develop our model.

The analysis of the results is divided into three parts. In the first part, the daily average temperature of each box will be put forward for two experiments: June 2020 and December 2020. In the second part, we will be interested in the daily variation of the temperature within the greenhouse. Finally, we shall look at the daily average temperature of each sensor during an experiment. Extra information can be found in Appendix A.
The different plots have been drawn for the 8 experiments. June 2020 and December 2020 have been chosen for this analysis on the one hand in order to be able to compare the climate during two different seasons, i.e. when different physical processes are used to heat the greenhouse and on the other hand, because during these two experiments, most of the sensors were operational.

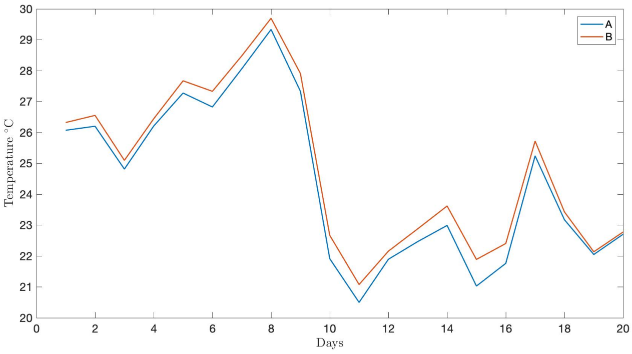
3.5.1 Daily average temperature of box A and B

In Figure 3.3a and 3.3b we can see the average daily temperature between box A and B for two different experiments, June 2020 and December 2020. These two graphs allow to see how the temperature in the greenhouse is regulated and evolves during two different periods of the year. First it is possible to see what happens in December, which is a month when it is quite cold in Belgium and when there is sunshine during a smaller part of the day. Secondly it is possible to see what happens in June, which is a month where it is generally warmer and the sun rises for a longer period of time in Belgium.

We can see here that the temperature of the greenhouse is higher in summer than in winter. In winter the temperature remains very close to 20 °C; it remains well within the range of 2 °C above or below the set temperature. Therefore, the control system is programmed to work properly in winter. It is also possible to see that between the 10th and the 15th day, the average temperature is higher than the



(a) During the December 2020 experiment.



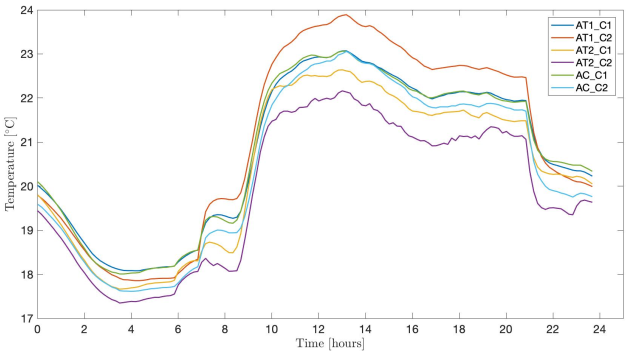
(b) During the June 2020 experiment

Figure 3.3 Average daily temperature of box A (blue) and B (red)

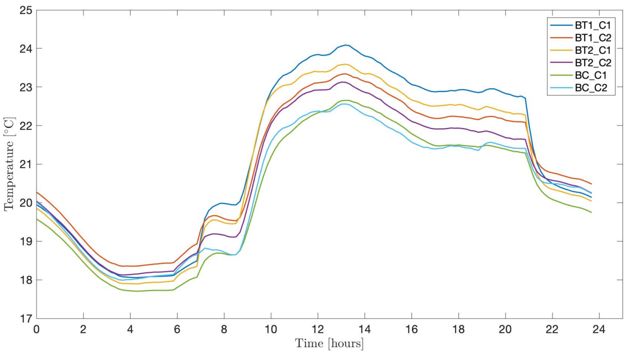
other days. This is explained by the fact that these days were very sunny and therefore the impact of light radiation on temperature was quite strong.
When looking at Figure 3.3b, it can be seen that the temperature in summer has a large number of fluctuations and at certain times is significantly higher than what was set. Indeed, the required temperature is between 20 and 21 °C . The outside climate is much more constraining here and therefore does not allow the desired temperature to be reached.

The average daily temperature of box B is higher than that of box A in both summer and winter. This can be explained by the fact that box B receives more solar radiation than box A according to what has been observed in the greenhouse. However it should be noted that this difference is not very significant since it is less than 1 °C. It will be interesting to see what happens more precisely at the sensors of each box in the following sections.

3.5.2 Daily variation of temperature



(a) Temperature variation by sensor in box A



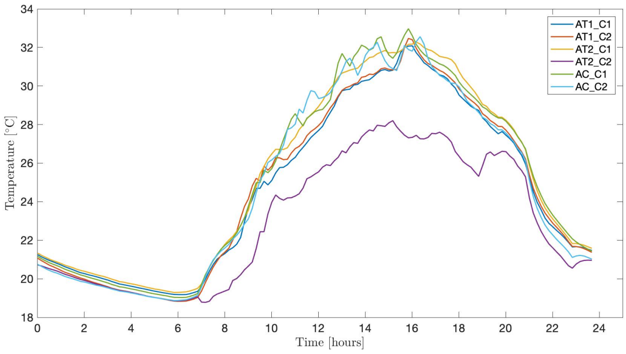
(b) Temperature variation by sensor in box B

Figure 3.4 Daily variation of temperature during the December 2020 experiment.

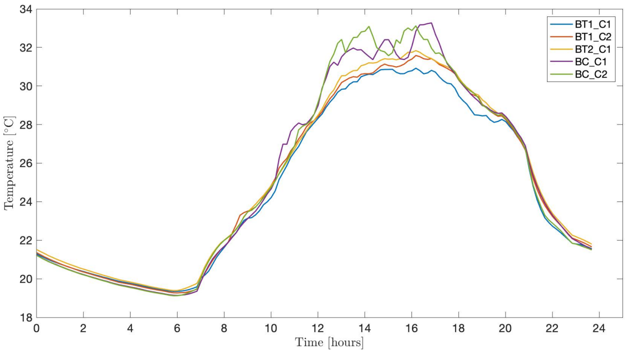
The hourly average temperatures during the entire December 2020 experiment are plotted in Figure 3.4a and 3.4b. The temperatures in Figure 3.4a are those of the sensors located on box A while those in Figure 3.4b are those of box B. To remember the position of each sensor, look at Figure 3.2. These two figures give two types of information. The first one is related to the way the temperature varies during the day, and the second one about the difference in temperature that there is at each place of the greenhouse.

Regarding the variation during the day, it is possible to observe 4 different zones in winter:

- At 6am: the lamps are activated, and the heating is turned on, it is possible to observe a first jump in temperature as the greenhouse starts to heat up.
- Between 7 and 8 am: the heating is fully working and has reached the desired



(a) Temperature variation by sensor in box A



(b) Temperature variation by sensor in box B

Figure 3.5 Daily variation of temperature during the June 2020 experiment.

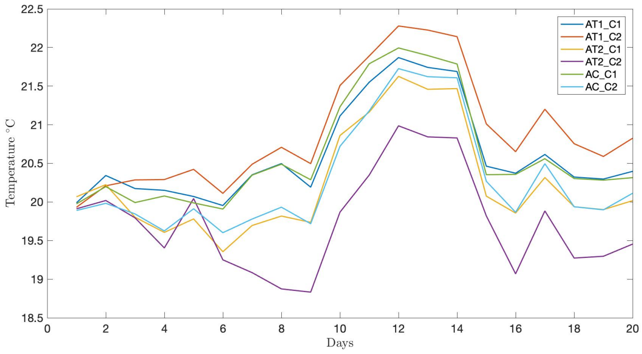
temperature; we can see a second jump in temperature.

- Around 9am: the sun rises so we start to see the impact of the light radiation on the temperature. There is a strong increase in temperature at this time.
- Around 8pm: the temperature starts to decrease. This is due to the fact that the lamps are turned off and that the heating is set at a lower temperature. The windows will also open to reach the desired lower temperature.

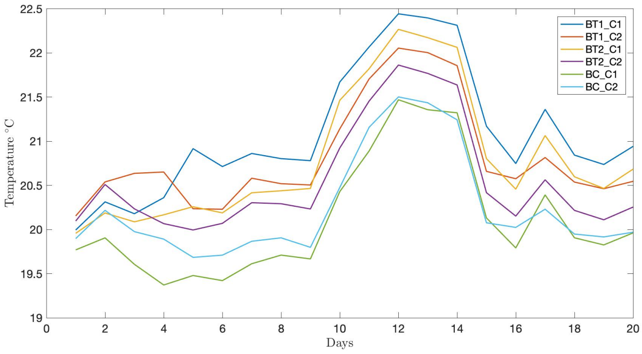
After seeing these results, it was observed that the 4-time zones defined by the greenhouse operators are clearly visible, which shows that the automatic temperature control system works relatively well. By looking at Figure 3.5, it can be observed that these 4 time slots are not visible in summer. Indeed, here the temperature seems to be influenced mainly by solar radiation. Due to the higher temperatures in summer, the heating system is not used, it is the outdoor conditions and the ventilation system that influence the temperature.

Another observation is that the temperature within the greenhouse can vary a lot from one place to another in the greenhouse at the same time of day. During the night, the temperature difference measured by the different sensors is smaller, this depends on where the sensor is located in the greenhouse and its proximity to the heater. On the other hand, during the day the difference in temperature recorded by the sensors is not negligible, which means that the distribution of solar radiation is very variable in the greenhouse.

3.5.3 Daily average temperature of each sensor



(a) Temperature variation by sensor in box A



(b) Temperature variation by sensor in box B

Figure 3.6 Average temperature variation during each day of December 2020 experiment.

The data presented in Figures 3.6a and 3.6b show the average daily temperature of each sensor during the December 2020 experiment. It can be observed on these figures that the temperature is not quite homogeneous within the greenhouse. Indeed, in some places of the greenhouse, the temperature is constantly lower than in others. For example, the sensor "AT2_C2" always registers a lower temperature than the other sensors, it is a sensor that is located just below the window and

quite close to the greenhouse door.
In box B, it can be observed, that the temperature is lower in the middle of the box, these are the places which are less close to the heating system. In general, it can be observed that the two northernmost sensors, i.e. "AT1_C2" and "BT1_C1" have a higher temperature.

It is important to note here that these observations are not necessarily valid for all experiments. It is therefore difficult to draw conclusions from these graphs related to the temperature at each location in the greenhouse. This can change depending on the season and the processes involved in the greenhouse climate. It is nevertheless possible to make hypotheses which are explained in the next part.

3.5.4 Interpretations

At first, it could be observed that the climate in summer and in winter does not work in the same way and this in spite of the automatic system which regulates the temperature. Indeed, in winter, 3 processes were identified as key: the first one is the heating system which works in different time ranges to heat the greenhouse. The second is the solar radiation which is present only during a small part of the day but during this part the temperature increases. The third is the ventilation system which is used to keep the temperature relatively constant. Ventilation is only used when the external weather allows it, if for example the wind is too strong in the direction of the window opening, the window will not be opened to avoid cooling the greenhouse too much. In summer, however, solar radiation seems to have the greatest impact on the temperature because the heating system is not working. Ventilation also has an impact on temperature. The greenhouse manager explained that to force ventilation in the summer, they often open the greenhouse door to create a draft. However, there are no values available for this effect because it is something that is done manually and not automatically.
In addition, it should be noted that the climate between summer and winter is very different. It would be interesting to be able to estimate the temperature of the greenhouse according to the outside climate, on the one hand to know which type of experiment can be carried out at which time of the year and on the other hand, to be able to think of alternatives to have a more constant temperature during an experiment.

The next observation is that the temperature within the greenhouse is not homogeneous. The different sensors record different temperatures at the same time of the day. It is not directly possible to identify what influences this effect. We can however put forward a number of hypotheses on the phenomena that would explain this difference in temperature:

- The natural convection induces a temperature gradient in the greenhouse. Indeed, the convection will allow having a movement of the air by moving the hot air up and the cold air down of the greenhouse. This movement repeats itself continuously. In addition, the heating system is located on the edge of the greenhouse, so the further away from the heating pipes, the less impact it will have. [48]
- The light radiation in the greenhouse is very variable. This can be explained by the sun's trajectory which changes according to the season and the day [49]. Some areas of the greenhouse are therefore more exposed to the sun than others. On the other hand, this compartment of the greenhouse is located between many other compartments. The structure of the greenhouse, the different pipes or even the material available in the neighboring greenhouses can cause shading in certain places of the greenhouse.
- The ventilation system may create some drafts when the door is opened.
- The structure of the greenhouse itself can have a significant influence on the climate. Each side of the greenhouse is in contact with another compartment that has a different climate, so depending on where you are in the greenhouse, the surrounding climate may be different.

3.6 Gaps and opportunities identified

After analyzing the obtained data, a number of opportunities were identified to improve the quality of these analyses. First it would be interesting to have more experiments for each month to see how significant the data are for each period of the year. To do this, it would be interesting to have the data for the same periods of the year for a period of 3 to 5 years.

In a second step, it could be interesting to add a sensor at the greenhouse door to know when it opens and for how long, but also to be able to quantify the ventilation caused by the opening of the door.

In a third time, it would be interesting to have the data of the light radiation that arrives at each place of the greenhouse, that is to say at the places where we already have the sensors that give us the information relative to the temperature. This will allow us to better understand how the light is distributed within the greenhouse and therefore to quantify the impact of shading.

Chapter 4

Physical model of greenhouse climate

4.1 Overview

In Chapter 2, it was possible to identify the different phenomena that influence the climate within greenhouses in general. Then in Chapter 3, the greenhouse that is of interest to us was studied to see which of these phenomena had the greatest influence on the climate of this greenhouse. Now the information obtained through these two previous chapters will be used to develop a first climate model for the greenhouse.

Our objective for this first time-dependent model is to be able to estimate the temperature in the greenhouse during the year according to the physical phenomena which occur inside it. The outdoor climate, as well as the indoor conditions, will be used to provide this temperature estimate. This model must be simple and reliable so that we can also develop a spatial model later on. As it was seen in Chapter 3, the temperature undergoes large variations during the year despite that the control system is set to the same temperature. Our aim is to establish a first model that will allow having more information related to the temperature that we could have in the greenhouse at different times of the year. Once this model is established, the next step will be to focus on the temperature differences observed within the greenhouse itself.

Different types of models have been identified in the scientific literature to model the climate within a greenhouse. It is possible to distinguish two main categories of climate models for a greenhouse. We either have static models used for the design of greenhouses, or we find dynamical models used for climate control. Here we will focus on the dynamical model, i.e. where the output describes a time dependency of the variable of interest. [25, 50]

Greenhouse models can also be classified as either physical or statistical models. Statistical models are purely empirical models that are considered black boxes [25, 51]. For example, Litago et al. in 2005 made a statistical model for the climate of a greenhouse entitled as follows: "Statistical Modelling of the Microclimate in a Naturally Ventilated Greenhouse"[52]. In this study, they developed a model to estimate the temperature and humidity in a greenhouse without a heating system and with natural ventilation, located in Lisbon. This type of model establishes relationships between input variables and output variables without physical meaning. It is therefore necessary to collect all the experimental data of the climate conditions inside and outside the greenhouse to find the correlation between these data.
Another way to model the climate is to focus on the modeling of each physical phenomenon and from these to try to estimate the temperature. It is possible to establish models of different complexity. It is for example possible to solve a very complex system of equations using Computational Fluid Dynamics (CFD) or to simplify the problem as much as possible and establish a model based on the conservation of energy with one or more equations depending on the complexity[32]. Here a simple physical model is used.

This chapter will be structured as follows. In the first part, the phenomena chosen for the modeling will be put forward. Then the general principle of the model will be explained. In the third part, the different physical processes will be modelled. Once these three parts are explained, it will be necessary to focus on the implementation of the model as well as the statistical analysis which will be carried out to check the validity of the model.

4.2 Description of the model

In this section, the model developed will be described. As seen in the previous chapters, a greenhouse is a system that is influenced by a large set of parameters and is subject to sudden large weather variations that have to be modelled in some way. It is impossible however to describe all the internal factors of the greenhouse in relation to all its external influences, so it is necessary to make a selection of the most relevant and dominant parameters within the greenhouse in order to develop a model.

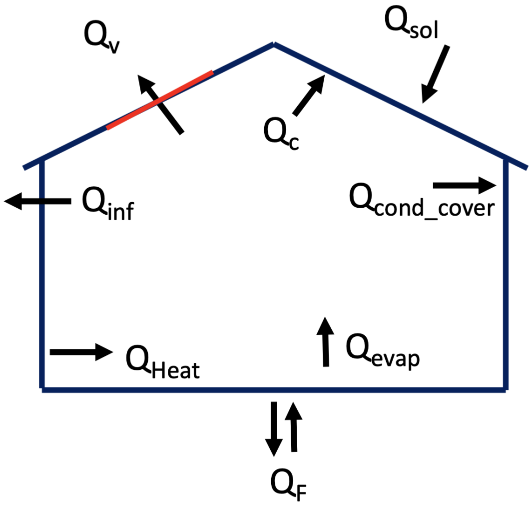


Figure 4.1 Energy transfer processes through the greenhouse building structure [27]. Where, Q_{sol} is the heat gain from solar radiaion,Q_V is the heat loss from ventilation,Q_H is the heat gain from the heating system, Q_{cond_cover} is the heat loss from conduction through the cover, Q_{evap} is the heat loss from evaporation,Q_{inf} is the heat loss from infiltration, Q_F is the heat exchange with the soil and Q_c is the heat loss from condensation.

The time-dependent model developed in this work is therefore based on the principle of energy balance within the greenhouse. As it can be observed in Figure 4.1, we consider the greenhouse as a control volume. Then we carry out the thermal balance of the greenhouse. This balance includes heat transfer and mass exchange to and from the greenhouse environment. Figure 4.1 shows several phenomena that influence the climate of the greenhouse. We then select the thermal transfers to be modelled here. The phenomena have been chosen using the results obtained in the previous chapter and the literature review. They are listed below:

- Conductive heat transfers with the cover of the greenhouse, Q_{cond_cover} .
- Heat transfers related to solar radiation, Q_{sol}.
- Heat transfer by natural ventilation, Q_V.
- Heat transfer related to the heating system, Q_H.

The heat balance can be expressed as follows [27]:

$$Q_{total} = Q_{gain} - Q_{loss} \tag{4.1}$$

with, Q_{total} the total energy balance [W], Q_{gain} the amount of energy entering the greenhouse [W] and Q_{loss} the amount of energy leaving the greenhouse [W].

We look at the amount of heat entering the greenhouse and the amount of heat leaving it at each instant. The internal temperature of the air in the greenhouse is calculated at each instant by solving a differential equation taking into account the energy conservation. In order to obtain this differential equation, it is necessary to express the physical phenomena in a mathematical equation in order to develop the terms Q__gain and Q__loss.

Before developing all these terms, we make an important assumption for our model. The air inside the greenhouse is considered to be well mixed which means that in this model we consider that the temperature inside the greenhouse is homogeneous. Let us look at the different physical processes expressed in a mathematical form.

4.2.1 Heating system

The heating system is part of the process that provides heat to the greenhouse. It is a system of surface heating of two parallel pipes of 6 cm diameter positioned all around the greenhouse. The first pipe is located at a height of 5 cm while the second at 1.5m above the ground.

The following formula for calculating the heat released by a horizontal cylinder is used [26, 53]:

$$Q_H(t) = n * S_p * a_p(t) * (T_p(t) - T_i(t)) \tag{4.2}$$

where

Q_H(t): amount of heat provided by heating system [W].

n_p: number of heating pipes [-].

S_p: surface area of one heating pipe [m^2].

a_p: heat transfer coefficient [$Wm^{-2}K^{-1}$].

T_p: water temperature inside the pipe [K].

T_i: inside air temperature of the greenhouse [K].

We have made certain assumptions so that we can simplify the calculations. The first one is that the temperature of the water inside the cylinder, T_p, is considered constant at each time t, i.e., the inlet temperature of the water is equal to the outlet temperature. The values of T_p used are those directly collected by the experimental data performed during the 2019 and 2020 experiments. T_p values had been recorded every 10 minutes during these different experiments. The second assumption is that the heat transfer coefficient can be calculated as suggested by G.P.A. Bot [26] (see equation (4.3)). This formula is widely used to estimate the heat transfer coefficient as a function of temperature. Only the values of the constants can change according to the different studies but their values remain very close [54]. Here the values found experimentally by G.P.A Bot during his thesis have been used [26].

$$a_p(t) = C_c(T_p(t) - T_i(t))^b \tag{4.3}$$

4.2.2 Solar Radiation

Solar radiation is the second element that provides heat to the greenhouse. Solar radiation is the main source of heat in summer during the day and a source not to be neglected in winter. Several parameters must be considered in order to express this phenomenon in mathematical form.

First it is important to distinguish between direct and indirect light radiation. Despite that the indirect light is not to be neglected, we only model the direct component of light in this work for the sake of simplicity. It is indeed quite complex to estimate the diffused radiation of light. The amount of light available varies greatly depending on the season and the time of day (see Figure 4.2). In winter the sun rises around 8 am and sets around 5 pm. It reaches its maximum height of 15° around noon. In summer, on the other hand, it rises around 4 am and sets around 8 pm. It reaches its maximum height of 63° around noon as well. The greenhouse is therefore warmed up by the light rays during a larger part of the day in summer. Finally the structure of the greenhouse is another important parameter for this phenomenon. In the case of the greenhouses in Louvain-la-Neuve, the structure is made of glass with a steel frame, which means that it will favor light transmission.

Equation (4.4) represents the heat input due to solar radiation [27]. In the context

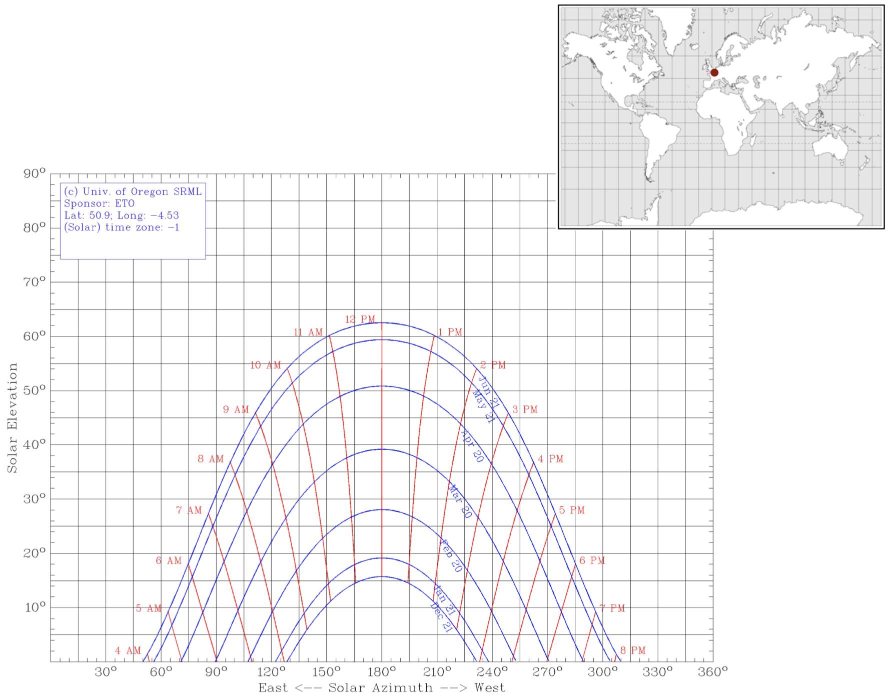


Figure 4.2 Height of the sun in Belgium for different time periods.[49]

of this study, the path of the sun is not included in the model, since the experimental measurements are used for the light intensity values. The weather station located outside the greenhouse records the light intensity at each moment of the day. We make the assumption here that for each experiment, the coefficient of transmission of light will be considered as constant throughout the day except when the shading system is activated. A shading system is activated when the light intensity exceeds a certain value. This greatly reduces the transmission of light. We, therefore, consider a constant transmission coefficient during the day, except when the light intensity I(t) is greater than 400 W/m^2. At this time, the shading system closes and allows only 30% of the light to pass.

The light transmittance also depends on the material and the external climatic conditions. We obtained the theoretical transmission coefficient of the glass roof (double glazing) through the plans of the greenhouse [16]. This one has probably decreased because of the degradation of the material but also because of different dirt linked to the weather conditions [18]. This element will be further discussed in the next chapter related to the results.

$$Q_{sol}(t) = I(t) * \tau * \gamma * S_{GH} \tag{4.4}$$

where

Q_{sol}(t): amount of heat provided by the solar radiation [W].

I(t): intensity of incoming solar radiation [Wm^{-2}].

τ: light transmission coefficient of the greenhouse cover [-].

γ: constant of the proportion of solar radiation entering the greenhouse, useful to increase internal temperature[-].

S_{GH}: surface of the greenhouse [m^2].

4.2.3 Ventilation

Ventilation is a phenomenon that induces heat loss and is used to regulate the climate in the greenhouse. In the case of the greenhouse that we study, we have natural ventilation, controlled by the opening of a window that is on the roof of the greenhouse. This window is located on the northwest part of the roof and has the following dimensions: 1,5m x 8 m. An insect-proof screen is placed at the opening of this window to protect the plants from different insects. This screen has the effect of reducing ventilation when the window is open.

It is necessary to better understand the mechanism that is activated when the window opens before the ventilation process can be expressed in mathematical form. T. Boulard et al. have studied the mechanism of natural ventilation on several occasions [36, 35, 37, 55]. Their different studies have allowed us to better understand the subject and are therefore discussed further.
The opening of the window causes a flow of air. This airflow through an opening is determined by pressure differences. The volume flow exchanged between the inside and outside of the greenhouse, G, is calculated by considering the sum of two independent pressure fields. These fields are induced by the buoyancy forces and by the wind forces [30].

$$Q_V(t) = C_a * G(t) * \Delta T(t) \tag{4.5}$$

where

Q_V(t): amount of lost heat due to natural ventilation [W].

C_a: heat capacity of air inside the greenhouse [$Jm^{-3}K^{-1}$].

G(t): volume flow rate exchanged between the inside and outside of the greenhouse [m^3s^{-1}].

ΔT(t): temperature difference between the inside and outside of the greenhouse [K]

$$G(t) = \frac{S_w}{(}t)2 * A_d * (2g * \frac{\Delta T * H_c}{T_{out}(t) * 2} + w(t)^2 * C_w)^{0.5} \tag{4.6}$$

$$\Delta T = T_i(t) - T_{out}(t) \tag{4.7}$$

where

S_w(t): surface area of the open vent [m^2].

A_d: discharged coefficient of the opening with insect-proof nets [-].

g: gravitational constant [ms^{-2}].

H_c: the height of the opening of the window [m].

w(t): outside wind speed [ms^{-1}].

C_w: wind effect coefficient [-].

A closer look at the equation (4.5) allows us to model the heat loss due to ventilation [35, 30]. This heat loss depends on the temperature difference between the inside and outside of the greenhouse. It also depends on the volume of air exchanged by the window opening, G (represented by equation (4.6)). G thus makes it possible to illustrate the two main forces which intervene in natural ventilation. The first is represented by the first term of the parenthesis of equation (4.6). It is the chimney or stack effect. The second term in the parenthesis is related to the wind effect. It is assumed that the input volume flow area is equal to the output area. The term A_d allows taking into account the fact that the ventilation is decreased because of the presence of the insect-proof screens. The different coefficients that have been used have been estimated in other studies for greenhouses equipped with similar material. The open vent area S_w is calculated using experimental data, i.e. the percentage of window opening collected during the various experiments.[30, 29]

4.2.4 Conduction with cover

The second important heat loss that has been observed in a greenhouse is related to its structure. Indeed the losses due to conduction are quite significant especially in winter when the outside temperature is clearly lower than the one inside the greenhouse.

$$Q_{cond\_general}(t) = S_c * k_c * (T_i(t) - T_c(t)) \tag{4.8}$$

where

Q_{cond_cover}: amount of heat lost due to conduction [W].

S_c: Surface of the cover of the greenhouse [m^2].

k_c: heat transfer coefficient of the cover material [$Wm^{-2}K^{-1}$].

T_c(t): cover temperature[K].

T_i(t): inside air temperature[K].

Equation 4.8 shows how conduction losses can be represented in a general form. The heat loss will be different depending on the environment next to the greenhouse and the materials at the interface. It is possible in this case to distinguish five different cases of conduction.
The first part of conduction losses comes from the roof of the greenhouse (Q_{cond_roff}). Double glazing is installed at the interface, and the glazing is in contact with the outside. In this case, we assume that the temperature of the cover is equal to that of the outside.
There are four other different elements of interface since we have four glass walls in the greenhouse. All of the glass walls in the greenhouse are single pane glass. Two of these walls are next to a corridor (Q_{cond_wall}) and the other two are next to two other greenhouses ($Q_{cond\_wall1} Q_{cond\_wall2}$). In all cases, we assume that the temperature of the cover is equal to the temperature of the room next to it. We consider therefore four additional parts of conductive losses. What changes in each case are the environmental conditions and the heat transfer coefficient of the material The area at the interface is the same for all four walls. We assume here that the heat transfer coefficient of each material is constant. While this heat transfer coefficient normally varies with temperature and material degradation, this variation in the coefficient should not be significant since the temperature remains in the same range. The temperature of the cover, i.e. the environment near the interface, is obtained from experimental data. The temperature of the exterior, the corridors, and the two other greenhouses were collected every 10 minutes during the experiments used in Chapter 3. It is therefore possible to see in equation (4.9) the entire conduction losses.

$$Q_{cond\_cover}(t) = Q_{cond\_roff}(t) + 2 * Q_{cond\_wall\_corridor}(t) + Q_{cond\_wall1}(t) + Q_{cond\_wall2}(t) \tag{4.9}$$

4.2.5 Inside air temperature

Now that each process has been studied separately, we focus on how they can all be linked in order to calculate the temperature within the greenhouse at each moment. We have a mathematical form for each process which allows us to obtain the total net heat exchanged in the greenhouse. To obtain the temperature of the greenhouse a differential equation of first order (4.11) needs to be solved.

$$V * C_a * \frac{dT_i(t)}{dt} = Q_{total}(t) = Q_{gain}(t) - Q_{loss}(t) \tag{4.10}$$

$$V * C_a * \frac{dT_i(t)}{dt} = Q_{sol}(t) + Q_H(t) - Q_V(t) - Q_{cond\_cover}(t) \tag{4.11}$$

$$C_a(t) = \rho * (C_{p,d} + q(t) * C_{p,wv}) \tag{4.12}$$

where

T_i(t): inside air temperature [K]

ρ: air density $[kgm^{-3}]$

C_a(t): heat capacity of air inside the greenhouse $[Jm^{-3}K^{-1}]$

$C_{p,d}$: heat capacity of dry air $[Jkg^{-1}K^{-1}]$

$C_{p,wv}$: heat capacity of water vapor inside the greenhouse $[Jkg^{-1}K^{-1}]$

V_{GH}: greenhouse volume $[m^3]$

q(t): specific humidity $[kgkg^{-1}]$

Q_{total}(t): total heat transfer of the structure [W]

4.3 Implementation of the model

Once the model has been developed, it is necessary to implement it to solve the differential equation. This implementation phase allows to improve the model several times and to find the most adequate ways to express the different physical phenomena in mathematical form (see Appendix B). The program is explained in this part.

MATLAB has been used to find an analytical solution to the differential equation (4.11). The standard function ode45 was used to find a solution to the energy equation represented as a first order time dependent differential equation.

The main steps of the model are as follows:

1. We start by defining all the constant parameters needed to model each heat brought or withdrawn by each phenomenon. The values used are listed in Table 4.1.
2. Then for each period of the year (i.e. for the period in which each experiment has been performed a file with the values present in the Table 4.1 is read. These values are modified at each call of the function.
3. For the data in the Table 4.2, a moving average is used to account for the fact that even if behavior changes, the climate in the greenhouse will not change instantly but only after a certain time. An example can be seen in equation (4.13).
4. The different energy flows are calculated using the equations described previously.
5. The last step is to solve the differential equation (4.11) using the function defined in MATLAB, ode45. A time step is needed for the resolution and here a time step of 10 minutes has been chosen. For the very first simulation, it is necessary to enter the initial value manually. When the solution for the first time step is obtained, this solution is taken as the initial value for the next time step. This procedure is performed several times until the time set at the beginning is reached.

$$x(t) = \frac{x(t-5) + x(t-4) + x(t-3) + x(t-2) + x(t-1) + x(t)}{6} \tag{4.13}$$

4.4 Statistical analysis of the model

To study the accuracy of the model, we need to look at various statistical indicators that allow us to compare the values obtained with the model and the values that were recorded during the experiments. The two indicators that have been chosen here are (i) the coefficient of determination R-squared and (ii) the root-mean-square error (RMSE). [30]

For a simple regression, the R-squared is equal to the square of the correlation coefficient. R-squared varies between 0 and 1. It is therefore an indicator that allows evaluating the quality of a simple linear regression between the observed data and the values predicted by the model. In other words, it measures how well the model fits the observed data. [56] A value of 1 indicates that the predictions are identical to the observed values. Conversely, a value of 0 indicates that there is no linear relationship between the observed and predicted values. [57]

$$R^2 = \frac{[\sum_{j=1}^{n}(T_{j,o} - T_{M,o})(T_{j,p} - T_{M,p}))]^2}{[\sum_{j=1}^{n}(T_{j,o} - T_{M,o})^2][\sum_{j=1}^{n}(T_{j,p} - T_{M,p})^2]} \tag{4.14}$$

where n is the number of measurements, $T_{j,o}$ is the observed temperature at time j, $T_{M,o}$ is the mean of the observed temperatures, $T_{j,p}$ is the predicted temperature by the model at time j ,$T_{M,p}$ the mean of the predicted temperatures.

The RMSE is the square root of the variance of the residuals and indicates the absolute fit of the model to the data [58]. It therefore allows to see how close the observed data points are to the values predicted by the model.

$$RMSE = \sqrt{\frac{1}{n}\sum_{j=1}^{n}(T_{j,o} - T_{j,p})^2} \tag{4.15}$$

Table 4.1 Constant parameters used for the model simulation.

Parameter	Value	Reference
A_d	0.42 [-]	[30]
$C_{p,d}$	1 [$Jkg^{-1}K^{-1}$]	[59]
$C_{p,wv}$	1.86 [$Jkg^{-1}K^{-1}$]	[59]
C_w	0.11 [-]	[30]
g	9.81 [ms^{-2}]	
H_c	5.8 [m]	[16]
k_{glass1}	1.65 [$Wm^{-2}K^{-1}$]	[16]
k_{glass2}	6.5 [$Wm^{-2}K^{-1}$]	[16]
S_{GH}	64 [m^2]	
S_p	5.84 [m^2]	[16]
S_w	13.6 [m^2]	[16]
V_{GH}	263 [m^3]	[16]
γ	0.3 [-]	[27]
τ	0.3 - 0.7 [-]	[27, 16]
ρ	1.21 [kgm^{-3}]	[60]

Table 4.2 Experimental parameters used for the model simulation. For each time step of the simulation, the value of the parameter is modified.

Parameter	Value	units
$I(t)$	$I(\text{data})$	$[Wm^{-2}]$
$q(t)$	$q(\text{data})$	$[kgkg^-1]$
$T_{cond\_roof}(t)$	$T_{cond\_roof}(\text{data})$	[K]
$T_{cond\_wall\_corr}(t)$	$T_{cond\_wall\_corr}(\text{data})$	[K]
$T_{cond\_wall1}(t)$	$T_{cond\_wall1}(\text{data})$	[K]
$T_{cond\_wall2}(t)$	$T_{cond\_wall2}(\text{data})$	[K]
$T_{out}(t)$	$T_{out}(\text{data})$	[K]
$T_p(t)$	$T_p(\text{data})$	[K]
$w(t)$	$w(\text{data})$	$[ms^{-1}]$

Chapter 5

Results and discussions

5.1 Overview

The model for predicting the climate inside the greenhouse was developed and explained in Chapter 4. This model was then implemented on MATLAB in order to solve the differential equation and thus obtain predictions of the temperature inside the greenhouse. It will now be necessary to study its validity and accuracy in order to see how it can be improved and to what extent it can be considered as the first basis for further development of a spatial model.

The structure of this chapter is as follows. First, it is shown how the developed model predicts the temperature for different periods of the year. The results obtained are then compared to the experimental data recorded in the different previous experiments. This is done using the statistical indicators presented in Chapter 4 but also by analyzing the different plotted graphs. Then we discuss the efficiency and accuracy of the model in general.

5.2 Model validation

The validation of the model and its accuracy are studied by comparing the experimental temperature data with the temperature data predicted by the model. Four different periods were selected for this analysis so that we can get a better idea of the model performance throughout the year. The selected periods are periods for which experimental data are available. The analyses are performed over a timeframe of 10 days each time. We examine the predicted and actual temperature for each period, but also the heating temperature and the intensity of light radiation. It is possible to find some additional information used when comparing the results in the Appendix C. For each period, the difference between the measured and predicted temperature by the model is plotted. There is also the average temperature over a whole day of each experiment which is plotted for the measured and predicted values.

The four periods are as follows:

- Period 1: February 27 to March 7, 2020
- Period 2: May 27 to June 5, 2020
- Period 3: September 26 to October 5, 2019
- Period 4: December 4 to December 13, 2020

Table 5.1 Values of the static indicators for the 4 periods considered.

Periods	R-squared	RMSE [°C]
Period 1	0.85	1.11
Period 2	0.97	1.05
Period 3	0.89	0.72
Period 4	0.85	0.7

5.2.1 Period 1: February 27 to March 7, 2020

The outside temperature was quite variable during this time of year. The minimum outside temperature was 0 °C while the maximum outside temperature was 20 °C . The heating system was set to higher temperatures on colder days. The intensity of the solar radiation varied greatly, as shown in Figure 5.2. The temperature of the heating system was lower during the days when the intensity of the light radiation was higher.

Figure 5.1 shows the predicted and measured temperatures inside the greenhouse. The measured values are taken from the central sensor of the greenhouse. The two statistical indicators, R-squared and RMSE, show that the model predicts the measured values quite well. The coefficient of determination is equal to 0.85 while the RMSE is equal to 1.11 °C (see table 5.1). The temperatures predicted by the model are therefore close to the values that have been measured. The maximum difference between the predicted and the measured temperature is 4.48 °C.
The two graphs have very similar shapes and are very close to each other. The predicted temperatures at night are closer to the measured ones than the temperatures during the day. During the day, the temperature predicted by the model

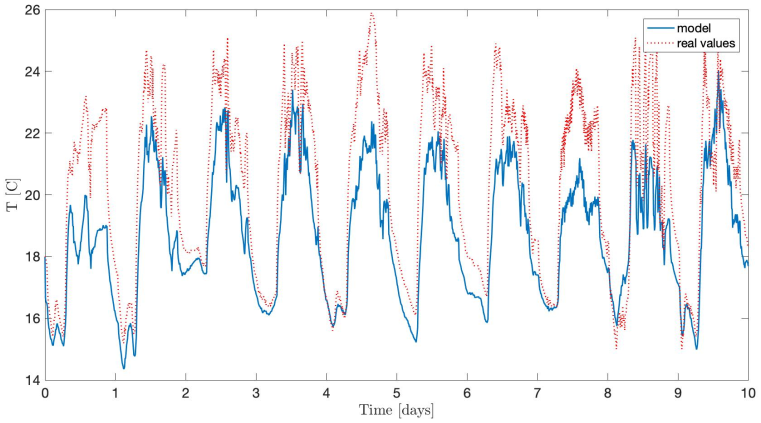


Figure 5.1 Period 1: Variation of the temperature inside the greenhouse as a function of time. Comparison between the values predicted by the model and those measured.

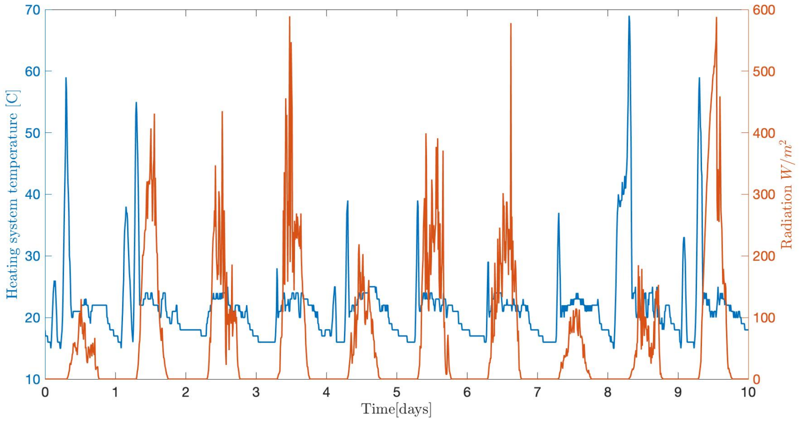


Figure 5.2 Period 1: Variation of the temperature of the heating system and of the intensity of the light radiation during the period of the experiment.

is between 2 and 4 °C lower than those measured. This is probably due to the fact that during the day the heating system and the intensity of solar radiation exhibit more fluctuations. During the night, the difference between the measured and predicted temperature is much smaller than during the day.

5.2.2 Period 2: 27 May to 5 June 2020

The outside temperature remained quite similar during the 10 days of period 2. At night, the minimum temperature is between 10 and 13 °C while during the day the maximum temperature is 24 °C the first days and 28 °C the last days. The heating

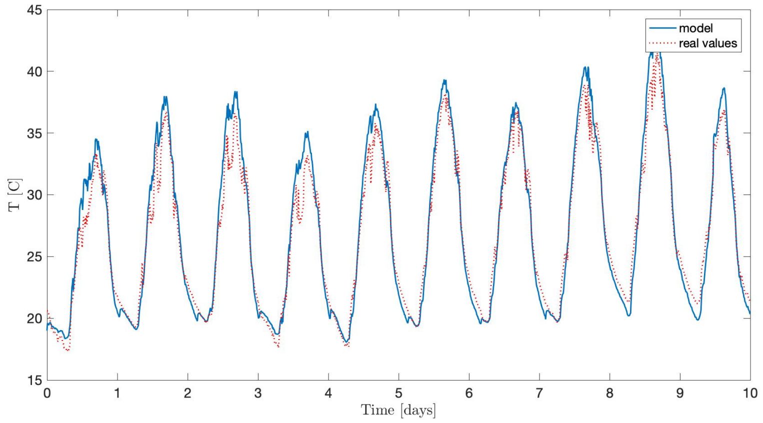


Figure 5.3 Period 2: Variation of the temperature inside the greenhouse as a function of time. Comparison between the values predicted by the model and those measured.

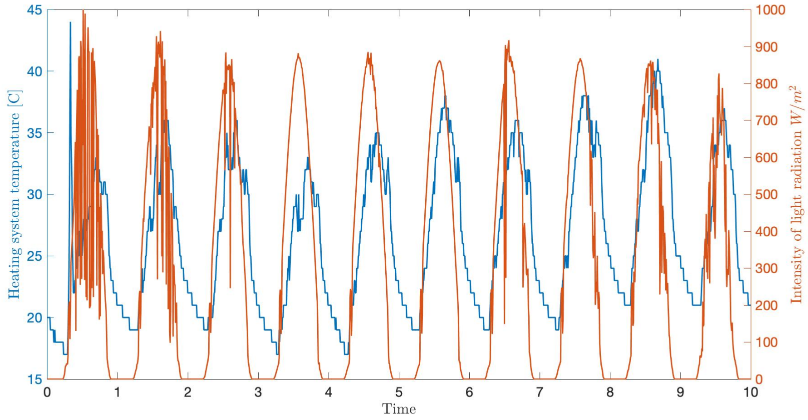


Figure 5.4 Period 2:Variation of the temperature of the heating system and of the intensity of the light radiation during the period of the experiment.

system behaves in the same way during the 10 days of the experiment with few fluctuations. The intensity of light radiation is substantially varying on the first day while on the following days, the behavior remains quite similar (see Figure 5.4). The maximum light intensity is seen each time around noon, with a value close to 900 W/m^2 each day. This intensity is measured outside the greenhouse. When the light intensity exceeds 400 W/m^2, the shading system is active, i. e. a curtain closes over the greenhouse, which then drastically reduces the amount of light entering the greenhouse.

Figure 5.3 shows that the temperatures predicted by the model and those measured by the central sensor of the greenhouse are almost overlapping each other. This means that the model is able to predict the temperature of the greenhouse fairly well for this second period. This is confirmed by the statistical factors. The R-squared has a value of 0.97 while the RMSE is 1.05 °C (see Table 5.1). The temperature predicted by the model is slightly higher than the one measured during the day. The difference is 5.42 °C at most. The reason why the daytime temperature predicted by the model is higher than the one recorded is probably related to the fact that we do not know the exact value of the light transmission coefficient (this will be developed further in the next section). At night, the temperature predicted by the model is in some cases lower than the measured temperature. This is probably due to the fact that during the day the greenhouse structure stores heat which is then released at night.

5.2.3 Period 3: September 26 to October 5, 2019

Period 3 is in late September early October 2019. This is a time of the year when the temperature in Belgium can be quite variable. The outside temperature drops to 12°C at night and reaches around 20°C during the first 5 days. The following days, the outside temperature is lower, with a minimum of 5°C Celsius at night between the 6th and 7th day and a maximum temperature of 15°C during the day. This can have an impact on the heating system. The heating system is hardly active during the first days, while from the 7th day onwards, when the outside temperature drops significantly, the heating system works more intensively (see Figure 5.6). The intensity of solar radiation is quite varying during these 10 days. The maximum light intensity is collected at noon and is generally between 500 and 900 W/m^2. The shading system is activated when the light intensity exceeds 400 W/m^2.

The temperature inside the greenhouse predicted by the model is again very close to the one measured by the central sensor of the greenhouse (see Figure 5.5). The statistical indicators give the following values here, R-squared is 0.89 while RMSE is 0.716 °C (see table 5.1). The indoor temperature predicted by the model is slightly higher during the day with a maximum of 2.89 °C. The opposite is observed in the evening. The higher temperature predicted by the model in the daytime can be explained by the fact that the opening of the greenhouse door could not be modeled while it can generate a significant airflow that will allow decreasing the temperature inside the greenhouse. The lower temperature values predicted by the model compared to the recorded temperatures could be due to the thermal mass mechanism.

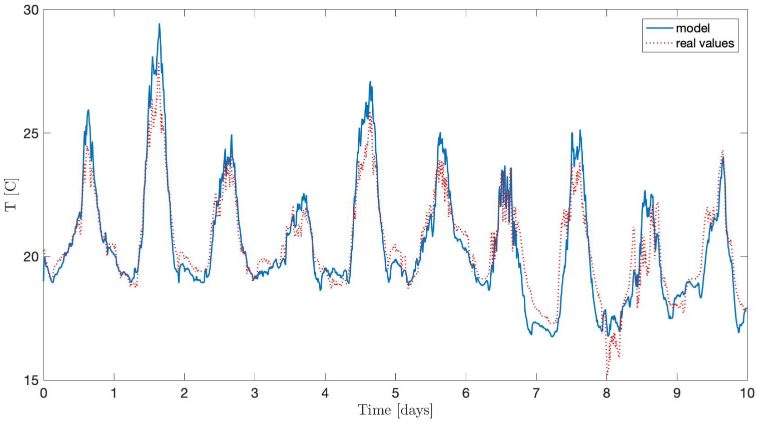


Figure 5.5 Period 3: Variation of the temperature inside the greenhouse as a function of time. Comparison between the values predicted by the model and those measured.

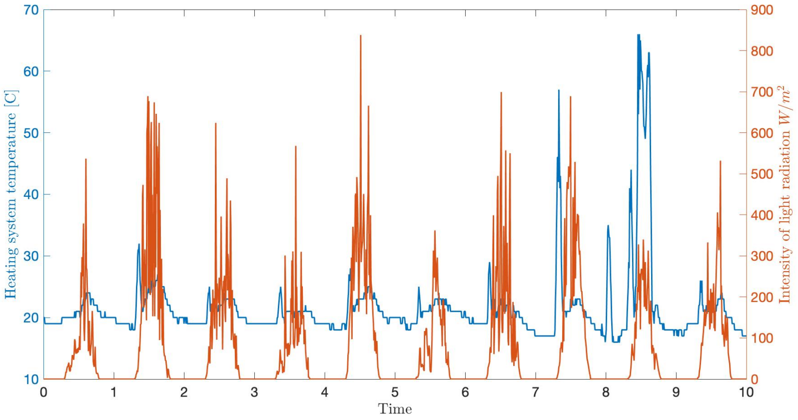


Figure 5.6 Period 3: Variation of the temperature of the heating system and of the intensity of the light radiation during the period of the experiment.

5.2.4 Period 4: December 4 to December 13, 2020

Period 4 is in the middle of winter. The outside temperatures of the greenhouse are therefore very low. The minimum temperature recorded is -0.4 °C at night and the maximum temperature is 11 °C during the day. The intensity of light radiation is quite low here (see Figure 5.8). Most of the heat brought to the greenhouse is due to the heating system. There is a big difference between the temperature of the heating system during the day and at night and this is due to the fact that at night a lower temperature is required from the control system.

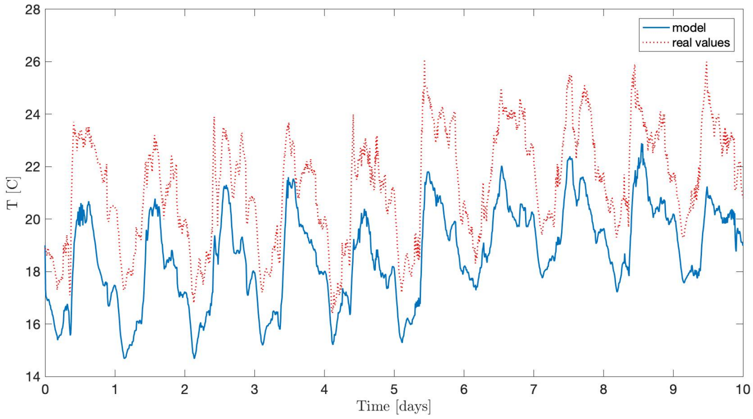


Figure 5.7 Period 4: Variation of the temperature inside the greenhouse as a function of time. Comparison between the values predicted by the model and those measured.

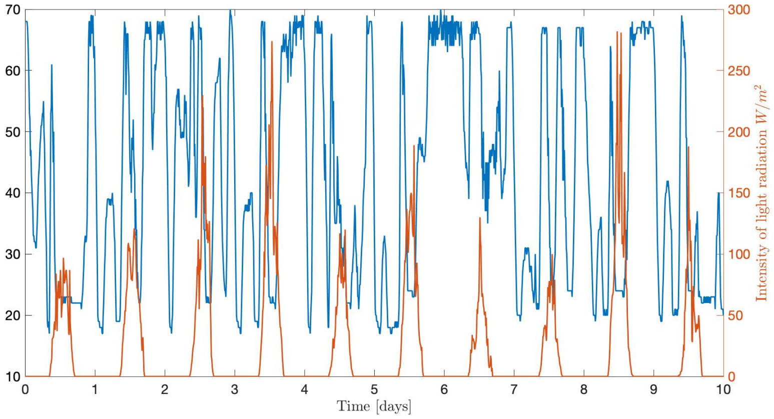


Figure 5.8 Period 4: Variation of the temperature of the heating system and of the intensity of the light radiation during the period of the experiment.

Figure 5.7 shows that the temperature inside the greenhouse and outside the greenhouse follow the same trend. The statistical indicators have the following values, R-squared is 0.85 and RMSE is 0.7 °C . The model consistently predicts a lower temperature than the one recorded by the central sensor of the greenhouse. The maximum difference observed is 5.38 °C . This difference between the predicted and recorded temperature may be due to the fact that the empirical formula developed by G.P.A Bot was used to estimate the heat transfer coefficient to calculate the heat input from the heating system. The constants used by G.P.A Bot were found experimentally and may in theory be slightly different in the case of our greenhouse [26]. They are however very close to the other values used in the literature [61].

5.3 Discussion for selected parameters

Let us focus in this part on a more in-depth analysis of some parameters used during the implementation of the model. One of the key phenomena to model the temperature inside the greenhouse is the intensity of the solar radiation. To better understand its impact on the temperature of the greenhouse, we studied two parameters that determine its magnitude, the light transfer coefficient and the shading system.

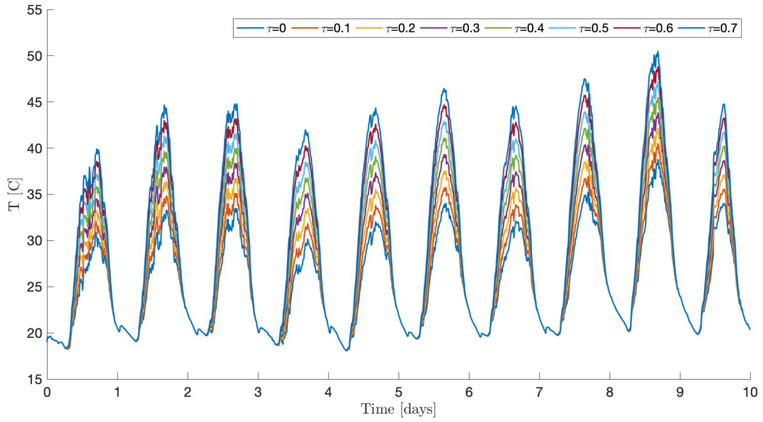


Figure 5.9 Variation of the temperature inside the greenhouse as a function of time for different values of τ. The data used are those of period 2.

Regarding the light transfer coefficient, the technical data sheets state that the double glazing of the roof has a theoretical light transmission coefficient of 0.79. This value remains a theoretical value when the material is new and clean. Over time, the material deteriorates and loses some of its characteristics. For example, its light transmission coefficient will decrease with time as William J. Roberts has studied [18]. Moreover, any dirt on the material can also have an impact on this aspect. To better understand the impact of the light transmission coefficient, we have run the model for different values of τ. Figure 5.9 shows the predicted temperature by the model for constant values of τ and ranging from 0 to 0.7. The period chosen to make this test is Period 2 i. e. from 27 May to 5 June 2020. This period was selected because the light intensity measured outside the greenhouse is quite high during this period and its influence on the temperature is thus important. It is possible to notice here that each time τ decreases by 0.1, the temperature decreases between 1 and 2 °C according to the light intensity. This indicates that this parameter, τ, is significant. One should therefore theoretically not only take into account the deterioration of the material over time but also the fact that even the cleanliness of the roof will have an impact on the amount of light that will be transmitted into the greenhouse. It is in practice impossible to account for these two effects constantly so an assumption about the value of τ is made based on what has been found in the literature.

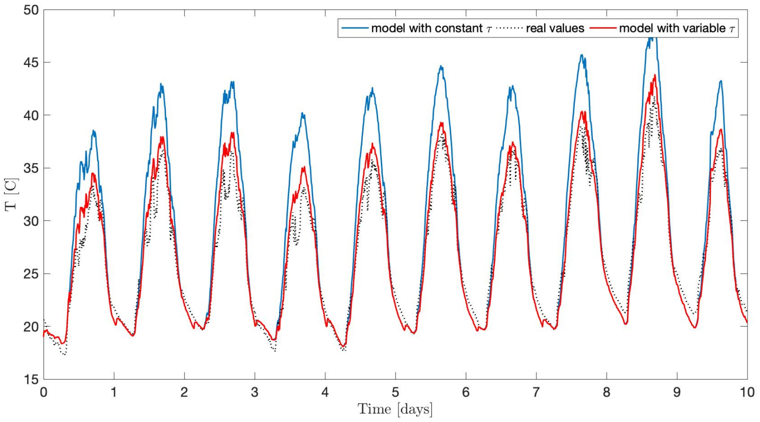


Figure 5.10 Variation of the temperature inside the greenhouse as a function of time. In black dotted line we see the measured values, in blue the values predicted by the model with constant τ throughout the day and in red the temperature when τ varies thanks to the shading system. The data used are those of period 2.

The second parameter that seems to be of great importance is the shading system that is activated when the external light intensity is too high. As a reminder, the shading system is activated when the light intensity exceeds 400 W/m^2. According to its data sheet, the screen that closes above the greenhouse only allows 35% of the light to pass through when it is activated. If we assume that the light transmission coefficient of the glass roof is 0.6, Figure 5.10 shows us the difference between having a shading system and not having one.

5.4 Discussion of the model

It has been generally observed that the model can realistically predict the temperature in different periods of the year. The different statistical indicators (see Table 5.1) show that the predicted and actual values are related. The different graphs allow seeing the various deviations between the values predicted by the model and those recorded by the central sensor of the greenhouse. The following observations have been made:

i The temperature predicted by the model is slightly higher than the one measured in the sunny periods and with a higher outside temperature. This can be due to two reasons. The first is that a constant coefficient of transmission has been used, without taking into account the degradation or dirtiness of the material. This can result in lower light transmission within the greenhouse. The second reason is that the person in charge of the greenhouse in some cases opens the door and thus creates a draught that decreases the temperature inside the greenhouse. The times and duration of the opening of the door are not known after the experiment. It would be interesting to record this information in the future.

ii The temperature predicted by the model is generally lower than that measured one during the night when the light intensity was high during the day. This temperature difference remains quite small. This is probably due to the fact that the whole greenhouse structure absorbs heat during the day and some of it can be released during the night. This phenomenon is called thermal mass.

iii The temperature predicted by the model is always lower in winter when only the heating system provides heat to the greenhouse. The temperature difference is more pronounced during the day than in the evening. The general trend, however, is almost identical between the predicted and measured temperatures.

The model can be considered as quite reliable, in spite of some discussions developed previously on the differences between the calculated and predicted values. It allows to give a first general idea about the temperature inside the greenhouse at different periods of the year. One should not forget that the objective here was to develop a simple model and given its level of complexity, the results are accurate and reliable enough. It can therefore be used as a model to choose at which time of the year an experiment will take place and eventually anticipate the control system setting according to the greenhouse's external climate. It can also be used as a basis for the development of a spatial model. This will be further developed in the next chapter.

Chapter 6

Future model development: Spatial temperature model

6.1 Overview

The model developed in the course of this work provided a good estimate of the temperature within the greenhouse for different periods of the year. The important assumption made in developing the model described in Chapter 4 is that the air temperature is considered homogeneous inside the greenhouse. The results of the experiments studied in Chapter 3 have shown that in reality this is not quite the case and that there is a temperature variation inside the greenhouse. This chapter therefore examines how the homogeneous model developed in this work can be further developed by considering the spatial variation of temperature.

This chapter is structured as follows. First, a discussion is made on the development of the previously established model into a spatial model and consequently on what should be considered in addition. Then we examine some options for implementing the spatial model.

6.2 Core principle of the model

We shall now discuss how the work done and described so far in this thesis can be used to develop a new model that can also predict spatial temperature in the greenhouse. This should be done in the same way as the model developed here, i.e. by focusing on a simple model that is based on physical phenomena and expressing them in mathematical form. Most of the physical phenomena can be modeled in a similar way as before, some parameters might just have to be modified or modeled a little differently.

The first step here is to see how the assumption that the temperature is homogeneous within the greenhouse should be modified. The results of the experiments explained in Chapter 3 and the structure of the greenhouse allow to focus on a 1D model. This 1D model should be developed along the East-West direction (see Figure 6.1). The main advantage of focusing on the East-West direction is that it allows to account more easily for the sun path. This is the direction in which temperature variations were most significant inside the greenhouse (see Chapter 3).

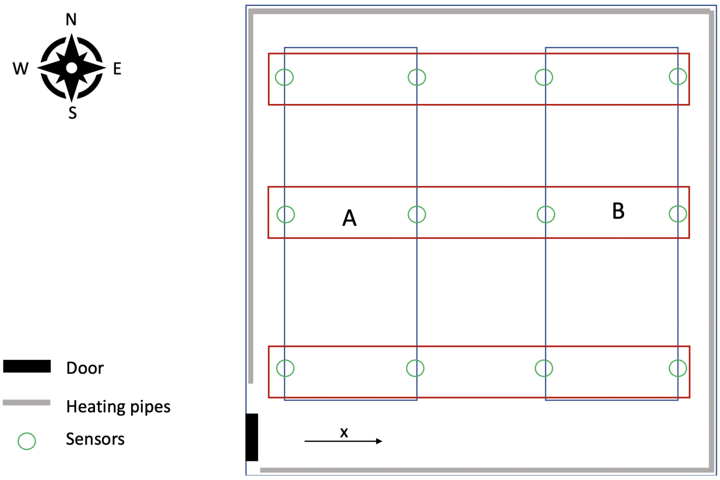


Figure 6.1 Illustration of how the 1D model will be applied three times

It is not of course very realistic to consider that the temperature is homogeneous in the North-South direction (see Appendix A). There are a number of layout differences between the north and the south part of the greenhouse. There are also differences in the boundary conditions that can be assumed in the north and the south part because of the layout differences. In order to account for the differences in the North-South axis while keeping the 1D model simple a proposal would be to divide the greenhouse into three compartments (see Figure 6.1). The 1D model will then be developed and run for each of these three compartments separately. The 3 compartments identified and their respective differences are as follows:

1. The northern part of the greenhouse:
    - The heating system is located at both ends and on the glass wall at the north of the greenhouse.

    - The window that opens and causes natural ventilation is located on the west side of the roof.

2. The central part of the greenhouse:
    - The heating system is located only at the east and west ends.
    - The window is also on the west side of the roof.
    - This compartment is located between the other two, resulting in different 'losses' to the external environment.
3. The southern part of the greenhouse:
    - The heating system is located at both ends and on the glass wall at the south of the greenhouse.
    - On the west side is also the door of the greenhouse that opens and closes.

The second step consists of focusing more on the modeling of the different physical phenomena by adding the spatial dimension. In this step we need to modify the differential equation (4.11). The major difference between the homogeneous model and this spatial model is that the medium here is subjected to a temperature gradient in the x direction (again, x axis is the East-West axis). We need thus to try to establish the equation which gives the evolution in space and time of the temperature field from a heat balance. Let us start here with the equation (6.1) which represents the conservation of spatial energy. Fourier's law will be used to develop the heat flux term q, which represents the amount of thermal energy that moves from hot to cold. The partial differential equation obtained is therefore the following one [43, 62, 48, 63]:

$$C_a \frac{\partial T_i(x,t)}{\partial t} + C_a v(x,t) \frac{\partial T_i(x,t)}{\partial x} = -\frac{\partial^2 q(x,t)}{\partial x^2} + Q(x,t) \tag{6.1}$$

Fourier's law states that:

$$q = -\lambda \frac{\partial T_i(x,t)}{\partial x} \tag{6.2}$$

$$C_a \frac{\partial T_i(x,t)}{\partial t} + C_a v(x,t) \frac{\partial T_i(x,t)}{\partial x} = \lambda \frac{\partial^2 T_i(x,t)}{\partial x^2} + Q(x,t) \tag{6.3}$$

where

T_i(t): inside air Temperature at any point x and any time t [K].

C_a: specific heat of air inside the greenhouse $[Jm^{-3}K^{-1}]$

v(x,t): velocity of the air inside the greenhouse $[ms^{-1}]$.

λ: thermal conductivity $[Wm^{-1}K^{-1}]$.

$Q(x,t)$: heat generated or lost by an external source $[Wm^{-3}]$.

We should now look at how each physical phenomenon is involved in this equation. For simplicity, we should not consider natural ventilation to begin with.
The second term on the left side of equation (6.3) involves the term for the velocity of air movement in the greenhouse. To begin with, we can assume that this term will be equal to 0. This is possible because the air velocity is considered very small in the absence of natural ventilation, i.e. when the window is closed. When the natural ventilation system is activated, this term can probably not be neglected anymore. It will therefore be necessary to leave the calculation of the air velocity for a future step.
The Q term is representing the additional heat gain or loss at a given location and time. This term includes 3 physical phenomena, light radiation, heat loss/gain by conduction and in some cases the heat input related to the heating system.
The air density, heat capacity and thermal conductivity should initially be considered as constant for reasons of simplicity. These values could then be modelled according to the location depending on the first results obtained. [62, 48, 63, 64]

To solve this partial differential equation, it will be very important to define the initial and boundary conditions. As the model will be used in three different compartments of the greenhouse, the initial and boundary conditions will be different. To give an example of the boundary conditions, in all three compartments, the heating system is at least at the east and west ends. Thus, at x=0 and x=L (where L is the distance between the two walls in the east-west direction), there will be a heat input from the heating system and a heat loss from conduction with the glass wall.

6.3 Implementation idea and new data needed

Let us focus now on the implementation of the model. To do so, we shall consider some data that could be collected to facilitate the implementation but also how to simplify the partial equation described previously to be able to use an implementation approach similar to the one of the homogeneous model.

In the experimental data collected for the time being, the intensity of the solar radiation is collected by the meteorological station located outside the greenhouse. It would now be necessary to know the dispersion of the intensity of the light radiation within the greenhouse, i.e. to have I(x,t), in order to implement this first version of the spatial 1D temperature model. One possibility could be to obtain the spatial data of I(x,t) from experimental data, i.e. by placing sensors during several periods of the year in the greenhouse at different locations and recording the intensity of light radiation arriving at each location. Knowing the light intensity recorded by the weather station and the intensity recorded by each sensor placed in the greenhouse, it would be possible to generalize the spatial dispersion of the light intensity of the solar radiation for certain periods of the year. This would mean that it would be necessary to get the sensors, to place them in the greenhouse and to carry out the experiments. Another possibility could be to consider that the light radiation is homogeneously distributed in the greenhouse to start with or even to try to find a link between temperature and light intensity from existing results. It would also be interesting to know the temperature at ground level to be able to calculate the heat exchange between the ground and the air in the greenhouse.

The implementation of this model can be done in the same way as the homogeneous model, i.e. on MATLAB and using the ode45 function. The major challenge here is that we have a partial differential equation and not an ordinary differential equation. This can be solved by simplifying the spatial derivative term using the finite difference approach, also called Euler's method [65]. This means that the spatial derivatives can be expressed in the following form:

$$T'(x,t) = \frac{T(x+1,t) - T(x-1,t)}{\Delta x} \tag{6.4}$$

$$T''(x,t) = \frac{T(x+1,t) - 2T(x,t) - T(x-1,t)}{\Delta x^2} \tag{6.5}$$

Where T(x) is the temperature at the spatial position x within [0 L], with L the distance between the two walls of the greenhouse in the East-West direction. The temperatures T(0) and T(L) are defined by the boundary conditions and the other temperature values have an initial temperature imposed by the initial conditions. Δx represents the distance between two points next to each other in space.

By substituting the (6.4) and (6.5) equations in our main equation (6.3), it is possible to solve it quite similarly to the one solved in the homogeneous model, i.e. by using the ode45 function predefined in MATLAB.

This spatial model has not been implemented in the frame of this work. This means that while this work constitutes a first base, it may still have to be developed further to obtain coherent results. It would be interesting in a next work to start again from this model and to implement it to see the coherence of the obtained results. At first sight, it should give the spatial temperature within the greenhouse for different times. The experimental data discussed in Chapter 3 should allow to test the accuracy of this model.

Chapter 7

Conclusion

The objective of this master thesis was to study one of the automated greenhouses of Louvain-la-Neuve.This greenhouse is part of the European program EPPN2020 which studies the phenotyping of plants and is therefore used a lot during the year to perform a number of experiments. Following the observations made that the plants do not grow in the same way in this greenhouse depending on the season in which the experiments take place and their position, we were asked to make a physical model in order to study the microclimate inside the greenhouse.

In Chapter 2 of this report, we established a literature review to understand the basic functioning of a greenhouse and to study the physical phenomena that influence its microclimate. This part allowed us to discover that a greenhouse is something quite complex and that a great number of physical and non-physical phenomena can influence its microclimate. The point to emphasize here is that apart from the climate outside the greenhouse, the type of greenhouse, its structure and its position are also elements that influence its microclimate. It is however not easy to model all the elements that can influence the microclimate of the greenhouse, so one must select the most important ones.

To select the parameters that have the most significant impact on the greenhouse microclimate, we analyzed a series of data collected from experiments conducted in 2019 and 2020. In Chapter 3, we analyzed all of these results with a focus on the temperature in the greenhouse. These data showed us that the temperature in the greenhouse varies greatly throughout the year even though a control system is in place to keep the temperature as constant as possible. It was observed that during cold periods, the control system works quite effectively in keeping the average

temperature of the greenhouse close to what is set. When the outside temperatures are high, the control system cannot maintain the temperature in the requested areas. The outdoor climate is, therefore, a limiting factor in this situation. The temperature of the greenhouse is therefore mainly influenced by solar radiation, the heating system (when used), and natural ventilation.
We also observed in this part that the the temperature within the greenhouse varies considerably from one place to another at the same time of the day. Following the analysis of the collected data, we suggested carrying out a larger number of experiments to draw more exhaustive conclusions but also to measure some additional elements during the next experiments. For example, it would be interesting to know when the door opens because it affects the ventilation.

We then developed our simple time-dependent physical model in Chapter 4. For this purpose, we expressed all the physical phenomena in mathematical form. The phenomena considered in this model are the intensity of the light radiation, the heating system, the natural ventilation, and the conduction losses. The model is based on an energy balance inside the greenhouse. To predict the temperature in the greenhouse, we look at the energy input and the energy output at each moment of the day. All this is represented by a differential equation which is then solved using MATLAB. To establish our model, the main assumption we made is that the air inside the greenhouse is well mixed, i.e. that the temperature is homogeneous.

The predicted results from the model have been compared with those recorded by the central greenhouse sensor for four different experiments to determine the validity of the model. In addition, the importance of light transmittance and the impact of the shading system were discussed. These two parameters are quite complex to model but have a significant impact on the temperature in the greenhouse. In general, the implemented model predicts relatively well the temperature for different periods of the year considering its complexity. It could therefore be used to determine what time of year is appropriate to conduct the desired experiment based on the temperature in the greenhouse.

As the last step, a discussion has been made on how the implemented homogeneous model could be developed into a spatial model. The objective is again to keep the physical model as simple as possible. It was therefore decided, based on the data analyzed in Chapter 3, that a 1D model could be developed to predict the spatial temperature difference in the greenhouse. To keep the model realistic, it will be applied three times in the East-West direction for different North-South positions. This seems to be a good first step to keep the model simple. The main difference with the homogeneous model is that in this case, a partial differential equation has to be solved and not an ordinary differential equation. Some insights have been developed to implement this spatial model.

To conclude, this work allowed us to learn more about the functioning of a greenhouse and more precisely the physical phenomena that influence its microclimate. We have developed and implemented a physical model that correctly predicts the temperature in the greenhouse that interests us for different periods of the year. This model has been further developed to propose a first version of the spatial model.

Now that this thesis is concluded, it is possible to consider future work that can be carried out from it in the future. In the first step, it would be interesting to see how the spatial model proposed here can be implemented to see what results it will provide. As we discovered in the literature review, the greenhouse is a very complex environment and there is always room to study new parameters to improve the growth of the plants inside. Depending on the results obtained by the implementation of the spatial model, it could be interesting to study how these models could be used to adapt an anticipatory control method and thus have more optimal plant growth.

Appendices

Appendix A

Additional analysis on experimental data

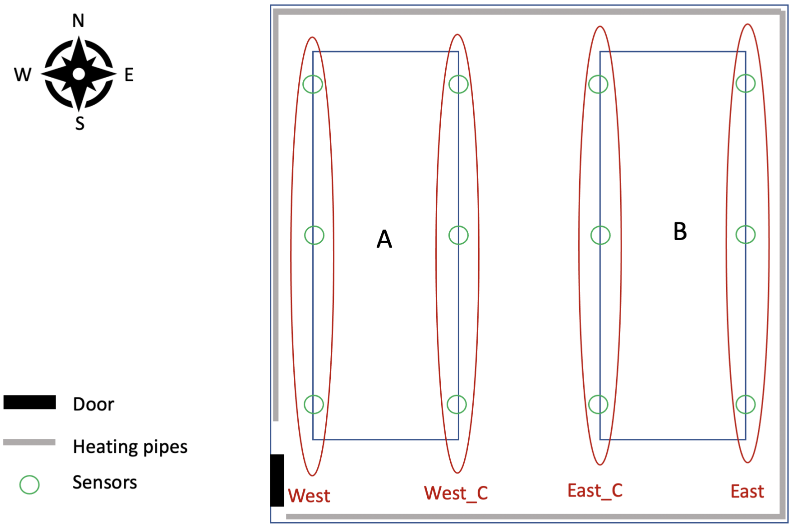


Figure A.1 Arrangement of the greenhouse taking into account the average temperature in the North-South direction.

To try to better understand how the spatial temperature varies within the greenhouse, we looked at the data to see what occurs when considering the East-West direction. To do this, we started by calculating the average temperature of the sensors located at the same position in the x-direction (the x-axis is the East-West axis). Figure A.1 illustrates what has been considered. As a reminder, the East-West direction was chosen because it allows taking into account more easily the path of the sun.

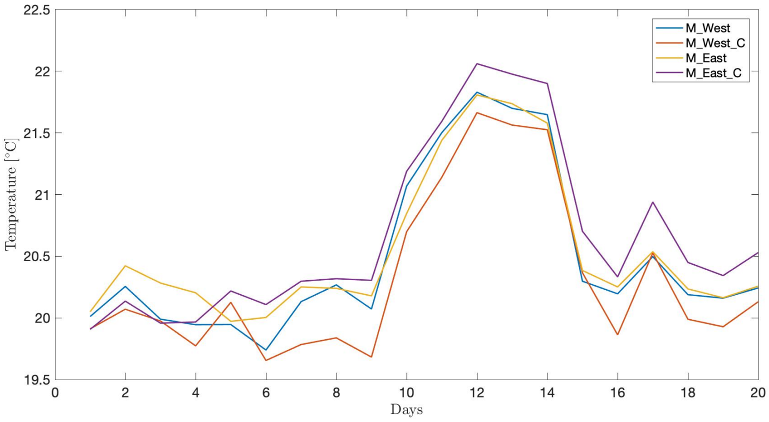
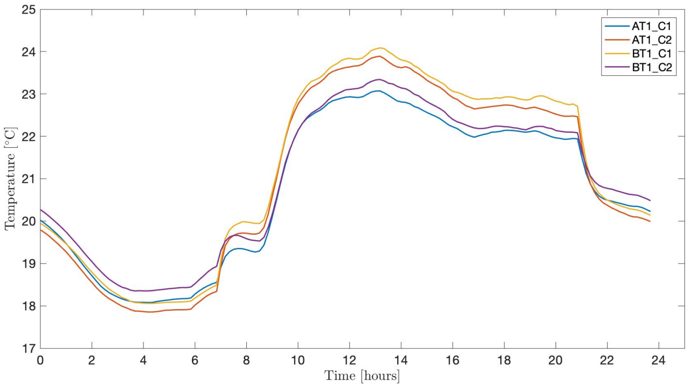


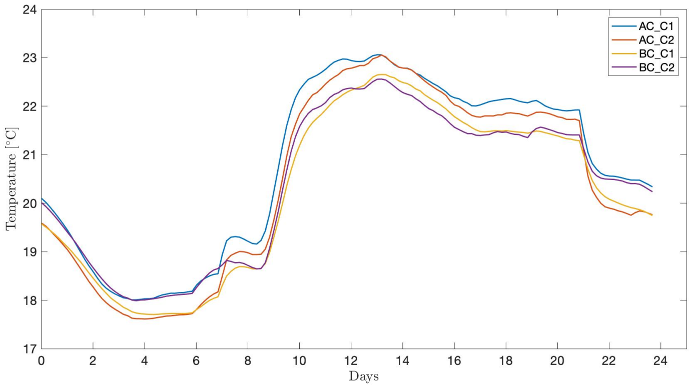
Figure A.2 Average temperature variation during each day of December 2020 experiment depending on the East-West direction.

Figure A.2 shows the average daily temperature as a function of the sensor position in the East-West direction. It is possible to observe a variation in this direction that hence may not be negligible. However, the difference is not constant every day, it is complicated to know which physical or non-physical phenomenon causes this difference. This may be because every day the outside conditions change and therefore impact the greenhouse differently. For example, on one of those days the window may not have been open for very long. It is still possible to see that the temperature at the M_West_C level is almost always lower than the others. This can be explained by the fact that the greenhouse window is located just on top.

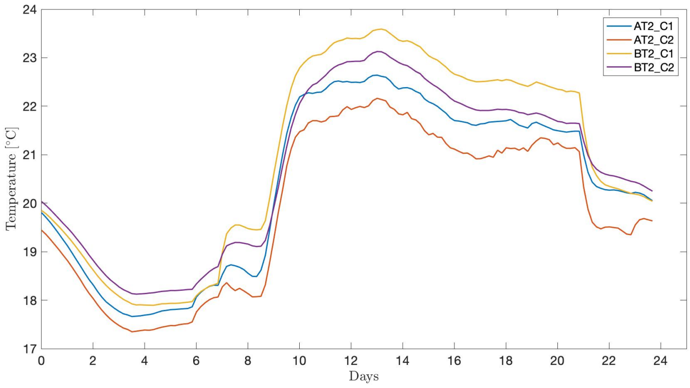
We can observe in Figure A.3 that for each environment, i.e. North Central or South, the temperature varies differently in the East-West direction. Depending on the environment, the lowest temperature can be found either in the East, West, or the center. For example, in the northern environment, the AT1_C1 sensor records the lowest temperature. As a reminder, this sensor is located furthest west (see Figure 3.2).
It is therefore interesting to consider the three environments when developing the spatial model and to see for each environment how the temperature varies in the East-West direction.



(a) Sensors located on the northern line of the greenhouse.



(b) Sensors located on the central line of the greenhouse.

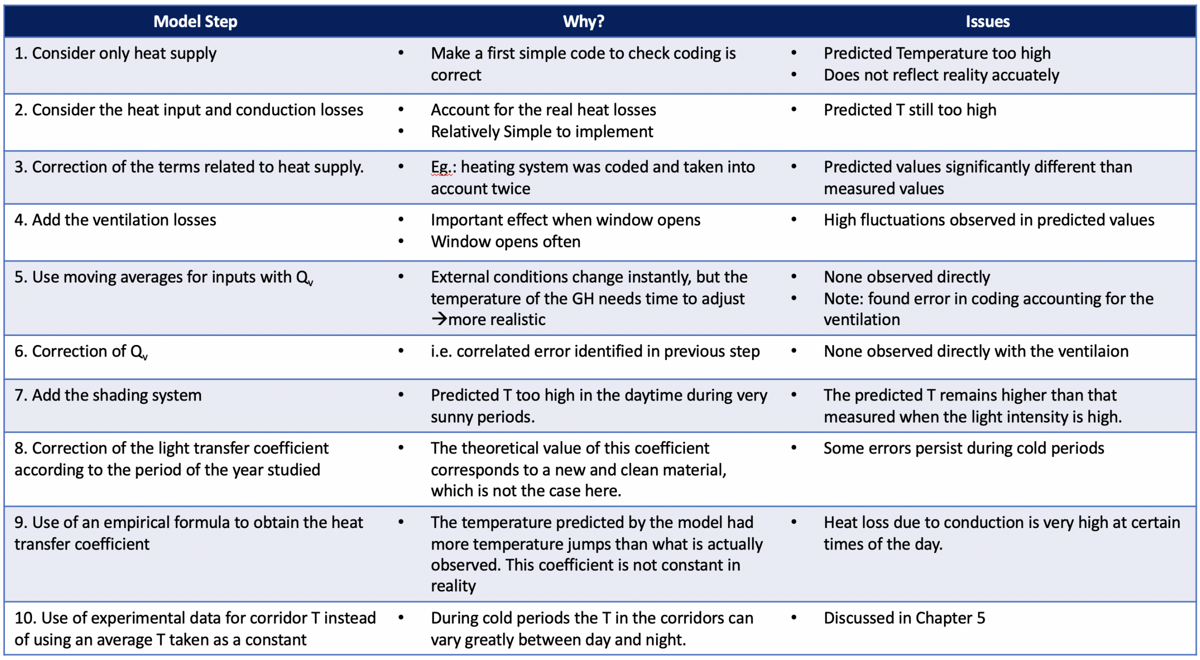


(c) Sensors located on the south line of the greenhouse.

Figure A.3 Daily temperature variation during the December 2020 experiment as a function of their position in the North-South direction.

Appendix B

Model development



Model Step	Why?	Issues
1. Consider only heat supply	• Make a first simple code to check coding is correct	• Predicted Temperature too high • Does not reflect reality accuately
2. Consider the heat input and conduction losses	• Account for the real heat losses • Relatively Simple to implement	• Predicted T still too high
3. Correction of the terms related to heat supply.	• Eg.: heating system was coded and taken into account twice	• Predicted values significantly different than measured values
4. Add the ventilation losses	• Important effect when window opens • Window opens often	• High fluctuations observed in predicted values
5. Use moving averages for inputs with Q_v	• External conditions change instantly, but the temperature of the GH needs time to adjust →more realistic	• None observed directly • Note: found error in coding accounting for the ventilation
6. Correction of Q_v	• i.e. correlated error identified in previous step	• None observed directly with the ventilaion
7. Add the shading system	• Predicted T too high in the daytime during very sunny periods.	• The predicted T remains higher than that measured when the light intensity is high.
8. Correction of the light transfer coefficient according to the period of the year studied	• The theoretical value of this coefficient corresponds to a new and clean material, which is not the case here.	• Some errors persist during cold periods
9. Use of an empirical formula to obtain the heat transfer coefficient	• The temperature predicted by the model had more temperature jumps than what is actually observed. This coefficient is not constant in reality	• Heat loss due to conduction is very high at certain times of the day.
10. Use of experimental data for corridor T instead of using an average T taken as a constant	• During cold periods the T in the corridors can vary greatly between day and night.	• Discussed in Chapter 5

Figure B.1 Steps taken to implement and correct the model.

Figure B.1 shows the different steps that were followed for the implementation of the final homogeneous model. It is possible to see the various corrections that were made to the model following each simulation.

Appendix C

Additional results

C.1 Model Validation

Some additional graphs plotted to evaluate the validity of the results predicted by the model can be seen here in this section.
It is possible to see the difference in temperature between the temperature measured by the sensor located in the center of the greenhouse and the temperature predicted by the model for each period studied. In addition, we see the average temperature per hour as measured and predicted by the model.

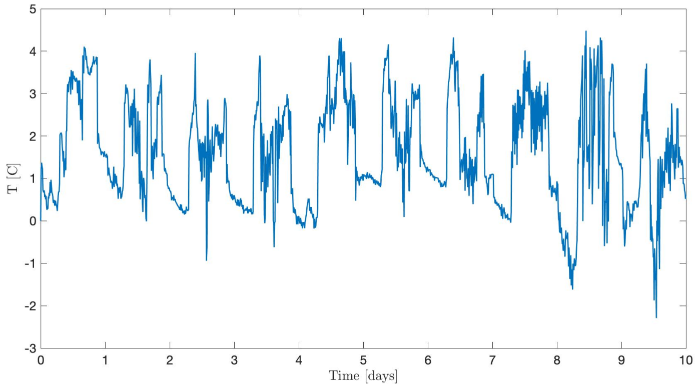


Figure C.1 Period 1: Differences between the measured temperature and the values predicted by the model.

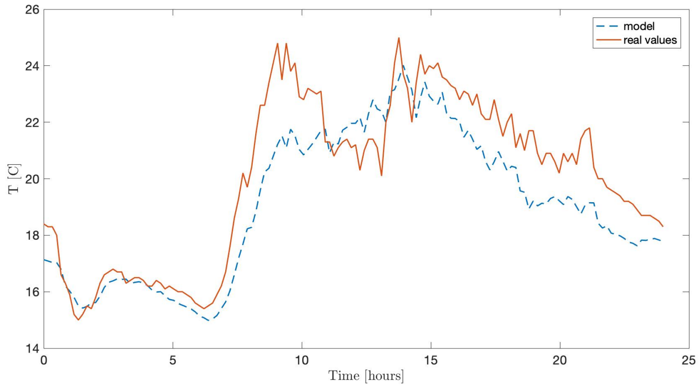


Figure C.2 Period 1: Average temperature over a day during the period of the experiment.

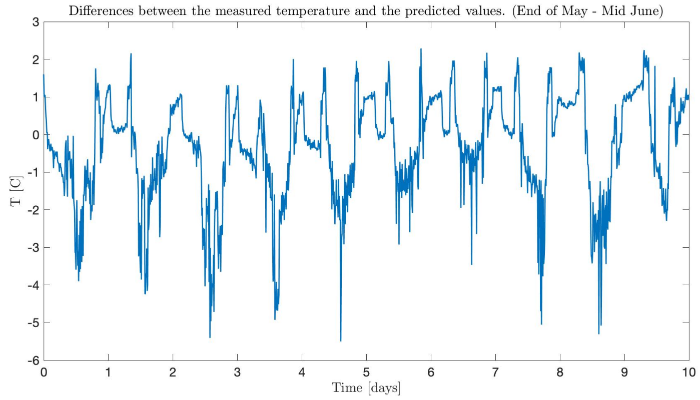


Figure C.3 Period 2:Differences between the measured temperature and the values predicted by the model.

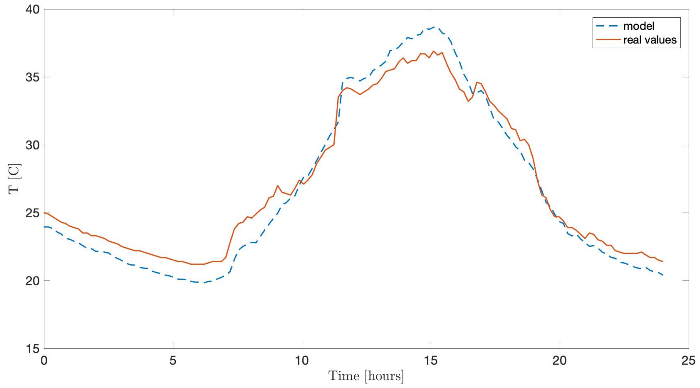


Figure C.4 Period 2: Average temperature over a day during the period of the experiment.

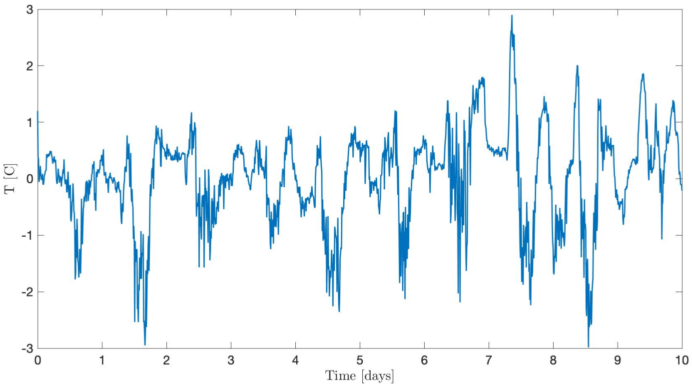


Figure C.5 Period 3:Differences between the measured temperature and the values predicted by the model.

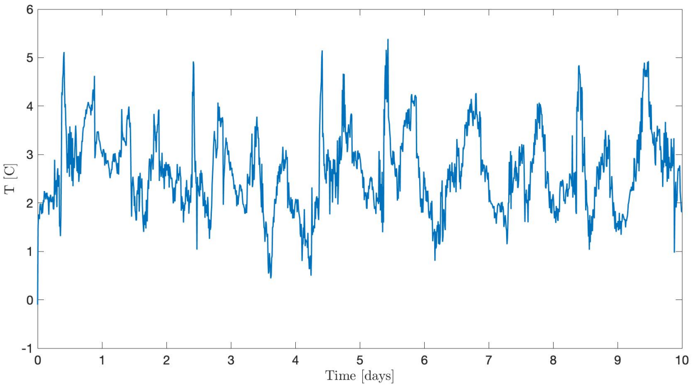


Figure C.6 Period 4:Differences between the measured temperature and the values predicted by the model.

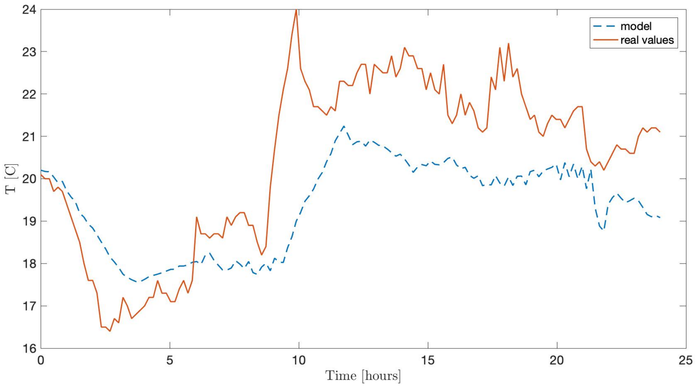


Figure C.7 Period 4: Average temperature over a day during the period of the experiment.

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