Simulation-based performance assessment of climate adaptive greenhouse shells

Citation for published version (APA):
Lee, C. (2017). *Simulation-based performance assessment of climate adaptive greenhouse shells*. [Phd Thesis 1 (Research TU/e / Graduation TU/e), Built Environment]. Technische Universiteit Eindhoven.

Document status and date:
Published: 31/01/2017

Document Version:
Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
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Link to publication

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Simulation-based Performance Assessment of Climate Adaptive Greenhouse Shells

Chul-sung Lee

/ Department of the Built Environment

bouwstenen 211

Simulation-based Performance Assessment of Climate Adaptive Greenhouse Shells

PROEFSCHRIFT

ter verkrijging van de graad van doctor aan de Technische Universiteit Eindhoven,
op gezag van de rector magnificus prof.dr.ir. F.P.T. Baaijens, voor een commissie
aangewezen door het College voor Promoties, in het openbaar te verdedigen op
dinsdag 31 januari 2017 om 16:00 uur

door

Chul-sung Lee

geboren te Hongcheon-gun, Zuid-Korea

Dit proefschrift is goedgekeurd door de promotoren en de samenstelling van de promotiecommissie is als volgt:

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Het onderzoek dat in dit proefschrift wordt beschreven is uitgevoerd in overeenstemming met de TU/e Gedragscode Wetenschapsbeoefening.

Simulation-based Performance Assessment of Climate Adaptive Greenhouse Shells

This research was connected to the Long Term Energy Research Strategy (EOS-LT) project, Climate Adaptive Glastuinbouw: Inverse Modelling (CAGIM), funded by RVO.

Rijksdienst voor Ondernemend
Nederland

A catalogue record is available from the Eindhoven University of Technology Library

ISBN: 978-90-386-3978-9

NUR: 955

Published under Bouwstenen series 211 of the Department of the Built Environment, Eindhoven University of Technology.

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Printed by Gildeprint, The Netherlands

Summary

Simulation-based Performance Assessment of Climate Adaptive Greenhouse Shells

In light of growing concerns regarding environmental issues, the reduction of energy-related CO_2 emissions is now accepted as a crucial measure to mitigate climate change. At present, the majority of CO_2 emissions are generated by fossil fuel combustion. As is the case in many other countries, in the Netherlands several policies have been introduced to decrease fossil fuel consumption in order to realise decreases in the associated CO_2 emissions.

Due to the mild climate and cold weather conditions in winter in which it operates, the Dutch greenhouse horticulture sector is a heavy user of (fossil fuel) energy because of the required heating and cooling of the greenhouse. In recognition of the need to improve the status quo, the Dutch government and the greenhouse horticultural industry reached agreement on a number of specific goals to achieve reductions in CO_2 emissions. In addition to these environmental reasons, achieving meaningful energy reduction is becoming a financial imperative for Dutch crop growers in terms of price competitiveness. Achieving energy savings is particularly important for Dutch crop growers, since they face competition from many countries that enjoy more favorable climate conditions for crop growth, most notably countries in Southern Europe. In sum, the Dutch horticulture sector must implement methods to reduce energy use (CO_2 emission) in order to meet environmental targets and to remain competitive in the international market place. This progress must be achieved, however, with no decrease in crop quality and quantity. In fact, if possible, any new methods to reduce energy use in horticultural greenhouses should also aim to increase crop quality and quantity. While achieving energy reduction and simultaneously realizing an increase in crop quality and quantity may at first glance seem contradictory goals, the current research aims to demonstrate that these two goals can indeed be reached in tandem.

In order to pursue these two goals, the current research proposes a new greenhouse concept, entitled climate adaptive greenhouse shell (CAGS). In the CAGS concept greenhouse the thermal and optical shell properties are controllable, which allows for both the minimizing of energy consumption and the maximizing of crop quality and quantity through optimum utilization of the climate conditions. The main goal of this study is to develop a performance

assessment methodology that can be used to demonstrate the potential of the proposed CAGS concept.

The study begins with a survey of promising greenhouse shells and concepts. The survey shows that existing studies aiming to improve greenhouse performance have focused on the development of new greenhouse materials, the introduction of the new means of operation and the implementation of high performance systems. What all of these studies have in common is that they have sought to improve the performance of the current, standard static greenhouse shells. It is notable that, despite static shells being responsible for the majority of the energy used by the greenhouse, the review found little evidence of new and alternative methods for their use. Thus, in order to fill this gap, the current research introduces CAGS as an innovative design for future greenhouses.

Since, at this stage, CAGS is an innovative greenhouse concept, it cannot yet be tested in a field experiment. Therefore, in the current research the performance of the proposed concept is computationally investigated. To this end, this study first investigated whether existing Building Performance Simulation (BPS) or Greenhouse Performance Simulation (GPS) tools would be suitable for the performance assessment of the CAGS concept. To be suitable, the tool should reproduce the overall greenhouse behavior and should satisfy the following requirements: control of shell properties, small simulation time step and the flexibility and connectivity to use the optimization algorithm. Unfortunately, none of the existing BPS or GPS tool meets these requirements. Therefore, it was necessary to develop a new GPS tool that was fit for purpose. This was done by taking the most suitable BPS tool (ESP-r) available and modifying it by including the required additional capabilities.

Existing simulation approaches also proved not to be valid for the testing of the CAGS concept, since they could not manage the requirement that the CAGS concept greenhouse needs, which is to determine the optimal set of shell properties for each adaptation period. Thus, in order to implement testing of the CAGS concept, this study developed a simulation-based multi-objective dynamic optimization, which is implemented in the virtual test environment using co-simulation. Ultimately, the virtual test environment with the developed methodology and the new GPS tool enables to performance assessment of CAGS concept.

The performance of the CAGS concept is demonstrated with case studies for three crops (tomato, phalaenopsis and chrysanthemum), each with different performance requirements. The case studies for tomato focus on two performance indicators (PI) (primary energy consumption and crop production), which leads to a multi-objective optimization problem, for which this study proposes net profit (= crop production in euro – primary energy consumption in euro) to determine an optimal solution. Since, unlike tomato, fresh matter production by photosynthesis does not guarantee the quality of the flower, the optimization becomes a single-objective problem with one PI, primary energy consumption. The investigation carried out the following three case studies: different adaptation frequencies, different system concepts and different cultivation scenarios. The studies investigated the potential of optimized static design, monthly adaptation and hourly adaptation. The potential of the CAGS concept is quantified in comparison to a reference greenhouse representing a common Dutch greenhouse.

The first case study investigated the influence of different adaptation frequencies for a typical Dutch greenhouse (NL) growing a tomato crop. The result shows that the greenhouse with monthly and hourly adaptation achieved a net profit increase of 9% and 20% respectively, which results from 23% and 37% of primary energy reduction and -1% and 2% of production increase. The reduction and minor increase of tomato production indicates that the greenhouse with the CAGS concept focused on primary energy saving while maintaining tomato production to maximize net profit. The hourly adaptation achieved a higher primary energy saving than the monthly adaptation, and the optimized static design only showed a minor improvement. Thus, as expected, a greenhouse with high adaptation frequency returns more net profit.

The second case study investigated the influence of different system concepts, which are implemented for three crops with five system concepts (SC): SC1 with active heating, cooling and dehumidification systems for tomato; SC2 with high performance heating systems for tomato; SC3 with CHP for propagation area for Phalaenopsis; SC4 with CHP for ripening area for Phalaenopsis; and SC5 with CHP for Chrysanthemum. The results show that the greenhouse with the CAGS concept achieved an increase of between 4% and 35% in net profit for the tomato crop (two PIs) and between 6% and 34% of primary energy saving for two flower crops (one PI). All greenhouses with high adaptation frequency returned more net profit and primary energy saving, but the amount of benefit is dependent on the system concept. The greenhouse with CAGS concept, which required a high energy demand resulting from low performance systems, achieved both more net profit increase and primary energy savings. This indicates that the CAGS concept is suitable for high energy demanding greenhouse to maximize the benefit of adaptation.

The third case study investigated the potential of CAGS concept greenhouses with different cultivation scenarios covering different growing seasons. In total, three greenhouses (NL, SC1 and SC2) growing tomato crops with artificial lighting are tested in three different cultivation scenarios (the dates of planting are April 15 (S1), July 25 (S2) and October 15 (S3).) and finally compared to common practice (the date of planting is January 15). The performance of CAGS concept greenhouses varied depending on cultivation scenario and system concept. The results show that none of the cultivation scenarios with monthly adaptation generated meaningful benefits. However, benefits were seen in the case of hourly adaptation during winter cultivation. Whereas S1 showed no increase in profit, S2 and S3 generated an increase in net profit of30% and 29% respectively. This huge increase in net profit comes from a significant increase in winter tomato production from both high adaptability and artificial lighting.

In conclusion, the simulation results of the case studies demonstrate that the CAGS greenhouse concept has great potential in terms of increasing net profit and reducing primary energy use (CO_2 reduction). This potential is dependent on adaptation frequency, the installed systems and the greenhouse's operation. The result of this study provides inspiration on how to develop the greenhouse shell for future greenhouses. In addition, the modified ESP-r for GPS can be used for the investigation of other greenhouse design concepts. Similarly, the developed simulation-based multi-objective dynamic optimization can be utilized for further study into optimization or investigation of adaptability of other building types.

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1 Introduction

1.1 Innovation and Dutch greenhouse

Over the past few decades, the debate about the effect of carbon dioxide (CO_2) emissions on climate change has been concluded. At present, the scientific and political communities are in agreement that the increased levels of CO_2 emitted by human activity, in large part due to the use of fossil fuels, has resulted in significant, harmful consequences for the environment.

In an effort to mitigate these negative consequences and to improve environmental protection moving forward, many national and international targets have been set to reduce CO_2 emissions. Among the most notable of these targets are those set out by the European Union (EU) commission in its climate action reports, which set limits for both CO_2 emissions and energy use for the following decades.

Accepting that achieving targets will be an incremental process, the EU has set out the following timetable for countries within Europe to follow: By the year 2020, EU countries should achieve a 20% cut in greenhouse gas emissions compared with 1990, should produce 20% of total energy consumption from renewable energy and also achieve a 20% increase in energy efficiency. By 2030, there should be at least a 40% reduction in greenhouse gas emissions compared with 1990, and at least a 27% increase in energy efficiency compared with 1990. The EU's long-term target of substantially cutting emissions should be reached by 2050, at which point reductions of 80-95% of the 1990 levels are expected.

In order to comply with the EU targets, Dutch government established policy measures and long-term voluntary agreements on energy efficiency in specific sectors such as building and agriculture (Gulbrandsen & Skjærseth 2014). These targets are also directly relevant to the research project described in this thesis as it takes place in the Netherlands and is concerned with agricultural and horticultural production within commercial greenhouses, which are currently responsible for relatively high energy use and relatively large CO_2 emissions. Recent studies show that within the Netherlands, the commercial greenhouse sector currently relies largely on natural gas, one of the fossil fuels, for heating and operational purposes in the greenhouse (Elzen et al. 2012). The agricultural sector currently accounts for around 5% of the total energy consumption in the Netherlands and the greenhouse horticulture sector uses 82% of the total in the Dutch agriculture sector, as shown Figure 1.1. It is estimated that about 80% of emissions of CO_2 from agricultural and horticultural production result from the combustion of fossil fuels. The energy used by the greenhouse sector represents around 20-30% of its total production costs. For example, energy cost accounts for 32 % of total production cost in a greenhouse tomato farm (see Figure 1.2).

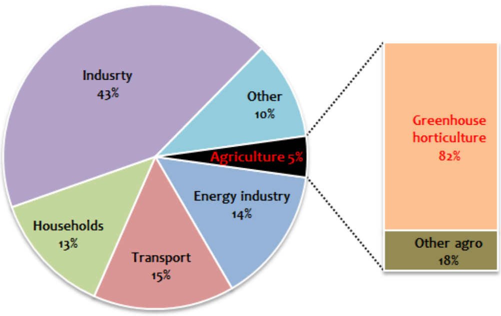


Figure 1.1 *Distribution of total energy consumption in The Netherlands and in agriculture sector; energy consumption in agricultures was approximately 142 PJ in 2009 (total 3260 PJ)* (NL Agency 2011).

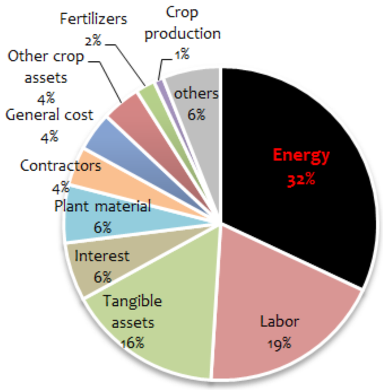


Figure 1.2 *Distribution of total production cost for tomato cultivation* (Wageningen UR 2011).

In order to reduce the usage of fossil fuels and their associated CO_2 emissions, the Dutch government and greenhouse horticulture industry have agreed on ambitions for a greener operation in the future and have set targets to drive the realization of these ambitions (WUR (LEI) 2015). To better understand these ambitions and related targets, they have been broken down into key areas. Their global targets for 2020 are reducing CO_2 emissions by 6.2 Mton as compared to 1990, and energy saving of 11 PJ as compared to 2011. By doing so, their ambitions are as follows: 1) that by 2020 all new greenhouses will be both climate neutral (zero CO_2 emission) and economically viable; 2) that by 2020 existing greenhouses will reduce fossil fuel use by half compared to 2011 by economically feasible techniques; 3) that by 2050 the sector should operate in a climate neutral way.

In reality, the overall energy efficiency rate (= primary energy consumption / unit production) has significantly decreased since 1990, as illustrated in Figure 1.3. The main reason that the rate did not change very much between the years of 2008 and 2013 is because of an increase in the use of primary energy.

However, the greenhouse sector in the Netherlands achieved a 56% reduction by 2013, which means that the sector requires only 1 % more reduction to meet the 2020 target (57% reduction) (Wageningen UR 2014). It is important to keep in mind, however, that this progress relates only to energy reduction, and has much further to go to begin speaking of climate neutral.

When it comes to CO_2 emissions, levels (fusel fuel consumption) have fluctuated since 1990 mainly due to weather conditions. However, total CO_2 emissions decreased to 6.8 Mton in 2013, which leaves 0.6 Mton of reduction to meet the 2020 target (6.2 Mton of CO_2 emission).

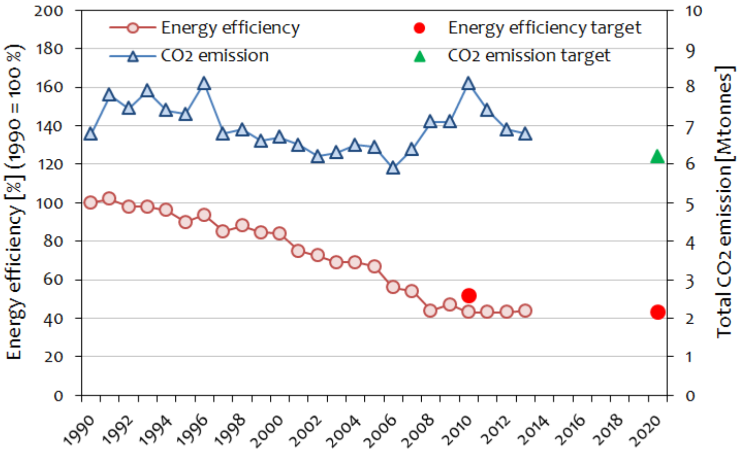


Figure 1.3 *Energy efficiency and total CO_2 emission from 1990 to 2013* (Wageningen UR 2014)

As Europe is an open market, Dutch agricultural and horticultural producers face strong competition from their European neighbours, many in Southern Europe who have climate conditions that are more favourable for crop growth and require less heating of the greenhouse. For example, light intensity on a daily basis is on average five times higher in Spain in winter and 60% greater on an annual basis compared to the Netherlands (Peet 2005). This competitive advantage has gained in importance as the price for energy has risen significantly over the past two decades.

Despite this competitive disadvantage, Dutch growers have been able to remain competitive through continuous innovation and optimization of the conditions for growth for a variety of crops, and by using advanced technologies to control the climate in a greenhouse (Elzen et al. 2012) as shown in figure 1.4. However, in order to achieve the agreed ambitions and to enhance competitiveness in the world market, there is a clear need to further improve the performance of greenhouses for agricultural and horticultural production in the Netherlands.

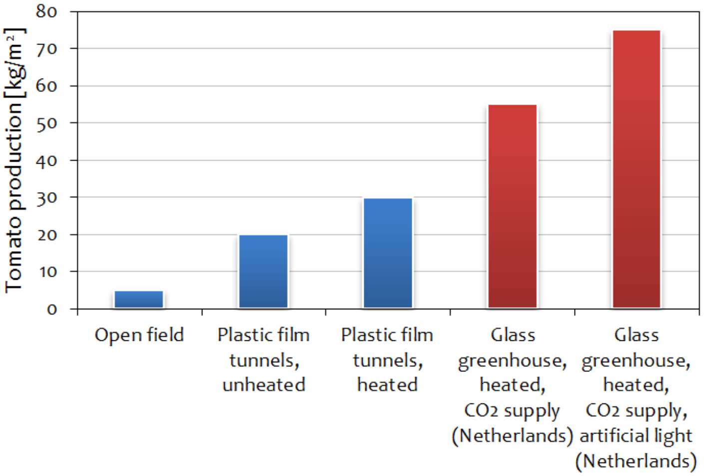


Figure 1.4 *A competitiveness of Dutch greenhouse horticulture for tomato cultivation* (Bakker 2012)

Within the Netherlands, two main stakeholders are driving the innovation of the greenhouse sector: The Dutch government (policy makers), who wish to reduce CO_2 emissions; and crop growers, who wish to increase crop production.

As stated earlier, some attempts have been made to improve the environmental performance and reduce the energy needs of commercial greenhouses in the Netherlands. However, while they do represent progress in terms of the stated targets, these approaches are largely based on existing 'energy-saving' technologies. Thus, there is still a need to improve greenhouse performances for CO_2 reduction and crop production increase in order to meet the targets and ambitions of 2020 and 2050. To do so, truly innovative approaches are required.

The current research develops and presents a new, innovative greenhouse concept entitled *climate adaptive greenhouse shells* (CAGS), and investigates its potential to reduce energy use while also increasing crop yields through the use of computational greenhouse performance simulation (GPS).

1.2 Objective and research questions

The main objective of this research is to develop a simulation methodology for performance assessment of the CAGS concept greenhouse. The research aims to explore the potential of greenhouse shell adaptation through case studies, which focus not only on minimizing energy consumption (CO_2 emission) but also on maximizing crop production.

It is hypothesized that the CAGS concept greenhouse will reduce energy consumption – and thus also CO_2 emissions – and increase crop production in comparison to the conventional Dutch greenhouse.

In order to guide the research, the following research questions were devised:

1) How can the performance of the CAGS concept greenhouse be predicted?
    a. What sorts of capabilities are necessary and which GPS tools are available for performance assessment?
    b. Which methodology is suitable to investigate the potential of the CAGS concept greenhouse?
2) What is the potential of the CAGS concept greenhouse in terms of the energy saving and the production increase?
    a. Does the CAGS concept greenhouse perform better than conventional Dutch greenhouses?
    b. How does the performance of CAGS concept greenhouse change with different system concepts and different performance requirements?
    c. How does the change of shell properties (adaptation frequency) influence the performance of the CAGS concept greenhouse?
    d. How do cultivation scenarios effect the performance of the CAGS concept greenhouse

The outcomes of the research will also provide a better understanding of the correlation between adaptation and performance, and will contribute to the development of future greenhouses.

1.3 Research methodology

The research begins by conducting a literature review on promising greenhouse shells and concepts, before turning to the future development of Dutch greenhouses. Based on the literature review, this research introduces a new, innovative greenhouse concept: climate adaptive greenhouse shells (CAGS)

This research computationally investigates the potential of the CAGS concept greenhouse to operate as a future greenhouse that is able to reach the desired targets. In order to enable this investigation, the research first reviews existing greenhouse performance simulation (GPS) tools and building performance simulation (BPS) tools for use in the performance assessment of the CAGS concept greenhouse. Two existing tools are identified and their capabilities are investigated and compared. For reasons described later, the research finally develops codes in an existing BPS tool in order to make them relevant and usable for the current research.

In order to reach the stated requirements, the CAGS concept greenhouse controls and changes its shell properties depending on outside climate conditions. Thus, it is necessary to identify the optimal set of shell properties for each adaptation period to demonstrate the potential of the CAGS concept greenhouse. To that end, this research develops a simulation-based multi-objective dynamic optimization for the performance prediction of the CAGS concept greenhouse. The new methodology is defined and implemented using co-simulation and optimization techniques.

The potential of the CAGS concept greenhouse is investigated by using modified ESP-r for GPS and the newly designed methodology. The potential is determined in three case studies: 1) the CAGS concept greenhouse with two adaptation frequencies for conventional Dutch greenhouse, 2) the CAGS concept greenhouse with different system concepts and performance requirements, 3) the CAGS concept greenhouse with different cultivation scenarios. The comparison focuses on the potential for energy saving and production increase.

1.4 Thesis outline

The subsequent chapters are as follows:

Chapter 2 presents a literature review of promising greenhouse concepts and technologies, and then introduces the CAGS concept greenhouse as a new and innovative greenhouse concept.

Chapter 3 reviews existing GPS tools and searches for a tool that can be used for the implementation of the CAGS concept greenhouse. This chapter investigates the availability and usability of BPS tools and describes the development of codes in an existing BPS tool.

Chapter 4 describes the new performance assessment methodology developed for the CAGS concept greenhouse.

Chapter 5 demonstrates the potential of the CAGS concept greenhouse through a case study involving a greenhouse with a tomato crop and quantifies advantages in terms of energy saving and crop production.

Chapter 6 further investigates the potential of the CAGS concept greenhouse by testing different performance requirements and different system concepts.

Chapter 7 concludes the investigation of the potential of the CAGS concept greenhouse by testing different cultivation scenarios.

Chapter 8 provides a summary of the research and discusses the main conclusions to be drawn.

2 Climate adaptive greenhouse shells concept

2.1 Introduction

Greenhouses used in agricultural production can be described as being like large solar thermal collectors. The typical commercial greenhouse in the Netherlands is a low-rise structure covered in transparent materials, as shown in Figure 2.1. Such greenhouses are used for crop production because they provide a range of conditions favourable for growth, such as protection from high wind velocities, avoidance of low ambient temperatures, and the provision of heat and light from solar energy.

Figure2.1 *A Typical Venlo-type Dutch greenhouse (www.prinsgroup.nl)*

Within the Netherlands the vast majority of commercial greenhouses use glass to cover the greenhouse shell. Glass is used to cover the greenhouse due to its stable optical properties and its durability. The typical Dutch greenhouse uses single or float glass for 95 % of the greenhouse covering material (Briassoulis et al. 1997). However, despite its extensive use, several attempts have been made to find alternative covering materials in order to overcome the main drawbacks of using glass.

While glass is a very durable product, it is a relatively heavy material, which means its installation is costly. In addition, glass has a relatively low thermal performance (e.g. low U-value and high emissivity), which has a significant impact on the energy costs for the running of the greenhouse and also has implications for crop yield. Due to the low thermal performance of glass, the inside greenhouse climate is highly dependent on the outside weather condition, which leads to increased usage of energy for both crop production and crop quality.

In order to mitigate these issues, many previous studies have attempted to improve covering materials with the simultaneous aims of energy reduction and production increase

(Zhang et al. 1996; Cemek et al. 2006). It is important to keep in mind that any greenhouse design must ensure that the crop is protected against low or high temperatures, and inclement weather such as wind, rain and snow. In addition, any greenhouse design must incorporate indoor climate control, as this is essential for meeting crucial performance requirements of crops such as temperature, humidity and amount of solar radiation.

This chapter proceeds by providing an overview of promising greenhouse shells (2.2.1) and concepts (2.2.2), before introducing the innovative greenhouse concept presented in this research, named the Climate Adaptive Greenhouse Shell (CAGS). The chapter ends with a brief conclusion containing information on how and when the CAGS concept may be further developed and tested for its suitability to improve key performance indicators which allow for reduced energy use and lead to greater crop production.

2.2 Promising greenhouse shells and concepts

2.2.1 Promising greenhouse shells

A wealth of studies has emerged whose aim is to increase the thermal performance and crop yields of commercial greenhouses. A study by Zabeltitz (2010), for example, presented an overview of integrated greenhouse systems and found that the main materials currently used for greenhouse shells are glass, rigid plastic sheets and plastic film. All of these materials are transparent, but they all produce a low thermal performance.

A review of the literature reveals that in order to increase thermal performance and crop production, some researchers have attempted to optimize the use of existing materials for greenhouse shells and others have introduced new, innovative materials and designs (Critten & Bailey 2002; Lamnatou & Chemisana 2013a; Lamnatou & Chemisana 2013b). For the sake of readability, the findings from the review are organized around four key thematic areas, which are as follows: 1) increase of solar transmittance; 2) increase of thermal performance; 3) control or filtration of solar radiation; 4) integration with renewable energy systems.

2.2.1.1 Increase of solar radiation

High solar transmittance from the greenhouse shell is a prerequisite for both an increase in production and a decrease in heating demand in winter (Baille 1999). Previous research has shown that a 1% reduction of PAR (photosynthetically active radiation) results in a decrease 0.46% of photosynthesis in a cucumber crop (Kläring et al. 2012). For many agriculturally produced crops, such as cucumber and tomato crops, photosynthesis is directly proportional to crop production. Therefore, delivering more solar radiation is important for production increase.

A number of different approaches to increasing solar radiation have been identified in the literature. The most noteworthy of the approaches are described in turn below.

Fresnel lenses

A Fresnel lens is an optical device to concentrate solar radiation by changing its direction. The efficiency of the Fresnel lens in relation to greenhouses was experimentally proved by Kurata, who built a scale-model with the Fresnel lenses applied to the south roof covering, as illustrated in Figure 2.2 (Kurata 1991). The results showed that the use of the Fresnel lenses resulted in high light transmittance in winter and low light transmittance in summer. The study concluded that use of the Fresnel lenses is promising in terms of decreasing cooling demand in summer and heating demand in winter.

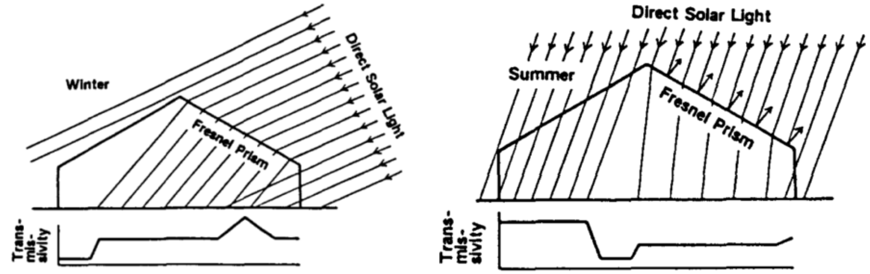


Figure 2.2 *Schematic illustration of the solar gain using Fresnel lens in winter and summer (Kurata 1991)*

Laser-cut panel glazing

Edmonds & Pearce (1999) produced a laser-cut panel by dividing a clear acrylic sheet into rectangular elements with a laser cutter. The effect of using laser-cut panel glazing was experimentally investigated. This was installed on the roof and on the north wall and the authors assessed the enhancement of illuminance in high latitude greenhouses in winter. They found under clear sky conditions in high latitude greenhouses (>50°) that utilizing the panel on the southern roof, as illustrated in Figure 2.3 (a), resulted in an average daily illuminance enhancement approaching 100% during winter. This study also demonstrated that the use of a double-glazing laser-cut panel does not reduce the contribution to illuminance from diffuse light in comparison to conventional clear double glazing.

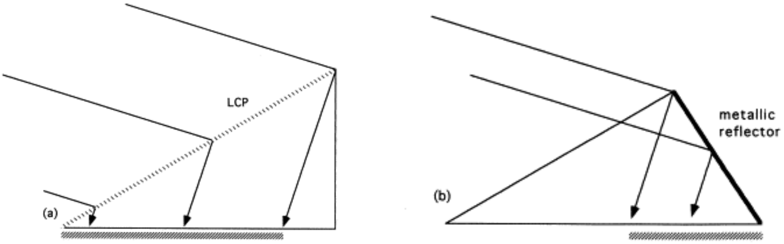


Figure 2.3 *Illustration of the relative areas of illuminance enhancement available by use of a laser-cut panel glazing on the roof of a greenhouse (a), and of that available using a reflective north wall (b).* (Edmonds & Pearce 1999)

Anti-drop (anti-condensation) film

If the temperature of the greenhouse shell is lower than the saturation temperature, then drops of water form on the shell surface. When light hits a drop of the water, the drop acts as a reflector, resulting in loss of solar radiation and high humidity in the greenhouse, which can ultimately result in the development of fungal disease (Cemek & Demir 2005). Pollet & Pieters (2000) experimentally demonstrated that the use of polyethylene (PE) film led to a 23% decrease of transmittance at normal incident angle when condensation was formed.

In order to overcome these problems from condensation droplets, usability of Anti-drop (anti-condensation) film was investigated. The light quality with anti-drop film was evaluated by Geoola et al. (2004). According to their experiment, in conditions where no anti-drop film was used, there was a decrease of 14 % ~ 19 % of solar transmittance in the wet state, but anti-drop film provided only a 3.5% transmittance decrease in comparison to the dry state. The examples of applications of anti-condensation film are shown in Figure 2.4.

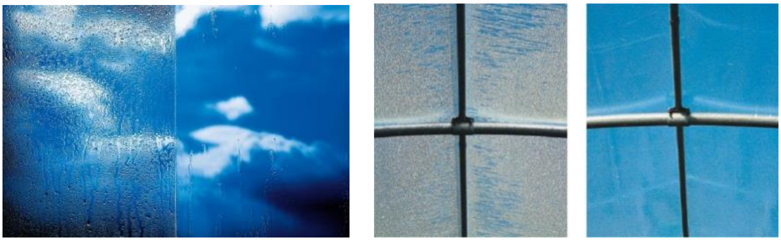


Figure 2.4 *Application of anti-condensation film with glass (www.glassolutions.co.uk) and Polyethylene Film (www.hitecfilms.com)*

Anti-reflective coating

The purpose of using anti-reflective (AR) coating on the greenhouse shell is to decrease reflective loss from the surface and to enhance transmission of the light, as shown in Figure 2.5. An increase of solar energy by using anti-reflective coating was demonstrated by (Rosencrantz et al. 2005). They showed that a double-glazed, glass window with anti-reflective coating increased light transmittance by 15% in total, and increased by 7% compared to clear double-glazed windows. This increase in transmittance led to a 4% decrease in heating demand and an increase in the daylight factor of 21%. Hemming et al. (2006) investigated the application of AR-glass with very high light transmittance (95% for direct incident light and 90% for diffuse incident light compared to traditional glass with 90% for direct and 83% for diffuse radiation) and their results showed a 5-8% increase of crop production. Another study combined anti-reflective coating with diffused glass, and this application lead to a 5.2% increase in crop production (Victoria & Kempkes 2012).

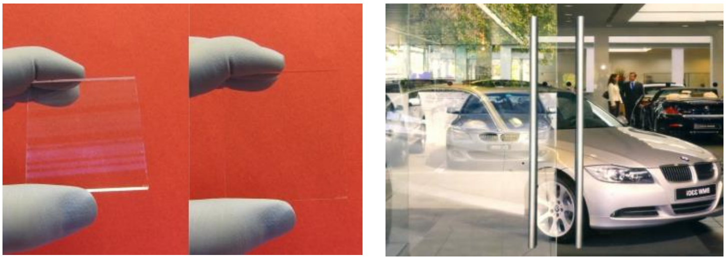


Figure 2.5 *Application of Anti-reflective coating (www.indiamart.com, www.safetyglass.com.vn)*

2.2.1.2 *Increase of thermal performance*

The traditional method used to improve the thermal performance of greenhouse shells is to apply a screen. However, this measure is not always applicable when solar radiation is necessary for crop growth and production increase. Another measure is to increase the number of covering layers by adding air or gases between layers of the shell. However, as the number of transmittance material layers increases, the solar transmittance of the material decreases in proportion. Ideally, it is necessary to increase thermal performance without losing transmittance of solar radiation.

Zigzag sheet

Research by (Sonneveld & Swinkels 2005) showed that the specific geometry of the Zigzag sheet, as shown in Figure 2.6, allows it to overcome the drawback of losing solar radiation in multi-layer cladding and that it provides better thermal performance. While a flat transmittance material increased reflected radiation in proportion to corresponding increases of incident angle, the Zigzag sheet increased light transmittance (90.5 % transmittance of direct solar radiation and 80 % transmittance of diffuse solar radiation) by capturing light reflected by another surface. Since this method is effective with high incident angles, the sheet leads to a 25% reduction of heating energy consumption in winter and to a 5% increase of diffuse light transmittance. In addition, since a greenhouse using the Zigzag sheet can be built without using bars, the total amount of solar radiation was increased. In short, the Zigzag panel offers light transmission greater than the single glazing, while providing high thermal performance equivalent to double glazing.

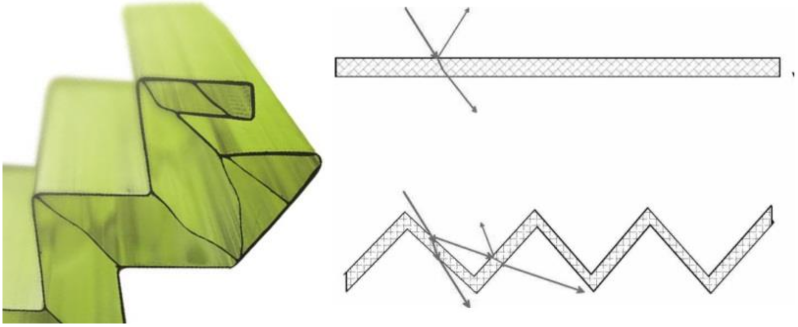


Figure 2.6 *The shape of the Zigzag sheet (www.sabic-ip.com) and the principle of the increasing transmittance with zigzag shape compared to flat shape* (Sonneveld & Swinkels 2005)

Low emissivity coating

Radiative heat loss at night and in winter is the most important factor affecting energy consumption. The low emissivity coating can be applied not only with maximum shortwave transmittance, but also with longwave radiation blocking, which results in a decrease of heating energy consumption. A double-glazed greenhouse shell (3 W/m²K) with low emissivity coating can achieve 0.8 ~ 1.8 W/m²K of the U-value (Dachselt et al. 1982). Another study showed that radiative heat loss from greenhouse shells was decreased by 40% with the application of low emissivity coating (Halleux et. al 1985).

2.2.1.3 *Control or filtration of solar radiation*

Global radiation that enters the greenhouse can be divided into ultraviolet radiation (UV, 300 nm ~ 400 nm), photosynthetically active radiation (PAR, 400 nm ~ 700 nm) and near infrared radiation (NIR, 800 nm ~ 2500 nm); UV affects plant morphology and insect orientation; PAR affects on warming, photosynthesis, transpiration and plant morphology; NIR affects on warming and transpiration (Winsel 2002). The fraction of solar energy is 5% of UV, 45% of PAR and 50 % of NIR as shown in figure 2.7.

PAR is the most important source for photosynthetic activities of the crops, whereas NIR is only useful for reducing heat energy consumption. Controlling these different types of solar radiation (NIR & PIR) separately is a promising approach in terms of saving energy and increasing crop quality.

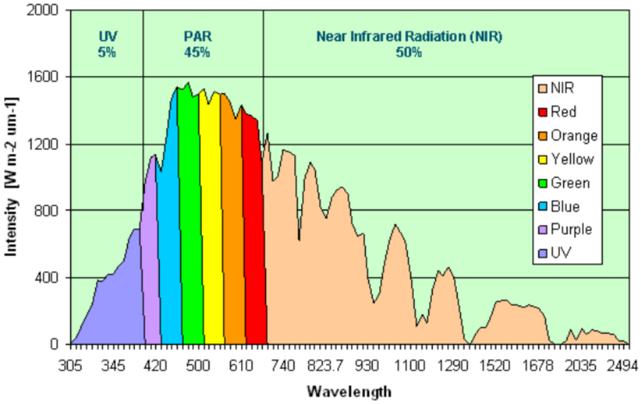


Figure 2.7 *Distribution of solar radiation at AM 1.5* (Sonneveld 2009).

NIR reflecting film

The introduction of NIR in the greenhouse helps to reduce heating energy consumption in winter. However, NIR increases inside humidity and temperature in summer, which results in a decrease in crop production and increase in dehumidification demand (Kempkes et al. 2008; Kempkes et al. 2009).

The potential of currently available NIR-filtering films was computationally investigated (Hemming et al. 2006). Most of the materials allow more than 90 % of PAR transmittance, which is good enough for crop growth. NIR-filtering plastic films reduced up to 25% of NIR transmittance, and NIR filtering-glass was able to reduce 50 % ~ 70 % of NIR transmittance. The transpiration which results in an increase of humidity reduces by 30% with 100 % of NIR reflection, and by 10 ~ 15 % with 50 % of NIR filtering. The investigation was backed up by a later simulation study (Kempkes & Hemming 2012) which concluded that the advantage of a NIR absorbing greenhouse shell is limited and that reflecting NIR is more favorable than absorbing it.

Further investigation into the potential of NIR-filtering materials in Dutch climate conditions was performed to reduce energy consumption and to increase crop growth and tomato production (Hemming, Kempkes, Braak, et al. 2006). Lowering NIR increased tomato production due to the low inside temperature and crop temperature (1 - 2 degrees of air temperature and 0.8 degrees of crop temperature lower than the reference greenhouse) and high CO_2 concentration with less ventilation. 100% NIR filtering resulted in an 8.6 % increase in tomato yield, and 50% of NIR filtering resulted in a 4.9 % increase of tomato yield, in both cases in summer. Together with anti-reflection coating, tomato production is expected to increase by 10 ~ 12%.

Photo selective film

Conventional greenhouse shells with shading controls, which are generally used for lighting control, may significantly affect light quality (Kittas et al. 1999). The light quality refers to the spectral composition of light which effects photosynthesis and plant growth. The light quality is important for the quality of the plant especially for flowering, and height and flowering can be controlled by using photo selective film.

The growth responses to an applcation of the photo selective film were investigated (Li et al. 2000). The study found that photo selective film reduced plant height and internode length by 10% - 35%, depending on crop and dye concentration in the film. This study also proves that a photo selective film with a R:FR (red and far-red light) ratio of 2.2 causes about 20% of height reduction in chrysanthemums and a 30% reduction in bell peppers. Oyaert et al. (1999) also found a 22% reduction in growth with colored plastic film.

The effect of light quality was investigated on flowering and stem elongation in 3 plant types: long-day, short-day and day-neutral plants (Cerny & Faust 2003). Their experimental results show that a far red light absorbing film (700 nm ~ 800 nm, A_{FR}) was effective in reducing stem elongation in most of the species. The A_{FR} films have the influence on the flowering period of long-day plants. The study concludes that light quality can be a factor in controlling height and delaying the flowering of the plant.

UV blocking film

Blocking UV spectrum is essential for lowering pesticide load and costs, and increasing crop growth. Papaioannou et al. (2012) investigated the effects of a UV-absorbing film on tomato yield and quality. They found that the amount of fruit injured by insects was reduced and the marketable yield was similar or higher than that under the common PE film, while fruit was of good commercial quality (size and shape and color) and nutritional values were similar.

The influence of the UV absorbing film on the behavior and production of eggplant crops was recently investigated by Kittas et al. (2006). The study found that the crops in the greenhouse with 0% UV transmittance were 21 % taller and had 17 % higher leaf production than crops in a greenhouse with standard polyethylene film with UV transmittance of 5 %. Finally, the production was increased in both quantity (20%) and quality (bigger fruit) without UV transmission compared to 5% UV transmission.

Another study found that crops under complete UV blocking films produced up to 2.2 times more total dry weight than crops under the UV transparent film (Tsormpatsidis et al. 2008).

Switchable glazing and coating

Switchable glass or coating is a material whose light transmission properties are altered when voltage, light or heat is applied (see Figure 2.8 (A)). Generally, the glass changes from translucent to transparent, changing from blocking some (or all) wavelengths of light to letting light pass through. In the building sector, the switch glazing technologies are frequently regarded as an alternative to traditional solar production elements such as blinds, louvers, overhangs etc. (Marchwiński 2014). Application of these technologies improves visual comfort and drastically reduces energy consumption by reducing cooling loads, heating loads and the demand for electric lighting (Kokogiannakis et al. 2014; Zheng et al. 2015; Fernandes et al. 2013; Tavares et al. 2014). This technology can be employed as a substitute for screens for lighting control in the commercial greenhouse.

Recently, light- and heat-blocking smart glass has been developed, as shown in Figure 2.8 (B) (Llordés et al. 2013; Korgel 2013; Li et al. 2010). Depending on the voltage applied to it, this switchable glass changes between three modes: 'bright', which is completely transparent to both light and heat; 'cool', which blocks infrared (heat) while still allowing visible light through; and 'dark', which blocks both heat and light.

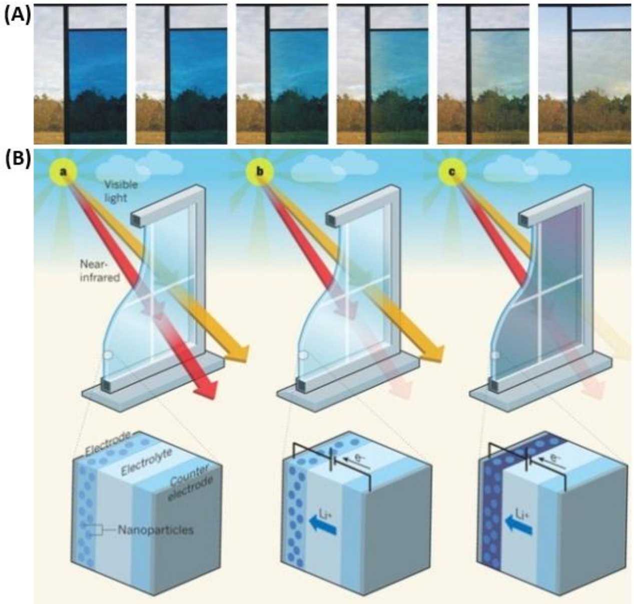


Figure 2.8 *Switching sequence of electrochromic glass (above)*(Baetens et al. 2010) *and smart glass that controllably and selectively absorb visible light and near-infrared light (heat): (a) bright mode, (b) cool mode and (c) dark mode*

2.2.1.4 *Integration with renewable energy systems*

Fluorescent solar concentrator (FSC)

The principle of FSC, or so called luminescent solar concentrators (LSC), is based on the Snell's law: a large fraction of the emitted photons will be trapped within the plate and transported by total internal reflections to the edge of the plate, as illustrated in Figure 2.9. where they will be converted by appropriate photovoltaic cells (Hammam et al. 2007).

Hammam et al. (2007) evaluated the performance of thin-film solar concentrators for greenhouse applications. These fluorescent polymethylmethacrylate films can act as promising photo-selective films, which increase the irradiance level for photosynthesis in greenhouses. The use of PVs is an attractive option for the utilization of the trapped photons since it offers photo-selective properties and production of electricity (Lamnatou & Chemisana 2013a) as illustrated in Figure 2.9.

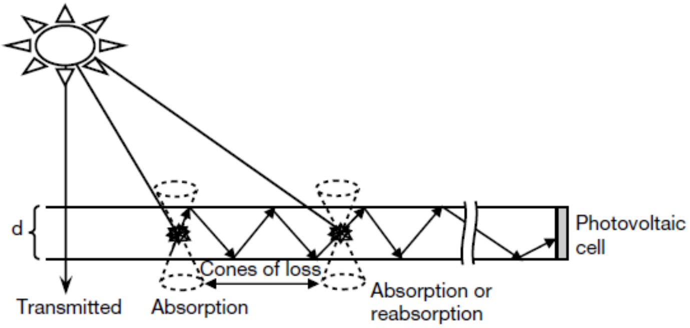


Figure 2.9 *Schematic representation of fluorescent solar concentrator (Hammam et al. 2007)*

Novoplansky et al. (1990) investigated increasing plant productivity by changing the solar spectrum. New greenhouse plastic covers with fluorescent dyes convert light from the green part of the spectrum into red light. The use of these sheets as greenhouse covers increased tomato production by 19.6% and the number of flowering branches on rose bushes by 26.7% in comparison to sheets without the dye.

Fresnel lenses with T, PV and PVT

The advantage of the linear Fresnel lenses to separate the direct from the diffuse solar radiation makes them suitable for lighting and temperature control of the greenhouse interior space. In addition, the Fresnel lenses provide light of suitable intensity level without sharp contrasts (Tripanagnostopoulos et al. 2005).

Tripanagnostopoulos et al. (2005) investigated irradiation aspects for the use of glass type Fresnel lenses, which is illustrated in Figure 2.10. The Fresnel lenses installed on the greenhouse roof, combined with linear absorbers to receive and convert the concentrated solar radiation into heat (T), electricity (PV) and both (PVT). The study estimated that the suggested systems with thermal absorbers can reduce thermal needs by about 25%, reduce the ventilation and cooling load of the greenhouse by 50%, and can greatly reduce the energy consumption when using PV or PVT.

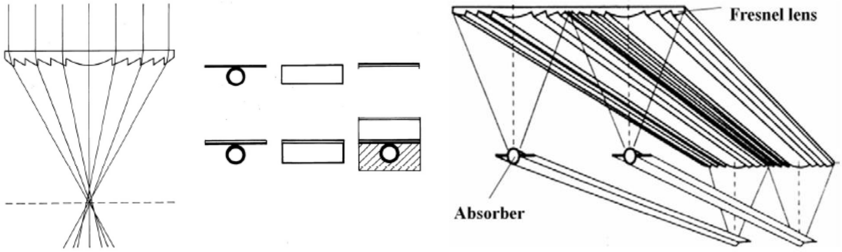


Figure 2.10 *The geometry and principle of the linear Fresnel lens (left), alternative absorbers of T, PV and PVT type (middle), and overview of application (right) (Tripanagnostopoulos et al. 2005)*

The energy flow in a greenhouse with glass raster lenses was investigated by (Jirka et al. 1999). The south-facing half of the roof of the solar greenhouse was equipped with a glass raster of linear Fresnel lenses which concentrate the heat energy from direct solar radiation in a collector while allowing diffuse light to pass into the greenhouse for crop growth. In central Europe, linear raster lenses absorbed 12% of the total solar radiation on the solar collector, which resulted in 50% less heating energy consumption compared to a conventional greenhouse. In addition, the greenhouse with Fresnel lenses led to no overheating in summer, less ventilation, less water consumption and less inside humidity while providing suitable growth conditions. The hot water from the collector can also be used for water disinfection (Tripanagnostopoulos and Rocamora 2008).

Another study developed and investigated the potential of Fresnel lenses with concentrated photovoltaic (CPV) systems, which is illustrated in Figure 2.11 (Sonneveld et al. 2011). The study found that the removal of all direct radiation blocked up to 77% of the solar energy from entering the greenhouse in summer, thereby reducing the cooling system capacity. All of the direct radiation is concentrated on a photovoltaic/thermal (PV/T) module and converted into electrical and thermal (hot water) energy. Incoming direct radiation resulted in a thermal yield of 56% and an electric yield of 11%, which equals a combined efficiency of 67%. The annual electrical energy production of the prototype system is estimated to be 29 kW h/m^2 and the thermal yield to be 518 MJ/m^2. The results show that this energy contribution is sufficient for the heating demand of well-isolated greenhouses located in north European countries.

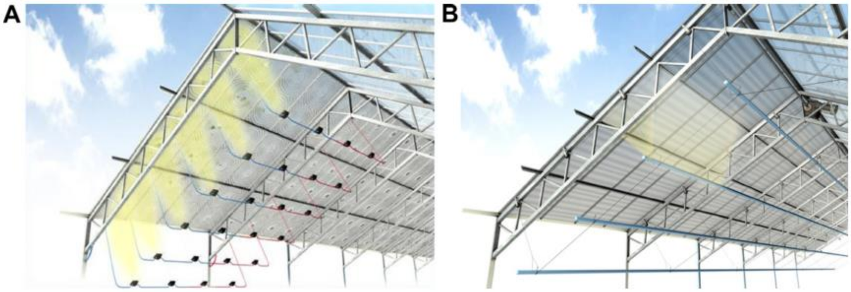


Figure 2.11 *Illustration of greenhouse roof with (A) Normal Fresnel lenses and PV/T modules, (B) Linear Fresnel lenses and PV/T modules* (Sonneveld et al. 2011)

Semi-transparent photovoltaic modules

The feasibility of electrical and shading characteristics of a semi-transparent PV module (see Figure 2.12), which provides electrical energy consumed in greenhouses for plant environment control, were investigated by Yano (2014). Two PV modules for greenhouse roof application were developed: Module PV1 is composed of crystalline silicon solar cells of 1.8 mm diameter with a density of 15.4 cells/cm$^{2.}$ The cells cover an area of 39% of the module, and the remaining 61% is transparent. Module PV2 is composed of the same size cells as PV1, but has a smaller density of 5.1 cells/cm^2 and therefore has a greater transparent area of 87%. Since each PV cell is small enough, the PV cells do not entirely block radiation from the sun. Thus, the PV greenhouse shell does not provide excessive shade, and this characteristic makes the developed PVs suitable for greenhouse application. Since PV1 has a threefold higher cell density than that of PV2, PV1 generates nearly three times more electricity and shading than PV2. The peak power output was 540mW under sunlight of 1213W/m^2 for PV1 and 202mW under sunlight of 1223W/m^2 for PV2. It is expected that these modules are suitable for greenhouses located in high-irradiation regions or greenhouse growing shade tolerant crops.

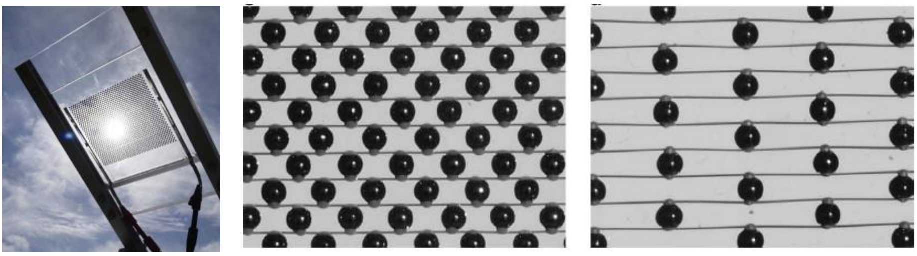


Figure 2.12 *the prototype PV modules (left) with15.4 cells cmL2 (PV1, middle) 5.1 cells cmL2 (PV2, d) cell density* (Yano et al. 2014)

2.2.2 Promising greenhouse concepts

In response to energy costs and CO_2 emission targets, a number of promising greenhouse concepts have emerged in recent times. The literature review below introduces the most noteworthy of these concepts.

Solar greenhouse

The solar greenhouse concept (Bot et al. 2005) was developed for greenhouses in the Netherlands that would be suitable for high value crop production without the use of fossil fuels. The main goals of the project were: 1) to design a greenhouse requiring less energy; 2) to use natural energy as much as possible to reduce energy demand; 3) to develop a control algorithm for dynamic systems.

The solar greenhouse reduced energy demand and peak load in winter by using improved insulation with high light transmittance and by integrated climate control strategies. The energy supply for heating in winter and cooling in summer was combined with the application of seasonal storage (aquifer) by harvesting excess solar energy in summer and using this for heating in winter (see Figure 2.13). The advantages of this storage system were significant. It provided cheap cooling in summer and an energy saving of 35% for heating compared to heating with a boiler.

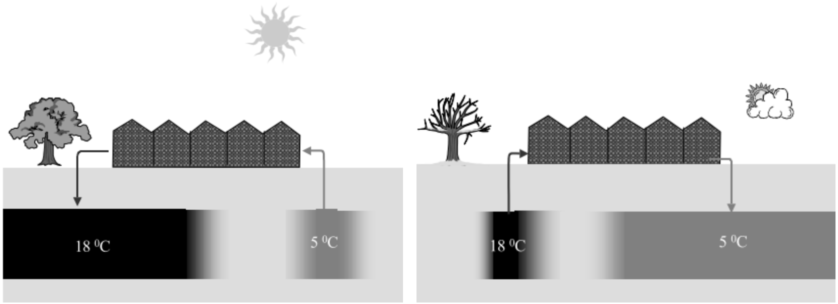


Figure 2.13 *Use of the aquifer: excessive heat is stored in summer (left) and stored heat is used in winter (right picture) (Bot et al. 2005)*

Use of high insulation materials that have high transmittance was also investigated to determine how far it is possible to decrease the size of heat exchanger/aquifer and heat pump/boiler. The benefit of these materials was computationally investigated. When a triple-layered cover (a double cover with thermal screen) was used, energy demand could be reduced to approximately 40 % of the reference situation, represented by a single cover and a boiler for heat supply. If the reference case was represented by a single cover with a thermal screen (as is a common situation for many crops grown in Dutch greenhouses), then a 50 % energy saving was possible under current conditions.

(Semi-) closed greenhouse

The greenhouses with reduced or no window openings were named as semi-closed or closed greenhouses. Since the greenhouse was 'closed', there were no windows to open to release excess heat and humidity throughout the year. This greenhouse was designed to maximize the utilization of solar energy through the use of seasonal storage. The reduced window ventilation in the (semi) closed greenhouses resulted in a continuously high CO_2 concentration in the air of about 800 ppm ~ 1000 ppm throughout the year, while the CO_2 concentration in conventional modern greenhouses in summer is 400 ppm ~600 ppm. The elevated CO_2 concentration enhanced photosynthesis and led to production increase (Qian et al. 2012).

The potential of the closed greenhouse concept was investigated by Opdam et al. (2005) . The feasibility of the closed greenhouse system was tested in a demonstration sized trial as well as a commercially scaled trial with an innovative tomato grower. The technical concept consists of a combined heat and power unit, heat pump, underground (aquifer) seasonal energy storage as well as daytime storage, air treatment units, and air distribution ducts. The main results were: 1) a reduction in primary energy (fossil fuel) use of 20 % and 35 % respectively for an "island" closed greenhouse and a closed-conventional combination greenhouse ; 2) an increase in tomato yield of 22% with high CO_2 concentration (1000~1200 ppm); 3) an 80% reduction in chemical crop protection; and 4) a 50% reduction in the use of irrigation water (Gelder et al. 2005).

Qiana et al. (2011) experimentally compared greenhouse climate and production in closed (700 W/m^2 of cooling capacity), semi-closed (350 W/m^2 and 150 W/m^2 of cooling capacity) and open greenhouses. Under sunny conditions the temperature in the closed greenhouse was 5°C higher at the top than at the bottom of the canopy. Cumulative production in the semi-closed greenhouses with 350 W/m^2 and 150 W/m^2 cooling capacity were 10% and 6% higher respectively than that in the open greenhouse. Cumulative production in the closed greenhouse was 14% higher than in the open greenhouse in week 29 after planting. Based on model calculations, the production increase in the closed and semi-closed greenhouses was explained by higher CO_2 concentration.

Energy producing greenhouse

The energy producing greenhouse was designed and installed for completely closed greenhouses with cooling and a heat recovery system using fine wire heat exchangers, which is shown in Figure 2.14 (Bakker et al. 2006). The energy producing greenhouse project focused on the design and optimization of a completely air conditioned greenhouse to minimize fossil fuel use and to increase both crop production and energy storage (in warm water). The concept of this greenhouse was the combination of a highly insulated greenhouse, long term heat storage (from summer to winter) in aquifers and a distributed system of efficient fine wire heat exchangers. According to their calculations, a yearly heat production of about 800 MJ/m^2 could be expected, which is equivalent of 25 m^3/ m^2 natural gas with this system.

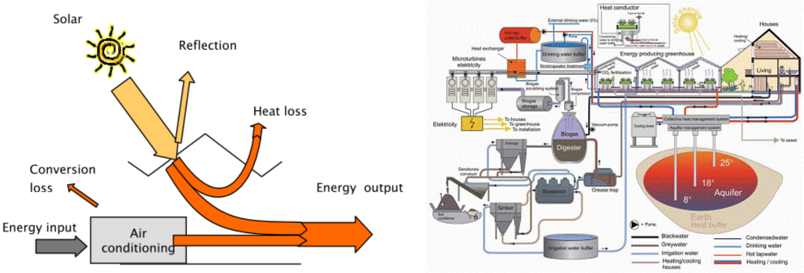


Figure 2.14 *Energy flows in the energy (heat) producing greenhouse (left)* (Bakker et al. 2006) *and Complete greenhouse installation (right) (Kristinsson 2006)*

Sunergy greenhouse

The Sunergy greenhouse(De Zwart 2011) is a type of semi-closed greenhouse which closes during periods with high solar radiation in order to harvest excess solar energy, but introduces outside air during cloudy days and during the night for dehumidification. The greenhouse employs the following systems: cooling systems in order to keep the greenhouse closed in high radiation periods; an air treatment unit, including heat exchanger for dehumidification and air circulation; double screens for the reduction of heating demand (see Figure 2.14).

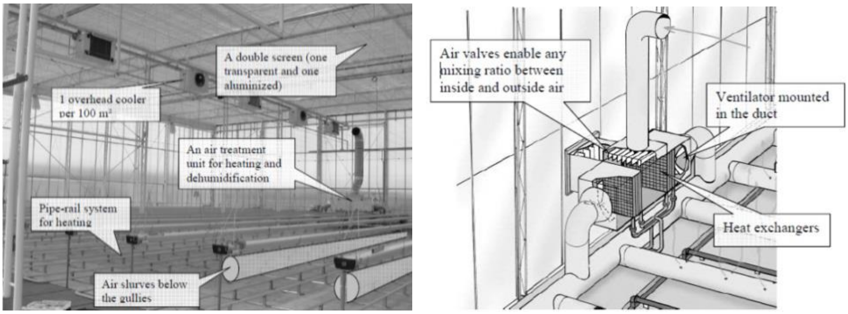


Figure 2.15 *Installation of Sunergy Greenhouse (left) and use of the air treatment unit (right)* (De Zwart 2011)

Based on field measurements, the greenhouse stored 460 MJ/m^2 of solar energy in summer and used 300 MJ/m^2 of stored heat for heating in winter, which means the greenhouse accumulates more solar heat than it uses for its own heating. The heat energy consumption of the greenhouse was 25% less than common practice in the Netherlands. This was achieved through the use of the thermal screens and the acceptance of high humidity. In addition, due to the closed state during sunny and warm days, the inside CO_2 concentration could be kept between 900 ppm and 1000 ppm, which allows a 50% reduction of the CO_2 supply rate.

Electricity producing greenhouse (ELKAS)

The electricity generating greenhouse (ELKAS, Elektriciteitsproducerende kas) concept (Sonneveld, Swinkels, Bot, et al. 2010; Sonneveld, Swinkels, Campen, et al. 2010; Sonneveld 2009) aimed to catch the radiation that is not used for crop growth and convert it into high grade power. To this end, two measures were used: 1) spectral selective cover material, which prevents the entrance of NIR radiation, was applied and this blocked up to 50% of the solar energy, which led to a reduction in cooling demand. 2) PV cells were integrated into the frame. When the NIR reflecting coating was designed as a circular shaped reflector integrated in the greenhouse, the reflected solar energy of a photovoltaic (PV) cell in the focus point delivered electric energy (see Figure 2.16).

Sonneveld et al. (2010) investigated the feasibility of this concept and their research provided a greenhouse design combining reduced heat load with generation of electricity. The study showed that the cooling load inside the greenhouse can be reduced with NIR-reflecting film and that the reflected NIR radiation can be focused with a circular trough reflector. Based on the feasibility study, a mock-up building of ELKAS was built and the electricity generation from PV was measured. Under Dutch weather conditions, yearly power generation was determined as a total electrical energy of 20kWh/m2 and a thermal energy of 160 kWh/m^2. In the near future, with the improvement of electricity generation (31kWh/m^2 of electrical energy and 270kWh/m^2 of thermal energy) the greenhouse will be operable without fossil fuel.

Figure 2.16 *Schematic description of application of NIR-reflecting film (left)* (Sonneveld, Swinkels, Bot, et al. 2010) *and Mock-up model of ELKAS (right)* (Sonneveld, Swinkels, Campen, et al. 2010)

DaglichtKas (Daylight Greenhouse)

DaglichtKas (Zwart & Noort 2012) was developed for shade tolerant crops, which grow in shade, and uses fully diffused light for cultivation. This greenhouse was equipped with Fresnel lenses in the south-facing roof to convert direct solar radiation into heat and electricity (15 % of PV-cells) using CPVT (PV/T concentrator) as shown in Figure 2.17. In 2011, it was experimentally observed that the system converted 19% of the direct solar radiation into heat

(360 MJ/m^2) and generated electricity of 15 kWh/m^2 in Dutch weather condition. The effect of the daglichtKas concept on crop growth was studied for 7 different types of potted plant cultivations, and achieved faster growth and development by up to 10% to 20%.

Figure 2.17 *A prototype of CPVT installed in DaglichtKas* (Zwart & Noort 2012)

Venlow greenhouse

The Venlow greenhouse concept (Kempkes & Janse 2012) used argon filled double glazing with anti-reflective coating, which provides a similar solar transmission to standard single glass. The greenhouse also used a balanced ventilation system for dehumidification, and heat recovery ventilators to reduce the heating and cooling demands from heat exchange, which they call the 'New Cultivation' method. The sensible heat exchange efficiency of the system was about 80%. The conclusion drawn here was that the Venlow greenhouse could achieve energy savings of over 50% compared to common Dutch greenhouses without any decrease in production or product quality.

2saveEnergy greenhouse

The 2saveEnergy greenhouse concept(Kempkes et al. 2014) used double glazing with film coatings: an outer layer of diffuse glass with a double anti-reflective coating and an inner layer of clear glass with ETFE (Ethylene tetrafluoroethylene) film. This composition provided the greenhouse with 10% more light in winter compared to a single glass greenhouse roof. The cavity of glazing layers was used for ventilation with warm air to melt snow in winter. The 2saveEnergy greenhouse concept was controlled by multiple screens with the New Cultivation method, which resulted in a decrease of more than 20% of energy consumption in greenhouses with the New Cultivation method or about a 50% reduction in those with common practices without any decrease in crop production.

Next Generation Semi Closed Greenhouse

The Next Generation Semi Closed Greenhouse concept is an improved greenhouse from (semi) the closed greenhouse concept. The concept is based on the New Cultivation method, which provides optimized air treatment. In the heating period, the greenhouse could be internally dehumidified with the cold heat exchanger while keeping the windows shut (closed greenhouse), which prevents losses of sensible and latent heat. The greenhouse stores excessive heat in an aquifer in a cooling period and the stored heat is used in winter by the heat pump system. The operation in summer time is the same as in the (semi) closed greenhouses. According to the experiment, the system could decrease heating energy demand by 25% in winter.

2.3 Climate adaptive greenhouse shells concept

The greenhouse is a structure that is more sensitive to ambient climate conditions than most other types of building structures due to its purpose in operation. Thus, the greenhouse has been developed in a manner to maximally exploit and to efficiently control ambient climate conditions. Therefore, the performance of greenhouse shells, which divide the inside and outside of the greenhouse, significantly affects the productivity and quality of crop and energy consumption. The influence of the greenhouse shell performance was proved with a sensitivity analysis by a model-based greenhouse design method (Vanthoor et al. 2011). The study determined that outdoor climate has a greater impact on the greenhouse performance than design parameters and climate set-point. In addition, the study concluded that the adjustable greenhouse shell properties such as PAR, NIR and FIR emission coefficients will be advantageous for achieving an increase in greenhouse performance.

The main purposes of these studies are to improve of the productivity and quality of the crop, and to reduce energy consumption. According to the literature review, achieving a significant energy saving is possible using current technology. However, in order to reduce energy demand further and realize an energy producing greenhouse, the greenhouse must have ‘adaptability’ to maximize benefits from weather conditions and to minimize negative influences from outside conditions. Adaptability is not a new concept in greenhouse horticulture as current greenhouses do employ some climate adaptability. For example, many greenhouses use shading control to protect crops from high solar radiation or to control inside climate conditions. Greenhouses also use natural ventilation to control inside humidity and temperature. Instead of the existing low level climate adaptability of the shells like examples above, high level climate adaptability is necessary for the desired improvement of greenhouse performance.

Based on the literature review and the result from the previous study (Vanthoor et al. 2011), this study proposes to develop a future greenhouse concept with high level climate adaptability by responding in real time to the continuously changing outside weather conditions in order to maintain the required inside climate conditions. Adaptation of the greenhouse shell is the key to realizing this concept. Thus, this study introduces the climate adaptive greenhouse shells (CAGS) concept. The CAGS concept is similar to the climate adaptive building shells (CABS) concept (Loonen et al. 2013). They defined CABS as:

> *A climate adaptive building shell has the ability to repeatedly and reversibly change some of its functions, features or behavior over time in response to changing performance requirements and variable boundary conditions, and does this with the aim of improving overall building performance.*

Based on this definition, in this study CAGS can be understood as: a greenhouse shell which has the capability to control its optical and thermal properties in order to minimize energy consumption (CO_2 emission) and to maximize crop production and quality. The control of the two stated properties could be achieved either through currently available technologies or through new, innovative means. Since the CAGS concept not based on current available technology, this research computationally investigates the potential of the CAGS concept by using greenhouse performance simulation (GPS). To do this, Chapter 3 describes the search for a tool that could be adapted for GPS, and then, in chapter 4, the developed implementation methodology of the CAGS concept is presented.

2.4 Conclusion

The literature review clearly demonstrated that there is still a real need to improve the performance of greenhouses, both in terms of reducing energy use and CO_2 emissions, and in terms of improving crop productivity. The review and the recent study (Vanthoor et al. 2011) further indicated that the performance of greenhouse shells is one of the most import factors in realizing the desired energy reductions and crop production increases.

In response to these findings, the current research proposed a new, innovative greenhouse concept, known as CAGS, which strives to achieve the desired outcomes by exploiting technologies that are currently unavailable in practice.

The potential of the CAGS concept will be tested by using a computational approach which incorporates greenhouse performance simulation (GPS). In the following chapter, this research reviews the capabilities of existing GPS tools and further develops new GPS tools that can be exploited within the current research.

3 Greenhouse performance simulation and code development

3.1 Introduction

The main aim of this chapter is to arrive at a means to evaluate the potential of the proposed CAGS concept greenhouse. Since there are currently no real world applications to study in the field, the potential of the CAGS concept greenhouse will have to be demonstrated by other means. In situations where new, innovative building designs need to be put to the test, computational assessment through the use of simulation tools has proved to be extremely useful. Thus, this chapter reviews currently available greenhouse performance simulation (GPS) and building performance simulation (BPS) tools and outlines their capabilities and limitations in terms of their efficacy for testing the proposed CAGS concept.

The chapter begins by highlighting the requirements of a GPS tool in order to be used for the performance assessment of the CAGS concept greenhouse, and then the available GPS and BPS tools are reviewed and their capabilities and limitations for this study are investigated.

3.2 Computational performance assessment tools

Since the main goal of the current research is to develop an innovative greenhouse design, the Climate Adaptive Greenhouse Shells developed here can be described at this stage as a conceptual development. Therefore, in this phase of the CAGS concept greenhouse, there are no physical structures as such that can be used for the testing of CAGS. Thus, in order to predict the performance of the CAGS concept greenhouse, the current research exploits a method commonly used for the testing of building design modifications or new building design concepts. This method is computational building performance simulation (CBPS).

CBPS has proved itself to be a particularly useful research tool because it allows the researcher to explore in detail the key performance requirements of a concept without the need and significant time and expense required to build a full-scale model of the design.

Due to the growing success of the field of CBPS, a number of general BPS tools now exist that can be applied to the analysis of a wide range of building designs. In addition, some more specific tools have emerged that target specific types of buildings, including Greenhouse Performance Simulation tools, which are of direct relevance to the current research.

3.2.1 Requirements for performance assessment of Climate Adaptive Greenhouse Shells

GPS tools predict the energy performance of a given greenhouse and the crop growth. In general, the tool supports the understanding of how a greenhouse operates to given criteria and describes the relations and the interactions between greenhouse crop processes and greenhouse environment (Luo et al. 2005). During the past decades, many research endeavors with a focus on GPS have contributed to the development of the mathematical greenhouse model. The main features and functions of the leading GPS tool are described in Zwart (1996). What can be learned from the literature is that in order to implement the CAGS greenhouse concept, the GPS tool needs three main mathematical models: a heat transfer model (conduction, convection and radiation) a mass transfer model (air, moisture and CO_2 exchange by ventilation, infiltration) and a crop model (crop growth). Vanthoor (2011) also described the following three requirements of a greenhouse model for model-based greenhouse design: 1) the model should predict the temperature, vapor pressure and CO_2 concentration of the greenhouse air, with sufficient accuracy for a wide variety of greenhouse designs under varying climate conditions, 2) the model should include the commonly used greenhouse construction parameters and climate conditioning equipment, and 3) the model should consist of a set of first order differential equations to ensure that it can be combined with a tomato yield model (of a similar structure) and to allow the use of ordinary differential equation solvers. However, for the sake of the performance assessment of the CAGS concept greenhouse, the GPS tool has to satisfy the following additional requirements: control of shell properties, small simulation time step and flexibility and connectivity to allow the use of optimization algorithms.

3.2.1.1 Control of shell properties

The control of shell properties for shortwave radiation, longwave radiation and heat conduction is necessary for the CAGS concept greenhouse. The importance of each of these properties is discussed below.

Shortwave radiation

Shortwave radiation is one of the most important factors affecting crop growth, production and quality, and energy consumption. The rate of crop growth, yield and quality are all strongly dependent on the amount and quality of shortwave radiation. In addition, since the environment of the greenhouse is only divided by transparent shells and the amount of shortwave radiation is considerable, the solar transmissivity of the shell has a significant influence on energy consumption.

The amount of shortwave radiation that is present inside the greenhouse is dependent on three optical properties of the greenhouse shell: transmission, absorption and reflection. Once shortwave radiation is transmitted, it is absorbed or reflected by the crop, the greenhouse structure and the growing medium, usually soil. The shortwave radiation that is absorbed by the crop, greenhouse structure and growing medium turns into longwave radiation, and this increases greenhouse temperature. This temperature increase will decrease the heating energy demand in winter and increase cooling energy demand in summer.

Shortwave radiation can be divided into PAR and NIR, as described in Chapter 2 and shown in figure 2.7. The majority of PAR is absorbed by the crop and is used to drive photosynthesis. Since absorbed radiation leads to a temperature increase in the crop, the crop responds with transpiration, which increases the relative humidity in the greenhouse. The rest of the shortwave radiation (some part of PAR and NIR radiation) is absorbed in the greenhouse or reflected to the outside greenhouse through the greenhouse shell.

The ability to separately control these two radiations, NIR and PAR, will help to increase overall energy performance of the greenhouse (Vanthoor et al. 2011). For example, blocking NIR in summer leads to cooling energy saving and maximizing NIR in winter results in heating energy saving.

Since the CAGS concept greenhouse relies on controlling these two types of shortwave radiation separately, the control of both PAR and NIR transmissivity during simulation run time are requirements for the GPS tool.

Longwave radiation

Longwave heat radiation exchange is dependent on surface emissivity. Most of the greenhouses materials have high emissivity (≈0.84 for glass), which results in high longwave radiation heat exchange. The exchange of longwave radiation mainly occurs between the greenhouse interior and greenhouse shell, and between greenhouse shell and the sky. Control of longwave radiation is achieved by applying shading control and/or aluminized screen.

Since longwave radiation heat loss is considerable during night time and in winter due to high emissivity, the control of inside and outside emissivity is crucial and as such is incorporated into the CAGS concept. Thus, the GPS tool must also be capable of controlling inside and outside emissivity during simulation run time.

Heat conduction

Heat transfers by conduction occurs through the floor and the greenhouse shell. Since most of the greenhouse shells in the Netherlands use single-glazing, which has a low thermal performance, the amount of heat gain and heat loss by conduction is considerable over the year. One promising option to mitigate these changes is the ability to control the thermal performance of greenhouse materials. For example, by achieving a high U-value in summer to get rid of inside heat from shortwave radiation, and achieving a low U-value in winter to preserve inside heat and to block heat loss to the outside. Since the control of heat conduction is key to the CAGS concept greenhouse, controlling heat conduction of a material during simulation run time is also necessary for the GPS tool.

3.2.1.2 Small simulation time step

The short simulation time step is required for the implementation of the CAGS concept greenhouse and accuracy. Since this study will investigate the performance of the CAGS concept greenhouse with high and low adaptation frequency (which refers to the period between changes of the shell properties) such as year, month and hour simulation, the time step should be smaller than the highest adaptation frequency. In addition, since the implementation of the greenhouse simulation in this study is based on detailed and complex greenhouse components, the accurate result of the GPS tools by a short simulation time step is desirable. According to previous research, less than 1 hour of simulation time step provides great accuracy (Santos & Mendes 2004).

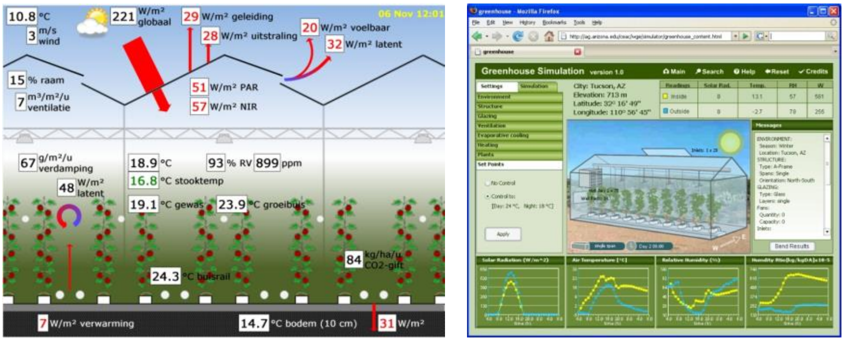
3.2.1.3 Flexibility and connectivity required to use the optimization algorithm

In order to implement the CAGS concept, a set of properties that meets the control objectives of the shell is required for each adaptation frequency. This study exploits an optimization algorithm to determine the set of optimal properties, which is described in Chapter 4. This optimization technique has been successfully applied in building design and a number of applications were described in Nguyen (2014). However, as yet, neither BPS tools nor GPS tools are fully capable of the implementation of optimization, which means that the GPS tool needs the 'flexibility' to modify some of its existing functions. In addition, in order to find the optimum set of input variables, accessing other functions from external tools (this is also described in chapter 4) is necessary. Thus, the desired GPS needs 'connectivity' with other external tools.

3.2.2 Greenhouse performance simulation tools for Climate Adaptive Greenhouse Shells

Most earlier greenhouse simulation models were developed based on simple steady state heat and mass balance equations without consideration of heat storage in the greenhouse structure and floor (Kimball 1973; Van Bavel et al. 1981; Jolliet et al. 1991; Gupta & Chandra 2002). These models were developed mainly to determine heating and ventilation system size or to study effects of location, orientation, heating and cooling alternatives, etc. (Gupta & Chandra 2002). However, in order to increase simulation accuracy, recent GPS tools use dynamic models, which consider weather condition and include a model of plant growth (Zwart 1996; Gauthier et al. 1997; Navas et al. 1998; Cunha 2007; Fitz-Rodríguez et al. 2010). Most of these tools are empirically validated before use. The state-of-the-art GPS tools provide a selection of locations, structure type, glazing type, natural and mechanical ventilation for cooling and dehumidification, infiltration, shading, heating and cooling systems, and crops.

Many studies have contributed to the development of greenhouse models. However, most of them were used for a single, or very limited number of specific purposes of investigation. Only a few of these research endeavors have specifically aimed to develop a 'GPS tool'. Surprisingly, only two GPS tools — KASPRO and Greenhouse environment simulator — are currently available for research and education purposes; the rest of them are not available anymore.



City: Tucson, AZ
Elevation: 713 m
Latitude: 32° 16' 49"
Longitude: 110° 56' 45"

○ No Control
● Control to:
[Day: 24 °C, Night: 18 °C]

ENVIRONMENT:
Season: Winter
Location: Tucson, AZ
STRUCTURE:
Type: A-Frame
Spans: Single
Orientation: North-South
GLAZING:
Type: Glass
Layers: single
Fans:
Quantity: 0
Capacity: 0
Inlets:

Figure3.1 *Interface of KASPRO Live (left)(www.wageningenur.nl) and Greenhouse environment simulator (right) (Fitz-Rodríguez et al. 2010)*

Greenhouse environment simulator (Fitz-Rodríguez et al. 2010) is a web-based GPS tool with a graphical user interface designed for education purposes and to provide a better understanding of the dynamic behavior of greenhouses with different configurations and climate conditions. However, this simulator only allows a simulation period of 28 hours and does not allow for the modifying of configurations.

KASPRO (Zwart 1996) was developed by Wageningen University in the Netherlands for energy saving in greenhouse cultivation. KASPRO calculates indoor climate, energy consumption, moisture balance, CO_2 balance and crop growth in the greenhouse while taking into consideration weather conditions, energy supply system and cultivation scenarios. The validity of KASPRO simulation outcomes has been demonstrated empirically by a number of research projects (Campen et al. 2009; Luo et al. 2005; Katsoulas et al. 2015) and research with different climate conditions (Vanthoor et al. 2011). Thus, KASPRO appears the most suitable, existing tool in that it not only has all of the features and functions to evaluate performance of the greenhouse, but is also developed and validated for Dutch climate conditions. Notwithstanding these pros, there are two important cons with KASPRO that prevent it being implemented as an off-the-shelf solution for the current research. First, KASPRO does not provide the option to modify its models and configurations, and second, it does not allow for the simulation code to be revealed to the public. In order words, KASPRO cannot be used for this research since it cannot implement a control of the shell properties and does not have the flexibility and the connectivity for use in the optimization algorithm.

To sum up, none of the existing GPS tools meet the requirements (described in section 3.2.1) that are necessary for the performance assessment of the CAGS concept greenhouse. As an alternative, the following section investigates if existing BPS tools are suitable for this research.

3.2.3 Building performance simulation tools for Climate Adaptive Greenhouse Shells

Since none of the existing GPS tools are suitable for direct application in the current research, this section investigates the possibility of using a BPS tool for the performance assessment of CAGS. BPS tools have largely been developed to mathematically test buildings in design and in operation by predicting thermal, visual and energy performance of the building.

State-of-the-art BPS tools provide detailed energy analysis and integrated solutions with a high degree of accuracy. Unlike GPS tools, some of these BPS tools are available under an open-source license. As such, many developers worldwide have been using these tools and have also contributed many innovative new features and enhancements to the tools.

From a review of the number of BPS tools[1] that currently exist the most promising for the current research turns out to be ESP-r[2]. ESP-r is a state-of-the-art BPS tool and, crucially, it is open source. In addition, it has significant power in modelling building physics. ESP-r has highly resolved and well validated methods for modelling the interactions between the indoor and outdoor environments and the building fabric (Beausoleil-Morrison et al. 2013). ESP-r provides small simulation time step for accurate calculation. EPS-r also has flexibility and connectivity for both control of shell properties and for using optimization algorithms from other tools, as shown Figure 3.2.

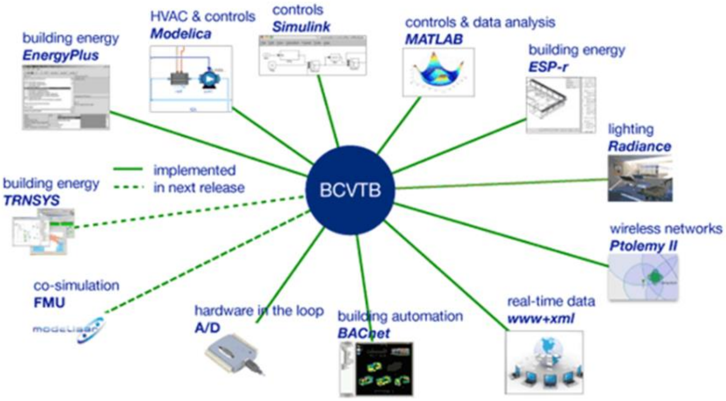


Figure3.2 *Example of a middleware, BCVTB, for co-simulation: connectivity of a BPS tools (http://eetd.lbl.gov)*

ESP-r meets the three key requirements — control of shell properties that can be implemented by code modification, various simulation time steps and flexibility and connectivity for use in the optimization algorithm — and seems therefore the most suitable tool for the performance assessment of the CAGS concept. The implementation, capability and algorithm of ESP-r can be found in (Hand 2015) and (Clarke 2001). However, since ESP-r was developed for building performance simulation, it is not validated for greenhouse performance prediction. In addition, several models and controls need to be added for GPS.

Thus, in the next two sections, this research preliminarily validates ESP-r with an existing GPS tool, KASPRO, to investigate if the thermal performance prediction of ESP-r is suitable for GPS and then describes code development for greenhouse simulation.

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[1] *www.buildingenergysoftwaretools.com*

[2] *www.esru.strath.ac.uk/Programs/ESP-r.htm*

3.2.4 Using ESP-r for greenhouse performance simulation

Although the capabilities of ESP-r have been validated for building performance assessment (Strachan 2000), validation of ESP-r for GPS is necessary before its use in this research. There are three validation philosophies: comparative testing, analytical verification and empirical validation. These methodologies can be found in (Neymark et al. 2002) and (Judkoff et al. 2008). KASPRO, one of the GPS tools developed for performance assessment of Dutch greenhouse, has been empirically validated by a number of research efforts (Zwart 1996; Luo et al. 2005; Campen et al. 2009; Vanthoor et al. 2011; Katsoulas et al. 2015). Examples of these validation results are provided in Figure 3.3.

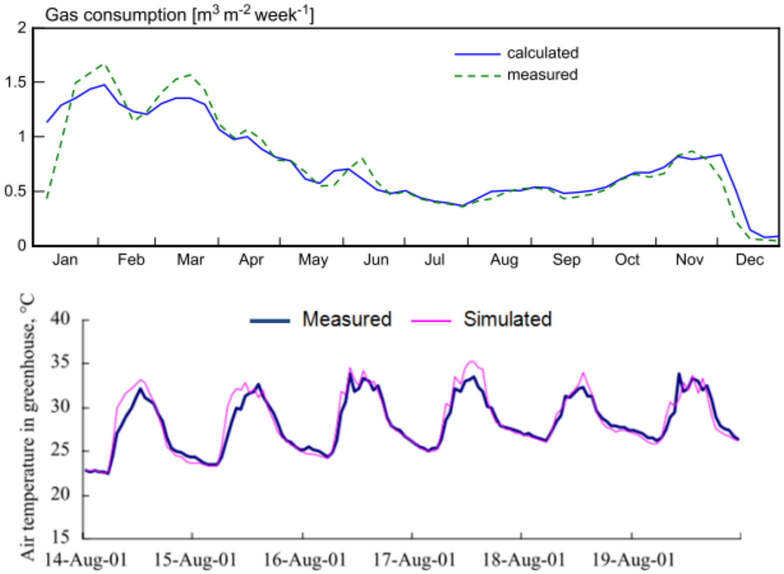

Figure3.3 *Validation of KASPRO: measured (––) and simulated (—) air temperature* (Luo et al. 2005) *and weekly gas consumption* (Campen et al. 2009) *in the greenhouse.*

The comparative study is a useful technique because it does not require data from a real greenhouse and the quality of simulation can be obtained quickly with little expense (Neymark et al. 2002). Therefore, ESP-r is comparatively tested using KASPRO (in cooperation with Wageningen University). The direct comparison of the results focuses on indoor air temperature in the greenhouse and solar radiation on the crop (canopy surface). Air temperature is one of the important factors in GPS since air temperature is strongly correlated with crop growth and air temperature fluctuations from outside weather conditions correlate with use of energy. The shortwave radiation on the canopy surface is also one of the important factors since intensity of shortwave radiation has a direct effect on transpiration (evaporative cooling), the amount of photosynthesis and the quantity and quality of the produced crop.

The simulation model and the specification of the comparative study are shown in figure 3.4 and table 3.1 respectively. Figure 3.4 illustrates the comparison model, which comprises an empty box-shaped greenhouse with no crop to investigate thermal performance prediction only. Since the commercial greenhouse is a low rise structure with a very large roof area, the center and edge of the greenhouse have different indoor climates. In addition, since the center accounts for most of the greenhouse's area, the GPS tool did not consider any heat exchange from the 4 walls (Zwart 1996). Table 3.1 provides the model specifications including size, boundary condition, thermal and optical properties. The location of simulation is the municipality of De-Bilt in The Netherlands and the climate file for both programs was generated with measured data from KNMI[3].

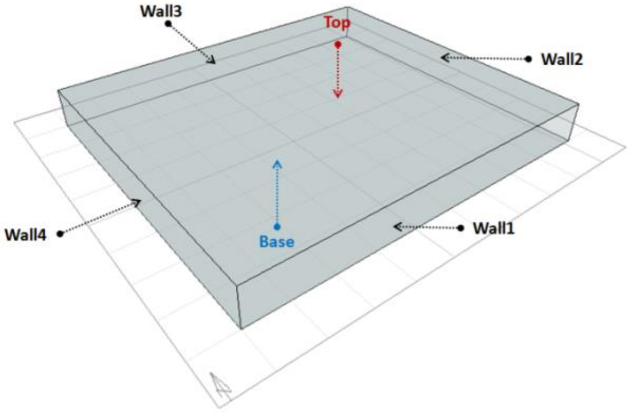

Figure3.4 *Simulation modelling for preliminary comparison study*

Table 3.1 Specification of the greenhouse validation model

Location		De-Bilt, The Netherlands	
Size (m)		100 (L)×100 (W) ×6 (H)	
Boundary condition		Wall 1~4	Adiabatic
		Top	Exterior
		Base	Ground
Optical properties of glass		Transmittance	0.85
		Absorptance	0.00
		Reflectance	0.15
Thermal properties	Glass	Conductivity [W/(m-K)]	1.05
		Density [kg/m^3]	2600
		Specific heat [J/(kg-K)]	840
		IR emissivity	0.84
		Solar absorptance	0.00
	Floor (Plastic)	Conductivity [W/(m-K)]	0.50
		Density [kg/m^3]	1050

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[3] *Koninklijk Nederlands Meteorologisch Instituut, Dutch meteorological institute*

		Specific heat [J/(kg-K)]	837
		IR emissivity	0.6
		Solar absorptance	0.25
	Ground (Soil)	Conductivity [W/(m-K)]	0.85
		Density [kg/m^3]	1640
		Specific heat [J/(kg-K)]	879

As mentioned in 3.2.1, the influence of longwave heat exchange between greenhouse roof and the sky is substantial due to the low thermal performance of shells and large roof surface. KASPRO uses measured cloudiness data to calculate the sky temperature for greenhouse simulation whereas ESP-r predicts the degree of cloudiness based on the climatic conditions (Čekon 2015). This algorithm difference between the two tools results in a difference in roof surface temperature, as shown in figure 3.5, which eventually leads to indoor air temperature difference.

In order to render ESP-r suitable for GPS, the code of the sky temperature required modification. The effects of this code modification are presented in Figure 3.5, which contrasts the values derived for roof temperature in winter with and without the code modification. The roof temperature in the figure indicates that the modified version of ESP-r calculates the effect of longwave radiation exchange more closely to KASPRO than the unmodified version (See section 3.3.1 for a detailed comparison of algorithms).

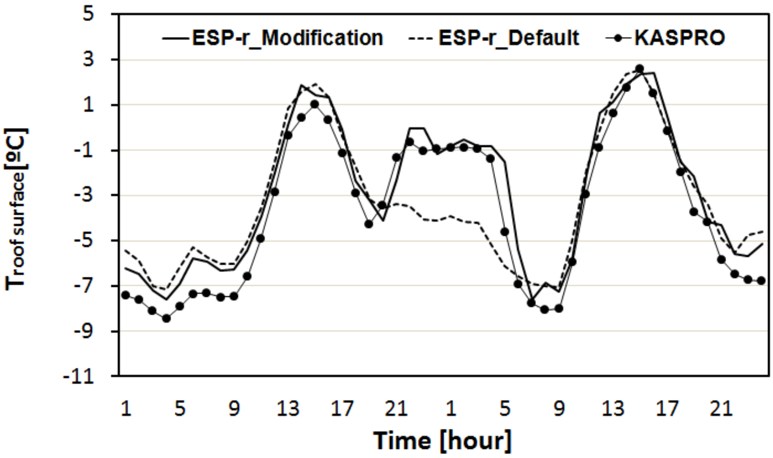


Figure3.5 Roof surface temperature with or without consideration of cloudiness

The following figures, 3.6 and 3.7, illustrate the comparative results of the two tools with regard to air temperature in the greenhouse and shortwave radiation on the canopy surface over the year. Curve fitting for both air temperature and SW radiation shows that ESP-r follows KASPRO well. In frequency analysis, ESP-r tends to predict slightly higher temperature and somewhat lower intensity of shortwave radiation than KASPRO.

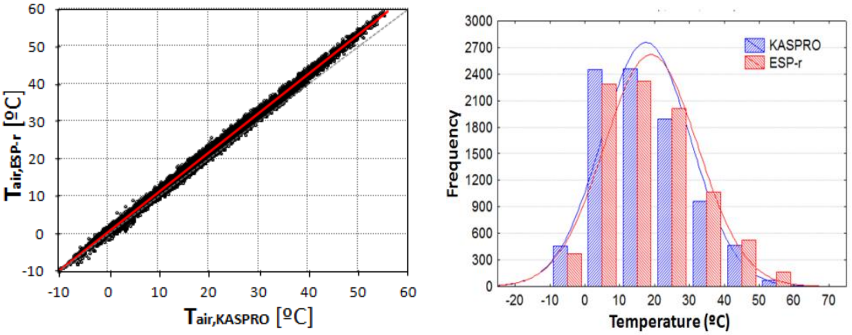


Figure3.6 *Relation of air temperature and distribution of temperature in greenhouse throughout the year*

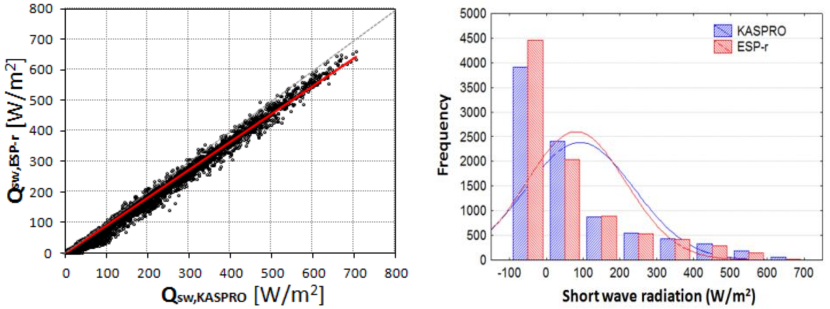


Figure3.7 *Relation of SW radiation and distribution of SW radiation on canopy surface throughout the year*

Table 3.2 provides the error analysis between the results from KASPRO and ESP-r: correlation coefficient (R), mean bias error (MBE) and root mean squared error (RMSE). The R explains linear correlation between two simulation results and the MBE and RMSE show how well ESP-r outcomes fit KASPRO results. In the table below, lower error value and percentages indicate better agreement of results.

Table 3.2 *Analysis results of error comparison between KASPRO and ESP-r for indoor air temperature and intensity of shortwave radiation*

	MBE		RMSE		R
Air temperature	1.40(°C)	8.1(%)	1.78(°C)	10.2(%)	0.998
SW Radiation	-10.39(W/m2)	-11.51(%)	19.67(W/m2)	21.8(%)	0.993

According to these error analysis results, correlations of the programs for two simulation results show a highly linear relation with a coefficient of 0.99. Air temperature shows a 1.4°C (8.1%) error in MBE and a 1.78°C (10.2%) error in RMSE. Shortwave radiation on the canopy surface shows a 10.39 W/m^2 (11.51%) error in MBE and a 19.67 W/m^2 (21.8%) error in RMSE. ESP-r shows a reasonable result for air temperature but a slightly higher error for SW radiation. This result is mainly due to the discrepancies in algorithms between the two tools.

However, this difference might not result in a significant error for estimation of energy and production of GPS, and thus it could be concluded that ESP-r is a suitable tool for GPS.

3.3 ESP-r code development for greenhouse performance simulation

This section introduces the required capabilities that need to be added to ESP-r and describes the code development of ESP-r to make it suitable for GPS. The code related to crop behavior is provided by Wageningen University and further theoretical description can be found in (Goudriaan 1994) and (Zwart 1996). The required and developed capabilities in ESP-r for GPS are shown in Figure 3.8.

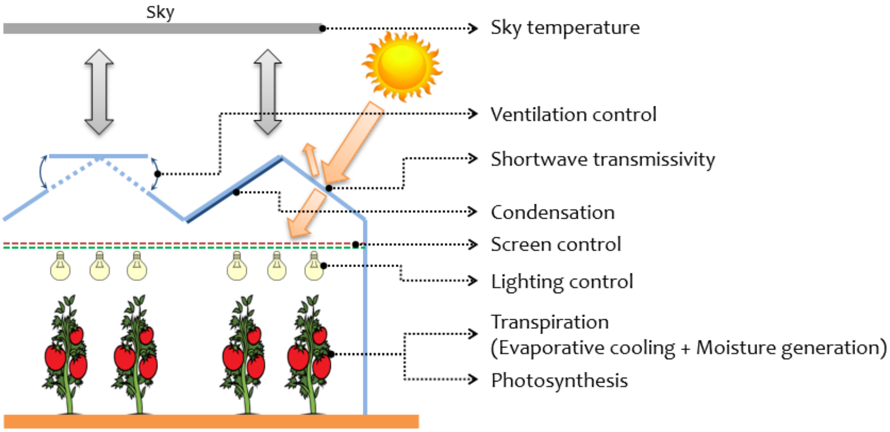


Figure3.8 *Overview of the code development in ESP-r for GPS*

3.3.1 Sky temperature

Due to the huge roof surface and low thermal performance of greenhouse shells, longwave heat exchange is one of the major heat gain and loss mechanisms in the greenhouse. Thus, accurate calculation of sky temperature is important to reproduce the thermal behavior of the greenhouse. KASPRO uses cloudiness data for calculation of sky temperature, whereas ESP-r predicts the degree of cloudiness based on the climatic conditions (Čekon 2015). This study first compared sky temperature between KASPRO and ESP-r using measured weather data from KNMI. ESP-r currently provides six sky temperature modules and the comparison result is shown in Figure 3.9. High sky temperature difference can be observed between the two tools, in particular, when cloudiness is high. The use of different sky temperature modules results from the different developmental purposes of the two tools.

Since KASPRO was developed for GPS and validated for Dutch greenhouses, the new GPS tool uses the KASPRO sky temperature module with its consideration of cloudiness.

The emissivity of clear sky ($\varepsilon_{clear.sky}$) is proposed by (Brunt 1939; John Monteith 1973) in moderate latitudes,

$$\varepsilon_{clear.sky} = 0.53 + 6 * 10^{-3} VP_{air}^{0.5} \qquad [-]$$

where, VP_{air} is air vapour pressure [Pa].

(Zwart 1996) proposed the sky temperature (T_{sky}) considering cloudiness as

$$T_{sky} = ((1 - c)\ \varepsilon_{clear.sky} * T_{air}^{\ 4} + c\ (T_{air}^{\ 4} - 9/\sigma))^{\ 0.25} \qquad [K]$$

where, T_{air} is air temperature, c is the flection of the sky covered by cloud and σ is the Stefan-Boltzmann constant (5.67 * 10 $^{-8}$ W/(m^{2}K^4)).

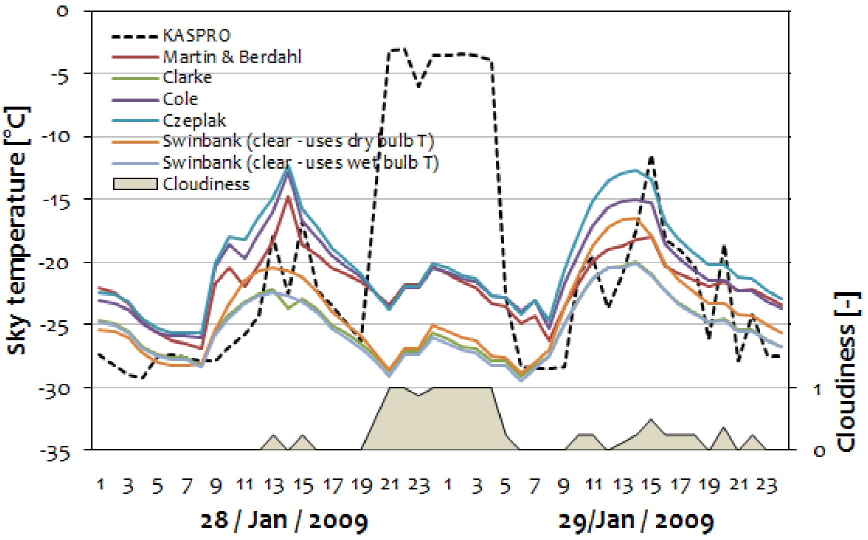


Figure3.9 *A comparison of the sky temperature between KASPRO and six ESP-r modules*

3.3.2 Photosynthesis and respiration

Photosynthesis is the process of capturing light energy and converting it into sugar energy using CO_2 and water. In general, the crop does not require the whole spectrum of solar radiation for growth. As shown in Figure 3.10 together with Figure 2.7, the whole solar spectrum can be dived into three parts for crop growth: Ultra violet (UV), Photosynthetically Active Radiation (PAR) and Near Infrared Radiation (NIR). The wave length range of PAR is more or less the same as the human eye's sensitivity and is used in the process of photosynthesis for crops.

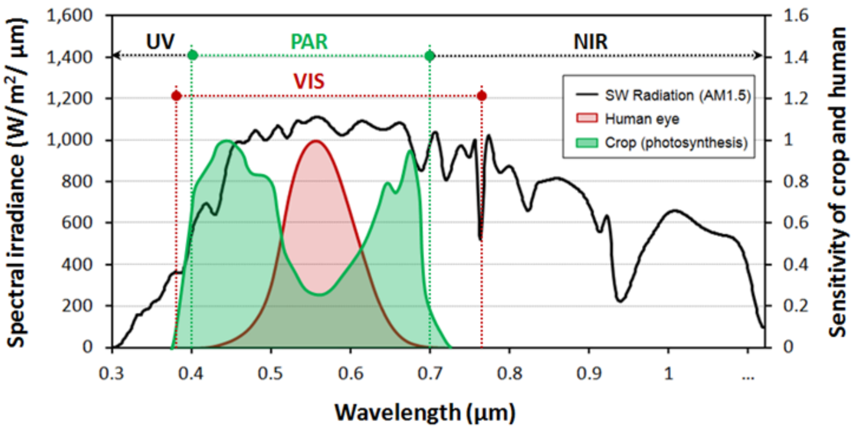


Figure 3.10 *Distribution of solar radiation and sensitivity of photosynthesis in spectral band.*

The amount of photosynthesis is dependent on the efficiency of PAR light (η_{PAR}) and this is estimated by

$$\eta_{PAR} = C1 * \gamma_{CO2} + C2 * \gamma_{CO2} + C3 * \gamma_{CO2} \qquad [-]$$

where, γ_{CO2} is CO_2 concentation [ppm] in the greenhouse. Three coefficients are function of PAR level on the crop (I_{PAR}) [W/m²] and given by

$$C1 = -4*10^{-16} * I_{PAR}{}^{3} + 3*10^{-13} * I_{PAR}{}^{2} - 8*10^{-11} * I_{PARy} - 3*10^{-8}$$

$$C2 = 6*10^{-13} * I_{PAR}{}^{3} - 6*10^{-10} * I_{PAR}{}^{2} + 1*10^{-7} * I_{PAR} + 6*10^{-5}$$

$$C3 = -2*10^{-10} * I_{PAR}{}^{3} + 2*10^{-7} * I_{PAR}{}^{2} - 1*10^{-4} * I_{PAR} + 0.0185$$

Therefore, gross assimilation (α_g) is calculated by

$$\alpha_g = I_{PAR} * \eta_{PAR} \qquad [kg/m^2/s]$$

The photosynthesis rate is the function of crop temperature, amount of PAR radiation and CO_2 concentration, as shown in Figure 3.11. The amount of photosynthesis has a proportional relation with increases in PAR radiation and CO_2 concentration, whereas it has an inverse proportional relation with increases in crop temperature. This photosynthesis rate is an indicator of crop growth and production. Therefore, amount of photosynthesis is one of the important performance aspects in the greenhouse. Based on the photosynthesis rate, the production of crop can be estimated.

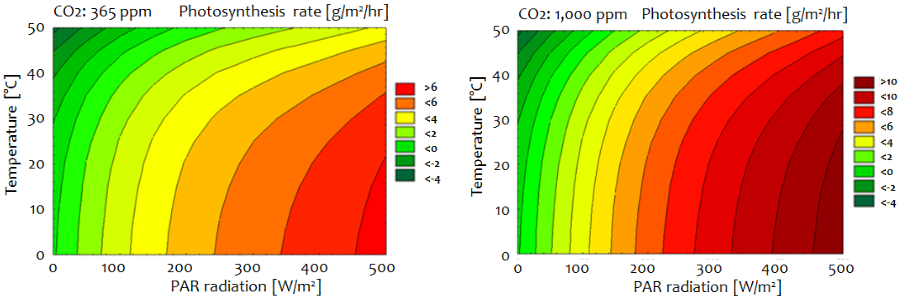


Figure3.11 *Photosynthesis rate depending on crop temperature, CO_2 concentration and PAR radiation*

In Figure 3.11, negative values indicate respiration. Respiration is the process of metabolizing sugars to use as energy for growth, reproduction, and other life processes.

The amount of respiration for maintenance (R_m) is:

$$R_m = 1.08 \quad \text{or} \quad R_m = 0.054 * (T_{canopy} - 20) \qquad [kg/m^2/s]$$

Whichever equation leads to the higher value becomes the calculation for respiration for maintenance. When it comes to the calculation of canopy temperature (T_{canopy}) this study assumed that the air temperature is equal to T_{canopy}. Therefore, net photosynthesis rate (P_{net}) can be calculated by

$$P_{net} = \alpha_g - R_m \qquad [kg/m^2/s]$$

This crop model is implemented in new GPS tool. The simple photosynthesis model provided here is based on Goudriaan (1994) and is successfully validated under normal humidity and temperature conditions for tomato cultivation (Heuvelink 1996).

3.3.3 Transpiration

Transpiration essentially describes the loss of water that occurs as a result of evaporation of water vapor, largely from leaves and stomata. Transpiration is crucial to the plant's development for two main reasons. It allows the plant to transfer nutrients from the roots to the parts of the plant above ground, and it allows the plant to cool down (Forbes 1996). The transpiration rate is dependent on the intensity of global radiation and the leaf area index (LAI). The LAI is the ratio of total upper leaf surface divided by the ground surface area in which the crop is growing.

$$LAI = A_{leaf} / A_{ground} \qquad [m^2 / m^2]$$

where A_{leaf} is one side green leaf area [m^2] and A_{ground} is ground surface area [m^2]. The daily growth of LAI can be calculated by

$$LAI = 0.2 + 2.8 / (1 + \exp(-0.1 * (E_{day} - 50))) \qquad [-]$$

where E_{day} is elapsed days since planting in the greenhouse. The fraction of absorbed global radiation (F_{abs}) at plant level is given by:

$$F_{abs} = 1.1 * \exp(-0.6 / LAI) \qquad [-]$$

Therefore, absorbed short wave radiation (I_{abs}) by crop is:

$$I_{abs} = F_{abs} * ((I_{global} * \tau_{PAR} + 0.3 * P_{lamp}) + (I_{global} * \tau_{NIR} + 0.25 * P_{lamp})) \qquad [W/m^2]$$

where I_{global} is outside global radiation [W/m²], τ_{PAR} and τ_{NIR} is PAR and NIR transmittance of the greenhouse shell respectively, and P_{lamp} is power of electric light [W/m²]. The crop absorbs shortwave radiation and evaporates water vapour to lower its body temperature. The evaporative cooling energy (L_t) from transpiration can be calculated by

$$L_t = T_{base} * LAI \qquad \text{or} \qquad L_t = I_{abs} * 0.4 \qquad [W/m^2]$$

where T_{base} is base transpiration [W/m²] and different T_{base} depends on the crop, as described in Table 3.3. Whichever equation leads to the higher value becomes the calculation for evaporative cooling energy.

Table 3.3 *Maximum LAI and base transpiration for tomato, phalaenopsis and chrysanthemum.*

	Maximum LAI	Base transpiration
Tomato	3	3.75
Phalaenopsis	2	2.80
Chrysanthemum	2	3.50

Finally, crop transpiration (e_t) is calculated by

$$e_t = L_t / (2.45 * 10^6) \qquad [g/(m^2\ s)]$$

According to Forbes (1996), a crop typically loses over 98% of all water absorbed from roots for cooling and the remaining 2% of water is used to build up the body and maintain metabolism. This results in an increase of moisture inside the greenhouse resulting in high relative humidity, which is controlled by natural or mechanical ventilation. The transpiration model is implemented in the new GPS tool and connected to calculation of inside humidity and evaporative cooling.

3.3.4 Condensation

Due to the transpiration from the crop, relative humidity of the greenhouse is always high. When the surface temperature of the greenhouse shell is lower than the dew point temperature of the air, water droplets are formed by the moisture on the greenhouse shell. According to the calculations with KASPRO, a typical greenhouse cover is fully or partly wet about 50% of the year and the amount of condensation water is 100ℓ/m² of the greenhouse shell (Stanghellini et al. 2012). Since this condensation decreases inside humidity, it is important in terms of moisture balance. In addition, the condensation releases energy that comes from evaporative cooling to the shell, thereby warming-up the cover and somewhat decreasing the heating demand of the greenhouse (Stanghellini et al. 2012).

The condensation model in modified ESP-r for GPS is from the IEA Report annex 14 condensation and energy. When temperature of the shell surface is lower than the dew point temperature of air, the model calculates vapour pressure of air ($P_{vap.air}$) and surface ($P_{vap.surface}$) by using internal ESP-r subroutines. Then, the surface coefficient of water vapour diffusion (β) simplified for building application is calcuated by

$$\beta = 7.4 * 10^{-9} * h_c$$

where h_c is the convective heat transfer coefficient [W/(m^2 K)]. The internal ESP-r module (Clarke 2001) is used for the calculation. The water vapor density ($\rho_{vap.cond}$) of condensation can be estimated by

$$\rho_{vap.cond} = \beta\,(P_{vap.air} - P_{vap.surface}) \qquad [kg/m^2/s]$$

Furthermore, absorbed latent heat (L_{abs}) to the shell is calculated by

$$L_{abs} = \beta * h_c * (P_{vap.air} - P_{vap.surface}) \qquad [W/m2]$$

Normally, since water from condensation on the shell is removed by drain in Dutch greenhouses, re-evaporation of moisture is not taken into account. In addition, the drawback with regard to losing transmittance of solar radiation and increasing U-value caused from the condensation is not considered.

3.3.5 Ventilation control

By capturing solar energy during the day, the greenhouse heats up due to the so called greenhouse effect. This effect causes high air temperature in the greenhouse, which has a negative effect on crop growth and quality. If the temperature inside the greenhouse is higher than a certain set-point, the crop suffers leaf distortion and delay of development, and ultimately suffers damage or dies. In addition, high temperature is a causative factor in the decrease of photosynthesis and increase of respiration, both of which are correlated with a reduction of crop production (see Figure 3.11).

Additionally, the crop loses water vapor through the stomata of the leaves during the metabolic processes, which increase the inside humidity of the greenhouse. The optimum relative humidity range is between 60% to 90% for most crops (Kittas et al. 2012). However, if relative humidity is higher than 95%, there is a serious risk of mold growth, which causes disease, decreases the photosynthesis rate and lowers the absorbed CO_2 by closing stomatal openings, and finally results in low growth and poor quality of the crop. In order for the greenhouse to reduce air temperature and to decrease relative humidity, natural or mechanical ventilation using outside air is employed in Dutch greenhouses. Therefore, the implementation of two ventilation controls is necessary in the GPS tool.

Since most of the time outside relative humidity is lower than it is inside the greenhouse, ventilation is the best means to control humidity in the greenhouse. In general, most of the BPS tools provide a control option to introduce natural or mechanical ventilation for cooling. However, they, including ESP-r, do not offer sufficient options to control inside humidity with outside air. Thus, this study adds the control of ventilation through the sensor monitoring inside humidity.

The ventilation control of the greenhouse is implemented in the new GPS tool to reduce temperature and to adjust relative humidity, as described in Figure 3.12. The natural and mechanical ventilation control works with set-points of inside temperature and relative humidity. Mechanical ventilation works independently regardless of the wind speed outside of the greenhouse (Maslak 2015). When it comes to dehumidification, mechanical ventilation is a more efficient way than natural ventilation in that the air exchange by mechanical ventilation occurs close to the crop. Natural ventilation achieves dehumidification by exploiting windows above of the greenhouse. The dehumidification takes place based on *buoyancy driven, wind driven* or *both buoyancy and wind driven ventilation* (Vox et al. 2010). However, the ventilation rate is not proportional to the amount of air change due to the stratification of moisture arising from the height of the greenhouse (≈ 7m). This observation means that the assumption made by most of the BPS tools, of fully mixed air for humidity, is not suitable for GPS. Therefore, a new value for ventilation efficiency needed to be included in the new GPS. Thus, an assumption of 0.5 of ventilation efficiency is applied for natural ventilation.

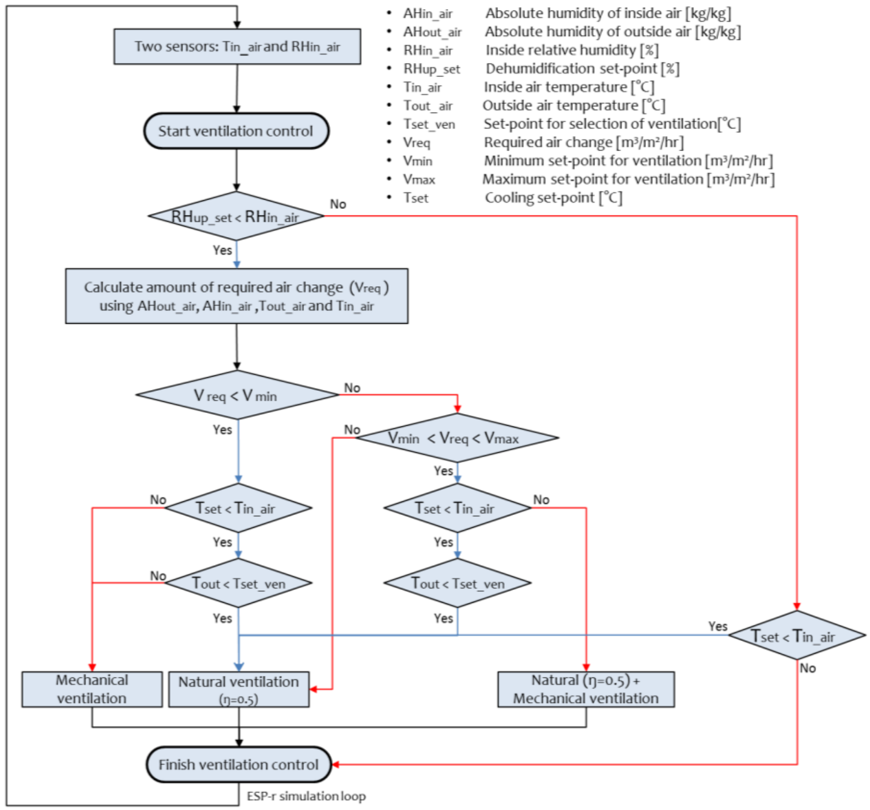


Figure3.12 *Control process of ventilation control in modified ESP-r for GPS*

3.3.6 Humidification

When greenhouse relative humidity becomes too low, crop transpiration increases. When this is the case, the nutrients or minerals do not transfer to the leaves, only the water does, which leads to nutrient deficiencies. In addition, the crop loses moisture and wilts very quickly. Therefore, low relative humidity ultimately results in a decrease of crop quality and quantity.

In order to raise the humidity level, a high pressure fogging system is employed in Dutch greenhouses. High pressure fogging has a direct effect on the energy balance through its use of evaporative cooling and on the moisture balance through water vapor increase. As such, this control is included in the modified ESP-r as shown in Figure 3.13.

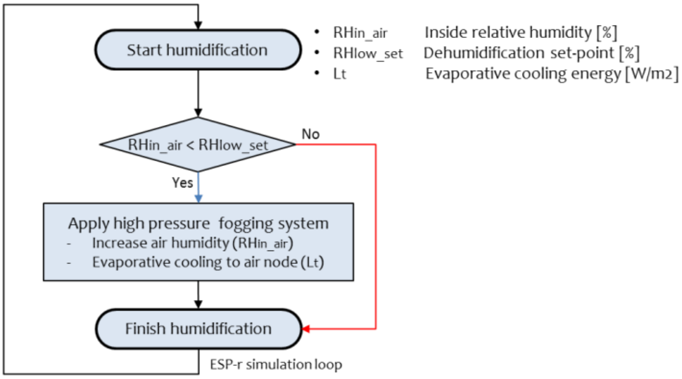
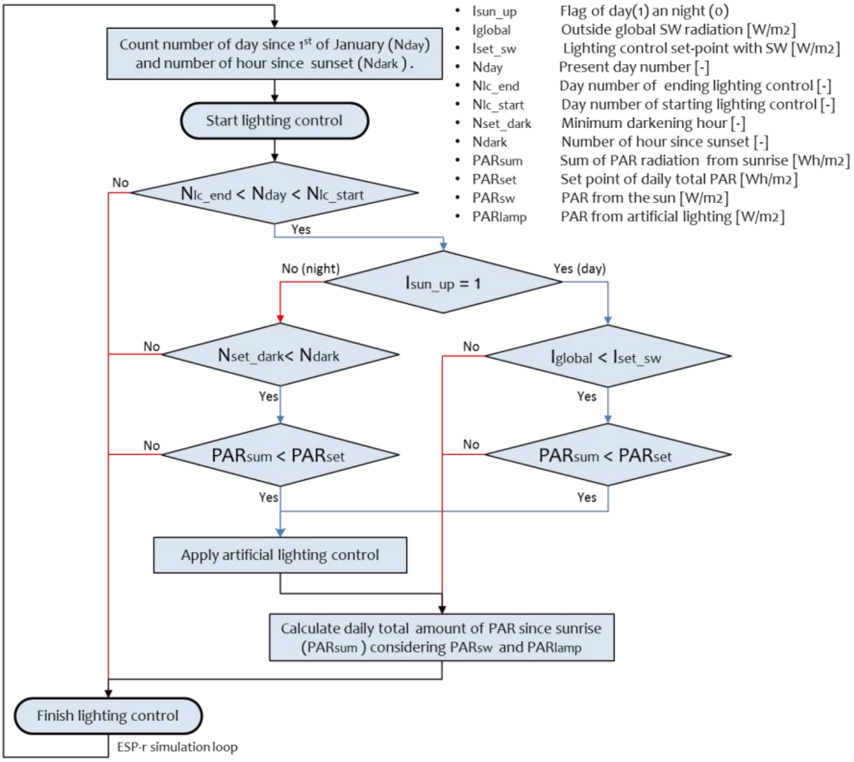


Figure3.13 *Control process of humidification in the modified ESP-r for GPS*

3.3.7 Artificial lighting control

Due to the solar radiation that it contains, light has a considerable effect on crop growth and development. However, the amount of solar radiation available varies according to the season. In order to produce good yields of good quality, the crop must absorb sufficient PAR radiation. Artificial lighting is used in the greenhouse to supply PAR radiation to the crop when the amount of PAR from natural light is not sufficient. Supplementing PAR in this manner is necessary to safeguard crop yields and maintain crop quality.

The artificial lighting plays an important role in the energy balance. Only a small percentage of the light turns into PAR radiation, which is used to enhance crop production. The remaining majority turns into longwave radiation, which is used to increase the greenhouse temperature. Since the main period of shortage of PAR radiation is winter, lighting helps greenhouse heating as a heat source. Since daily light integral (DLI) is important for crop growth and development (Warner & Erwin 2003), light control is depending on the daily sum of PAR radiation and this is implemented in the modified ESP-r, as shown in Figure 3.14.



Isun_up	Flag of day(1) an night (0)
Iglobal	Outside global SW radiation [W/m2]
Iset_sw	Lighting control set-point with SW [W/m2]
Nday	Present day number [-]
Nlc_end	Day number of ending lighting control [-]
Nlc_start	Day number of starting lighting control [-]
Nset_dark	Minimum darkening hour [-]
Ndark	Number of hour since sunset [-]
PARsum	Sum of PAR radiation from sunrise [Wh/m2]
PARset	Set point of daily total PAR [Wh/m2]
PARsw	PAR from the sun [W/m2]
PARlamp	PAR from artificial lighting [W/m2]

Figure3.14 *Control process of artificial lighting in modified ESP-r for GPS*

3.3.8 Screen control

Three types of screen — thermal, shading and black screen — are used in Dutch greenhouses, depending on their purpose (Bakker et. al 1995). The purposes of the screen control are: to prevent crop damage from high solar radiation; to adjust day length for flowering; to reduce cooling demand in summer; and to block heat loss to the outside in winter (Montero et al. 2013). The reduction of heating and cooling demand is the main goal for most greenhouses, and is achieved by using different set points of shortwave radiation and outside air temperature. However, the adjustment of day length is also important for some crops because length of light triggers flowering. Flowering crops can be categorized into short-day, long-day or day-neutral plants, depending on the duration of darkness for flowering. Short-day (long night) plants form flowers when the day length is less than about 12 hours and long-day (short nights) plants form flowers when day lengths is more than 12 hours, while day-neutral plants form flowers regardless of day length (Durner 2013). These screen controls are implemented in the new GPS for different purposes with different crops as shown Figure 3.15.

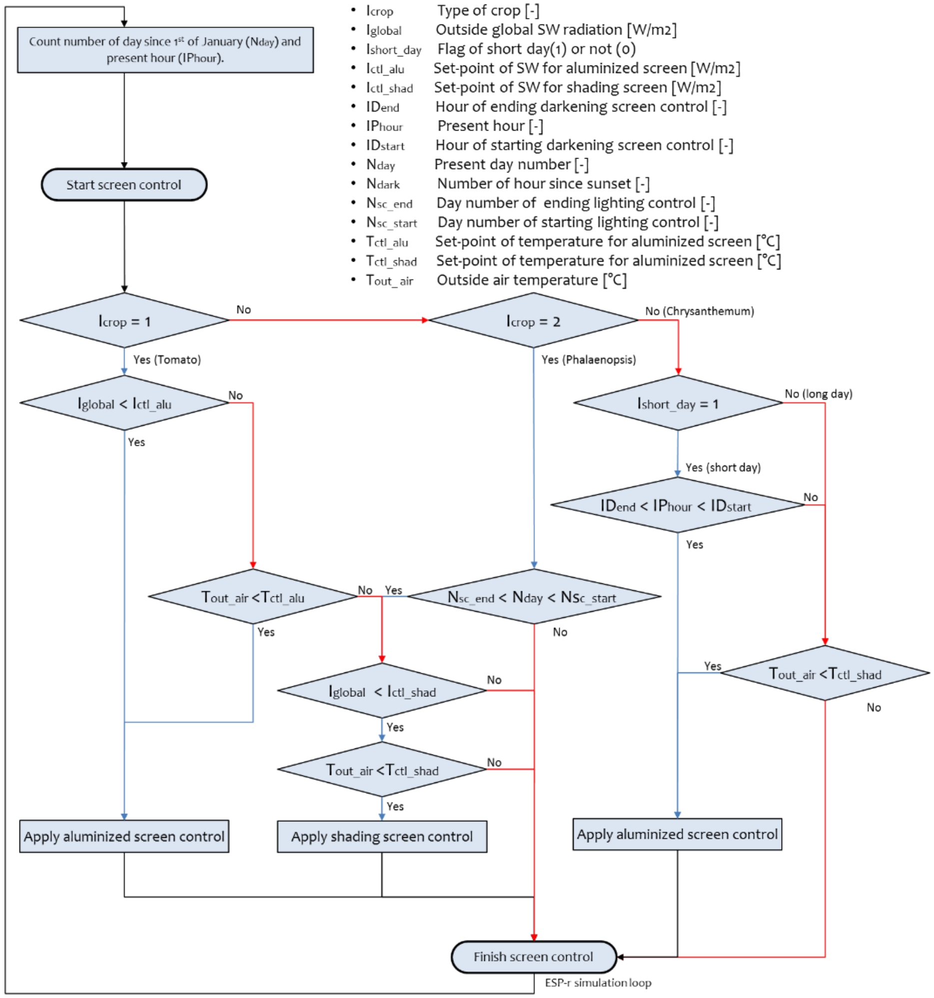


Figure3.15 *Control process of screen in modified ESP-r for GPS*

3.3.9 Shortwave transmittance of greenhouse roof

The transmittance of glass varies with the incident angle of direct radiation. In general, the transmittance is maximal when the angle of incidence is normal to the glass surface and is decreased when the angle is close to horizontal. Since most Dutch greenhouses have saw-tooth roofs, the transmittance of solar radiation depends on both the angle and orientation of solar radiation. The variation of transmittance is caused by differences in shading due to greenhouse structures composed of glass, bars and gutters (Zwart 1993). The variation of transmittance is shown Figure 3.16. The difference in transmittance between 40 degree to 80 degree orientation results from roof shape and shading. The different shape of roof and shading from greenhouse structures should be considered in order to properly predict radiation entering the greenhouse. The change of optical properties depends on incident angle and orientation, and is implemented in the modified ESP-r.

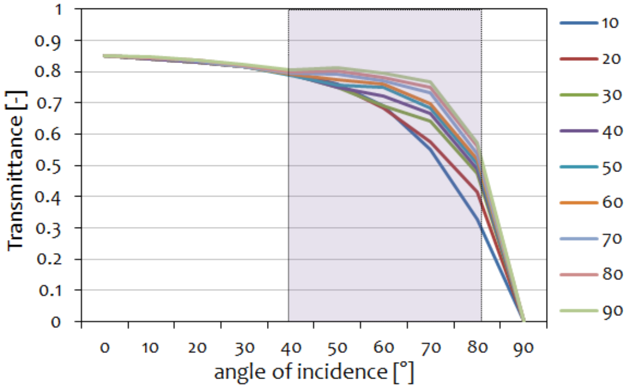


Figure3.16 *Shortwave transmittance of typical Venlo-type greenhouse roof considering angle of incidence and orientation*

3.4 Implementation of greenhouse performance simulation

Using the existing heat transfer algorithm in ESP-r and newly developed model, GPS was implemented. The implementation of heat and mass transfer is illustrated in Figure 3.17. Due to lack of available information for greenhouse thermal model, some thermal behaviour of the greenhouse in ESP-r is not implemented and therefore simplified.

When the shading screen is closed, greenhouse can be divided into two zones: air compartment (below shading screen) and top compartment (above shading screen). In this study the longwave heat exchange and mass transfer in the top compartment is not implemented, and optical properties of screen is integrated into layer of the shell. However, this simplification do not lead to critical problem in the CAGS concept greenhouse because shading is controlled in the shell.

Thermal behaviour of the crop is not implemented on the canopy surface (see (Zwart 1996)) and, instead, evaporative cooling and moisture generation from the crop is applied in air nod. In addition, this study assume that canopy temperature is the same as the air temperature for calculation of the respiration. Since a validation of the simplified implementation was not available, it is unknown how much canopy surface affects the thermal behaviour in greenhouse and finally simulation result.

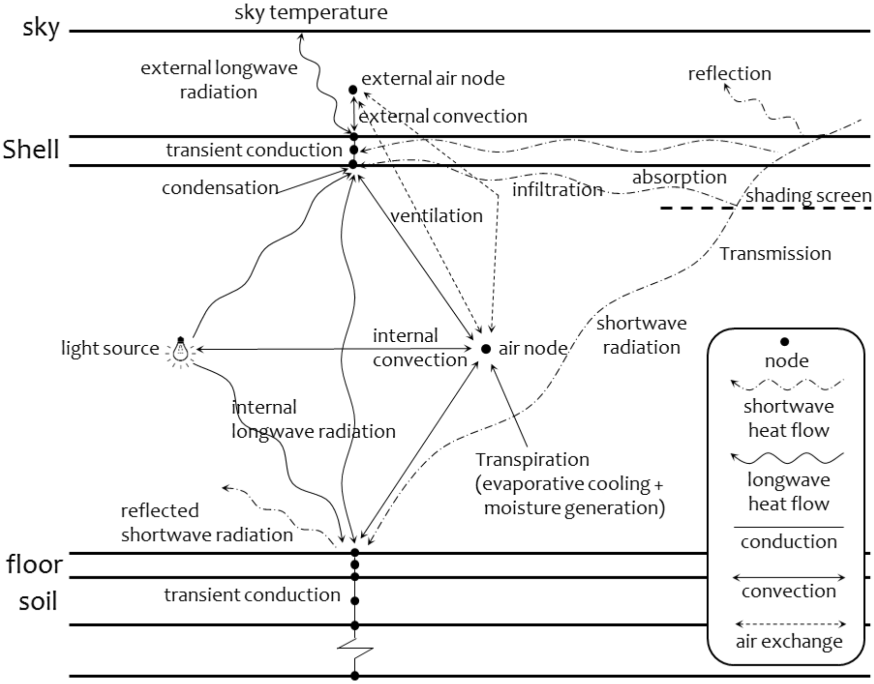


Figure3.17 *Greenhouse energy flow paths of simplified GPS implementation*

3.5 Conclusion

The main goal of this chapter was to deliver a GPS tool to assess the performance of the CAGS concept greenhouse. The starting point was to review existing GPS and BPS tools. As the review demonstrated, none of the existing GPS tools are suitable for a rigorous performance assessment of the CAGS concept. However, particular BPS tools, which provide sufficient flexibility and connectivity, do appear to represent a suitable foundation for the performance assessment methodology.

Thus, after selecting the most suitable, currently available BPS, ESP-r, the research investigated its viability for use as a GPS tool that could be used to later assess the performance of the CAGS concept. This investigation concluded that ESP-r is a suitable tool for the research purpose, but it is necessary to modify it somewhat and add the following key functions for GPS: sky temperature, photosynthesis and respiration, transpiration and evaporation, humidification, condensation, ventilation control, artificial lighting control, screen control and transmittance of greenhouse roof. Many assumptions of heat and mass transfer models from ESP-r are employed for GPS (see (Clarke 2001)). Using the modified ESP-r for GPS, a simulation methodology was developed and is presented in the next chapter.

4 Computational performance prediction of climate adaptive greenhouse shells

4.1 Introduction

Presuming that the structure and operational conditions are known, the typical Venlo-type greenhouse can be assessed using the modified ESP-r developed in Chapter 3. However, the tool does not yet have sufficient capabilities to simulate the CAGS concept greenhouse, largely due to its 'adaptability', which will be explained below.

As defined in Chapter 2.3, the CAGS concept greenhouse changes or 'adapts' its shell properties by considering outside climate conditions in order to meet predefined objectives. Depending on the objective, a small or large set of adaptive shell properties are required, which translates to number of shell changes in a certain period. In this study, 'adaptation period' refers to the period between changes of the shell properties and 'adaptation frequency' refers to the number of changes over the assessment period.

In order to implement the CAGS concept greenhouse, the simulation model should be able to use an optimized set of shell properties for each adaptation period. However, since no single simulation tool can currently manage the performance prediction encompassing adaptability, this chapter develops a new simulation methodology suitable for this purpose. The chapter first investigates and introduces previous approaches to the simulation of adaptive concepts. Based on insights gained from this review, this study then develops a new methodology for computational performance prediction of the CAGS concept greenhouse.

4.2 Review of computational performance prediction methodology and implementation of adaptive concepts

This section introduces previous studies that used a computational approach to implement an adaptive concept.

Hoes (2014) investigated the potential of the hybrid adaptive thermal energy storage (HATS) approach, which aims to reduce energy use while maintaining thermal comfort by changing the thermal storage capacity of a building. The two proposed active operated HATS concepts — high thermal storage with dynamic or movable insulation and phase change material (PCM) — are 'adaptive' concepts due to the way that the control sequence varies to meet predefined goals. In order to determine the multi-objective optimal control sequence of active HATS concepts, Hoes used a design optimization method with a Pareto front, which provides trade-off solutions. In addition, Hoes eventually developed a virtual test environment for the operation of active HATS concepts. The virtual test environment consists of ESP-r for BPS ('Real'building) and Matlab for optimization of operation (Controller); it is shown in Figure 4.1.

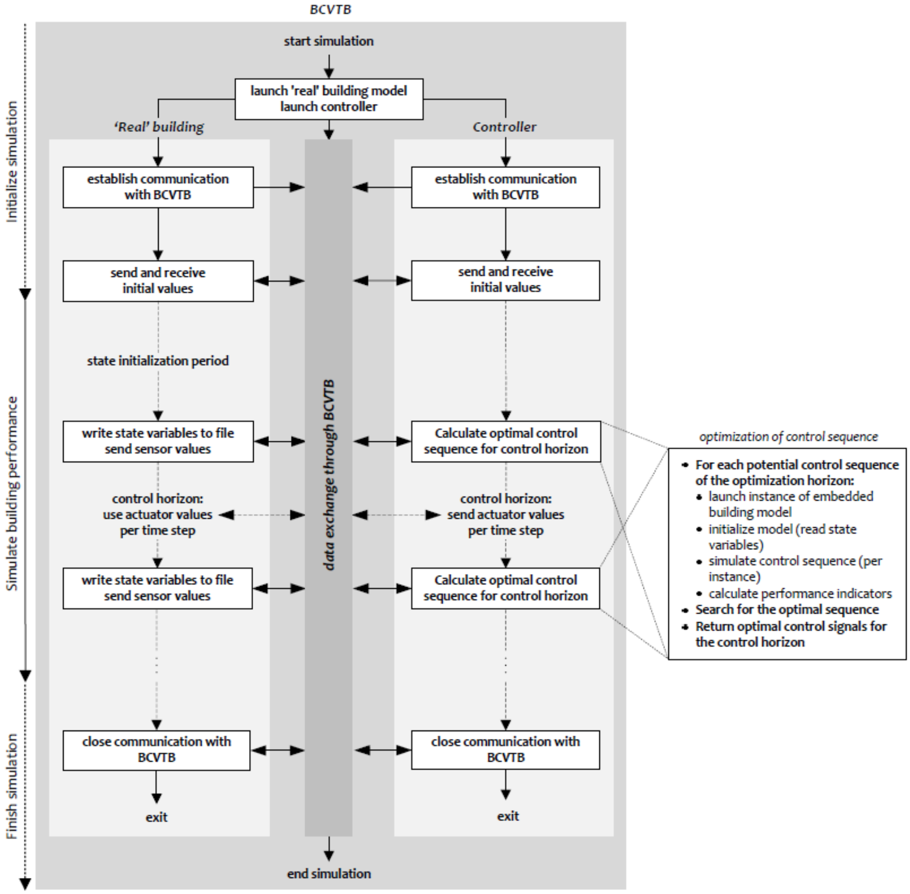


Figure4.1 *Simulation workflow of the virtual test environment (Hoes 2014)*

The virtual test environment connects two different tools and exchanges data during simulation run time using the Building Controls Virtual Test Bed (BCVTB) as Middleware. The 'Real' building writes state variables and sends sensor values to the Controller through BCVTB before the next control horizon starts. Then, the Controller calculates the optimal control sequence for the control horizon by reading state variables and receiving sensor values from the 'Real' building. The Controller sends the optimal control sequence (actuator values) to the 'Real' building. Finally, the 'Real' building runs the next control horizon with the received optimal control sequence. This calculation and data exchange continues until the simulation period is finished.

Loonen (2013) uses the virtual test environment and a similar approach to Hoes to implement a climate adaptive building shells (CABS) concept. Loonen predicted the performance of the CABS concept building by coupling the ESP-r and Radiance tool using the BCVTB middleware. Using multi-objective optimization with a genetic algorithm, Loonen optimized the façade by model-based building shell control with a receding optimization horizon, as shown Figure 4.2.

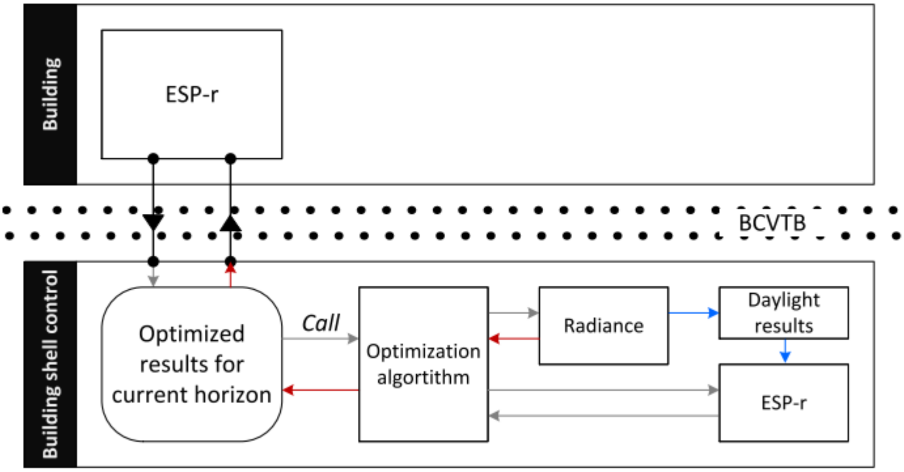


Figure4.2 *Overview of framework for climate adaptive building shells (CABS)* (R.C.G.M. Loonen 2014)

Favoino et al (2015) developed a simulation method and evaluated the energy saving potential of monthly and daily adaptive glazing properties, as shown Figure 4.3. This newly developed tool consists of an evaluation module (EnergyPlus), an optimization module (GenOpt) and a control module (Matlab): Energyplus calculates the performance of glazing systems with a predefined control strategy and evaluates cost function; GenOpt optimizes optical and thermal properties of glazing systems and determines the optimal control strategy; Matlab modifies the optimization and evaluation settings.

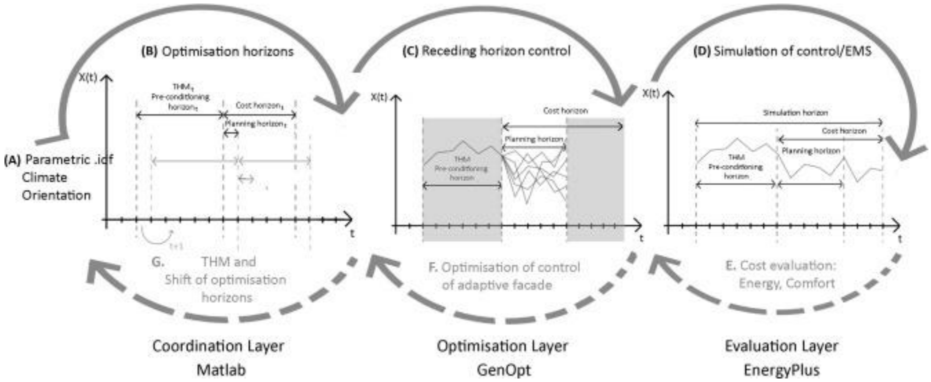


Figure4.3 *Simulation framework for adaptive glazing properties. The arrow indicates the flow of the inputs/models (continuous line) and of the outputs/results (dashed line)* (Favoino et al. 2015)

The usefulness of many simulation programs, optimization tools and optimization methods have been demonstrated (Nguyen et al. 2014). Based on the previous studies, it is assumed that optimization techniques using simulation tools are suitable for determining the proper set of shell properties for each adaptation period. The next section introduces a methodology.

4.3 Simulation-based multi-objective dynamic optimization

Optimization is a process of finding a solution which achieves the desired goal or performance. As explained earlier, in order to implement the CAGS concept greenhouse, a set of shell properties that meets two objectives — minimizing energy consumption and maximizing production — is needed for each adaptation period, which results in a multi-objective optimization problem. Therefore, this study proposes simulation-based multi-objective dynamic optimization to determine an optimal set of shell properties.

There are many ways to search for a solution. The most extreme way is to use the brute force method, which investigates all possible solutions before deciding on the optimal solution. However, this approach is computationally very expensive. Therefore, a genetic algorithm (GA) in the optimization process is used to quickly find as optimal a solution as possible, thereby avoiding high computation cost. The GA, a heuristic approach, provides an optimum or near optimum solution without full investigation of the possible set of input variables, which ultimately saves computational time. There are many applications of the GA for multi-objective optimization with the BPS tool (Nguyen et al. 2014). Based on the previous approaches, this study develops a methodology for the performance assessment of the CAGS concept greenhouse.

The overall methodology of simulation-based multi-objective dynamic optimization is illustrated in Figure 4.4. The CAGS concept greenhouse requires optimal shell properties (thermal and optical properties of greenhouse shells) during the assessment period (T0 ~ Tn). The number of optimal properties is dependent on the length of the adaptation period (Ap_x ~ Ap_{x+1}), which represents a period of adaptive control, or the adaptation frequency, which represents the number of shell changes over the assessment period. During each adaptation period, an optimal set of shell properties is provided by simulation-based multi-objective optimization. The sets of shell properties (S1 ~ S6) are generated by using a sampling technique and by crossover and mutation from a GA. The new GPS tool then runs simulation for the adaptation period with the sets of shell properties. Then, the calculated results (R1 ~ R6, corresponding to S1 ~ S6) are investigated with objective functions and the optimal set of shell properties (S6) that shows the desired performance (R6) is selected by trade-off decision making. Finally, the CAGS concept greenhouse runs the present adaptation period (Ap_x ~ Ap_{x+1}) with the optimal set of shell properties (S6) and the optimization moves to the next adaptation period (Ap_{x+1} ~ Ap_{x+2}). Through this methodology, the CAGS concept greenhouse can be implemented without losing any thermal history effect in the ground during the assessment period.

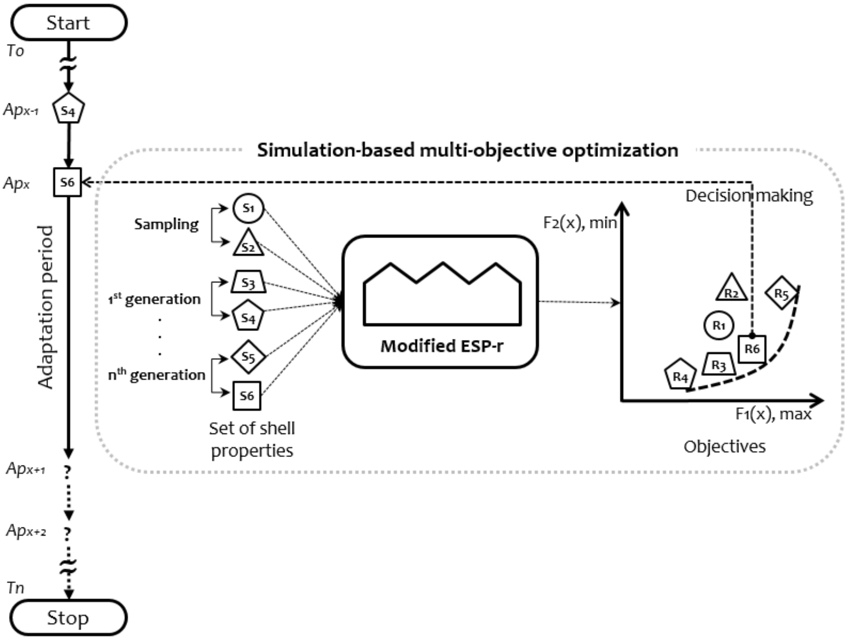


Figure4.4 *Schematic description of multi-objective dynamic optimization for CAGS concept*

4.4 Virtual test environment for Climate Adaptive Greenhouse Shell concept

This section describes the implementation of the CAGS concept greenhouse using simulation-based multi-objective dynamic optimization. In order to implement the CAGS concept, simulation iterations for optimization per adaptation period and the continuous simulation with optimal properties are necessary. However, no single tool fully provides this implementation yet. Thus, as previous studies did, this research uses a co-simulation approach rather than develop a new tool. The co-simulation approach indicates that two or more separate programs are linked, solve a problem and exchange data at run-time. Co-simulation provides capabilities and flexibilities to manage complicated and innovative systems (Trcka 2008), such as the CAGS concept greenhouse in this research.

In order to implement simulation-based multi-objective dynamic optimization for the CAGS concept, this research adopts Hoes' approach, which is shown in Figure 4.5. In The implementation, ESP-r represents the model of the CAGS concept greenhouse, Matlab acts as the greenhouse shell controller, and BCVTB operates as middleware.

In the optimization with GA, many simulation iterations for the same adaptation period but with different sets of shell properties are required. At each iteration, the same initial boundary condition is necessary at Ap_x in the CAGS concept greenhouse. In order to use the same initial boundary condition and decrease state initialization time, Hoes (2014) proposed overwriting initialization values of conservation equations (Clarke 2001) during simulation:

$$\boldsymbol{A}\theta_{n+1} = \boldsymbol{B}\theta_n + \boldsymbol{C}$$

Where $\boldsymbol{A}$ and $\boldsymbol{B}$ contains nodal temperature or heat injection terms of the conservation equations for future and present time steps respectively, and contains the boundary condition. The matrices θ_n and θ_{n+1} contain the nodal temperatures and heat injections/extractions at the future and present time row (state variables) respectively. Thus, column matrix θ_n in the CAGS concept greenhouse stores state variables at the start of each optimization horizon while the greenhouse shell controller reads θ_n at the start of each optimization horizon. In addition, sensor values, which contain numbers such as solar radiation or temperature to control shells, are delivered to the greenhouse shell controller.

ESP-r simulates the CAGS concept greenhouse and pauses just before the start of the next adaptation period. Then, the CAGS concept greenhouse sends sensor values and state variables to the controller via BCVTB, and waits for an optimal set of shell properties from the greenhouse shell controller. Matlab, which embeds the same greenhouse model as the CAGS concept greenhouse by using the saved state variables, implements optimization with GA to search for optimal shell properties for the next adaptation period. In the optimization process, this research uses the Latin Hypercube Sampling (LHS) method for initialization and the Non-Sorting Genetic Algorithm-II (NSGA-II) for optimization. The optimization iterations continue until the stopping criteria are met. Matlab then uses the CAGS concept greenhouse for evaluation of population from initialization and reproduction. When the optimization is finished, an optimal set of shell properties is automatically selected by predefined decision making. In order to select optimal solutions this study used an economic approach that calculates the ‘net profit’, which is described in Chapter 5.3.3. Then, the CAGS concept greenhouse continuous the simulation with the optimal shell properties for the next adaptation period. This process continues until the assessment of the CAGS concept greenhouse is finished.

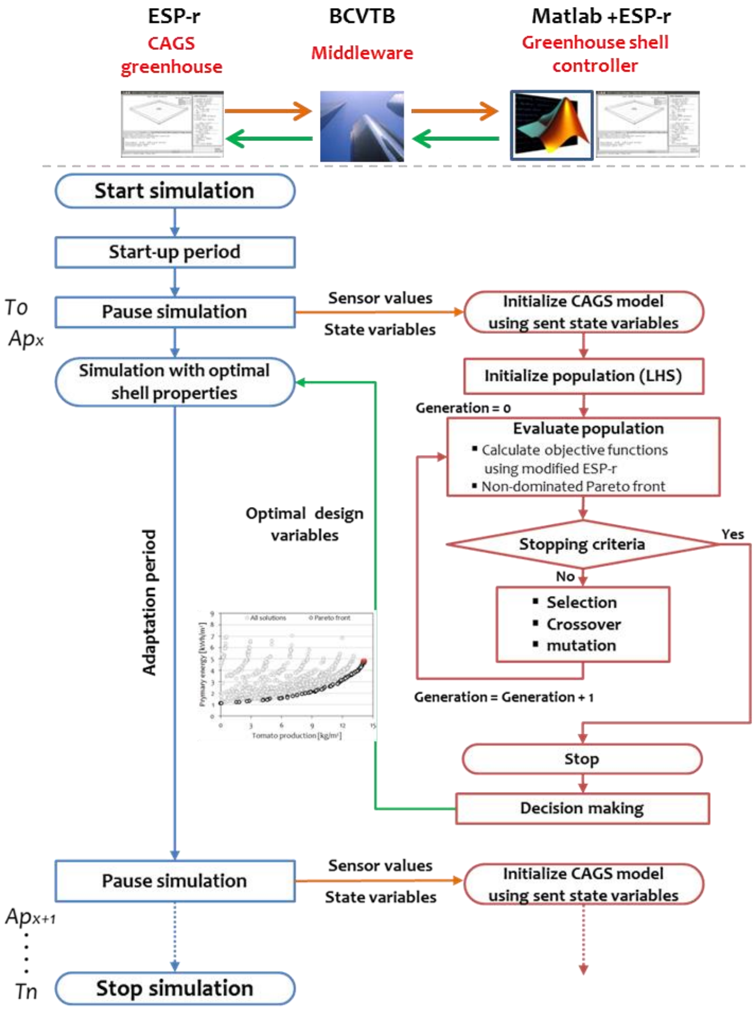


Figure 4.5 *Toolchain for implementation of dynamic optimization for CAGS concept*

As described above, during optimization, in order for the embedded CAGS model in the controller to determine the optimal shell properties, it is necessary for the controller to use the same initial boundary condition as the CAGS concept greenhouse. However, if the adaptation frequency is low, e.g. set to monthly or seasonal adaptation, the effect of the initial boundary condition is minor, and therefore the use of the start-up approach is sufficient (Corbin et al. 2012). External coupling for the investigation of adaptability requires a lot of effort for implementation. Thus, if adaptation frequency is low enough (month or season), the performance of the adaptive concept can be assessed without the establishment of coupling.

4.5 Conclusion

This chapter develops a simulation methodology for computational performance prediction of the CAGS concept greenhouse. Based on a review of existing tools, a new methodology was developed to determine the optimal set of greenhouse shell properties. The new methodology was created by establishing a simulation-based multi-objective dynamic optimization approach. In addition, to save computation cost in the optimization process, a genetic algorithm (GA) and a sampling method have also been incorporated into the methodology.

The proposed methodology is implemented in a co-simulation approach. The connection between ESP-r (CAGS concept greenhouse) and Matlab (greenhouse shell controller) is established through BCVTB (middleware). Modified ESP-r simulates the CAGS concept greenhouse by receiving the optimal set of shell properties from the controller for each adaptation frequency and this process runs continuously until an assessment is complete. Therefore, the implementation is able to retain thermal history effects, which will improve the accuracy of adaptations.

In the following chapters, the newly developed simulation methodology and modified ESP-r will be used to test the performance of the CAGS concept greenhouse. This testing is organized around a number of case studies. In chapter 5 the CAGS greenhouse is compared to the typical Venlo-type greenhouse, in order to determine its general performance. Next, to determine how it operates under different conditions with different crops, five more case studies are presented.

5 Case study I: Computational performance prediction of Climate Adaptive Greenhouse Shells

5.1 Introduction

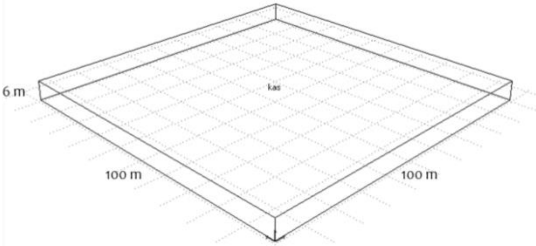
In order to lay the foundations for the proper testing of the proposed CAGS concept greenhouse, two crucial preliminary steps needed to be taken. First, the research needed to modify a BPS tool capable of managing the complex greenhouse design. For clarity's sake, the complexity of the design arises from the adaptability of the greenhouse shell. This tool was presented in Chapter 3. Second, a new simulation methodology for the performance assessment of the CAGS concept greenhouse was required, which was presented in Chapter 4. Based on these two developments, this chapter investigates the potential of the CAGS concept greenhouse by means of a case study. The case study used for investigation is a typical Venlo-type greenhouse growing a tomato crop.

Figure 5.1 *A typical Venlo-type greenhouse growing tomato crop (www.horconex.nl)*

The chapter first introduces a simulation model of the 'reference greenhouse', which represents the typical Venlo-type greenhouse. The study then describes the two key performance indicators used in the testing of the new greenhouse design, and the decision making used to determine the optimal shell properties. The investigation starts with a sensitivity analysis to determine the most influential design parameters of the greenhouse. Based on the selected design parameters, design variables of the CAGS concept greenhouse are generated and investigated in the optimization process. The potential of the CAGS concept greenhouse is investigated for design optimization and monthly and hourly adaptation. Finally, the study compares the potential of the CAGS concept greenhouse to the reference greenhouse and demonstrates variations of optimal properties and sensitivities.

5.2 Case study greenhouse model

The case study greenhouse is modeled with the newly developed GPS tool. Figure 5.2 shows a schematic of the greenhouse with information about its geometry, thermal and optical properties and other relevant details. The shell consists of a single layer of glass with a U-value of 5.75 $W/m^2.K$. The boundary conditions of the four walls are set as adiabatic, since it is assumed that the optical and thermal effects from the walls are small and can be neglected for the huge low-rise greenhouse. Openings on the roof are available for cooling and dehumidification by ventilation. It is assumed that half of the openings face the south and the other half face the north. The roof appears flat in the schematic of the simulation model, but the GPS tool calculates angular dependence of a saw tooth roof for incident solar radiation (see Chapter 3.3.9).



Location: De Bilt, The Netherlands
Opening size[m^2]: 3.25
Opening fraction [m2/m2]: 0.0417
U shell - value [$W/m^2.K$]: 5.75
ε shell inside: 0.84
ε shell outside: 0.84
τ shell SW radiation: 0.85
α shell SW radiation: 0.04
ρ shell SW radiation: 0.11

Figure 5.2 *Simulation model of reference greenhouse for tomato growing.*

Figure 5.3, below, provides a brief overview of the assumptions of the system and controls of the greenhouse. The case study greenhouse is based on the currently available and widely used typical Venlo-type greenhouse. The greenhouse is heated with a boiler with $\eta_{\text{overall boiler}} = 0.9$ and is cooled by natural ventilation. Indoor relative humidity is controlled by natural ventilation with $\eta_{\text{ventilation}} = 0.5$[4] and mechanical ventilation by fan with $\eta_{\text{ventilation}} = 1.0$. CO_2 is only supplied during day time to meet a concentration of 800ppm at each time step, but the concentration changes depending on the ventilation. Indoor air temperature is controlled with hourly set-points commonly used by Dutch tomato growers. Two screens, aluminized and transparent screens, are used not for shading control but only for energy saving purpose. The screens are controlled using set-points of solar radiation and outdoor air temperature. All

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[4] A ventilation efficiency of 0.5 means that only 50% of moisture is transferred to air exchange by the ventilation air, i.e. concentration of moisture is half of complete mixing. The Ventilation efficiency is only applicable for the dehumidification. (See section 3.3.5)

set-points and detailed information about the greenhouse configuration can be found in Appendix A.

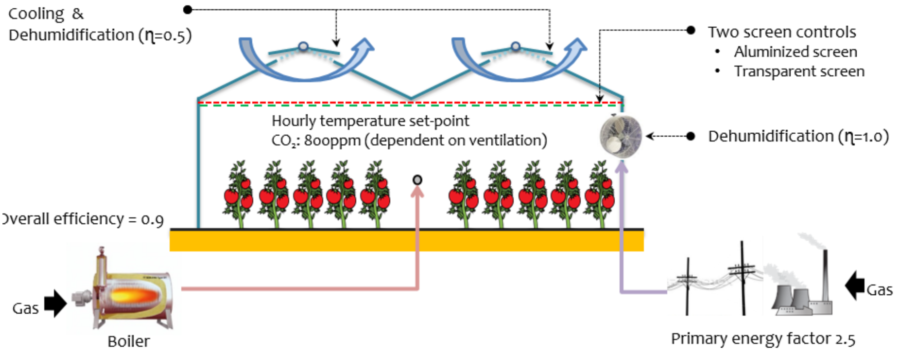

Figure 5.3 *Overview of control and operation of case study greenhouse.*

This study uses a weather file of the reference year 2009 from KNMI[5]. Figure 5.4 shows monthly weather conditions in 2009.

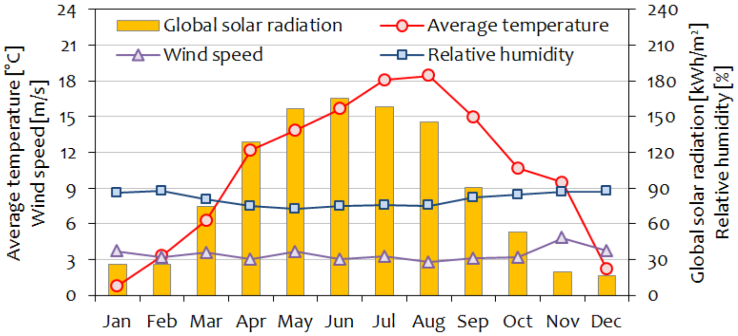

Figure 5.4 *Overview of monthly climate condition in 2009.*

5.3 Performance indicators and decision making

New design concepts for greenhouses should lead to solutions that reduce both energy consumption and CO_2 emissions while also increasing crop production. However, achieving these two objectives simultaneously raises conflict since both objectives cannot be optimized at the same time. For example, when it comes to the control of solar transmittance, the greenhouse should block out shortwave (SW) radiation as much as possible in summer to minimize the energy consumption for cooling and dehumidification. However, doing so would result in low or no crop production. A clear implication here is that any new design concept

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[5] The Royal Netherlands Meteorological Institute (Koninklijk Nederlands Meteorologisch Instituut, KNMI)

for greenhouses must be judged on its ability to manage these conflicting objectives and provide the best possible overall pay off. Therefore, the potential of the CAGS concept is evaluated using the following two performance indicators (PI): primary energy consumption and crop production, which are described in more detail in the following sub-sections. The optimal greenhouse is determined by using these performance indicators and a decision making strategy; this strategy is defined in Section 5.3.3.

5.3.1 Primary energy consumption

Figure 5.3 shows that the typical Venlo-type greenhouse uses a gas boiler for heating and fans for cooling and dehumidification. Both the gas consumption and the fan's electricity consumption are calculated by GPS. These two energy consumptions are converted into primary energy (gas) with a primary energy conversion factor of 1.1 (1/0.9) for heating (which is derived from ŋ overall boiler=0.9) and 2.5 for electricity.

5.3.2 Tomato production

The GPS tool calculates the amount of fresh matter (FM) production in kilograms from dry matter (DM) production with a fresh matter conversion factor of 10. This assumption was derived from a greenhouse expert for the FM calculation with simplified crop model (see Section 3.3.2). While indoor temperature is fully controlled by the heating and ventilation systems, CO_2 concentration, one of the most influential factors in DM production, is dependent on the air change rate provided by natural and mechanical ventilation. This case study assumes and simplifies the CO_2 supply scenario with infinite and ideal supply systems. At the beginning of each time step, CO_2 is always supplied to meet a concentration of 800 ppm and then the final CO_2 concentration is calculated taking into account the ventilation rate during the time step. Since the CO_2 supply scenario is detached from energy systems, it does not influence the use of gas and electricity.

5.3.3 Decision making

In order to facilitate decision making with the two conflicting PIs, this case study used Pareto optimization with a 'posteriori' approach. This means that the optimal solutions (in this case, an optimal solution is a set of optimal shell properties) have to be found before the decision is taken. As shown in Figure 5.5, the optimal solutions from Pareto optimization are non-dominated solutions. The set of solutions provided are known as Pareto front[6]. For example, solution 'a' outperforms the others in tomato production while solution 'b' outperforms solution 'a' in primary energy saving. Therefore, all of the solutions in Pareto front are incomparable with each other and thus, how to make decision is not clear. This lack of clarity means that many different decision making options are possible for decision makers. For example, a policy maker may want to minimize CO2 emissions, while a crop grower may rather want to maximize tomato production. Since there is no single best solution due to the conflicting nature of the performance indicators, trade-off decision making needs to be carried out after the search.

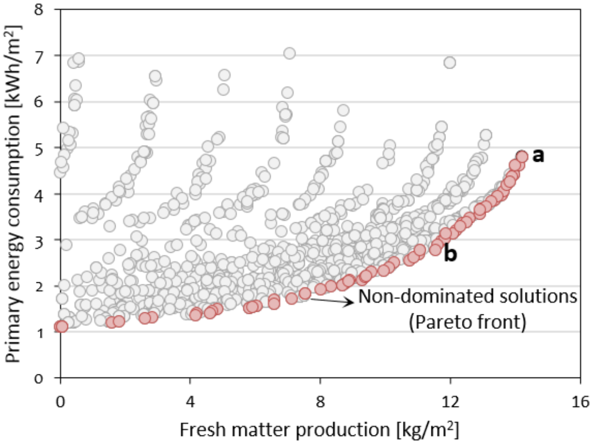

Figure 5.5 *An example of selection of the optimum solution with maximum net profit in August.*

5.3.3.1 Net profit

A practical approach to decision making to select an optimal solution for greenhouse design can be found in (Vanthoor 2011). The study used the annual financial result (NFR) considering crop yield, variable costs and depreciation and maintenance of the construction. However, since the CAGS concept greenhouse is based on non-existing technology, this case study proposes a simple and economical approach that calculates the 'net profit' to determine an optimal solution for this multi-objective optimization problem. To do this, both tomato production and primary energy consumption are first converted into Euros per square meter. This conversion then allows the calculation of the net profit (Q_{net_profit}), which is used for decision making:

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[6] *For a multi-objective optimization problem, there does not exist a single solution that simultaneously optimizes each objective. In such cases, the objective functions are said to be conflicting, and there exists a (possibly infinite) number of Pareto optimal solutions. (en.wikipedia.org/wiki/Multi-objective_optimization)*

$$Q_{net\_profit}(t_f) = \int_{t_0}^{t_f} Q_{tomato\_yield} - Q_{p\_energy}\, dt \qquad [€/m^2]$$

Where t_0 and t_f are the beginning and the end of the adaptation period respectively, Q_{net_profit} (€/m^2) is tomato production, and Q_{p_energy} (€/m^2) is the primary energy consumption. The gas price is assumed to be 0.028436 €/kWh (price of natural gas 0.25 €/m^3 and energy conversion of gas use is 31.65 MJ/m^3). Thus, primary energy consumption (Q_{p_energy}) is calculated by:

$$Q_{energy} = \{(E_{gas} * 1.1) + (E_{eletricity} * 2.5)\} * q_{gas} \qquad [€/m^2]$$

Where E_{gas} (kWh/m^2) is gas consumption, $E_{eletricity}$ (kWh/m^2) is electricity energy consumption, and q_{gas} (€/kWh) is gas price. The outcome of the fresh matter (FM) production is calculated and is also converted into tomato production in Euros per square meter. Since the tomato price varies over the year, this will have a large impact on the decision making. Nevertheless, this case study mainly focuses on investigating the potential of the CAGS concept greenhouse rather than investigating all future economic uncertainties. Therefore, the existing monthly average tomato prices in The Netherlands from 2007 to 2009 are used (see Figure 5.5). In general, the produced DM takes four to six weeks before it is ready to harvest. Thus, the monthly tomato price in Figure 5.6 is shifted one monthly ahead to consider this delay of the harvest. Finally, the tomato production (Q_{tomato_yield}) is calculated by:

$$Q_{tomato\_yield} = FM_{har} * q_{tomato} \qquad [€/m^2]$$

Where, FM_{har} (kg/m^2) is harvested tomato production and q_{tomato} (€/kg) is tomato price.

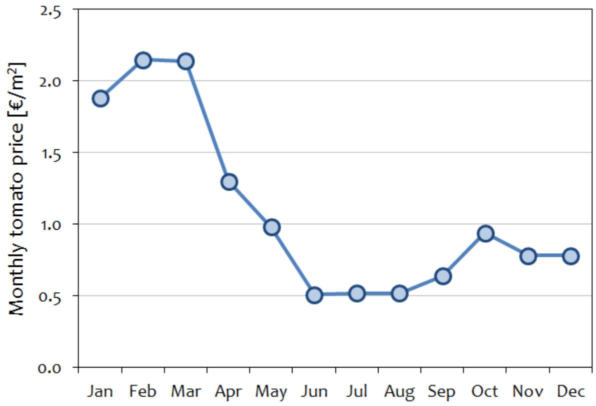

***Figure** 5.6 Average monthly tomato price from 2007 to 2009 in The Netherlands.*

After the optimization, the Pareto front is determined (red dots in figure 5.5) and the optimal solution is selected using the proposed decision making criteria. The whole optimization and decision procedure is automated during the optimization process.

5.3.3.2 *Average setting temperature*

When adaptation frequency is high, adaptation periods may occur in which no PI is considered (e.g. a CAGS concept greenhouse with passive cooling in summer). Such optimization periods occurred in the following three conditions: no tomato production with low solar radiation and no primary energy consumption during day time (No PI); no primary energy consumption during night time (No PI); the same primary energy consumption regardless of changing design variables (The same PI).

However, at least one PI, which becomes the objective function in an optimization problem, is necessary for the decision making. Although there is no calculated objective function, a set of optimal properties has to be selected to continue a simulation. Therefore, this study employs 'average setting temperature' to select the optimum solution in the above three cases. The average setting temperature is the average of the heating and cooling set points, and the optimum solution will be the set of properties that has the closest air temperature to the average setting temperature.

5.4 Sensitivity analysis for determination of design parameters

Before investigating the potential of the CAGS concept greenhouse, it is important to determine which properties should be controlled for the CAGS concept greenhouse. Therefore, the influence on the primary energy consumption is first investigated for seven parameters describing the thermal and optical properties of the greenhouse floor and shell. The main reason for selecting parameters only for primary energy consumption is that the transmittance of shortwave radiation is undoubtedly the most influential factor for growing tomatoes if other growing conditions, such as temperature, humidity and CO_2 concentration, are fully controlled by the greenhouse climate systems. In addition, The strong influence of SW radiation to crop production was demonstrated by Vanthoor (2011) with multi-variate sensitivity analysis. Therefore, it is of little interest to determine the influence of the other greenhouse design parameters for tomato production.

Table 5.1 presents the considered thermal and optical greenhouse parameters and gives the ranges of these properties. The table shows that the U-value and emissivity of the greenhouse shell are considered as two separate parameters, although the U-value varies depending on the inside and outside emissivity. It is presented in this manner since the U-value is used extensively as an indicator of thermal performance, and is therefore also used in most of the building energy simulation programs (including ESP-r) as input for calculations of the thermal performance. However, in these calculations the programs use the conductivity of the glazing rather than the U-value itself. The current research retains this logic and uses the U-value of the construction since it is so commonly used. In the current research, the actual input of the conductivity is calculated from the U-value using the method from ISO 6946 (with Rsi=0.13 and Rse=0.04); the range of the U-value 0.08 W/m^{2}K ~ 5.8 W/m^{2}K is equivalent to the range of thermal conductivity 0.000324 W/m.K ~ 1.657143 W/ W/m.K.

Table 5.1 *Selected greenhouse design parameters (floor and shell) and considered ranges for the sensitivity analysis.*

Construction	Parameters	Range	Description
Shell	τ-radiation [-]	0.05 ~ 0.95	Transmittance of short wave radiation
	U(s)-value [W/m^{2}K]	0.08~5.8	U-value of shell calculated by ISO 6946
	ε-inside [-]	0.05 ~ 0.95	Inside emissivity
	ε-outside [-]	0.05 ~ 0.95	Outside emissivity
Floor	U(f)-value [W/m^{2}K]	0.08~5.8	U-value of floor calculated by ISO 6946
	C-floor [Mj/m^{3}K]	0.24 ~ 2.4	Thermal capacity per unit volume of floor
	C-shell [Mj/m^{3}K]	0.24 ~ 2.4	Thermal capacity per unit volume of shell

The parameters from Table 5.1 are selected intuitively, since the influence of each design parameter on the energy consumption of the case study greenhouse is not known. Therefore, these influences are investigated using global sensitivity analysis. The sensitivity analysis (SA) provides a clearer picture of the relationships between the design parameters and the primary energy consumption in the greenhouse. Furthermore, it is used to identify which parameters have a significant effect on the primary energy consumption. This information can be used to simplify the greenhouse model by excluding the non-influential parameters in the design optimization. In this study the sensitivity is investigated using Partial Rank Correlation Coefficients (PRCC) with Latin Hypercube Sampling (LHS). It is hypothesized that the sensitivity of the design parameters changes continuously due to changing weather conditions. As Vanthoor (2008) showed, it is expected that this results in a variation of the sensitivity index depend on the analysis period. Therefore, in this study, the sensitivity index is investigated for three different periods: year, month and hour.

Figure 5.7 shows the results of the sensitivity analysis for a year. The design parameters are ranked from most influential (top) to least influential (bottom) and the size of the bar indicates the degree of the influence. If the sensitivity index value of a design parameter is close to 1 or -1, then its influence on the primary energy consumption is higher than a parameter with an index value close to 0. The sign of the index indicates if the parameter has a positive or negative impact on the energy consumption. For example, according to Figure 5.7, if the shell transmittance becomes higher, then the primary energy consumption in the greenhouse will decrease. If the U-value becomes higher, then the primary energy consumption will increase. Thus, in order to reduce the primary energy consumption, the transmittance should be high and the other design parameters should be low for this year.

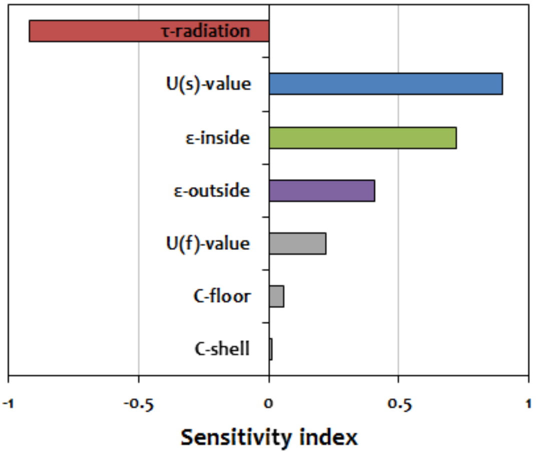

***Figure* 5.7** *Results of sensitivity analysis on the primary energy consumption over the year.*

As shown in Figure 5.7, the most sensitive design parameter is the transmittance of solar radiation. The main reason for this finding is that the greenhouse is normally covered by transparent materials to allow for the entering of Photosynthetically Active Radiation (PAR) for crop growth, which results in high primary energy consumption. The U-value is the second most influential design parameter. In general, current Venlo-type greenhouse uses glass for the covering material, although the thermal performance is not as good as the glass used in other buildings. Both inside and outside emissivity have an influence on primary energy consumption as well. The sensitivity ranking shows that the influence of the inside emissivity is larger than the influence of the outside emissivity. In fact, large energy losses occur at night time, but in this case study model the control of aluminized screens with low emissivity ($\varepsilon \approx 0.2$) influences the sensitivity of the outside emissivity. The remaining three parameters show a minor influence (sensitivity index less than 0.3) on the energy consumption as compared to the top ranked parameters mentioned above.

Figure 5.8 presents the results of the monthly sensitivity analysis. It can be observed that the sensitivity of both the transmittance of solar radiation and the U-value of the shell is high throughout the year. It can be also seen that the influence of the transmittance is negative even in the winter; in general, it is expected that solar radiation reduces the heating energy consumption. However, solar radiation entering the greenhouse not only correlates with reducing heating demand by solar heating but also with increasing heating demand by evaporative cooling from the crop and ventilation for the dehumidification. These findings are observed in the trajectory of the transmittance with negative values but with lower sensitivity indices in winter.

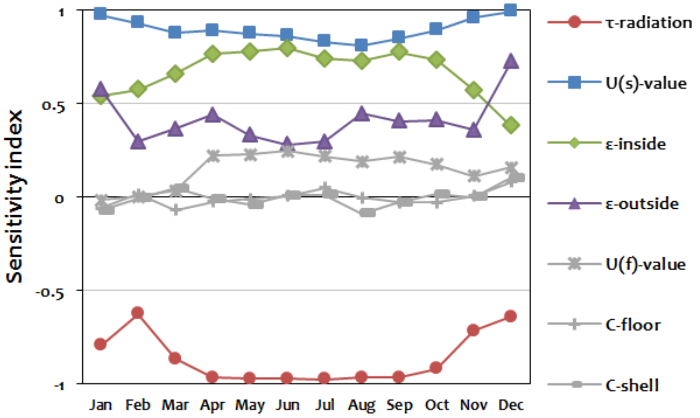

Figure 5.8 *Results of sensitivity analysis on the primary energy consumption over the year.*

In regard to hourly sensitivity analysis, this study investigates four day types: dry and sunny days, hot days, cloudy and humid days, and cold days. Figure 5.9 presents the hourly sensitivities of the design parameters. It can be observed that the sensitivities change every hour. In dry and sunny days (April) there is no highly influential parameter during day time, since the outdoor climate is moderate and indoor moisture can be sufficiently controlled by natural ventilation with dry air. In contrast, in cloudy and humid days (September) the sensitivities fluctuate more during day time. Although the intensity of solar radiation is less than in the dry and sunny day, its degree of influence is higher here because of the presence of humid air, which requires more ventilation. For the hot day (July), the changing sensitivity of the design parameters during day and night time can be seen clearly. Both U-value and inside emissivity have a negative and positive influence during day and night respectively. During day time the greenhouse shell should prevent solar radiation from entering as much as possible in order to keep the greenhouse cool, while during night time the internal heat should be preserved to reduce the heating demand. For the cold day (December), the U-value is the most influential parameter next to the inside and outside emissivity. An interesting sensitivity trend can be identified in the trajectory of the inside emissivity. During day time, the inside emissivity should be higher to get rid of the inside moisture from condensation, which leads to less dehumidification energy consumption than is required by ventilation.

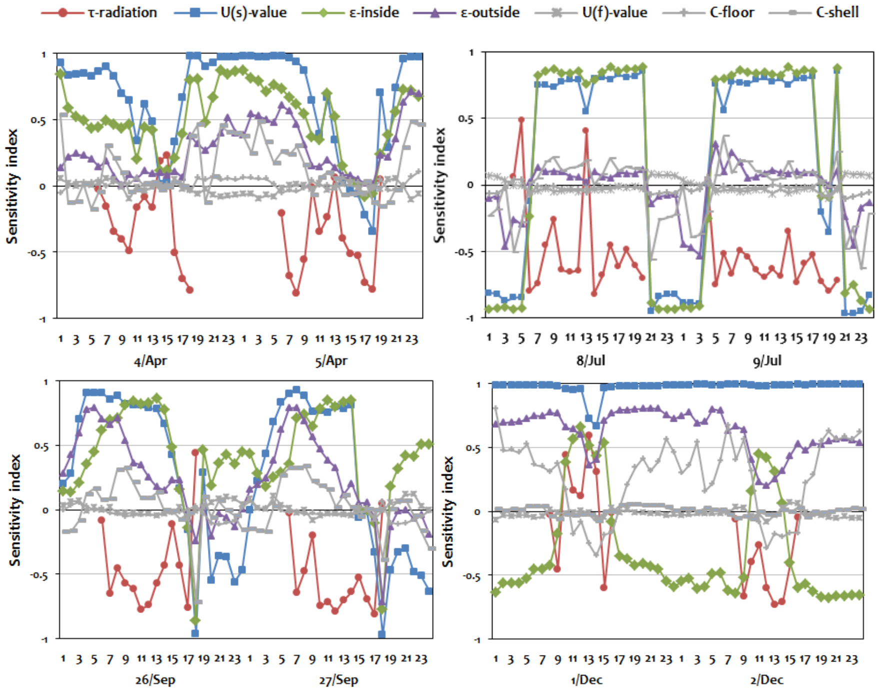

Figure 5.9 *Results of sensitivity analysis on the primary energy consumption with four types and eight selected days; 4/Apr ~ 5 /Apr of dry and sunny day, 8/Jul ~ 9/Jul for hot day, 26/Sep ~ 27/Sep for cloudy and humid day, 1/Dec ~ 2/Dec for cold day.*

According to the three sensitivity analyses described above, the most sensitive design parameters are solar transmittance, U-value of the shell, and inside and outside emissivity, while the other three investigated design parameters (U-value of the floor, heat capacity of floor and shell) are less sensitive. Therefore, it can be concluded that the greenhouse shell properties are the most influential parameters on the primary energy consumption.

In general, the crop does not require the whole spectrum of solar radiation for growth. If the greenhouse shell is able to adjust the transmittance of the solar wavelength, then there is a possibility of saving energy, since solar radiation influences the heating, cooling and dehumidification energy demands at the same time. As described in section 3.3.2, the whole solar spectrum can be divided into two parts for plant growth: Photosynthetically Active Radiation (PAR) and Near Infrared Radiation (NIR). Since the influence of each radiation is different on the crop growth, controlling these two wavelength ranges can lead to primary energy saving. For instance, if the greenhouse shell allows more PAR and less NIR to enter in summer, the greenhouse achieves greater production with high PAR, and also spends less primary energy due to a reduction in the need for mechanical ventilation for cooling and dehumidification. Following KASPRO, this study assumes that solar radiation is always 50% of PAR and 50 % of NIR.

In the next section, based on the results of the sensitivity analysis, the potential of the climate adaptive greenhouse concept is investigated by focusing on the five most influential design variables of the shells: U-value, inside emissivity (ε-inside), outside emissivity (ε-outside), PAR transmittance (τ-PAR) and NIR transmittance (τ-NIR).

5.5 Preliminary investigation into the potential of the Climate Adaptive Greenhouse Shell concept

This case study quantifies the performance of the CAGS concept for a tomato greenhouse and compares its performance to the reference case, the typical Venlo-type greenhouse. In the analysis of the results, this study investigates the optimal property values and the sensitivity of the design parameters over the year. The analysis provides insight and inspiration for future greenhouse designs and indicates which directions are promising to follow in order to maximize net profit.

5.5.1 Potentials of Climate Adaptive Greenhouse Shell concept

The potential of the CAGS concept is demonstrated by simulating a greenhouse shell with adaptive shell properties and comparing its performance to an optimized design of the reference greenhouse. Two adaptation frequencies for the CAGS concept greenhouses are investigated: monthly adaptation (the shell properties can change every month, in the results analysis referred to as $C11_{NL}$) and hourly adaptation (the shell properties can change every hour, referred to as $C8759_{NL}$); the C stands for change, the number indicates the possible changes (adaptation frequency) per year and NL indicates operations of the typical Venlo-type greenhouse. C0 refers to an optimized static greenhouse without any change of the design parameters during the year.

Figure 5.10 and Table 5.2 compare the simulated performance of the reference greenhouse with the optimized design and the two CAGS concept greenhouses. The results shown are tomato production, energy consumption and net profit. Total tomato production in Kg/m^2 is meaningless for economic analysis since monthly changing tomato prices have to be considered (see figure 5.6). Therefore, tomato production is converted into €/m^2. The optimized design and the two CAGS concept greenhouses show a higher net profit compared to the reference greenhouse. The difference in net profit increase between the optimized static greenhouse $C0_{NL}$ (7% compared to the reference greenhouse) and the adaptive greenhouse $C11_{NL}$ (9% compared to the reference greenhouse) is small. Tomato production in $C11_{NL}$ is less than in $C0_{NL}$, which is even less than in the reference greenhouse, but the net profit of $C11_{NL}$ is higher than for $C0_{NL}$ and the reference greenhouse. This is caused by the trade-off between the two objectives made during the decision making to maximize the net profit. Meanwhile, the hourly adaptive greenhouse $C8759_{NL}$ shows the highest potential in terms of tomato production increase, primary energy saving and finally net profit increase (20% compared to the reference greenhouse). It can be concluded that once the greenhouse design is optimized for this tomato crop, monthly adaptation does not lead to many advantages, but hourly adaptation, however, demonstrates great potential to provide significant benefits.

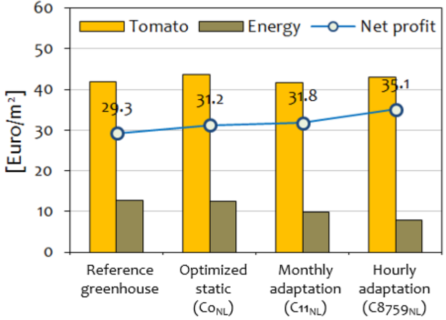

Figure 5.10 *Simulated results of tomato production, energy consumption and net profit*

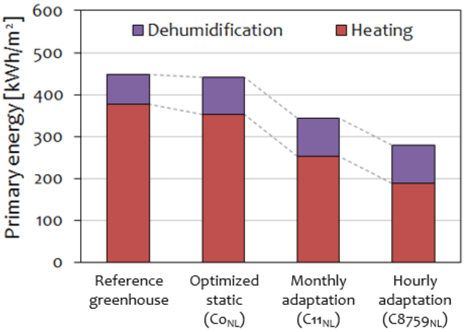

Figure 5.11 *Distribution of primary energy consumption.*

Figure 5.11 shows the energy consumption over the year for dehumidification and heating. $C0_{NL}$, $C11_{NL}$ and $C8759_{NL}$ use more energy for dehumidification compared to the reference greenhouse. This is caused by the used ventilation strategy, which aims to increase the tomato production by maintaining a high CO_2 concentration. This case study uses two ventilation systems for dehumidification: mechanical ventilation with a ventilation efficiency of 1, and natural ventilation with a ventilation efficiency of 0.5. Therefore, in order to minimize air change (which leads to CO_2 decrease), the optimization algorithm tries to use mechanical ventilation with high ventilation efficiency rather than natural ventilation. As a result, the overall inside temperatures of the three cases is higher than the reference greenhouse in order to make the relative humidity lower than 85% or to reduce the required air changes.

The difference in heating energy consumption between the reference greenhouse and the optimized design is small; the adaptive greenhouses show 23% ~ 37% of heating energy saving compared to the reference greenhouse. As mentioned in the sensitivity analysis section, due to the changing weather conditions, changes between day and night and changes arising from different seasons, the climate adaptive concept provides many opportunities to reduce the use of heating energy. As demonstrated, these reductions can result in huge energy savings (and significant CO_2 reductions). This result gives the CAGS concept greenhouses a clear advantage over the traditional static (optimized) designs.

Table 5.2 *Performance of design optimization and two CAGS concept greenhouses in comparison to reference greenhouse*

	Unit	Reference greenhouse	Optimized static greenhouse ($C0_{NL}$)	Monthly adaptation ($C11_{NL}$)	Hourly adaptation ($C8759_{NL}$)
Tomato production	kg/m^2	65.6	67.5	67.3	66.4
Energy consumption	kWh/m^2	447.1	441.4	343.7	280.1
Tomato production	€/m^2	42.0	43.8	41.6	43.0
Energy consumption		12.7	12.6	9.8	8.0
Net profit		29.3	31.2	31.8	35.1
Tomato production	%	-	4	-1	2
Energy consumption		-	-1	-23	-37
Net profit		-	7	9	20

5.5.2 Optimum properties and sensitivity analysis

This section provides an in-depth analysis of the CAGS simulation results. This analysis presents the optimal values of the shell properties over the year together with the sensitivity of each property. The sensitivity index was calculated during the optimization process using LHS. It is important to consider the optimal value and the sensitivity at the same time in order to determine if the optimal property is important for the greenhouse performance. These results could inspire the designs of future greenhouse shells; what properties should be made adaptive and what values (ranges) should these properties have?

The two graphs in Figure 5.12 provide yearly and monthly optimum property values and sensitivities for $C0_{NL}$ and $C11_{NL}$. PAR and NIR transmittance show the highest influence on net profit for $C0_{NL}$ and $C11_{NL}$ during midseason and summer. PAR and NIR transmittance show contrary influences on the net profit during the main part of the year. This can be explained with the same reasoning as discussed in the previous section. High PAR and NIR transmittance help to reduce heating energy consumption; PAR transmittance should be as high as possible to increase tomato production. However, always having a high NIR transmittance would lead to the following: 1) Increase of fan use (by mechanical ventilation) or heating and cooling (by natural ventilation) increases in energy use for dehumidification to remove moisture emitted from the plant; 2) Increase of heating energy to mitigate evaporative cooling of the crop; 3) decrease of tomato production resulting from a decrease of CO_2 concentration from ventilations. The U-value of $C11_{NL}$ shows a large influence during winter and summer in contrast to the sensitivity of the U-vale for Co_{NL}. Whereas the U-value of $C11_{NL}$ changes every month, the U-value of Co_{NL} is integrated over the year, which results in a low sensitivity index. The distribution of the U-values over the year shows low values in winter to prevent heat loss to the outside and high values in summer to remove indoor heat. Inside and outside emissivity show a minor influence for Co_{NL} and also for $C11_{NL}$ throughout the year except for November and December, in which months the net profit is dominated by the heating energy consumption due to less tomato production.

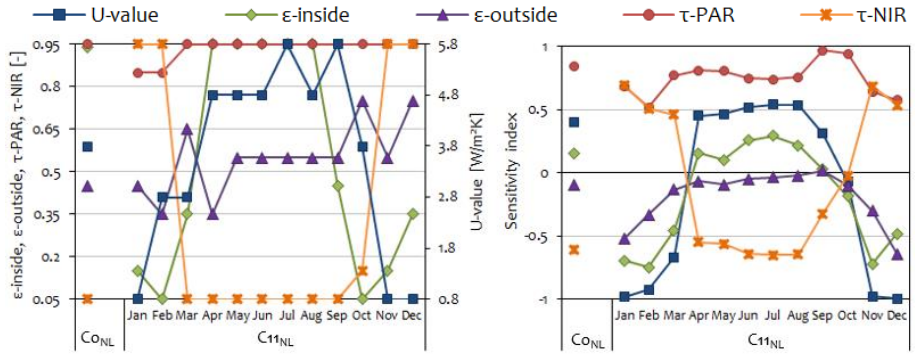

Figure 5.12: *Optimum properties (left) and sensitivity (right) of Co_{NL} and $C11_{NL}$*

Figure 5.13 illustrates the hourly optimum properties ($C8759_{NL}$) of eight selected days. The graph shows that optimal properties were not constant but varied over the day. This is due to the continuously changing performance requirements and weather conditions. In order to maximize the net profit, optimal properties of the PAR transmittance are always high during daytime in mid-season and summer; the U-value is always low all day in winter. Apart from these two properties in specific seasons, all properties fluctuated over the day and thus year.

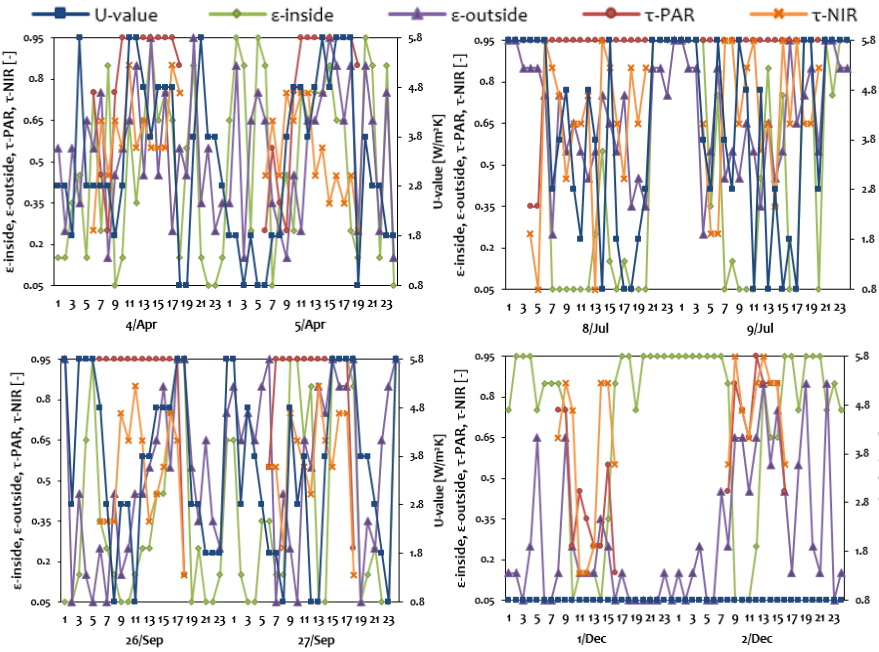

Figure 5.13 *Results of hourly optimum properties (C8759$_{NL}$) with four types and eight selected days*

Although the hourly variation of optimal properties is useful, the fluctuations make it difficult to interpret the result by visual inspection. In order to aid further analysis, this study showed the hourly optimal properties and sensitivity index using a 'moving average' (Loonen & Hensen 2012). In addition, the analysis was divided into day and night to avoid combining the influences of the sun.

Figure 5.14 shows the hourly sensitivity and optimum properties (C8759$_{NL}$) during day time with a 'moving average' of five days. The moving average method is used to express the overall trends without intricacy by smoothing graphs; this method avoids short-term fluctuation and highlights long-term trends in data. The results without moving average can still provide useful information, but this analysis focuses on long term variations. During day time the U-value shows a high influence during the period from January to March, when there is no tomato production due to the growing stage, and during the period from November to December, when the tomato production is minimal due to less solar radiation. The influence of PAR transmittance is high during mid-season and summer. It can be observed that the optimum U-value is low in winter and the transmittance of PAR is high in mid-season and summer. The fluctuation of the optimal PAR transmittance results from the trade-off between tomato production and energy consumption during sunrise, sunset and cloudy days. In the

Pareto optimum, tomato production dominates energy consumption most of time. However, when solar radiation is lower than a certain amount (e.g. 50 W/m^2), the crop turns to respiration rather than photosynthesis. Therefore, it is not always optimal to have a high PAR transmittance during those periods. Unlike for C0$_{NL}$ and C11$_{NL}$, the sensitivity of NIR transmittance of C8759$_{NL}$ shows a minor influence over the year. In order to maximize net profit, the adaptive shell balances the amount of NIR radiation in terms of both heating and cooling. This can be observed in the figure below, which shows the optimal values around 0.5~0.8.

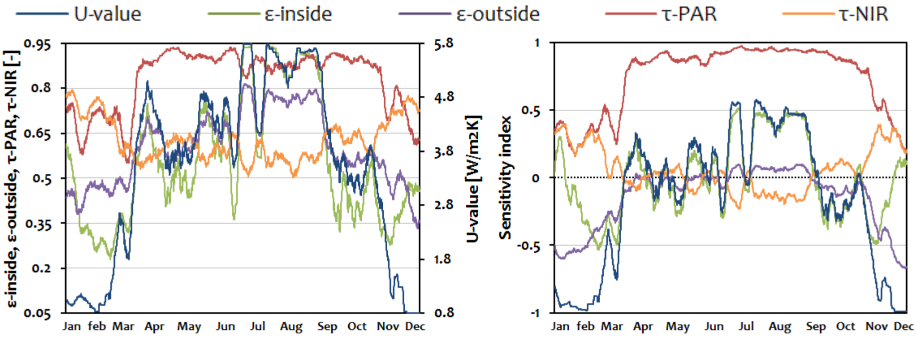

Figure 5.14 *Optimum properties (left) and sensitivity (right) of C8759$_{NL}$ during day-time with five days of moving average*

Figure 5.15 shows the hourly sensitivity and optimum properties (C8759$_{NL}$) during night time. Since the tomato crop is not engaged in photosynthesis at night, the optimization turns into a single-objective problem which only needs to minimize primary energy consumption. During night time, the optical properties are not relevant, and therefore only the three thermal properties are discussed below. All three properties show a high influence during the winter. The optimal U-value and outside emissivity value are low to prevent heat losses to the outside. Since the crop also emits moisture at night time, this results in a humidity increase. Thus, the optimal inside emissivity is high to remove moisture from condensation. For humidity control, this greenhouse uses condensation or ventilation. Considering crop growth and heat preservation in winter, using condensation is a more efficient method than using ventilation since there is no air exchange. In order to increase condensation, the greenhouse shell temperature should be low, which results in a positive sensitivity index and a high optimal value of inside emissivity. During summer, the sensitivity index of the properties shows negative values but the optimal property values are high. This is caused by decision making criteria of the average setting temperature. As defined in the decision making section (Section 5.2.3), there are some periods without any heating, cooling and dehumidification demand when the CAGS concept greenhouses have a high adaptive frequency. Since some values should be selected to find an optimal solution, the average setting temperature is employed to substitute primary energy consumption.

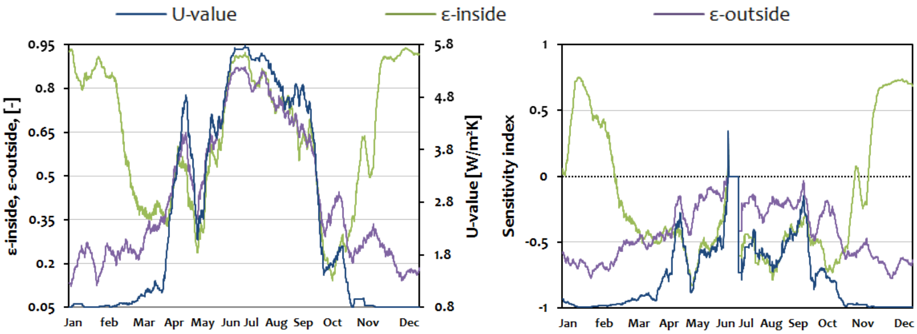

***Figure* 5.15** *Optimum properties (left) and sensitivity (right) of C8759$_{NL}$ during night-time with five days of moving average*

5.6 Conclusion

This study investigated the potential of the CAGS concept greenhouse for a typical Venlo-type greenhouse growing a tomato crop. To do so, the net profit of an optimized static greenhouse and two CAGS concept greenhouses were computationally assessed and compared to a reference greenhouse (current Dutch greenhouse). The results show that the optimized static greenhouse (no adaptation during the year, C0$_{NL}$) and the two CAGS concepts (monthly adaptation, C11$_{NL}$, and hourly adaptation, C8759$_{NL}$) yield an increase in net profit of 7% ~ 20 % compared to the reference greenhouse. The CAGS concept with the higher adaptation frequency demonstrates greater potential in terms of primary energy saving and net profit increase; C11$_{NL}$ and C8759$_{NL}$ show a decrease of primary energy consumption of 23% and 37% respectively, while C0$_{NL}$ (yearly static but optimal design) yields no energy savings. In other words, there is large potential to decrease CO_2 emissions with the CAGS concept.

Next, an in-depth analysis is performed of the CAGS simulation results. This analysis presents the optimal values of the shell properties over the year together with the sensitivity of each property. The results show that optical properties (PAR and NIR transmittance) are the most influential variables in the optimized static greenhouse (C0$_{NL}$) and the CAGS concept greenhouse with low adaptation frequency (C11$_{NL}$); U-value and PAR transmittance at day time and U-value and inside sensitivity at night time are the most influential variables in the CAGS concept greenhouse with high adaptation frequency (C8759$_{NL}$).

To conclude, the CAGS concept greenhouse shows great potential for the Dutch tomato greenhouses to increase net profit and reduce energy use (as well as CO_2 emissions).

Note that this study did not consider additional increases in expenses, such as investment costs and maintenance costs, etc. This conclusion is only valid for the investigated tomato greenhouse with this specific system and the specified performance requirements for the tomato crop. For example, a different price trajectory of the tomato price can lead to a change of overall greenhouse performance (Vanthoor et al. 2012).

In the next chapter, this study extends the investigation of the potential of the CAGS concept greenhouse by testing five system concepts and three crops, which use different systems and have different performance requirements.

6 Case study II: Testing Climate Adaptive Greenhouse Shells with different system concepts

6.1 Introduction

In the previous chapter the new CAGS concept greenhouse was tested and compared to the typical Venlo-style greenhouse that is commonly used in the agricultural sector in the Netherlands. This test focused on only one crop type and was restricted to one system concept. In order to build on the results gained in this test, the current chapter reports on the investigation of the performance of the CAGS concept greenhouse under five different system concepts with three different crops. The investigated crops are tomato, phalaenopsis and chrysanthemum.

The chapter first introduces the five different system concepts of reference greenhouses, and then discusses design parameters and the performance indicators for optimization of the two flower crops, phalaenopsis and chrysanthemum. The potential of the CAGS concept greenhouse is investigated for design optimization and monthly and hourly adaptation. The chapter presents the results and compares the potential of the CAGS concept greenhouse to the reference greenhouse for five system concepts.

6.2 System concepts for investigation

The five system concepts for the performance assessment of the CAGS concept greenhouse are described in Table 6.1. Detailed information about the control and the set-points can be found in Appendix A. The performance of the CAGS concept greenhouse is compared with the reference greenhouses of each system concept. Both the reference and the CAGS concept use the same operation, but the reference has a traditional static greenhouse shell and the CAGS concept greenhouse has the adaptive greenhouse shell. Therefore, the CAGS concept greenhouse does not use shell performance related control such as shading and darkening screens for radiation control or aluminized screens for thermal control.

***Table 6.1** Description of the five system concepts (SC) with three crops*

	Crop	Description
System concept 1 (SC1)	Tomato	Closed greenhouse with active heating, cooling and dehumidification
System concept 2 (SC2)	Tomato	Venlo-type Dutch greenhouse with high performance heating
System concept 3 (SC3)	Phalaenopsis	Propagation area with CHP
System concept 4 (SC4)	Phalaenopsis	Ripening area with CHP
System concept 5 (SC5)	Chrysanthemum	Short day and long day control with CHP

While the quantity of the fresh matter (FM) production is important for the tomato crop, this is not necessarily the case for the flowers. The quality is more relevant to the price of flowers than the quantity, which means that a high FM production does not guarantee an increase in net profit. In order to take this into account, this study assumes that all of the greenhouses growing flower crops produce the same quality of flowers with the same PAR supply. Therefore, PAR transmittance is excluded from the shell optimization. The following four shell properties are considered for the adaptive flower greenhouses: U-value, inside emissivity, outside emissivity and NIR transmittance. Furthermore, the GPS tool calculates only one PI, the primary consumption, and therefore the optimization of the flower greenhouses turns into a single-objective problem (minimizing primary energy consumption).

When the capacity of a cooling system is not enough (e.g. natural ventilation), the greenhouse with high performance shell sometimes cannot meet the required set point of air temperature; for instance, the set-point of cooling for Phalaenopsis in the ripening area is 20 ° C, even in summer. Since a high greenhouse temperature results in decreasing quality of the flower, the greenhouse should maintain the set-point temperature. Therefore, a constraint is introduced in the optimization process; if a certain set of design variables does not meet the air temperature set-point, as shown in Table 6.2, this set of optimal properties is ignored. The constraint of temperature is not considered for the tomato crop since the photosynthesis model takes high inside air temperature into account when calculating net profit.

***Table 6.2** Maximum and minimum temperature limitation for flowers*

	Phalaenopsis		Chrysanthemum			
	Propagation area	Ripening area	Long -day		Short-day	
			Day	Night	Day	Night
Maximum (°C)	35	22	35	27	35	27
Minimum (°C)	27	17	16	15	16	15

6.3 System concept 1: closed greenhouse for tomato

System concept 1 (SC1) is a closed greenhouse concept for tomato cultivation with active heating provided by gas boiler, active cooling by heat pump and dehumidification by active condensation, which is illustrated in Figure 6.1. Due to the high CO_2 concentration in the greenhouse resulting from no air change, the closed greenhouse produces a higher tomato yield in comparison with the traditional tomato greenhouse; in this study, while the reference Venlo-type greenhouse produced 65.6 kg/m^2 of tomatoes (see Chapter 5), the reference closed greenhouse produced 83.8 kg/m^2 of tomatoes (see Table 5.2).

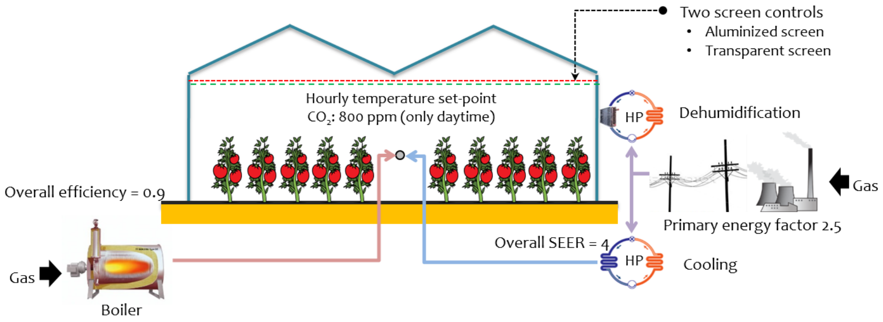

Figure 6.1 *Overview of system concept 1: closed greenhouse with boiler heating, mechanical cooling and mechanical dehumidification*

Figure 6.2 presents the simulation results of the reference greenhouse, the optimized static greenhouse ($C0_{SC1}$) and two CAGS concepts ($C11_{SC1}$ and $C8759_{SC1}$) in €/m^2. As can be seen, the optimized static greenhouse ($C0_{SC1}$) shows a 20 % increase in net profit compared to the reference greenhouse, which is caused by an increase of the PAR transmittance; meanwhile, there is a small net profit improvement between the optimized static greenhouse and the two CAGS concepts: $C0_{SC1}$, $C11_{SC1}$ and $C8759_{SC1}$ show an increase in net profit of 29%, 31 % and 35 % respectively compared to the reference greenhouse. Although energy costs can be reduced in the two CAGS concept greenhouses, these reductions have relatively little influence on the net profit due to high tomato production. However, as shown in Figure 6.3, both the design optimization and the CAGS concept greenhouses lead to significant reductions in energy use: $C0_{SC1}$, $C11_{SC1}$ and $C8759_{SC1}$ show a decrease in primary energy consumption of 34 %, 46 % and 61 % respectively. Here, the decrease of the cooling and heating energy consumption is considerable; the cooling energy decrease mainly results from controlling NIR transmittance and the heating energy decrease results from changing optimal properties throughout the year.

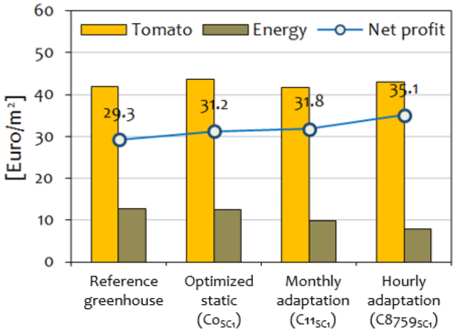

Figure 6.2 *Simulated results of tomato production, energy consumption and net profit for system concept 1 (SC1).*

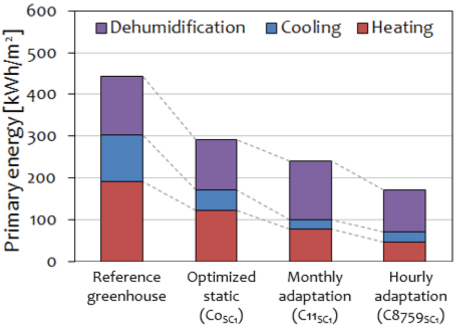

Figure 6.3 *Breakdown of the simulated primary energy consumption (dehumidification, cooling and heating) for system concept 1 (SC1).*

Table 6.3 *Potentials of the design optimization and the CAGS concept with SC1.*

	Unit	Reference greenhouse	Design optimization (Co)	Monthly adaptation (C11)	Hourly adaptation (C8759)
Tomato production	kg/m²	83.8	94.3	94.3	93.9
Energy consumption	kWh/m²	443.7	290.8	240.7	171.2
Tomato production	€/m²	55.8	63.9	63.3	63.3
Energy consumption		12.6	8.3	6.8	4.9
Net profit		43.1	55.6	56.5	58.4
Tomato production	%		15	14	14
Energy consumption			-34	-46	-61
Net profit			29	31	35

Two graphs in Figure 6.4 provide the optimal properties and sensitivities of Co_{SC1} and $C11_{SC1}$ respectively. The two optical properties of $C11_{SC1}$show high sensitivity in summer and winter, and the other three thermal properties show high sensitivity in winter. PAR and NIR transmittance demonstrate the highest influence on both Co_{SC1} and $C11_{SC1}$ in terms of maximizing net profit. Since the closed greenhouse has no ventilation systems but does have mechanical cooling and dehumidification systems, minimizing cooling and dehumidification energy consumption is necessary to increase net profit. This is done by adjusting solar radiation in summer, which is reflected in the sensitivity and optimal properties with low NIR and transmittance. The PAR transmittance should always be high in summer to maximize net profit. Due to low outside solar radiation, sensitivity of the PAR transmittance in winter is lower than in summer, but is still positive and highly valuable in helping reduce the heating demand. The three thermal properties show a high (negative) sensitivity index in winter and therefore decreasing the values will increase net profit. High sensitivity of outside emissivity is also observed in Co_{SC1}, but this can be negligible due to its small sensitivity index.

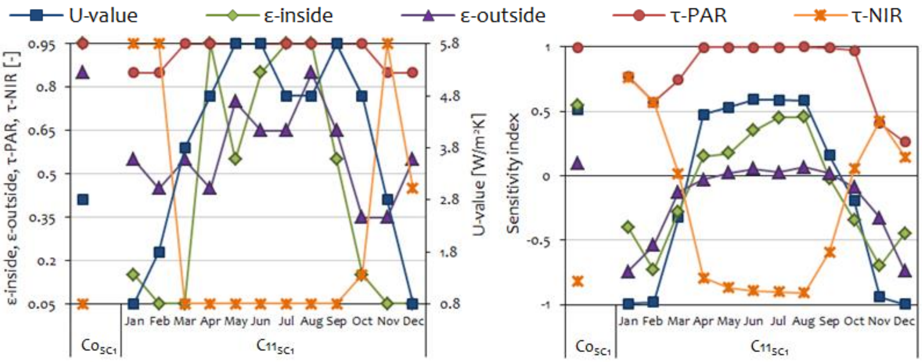

Figure 6.4 *Optimal properties (left) and sensitivity (right) of five design variables for the optimized greenhouse shell with system concept 1 (Co$_{SC1}$) and monthly adaptive greenhouse with system concept 1 (C11$_{SC1}$)*

Figure 6.5 presents hourly optimal properties and sensitivity of the design variables (C8759$_{SC1}$) on the net profit with the five days of moving average during day time. The U-value is the most influential design variable in winter for net profit increase by minimizing primary energy consumption; PAR transmittance is the most influential design variable in mid-season and summer for net profit increase by maximizing tomato production. With respect to the high cooling demand in summer, the positive sensitivity index and high optimal values demonstrate that the three thermal properties are effective in removing inside heat. Unlike Co$_{SC1}$ and C11$_{SC1}$, NIR transmittance shows only a minor influence in C8759$_{SC1}$ over the year. This is explained by the following two reasons: influence of energy consumption to the net profit is lower with high frequency adaptation than with low frequency adaptation; high NIR transmittance increases cooling demand by solar heating but decreases cooling demand by stimulating evaporative cooling.

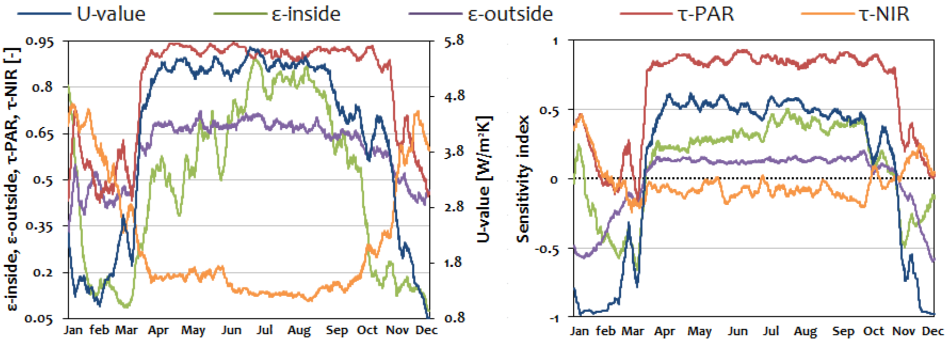

Figure 6.5 *Optimal properties (left) and sensitivity (right) of five design variables with five days moving average for hourly adaptive greenhouse with system concept 1 (C8759$_{SC1}$) during daytime.*

Figure 6.6 presents hourly optimal properties and sensitivity of the design variables (C8759$_{SC1}$) on the net profit with the five days of moving average during night time. The U-value and outside emissivity show negative sensitivity and low optimal values in winter in order to minimize heat loss to the outside. The optimal inside emissivity is high to increase condensation, which leads to minimal mechanical ventilation for dehumidification. The three thermal properties show highly positive sensitivity and high optimal values to remove heat in summer.

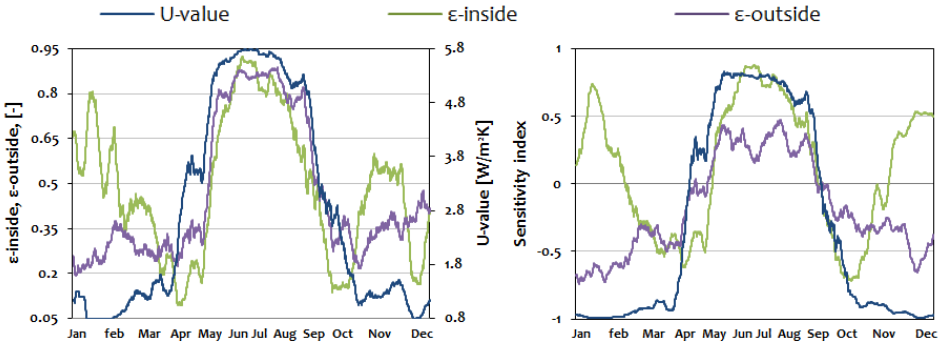

Figure 6.6 *Optimal properties (left) and sensitivity (right) of three design variables with five days moving average for system concept 1 (C8759$_{SC1}$) during nighttime.*

6.4 System concept 2: high performance heating for tomato

System concept 2 (SC2) represents a tomato greenhouse with a high performance heating system with natural (for cooling and dehumidification) and mechanical (for dehumidification) ventilation, which is illustrated in Figure 6.1. Apart from the high performance heating system, the operations and controls of the greenhouse are the same as the typical Venlo-type greenhouse.

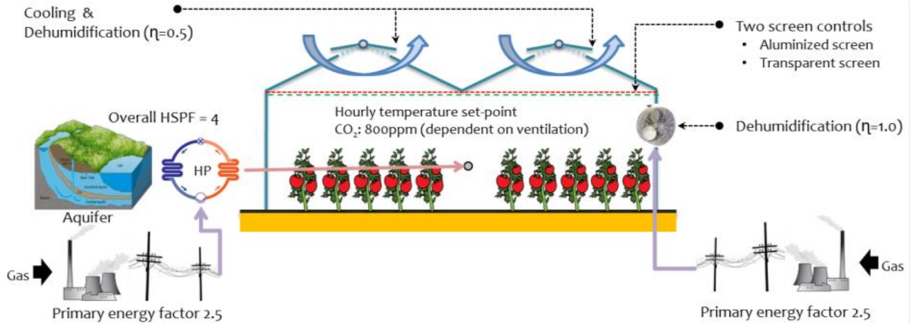

Figure 6.7 *Overview of system concept 2: common Dutch greenhouse with high performance heating*

Figure 6.8 compares simulation performance of the reference greenhouse, the design optimization and two CAGS concepts in SC2. It can be observed that there is only a small net profit increase of around 4% ~ 7% for the optimized static greenhouse and the CAGS concept greenhouses. Since heating energy consumption is significantly decreased through the use of high performance heating systems, there is little chance to reduce primary energy consumption with the adaptations. This can be seen when comparing the energy consumption of the typical Venlo-type greenhouse (NL) described in Chapter 5. While decreases of 103.4 kWh/m² and 167.0 kWh/m² of primary energy consumption were identified in the typical Venlo-type greenhouse concept, the reductions identified in the two CAGS concept greenhouses in SC2 were significantly lower at 42.9 kWh/m² and 108.1 kWh/m², which is shown in Figure 6.9 and Table 6.4.

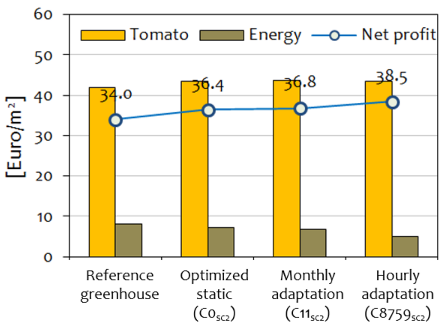

Figure 6.8 *Simulated results of tomato production, energy consumption and net profit for system concept 2 (SC2).*

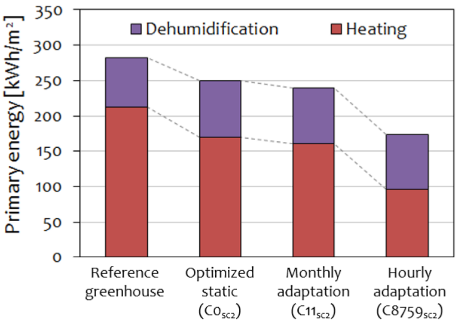

Figure 6.9 *Breakdown of the simulated energy consumption (dehumidification and heating) for system concept 2 (SC2).*

Table 6.4 *Potentials of the design optimization and the CAGS concept with SC2*

	Unit	Reference greenhouse	Design optimization (C0)	Monthly adaptation (C11)	Hourly adaptation (C8759)
Tomato production	kg/m²	65.6	69.9	71.3	72.5
Energy consumption	kWh/m²	281.7	249.5	238.8	173.6
Tomato production	€/m²	42.0	43.5	43.6	43.4
Energy consumption		8.0	7.1	6.8	4.9
Net profit		34.0	36.4	36.8	38.5
Tomato production	%		4	4	3
Energy consumption			-11	-15	-38
Net profit			7	8	13

Two graphs in Figure 6.10, below, provide the optimal properties and sensitivities of Co$_{SC2}$ and C11$_{SC2}$ respectively. The overall trend of sensitivity relating to net profit is similar to SC1 and the common Dutch greenhouse, since tomato production dominates the net profit in summer and energy consumption does so in winter. PAR and NIR transmittance show the highest influence on the net profit over the year in both Co$_{SC2}$ and C11$_{SC2}$. The sensitivity and optimal values of the PAR transmittance are always high in summer to maximize tomato production. The NIR transmittance shows high negative sensitivity and low optimal values to reduce cooling and dehumidification demand in summer. Since there is little or no tomato production in winter, sensitivity of PAR transmittance is less in winter than in summer. The other three thermal properties present negative and high sensitivity in winter to minimize heating energy consumption in $C11_{SC2}$.

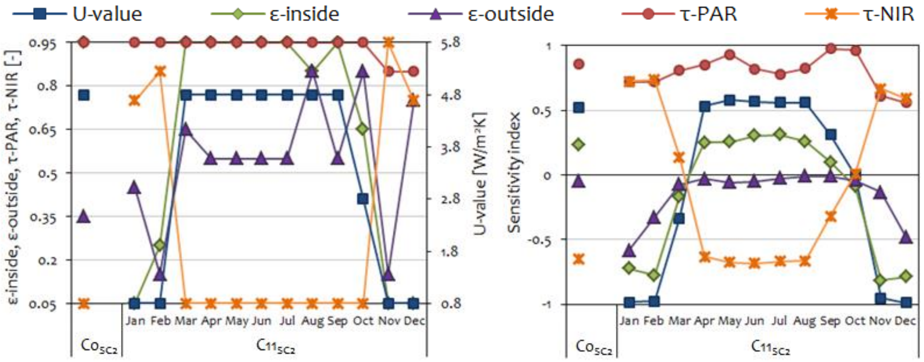

Figure 6.10 *Optimal properties (left) and sensitivity (right) of five design variables for the optimized greenhouse shell with system concept 2 ($C0_{SC2}$) and monthly adaptive greenhouse with system concept 2 ($C11_{SC2}$).*

Figure 6.11 shows hourly optimal properties and sensitivity of the design variables ($C8759_{SC1}$) on the net profit with the five day moving average during day time. The U-value is the most influential design variable in winter in terms of minimizing the primary energy consumption; the PAR transmittance is the most influential design variable in summer in terms of maximizing tomato production. The three thermal properties show a high influence in winter, which is largely due to energy consumption and thus relates to net profit, whereas these three properties show only a minor influence in summer.

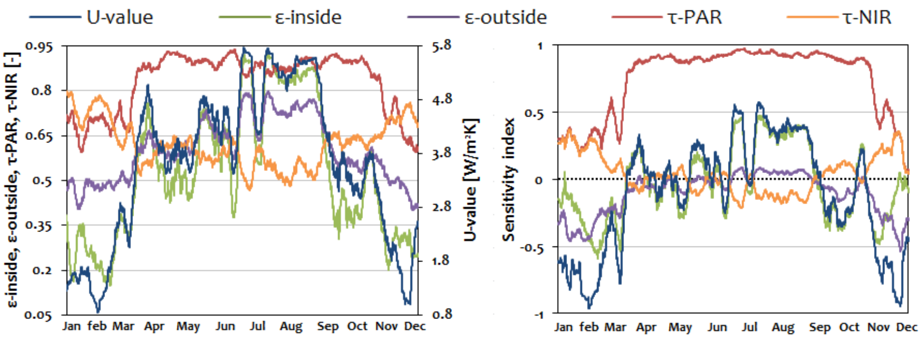

Figure 6.11 *Optimal properties (left) and sensitivity (right) of five design variables with five days moving average for hourly adaptive greenhouse with system concept 2 (C8759$_{SC2}$)*

Figure 6.12 shows the hourly optimal properties and the sensitivity of the design variables (C8759$_{SC2}$) on the net profit with the five-day moving average during night time. In winter, the U-value and the outside emissivity show negative sensitivity and low optimal values to block heat loss to the outside. However, the optimal inside emissivity value remains high to increase condensation for dehumidification since the crop emits moisture even at night time. In summer, the three optimal thermal properties have high values to remove inside heat.

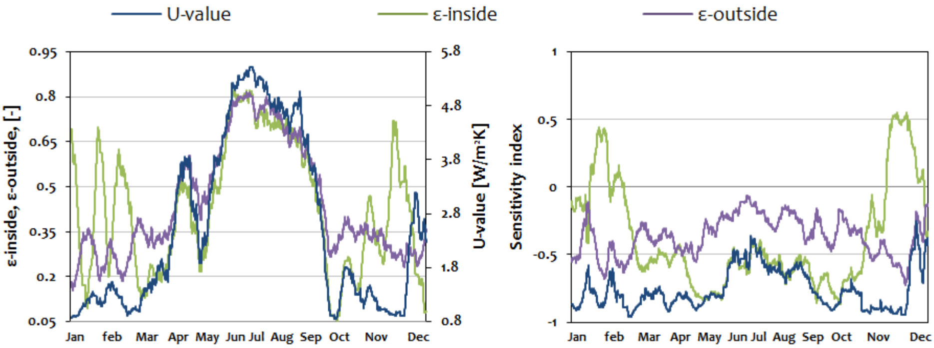

Figure 6.12 *Optimal properties (left) and sensitivity (right) of three design variables with five days moving average for system concept 2 (C8759$_{SC2}$)*

6.5 System concept 3: propagation area for phalaenopsis

System concept 3 (SC3) investigated the potential of the CAGS concept greenhouse in a propagation area for Phalaenopsis, which is illustrated Figure 6.13. As mentioned in Section 6.1, the CAGS concept greenhouse for flowers has adaptation of four design variables: U-value, inside emissivity, outside emissivity and NIR transmittance. Since the case studies assume that the quantity and the quality of flowers are the same for all cases, the potential of adaptability is investigated with one objective function, the primary energy consumption.

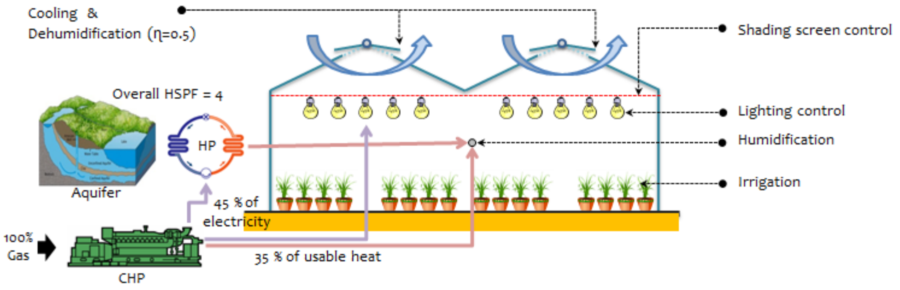

Figure 6.13 *Overview of system concept 3: propagation area with CHP for heating and lighting*

The temperature set-point in the propagation area is high and tight: 28 °C for heating and 29 °C for cooling. SC3 uses combined heat and power (CHP) systems for electricity generation (for both artificial lighting and heat pump (HP) heating with an aquifer) and for heating. The operation of the CHP system in SC3, SC4 and SC5 is as follows. 1) If there is only a lighting demand, the CHP then generates electricity with an efficiency of 45%; the additional heat is wasted, since no additional heat storage system is applied. 2) If there are only heating demands, then the CHP supplies heat with 35% efficiency; at the same time, the generated electricity with 45% efficiency is used by HP with the aquifer for heating. 3) If there is both heating and lighting demand, CHP generates electricity for lighting and uses the additional heat for heating; when heating demand is higher than the additional heat, the CHP generates more electricity for HP and more additional heat for the remaining heating demand. Since the lighting control period overlaps with the heating season, wasted heat during electricity generation can be minimized.

Figure 6.14 illustrates the primary energy consumption of the reference greenhouse, the optimized static design and the two CAGS concept greenhouses in €/m². Since the lighting is controlled based on the outside solar radiation and PAR transmittance is the same, the lighting energy consumption is constant for all cases. In addition, since the lighting control period is from January to February and from September to December, the use of lighting helps to reduce the heating energy demand in winter. The low dehumidification set-point (70 %) leads to high air exchange by natural ventilation, which leads to high heating energy consumption. Unlike tomatoes, whose leaf area index (LAI) gradually increases from the date of planting, the study assumes that the LAI index of Phalaenopsys is constant over the year. Therefore, significant moisture emission from the flower increases the dehumidification demand by condensation or natural ventilation, which finally increases heating demand in winter.

$C0_{sc3}$, $C11_{sc3}$ and $C8759_{sc3}$ decrease primary energy consumption by around 4 % ~ 29 %. Since heating energy demand is decreased due to the extra heat provided by CHP during electricity generation in winter and due to the use of the high performance heating system (HP), energy saving potential of the CAGS concept greenhouse is not as much as SC1 and SC2. $C0_{sc3}$ and $C11_{sc3}$ only reduce 4 % and 12 % of energy consumption respectively, which is due to the temperature constraint in the optimization process and low adaptibility. In contrast, the primary energy reduction of the CAGS concept greenhouse with high adaptation frequency ($C8759_{sc3}$) is 29 %.

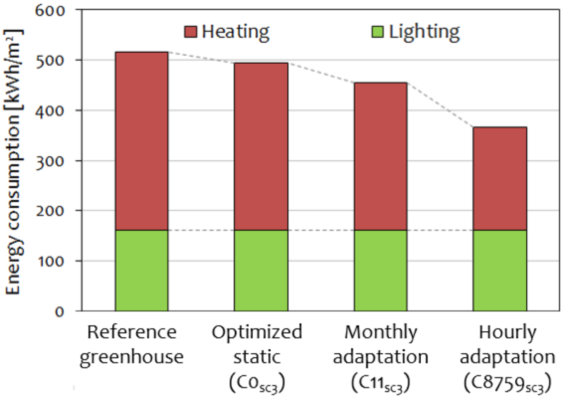

Figure 6.14 *Simulated energy consumption for system concept 3*

Table 6.5 *Potential of the design optimization and the CAGS concept with SC3*

	Unit	Reference greenhouse	Design optimization ($C0_{sc3}$)	Monthly adaptation ($C11_{sc3}$)	Hourly adaptation ($C8759_{sc3}$)
Energy consumption	kWh/m²	515.9	495.2	455.8	367.0
	€/m²	14.7	14.1	13.0	10.4
	%		-4	-12	-29

Two graphs in Figure 6.15 provide the optimal properties and the sensitivities of $C0_{sc3}$ and $C11_{sc3}$. The U-value and NIR transmittance are the most influential design variables in summer to minimize heating due to the high heating set-point of 28 °C. Due to the free heat from CHP during electricity generation for the lighting, the advantage of greenhouse shell adaptability declines in winter. Thus, the sensitivity of adaptive shell properties to the energy consumption in winter is lower than in summer. This finding can be observed in the sharp change of sensitivity and optimal properties in April and in September in which the lighting control begins and ends.

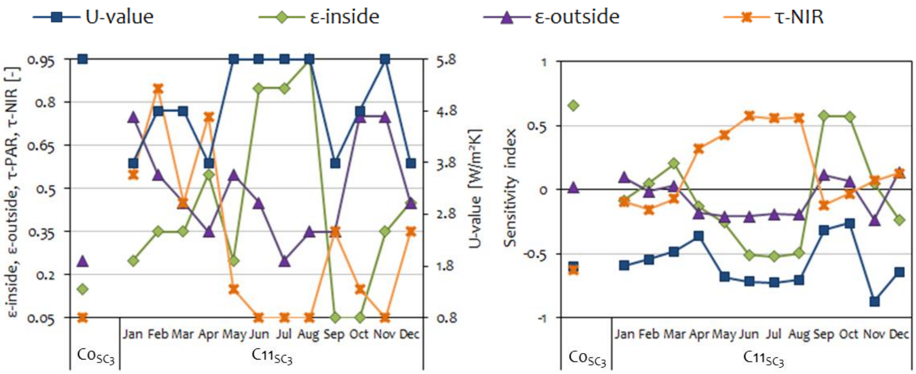

Figure 6.15 *Optimal properties (left) and sensitivity (right) of five design variables for the optimized greenhouse shell for system concept 3 (C0$_{sc3}$) and monthly adaptive greenhouse for system concept 3 (C11$_{sc3}$).*

Figure 6.16 presents hourly optimal properties and sensitivity of the design variables (C8759$_{sc3}$) on the energy consumption with the five-day moving average during day time. The figure detailing the sensitivity analysis suggests that hourly control of the U-value, inside emissivity and NIR transmittance decrease heating energy consumption in summer. Unlike tomato greenhouses, there is no radical change of sensitivity and optimal properties between summer and winter. This finding results from the high heating temperature set-point in summer and from free heat by use of the CHP during electricity generation in winter. The latter can be observed in the low indices in the graph on sensitivity. Due to the tight temperature set-point between heating and cooling (1°C), trajectories of both sensitivity and optical properties fluctuate every hour; however, these fluctuations are flattened out by the moving average. Since this study focuses on the overall performance of CAGS concept, the hourly fluctuation is not presented here.

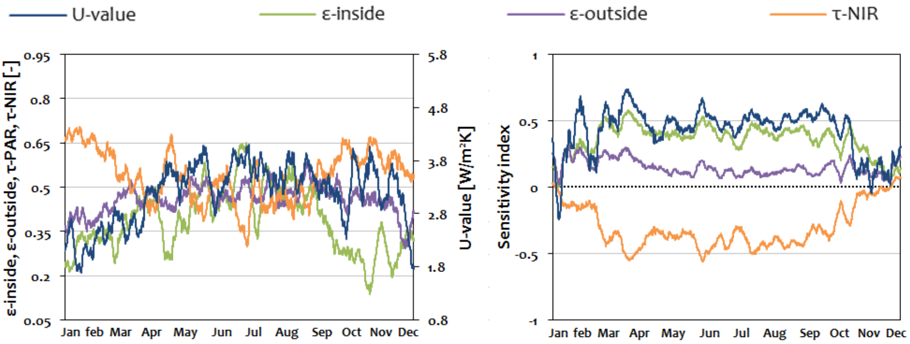

Figure 6.16 *Optimal properties (left) and sensitivity (right) of five design variables with five days moving average for hourly adaptive greenhouse with system concept 3 (C8759$_{sc3}$) during daytime.*

Figure 6.17 presents the hourly optimal properties and sensitivity of the design variables (C8759$_{sc2}$) on the energy consumption with the five-day moving average during night time. Low U-value and low outside emissivity are required for heating energy saving in winter. In contrast to day time, the sensitivity of thermal properties to the energy consumption is more obvious at night due to less electricity use from the CHP during the darkened hours of the crop.

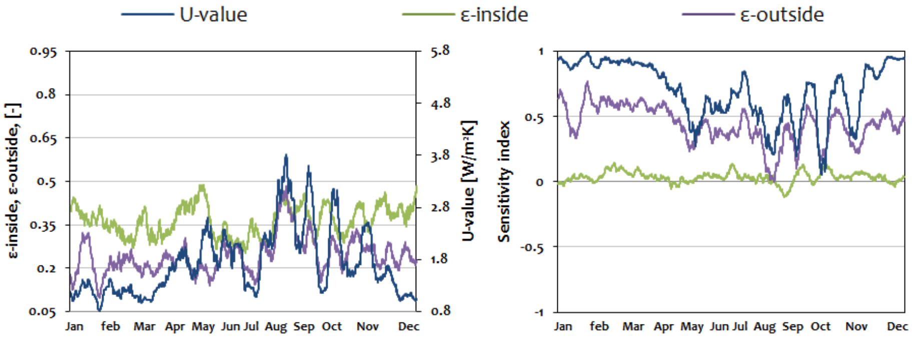

Figure 6.17 *Optimal properties (left) and sensitivity (right) of three design variables with five days moving average for system concept 3 (C8759$_{SC3}$) during nighttime.*

6.6 System concept 4: ripening area of phalaenopsis

System concept 4 (SC4) investigated the performance of the CAGS concept greenhouse for Phalaenopsis in the ripening area, which is illustrated in Figure 6.18. SC4 has PV power generation covering 10% of the greenhouse area (1000m^2) and uses CHP for electricity generation and heating. PV power generation, calculated from TRNSYS, (http://www.trnsys.com) is 12.1 kWh/m^2/year from 2009 weather data. This study assumes that generated PV power is first sent to the grid and then used when mechanical ventilation is necessary in summer without any cost difference between them. Such an assumption is proposed since not only high power generation is expected with high solar radiation but high cooling demand is also anticipated in summer. The temperature set-point is very low and tight: 19 °C for heating and 20 °C for cooling. The cooling is controlled by natural or mechanical ventilation and heating is controlled by CHP.

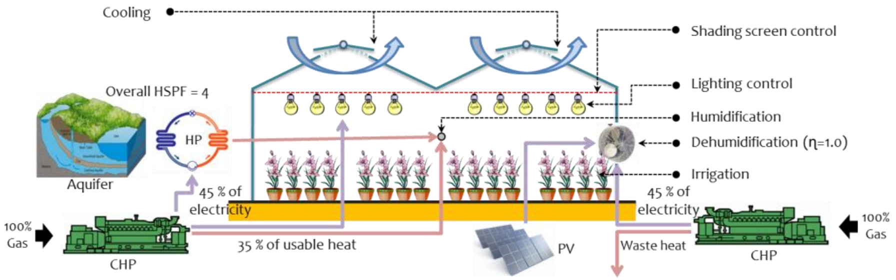

Figure 6.18 *Overview of system concept 3: ripening area with CHP for heating, cooling and lighting. PV also installed for electricity generation.*

Figure 6.19 presents the primary energy consumption of the reference greenhouse, the optimized static greenhouse ($C0_{sc4}$) and the two CAGS concept greenhouses ($C11_{sc4}$ and $C8759_{sc4}$) in €/m². Due to the set-point of the outside solar radiation, the lighting energy consumption is constant for all cases. As assumed above, PV power generation is used for cooling; therefore, the amount of generated power is deducted in cooling energy consumption, but is not presented in Figure 6.19. $C0_{sc4}$, $C11_{sc4}$ and $C8759_{sc4}$ show a decrease in primary energy consumption of around 17 % ~ 34 %. The low adaptation frequency in $C11_{sc4}$ led to a minor improvement in energy saving compared to the optimized static greenhouse, $C0_{sc4}$, whereas $C8759_{sc4}$ with high adaptation frequency achieved higher energy saving than $C0_{sc4}$ and $C11_{sc4}$.

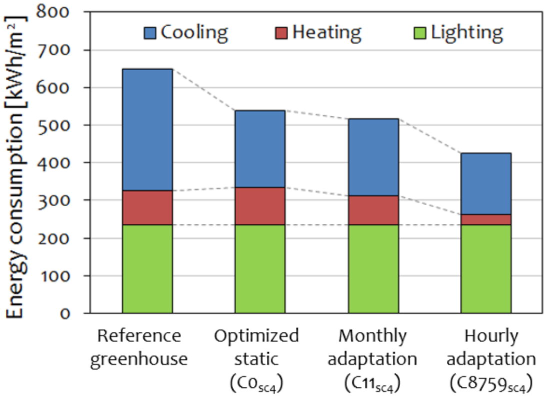

Figure 6.19 *Simulated energy consumption for system concept 4.*

Table 6.6 *Potentials of the optimized static greenhouse and the CAGS concept with SC4*

	Unit	Reference greenhouse	Design optimization ($C0_{sc4}$)	Monthly adaptation ($C11_{sc4}$)	Hourly adaptation ($C8759_{sc4}$)
Energy consumption	kWh/m²	648.4	538.6	516.5	424.9
	€/m²	18.4	15.3	14.7	12.1
	%		-17	-20	-34

The two graphs in Figure 6.20 provide the optimal properties and sensitivities of Co_{sc4} and $C11_{sc4}$. According to the sensitivity analysis, the most influential design variables in winter are the U-value and inside emissivity, and in summer are inside emissivity and NIR transmittance. However, a discrepancy between sensitivity and optimal properties can be observed in summer; although sensitivity indices of the U-value are lower than inside emissivity, the optimal properties of the U-value are always the highest value, but inside emissivity does not follow this trend. Upon investigation, the discrepancy arises from the following constraint; sets of the optimal properties which achieve minimum energy consumption are ignored to meet the temperature limitation of 22 °C. Therefore, a high U-value and low NIR transmittance are always required in the ripening area to meet the temperature constraint in summer. Ultimately, this constraint leads to less energy saving in $C11_{sc4}$ as compared to $Co_{sc4,}$ as shown in Figure 6.19.

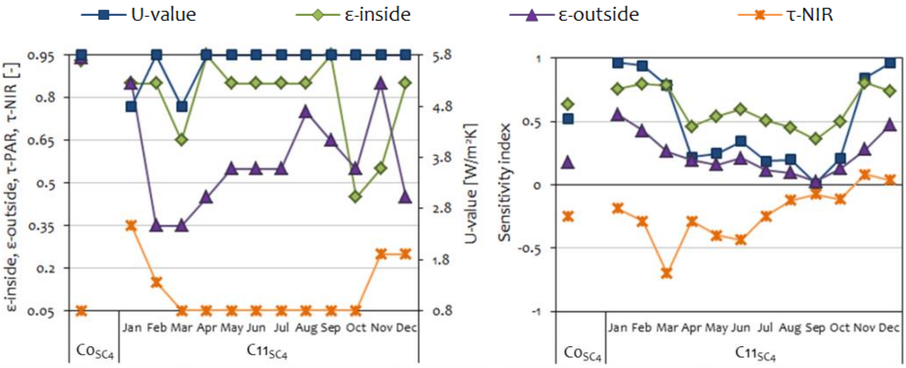

Figure 6.20 *Optimal properties (left) and sensitivity (right) of five design variables for the optimized greenhouse shell with system concept 4 (Co_{sc4}) and monthly adaptive greenhouse with system concept 4 ($C11_{sc4}$)*

Figure 6.21 presents hourly optimal properties and sensitivity of the design variables ($C8759_{sc3}$) on the energy consumption with the five-day moving average during day time. Since fluctuation of sensitivity is flattened out by the moving average and use of the constraint, the trajectories of optimal properties do not follow the sensitivity trajectories. Due to the free heat from CHP and high adaptability of the shell, low sensitivity indices of design variables are observed in winter. In order not to exceed the temperature limitation, high values of the three thermal properties and low NIR transmittance are required in mid-season and summer.

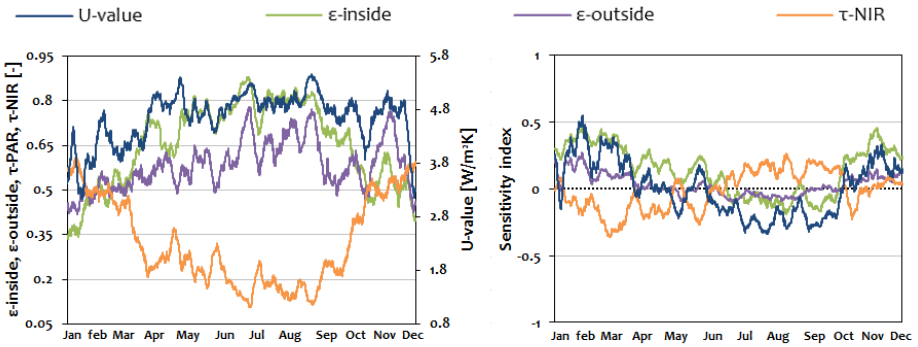

Figure 6.21 *Optimal properties (left) and sensitivity (right) of five design variables with five days moving average for hourly adaptive greenhouse with system concept 4 (C8759$_{sc4}$) during daytime.*

Figure 6.22 presents the hourly sensitivity and optimal properties of C8759 $_{SC4}$ with the five-day moving average during night time. It can be observed that a low U-value and outside emissivity are the most influential design variables for heating energy saving over the year. Meanwhile, inside emissivity shows a minor effect over the year with the CAGS greenhouse with high adaptation frequency.

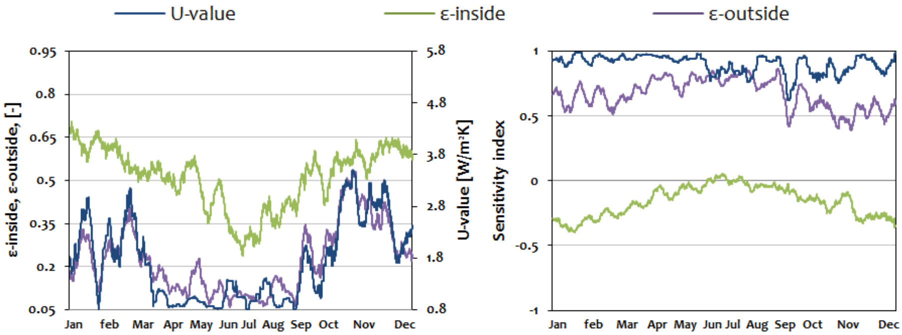

Figure 6.22 *Optimal properties (left) and sensitivity (right) of three design variables with five days moving average for system concept 4 (C8759$_{sc4}$) during nighttime.*

6.7 System concept 5: Short and long day for chrysanthemum

System concept 5 (SC5) investigated the potential of the CAGS concept for chrysanthemums and is described in Figure 6.23. The greenhouse with SC5 has 75 days of cultivation cycle: 14 days of short-day and 61 days of long-day. SC5 uses CHP systems to generate electricity for lighting and heating, and to supply heat for heating. The temperature set-point of heating and cooling is around 19 °C and the set-point changes during day and night. Cooling and dehumidification are controlled by natural ventilation. Darkening screen control is applied for control of solar radiation and lighting is employed for control of day length for both short day and long day period.

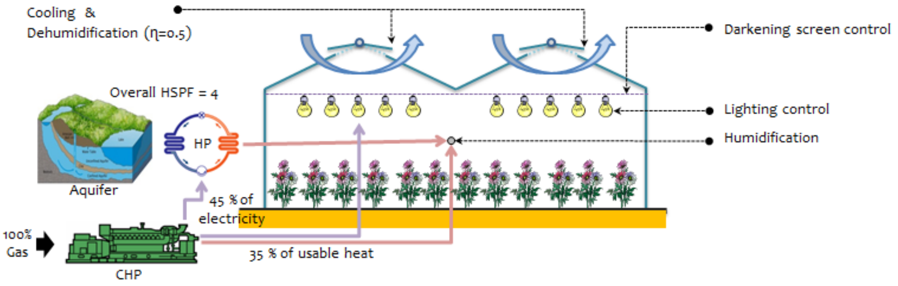

Figure 6.23 *Overview of system concept 5*

Figure 6.24 illustrates the primary energy consumption of the reference greenhouse, the design optimization (Co$_{sc5}$) and the two CAGS concept greenhouses (C11$_{sc5}$ and C8759$_{sc5}$) in €/m^2. Since the lighting is controlled based on the outside solar radiation and PAR transmittance is not controlled, the lighting energy consumption is constant for all cases. Co$_{sc5}$, C11$_{sc5}$ and C8759$_{sc5}$ show a decrease in primary energy consumption of around 2 % ~ 32 %. Co $_{sc5}$ and C11 $_{sc5}$ shows only a few percent reduction of primary energy consumption due to the use of temperature constraint. However, C8759 $_{sc5}$ achieves significant primary energy saving under the temperature constraint, which is mainly due to its high adaptability.

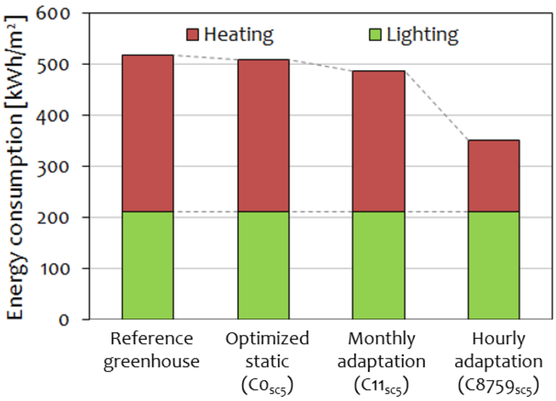

Figure 6.24 *Primary energy consumption for system concept 5*

Table 6.7 *Potentials of the design optimization and the CAGS concept with SC5*

	Unit	Reference greenhouse	Design optimization (Co$_{sc5}$)	Monthly adaptation (C11$_{sc5}$)	Hourly adaptation (C8759$_{sc5}$)
Energy consumption	kWh/m^2	517.4	508.4	485.8	349.9
	€/m^2	14.7	14.5	13.8	10.0
	%		-2%	-6%	-32%

Two graphs in Figure 6.25 provide the optimal properties and sensitivities of $C0_{sc5}$ and $C11_{sc5}$ respectively. Due to the combined operations (14 days for long-day control and 61 days of short-day) in cultivation cycle, both controls cycle by month and year, and therefore optimal properties and sensitivity vary over the year. The influence of this control cycle can be seen in the fluctuations in the monthly optimal properties and sensitivity values.

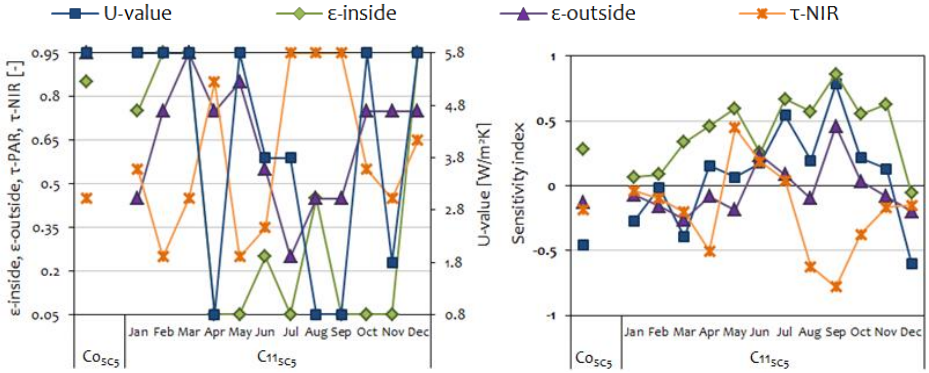

Figure 6.25 *Optimal properties (left) and sensitivity (right) of five design variables for the optimized greenhouse shell with system concept 5 ($C0_{sc5}$) and monthly adaptive greenhouse with system concept 5 ($C11_{sc5}$).*

Figure 6.26 presents hourly optimal properties and sensitivity of the design variables ($C8759_{sc5}$) on the primary energy consumption the five-day moving average during day time. Due to the moving average, which flattens out hourly fluctuation, only the overall trend only can be observed; none of the shell properties has a great influence on the primary energy consumption and the combined cultivation leads to fluctuations of the optimal properties and sensitivity in spite of moving average.

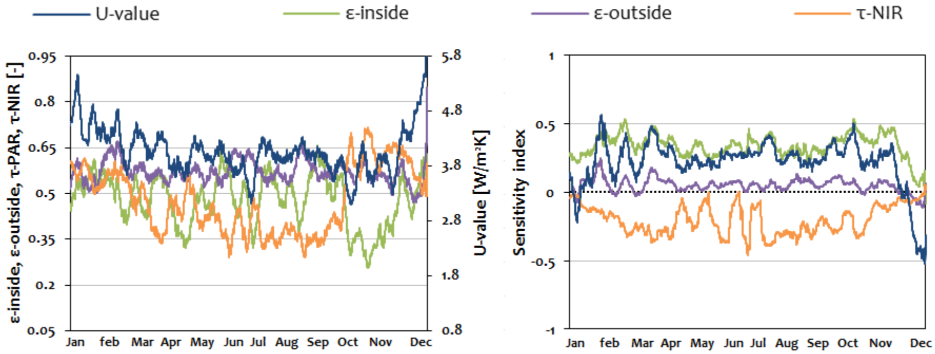

Figure 6.26 *Optimal properties (left) and sensitivity (right) of five design variables with five days moving average for hourly adaptive greenhouse with system concept 5 ($C8759_{sc5}$)*

Figure 6.27 presents the hourly sensitivity and optimal properties of C8759$_{sc4}$ by the five-day moving average during night time. The influence of sensitivity and optimal properties to the primary energy consumption is more obvious at night than during the day. It can be observed that low U-values and outside emissivity are the most influential design variables for energy saving with high adaptation frequency, whereas inside emissivity shows a minor influence over the year.

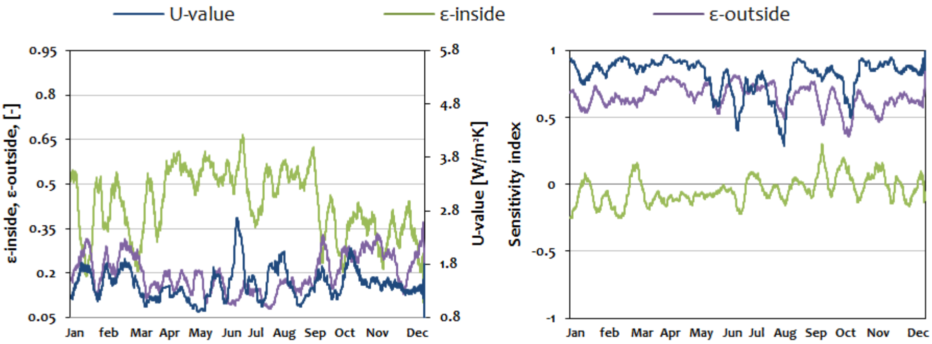

Figure 6.27 *Optimal night time properties (left) and sensitivity (right) of three design variables with five days moving average for system concept 5 (C8759$_{sc5}$)*

6.8 Conclusion

This chapter extended the investigation of the performance of the CAGS concept by testing different system concepts for three crops. To do so, first, five system concepts were defined. Then, the study investigated and compared the performance of an optimized static greenhouse (C0) and two CAGS concept greenhouses (C11 and C8759) using simulation-based dynamic optimization. The study compared the results of these three greenhouse concepts for performance assessment, and also investigated the distribution of optimal properties and sensitivities to provide a better understanding of the relationship between greenhouse performance and behavior of greenhouse shell.

Table 6.8, below, provides a broad overview of the potential of the CAGS concept greenhouses. Before considering this overview, however, a number of important findings concerning net profit and primary energy consumption are first presented.

***Table 6.8** Overview of the results for the five system concepts*

Tomato	**System concept 1**				**System concept 2**			
	Reference greenhouse	**$C0_{sc1}$**	**$C11_{sc1}$**	**$C8759_{sc1}$**	**Reference greenhouse**	**$C0_{sc2}$**	**$C11_{sc2}$**	**$C8759_{sc2}$**
Tomato production [kg/m^2]	83.8	94.3	94.3	93.9	65.6	69.9	71.3	72.5
Primary energy consumption [kWh/m^2]	443.7	290.8	240.7	171.2	281.7	249.5	238.8	173.6
Tomato production [€/m^2]	55.8	63.9	63.3	63.3	42.0	43.5	43.6	43.4
Primary energy consumption [€/m^2]	12.6	8.3	6.8	4.9	4.4	4.2	4.0	3.3
Net profit [€/m^2]	**43.1**	**55.6**	**56.5**	**58.4**	**37.6**	**39.3**	**39.6**	**40.1**
Tomato production [%]	-	15	14	14	-	4	4	3
Gas reduction [%]	-	34	46	61	-	4	8	25
Net profit [%]	**-**	**29**	**31**	**35**	**-**	**4**	**5**	**7**
Phalaenopsis	**System concept 3**				**System concept 4**			
	Reference greenhouse	**$C0_{sc3}$**	**$C11_{sc3}$**	**$C8759_{sc3}$**	**Reference greenhouse**	**$C0_{sc4}$**	**$C11_{sc4}$**	**$C8759_{sc4}$**
Primary energy consumption [kWh/m^2]	515.9	495.2	455.8	367.0	648.4	538.6	516.5	424.9
Primary energy consumption [€/m^2]	14.7	14.1	13.0	10.4	18.4	15.3	14.7	12.1
Primary energy **reduction** [%]	**-**	**4**	**12**	**29**	**-**	**17**	**20**	**34**
Chrysanthemum	**System concept 5**							
	Reference greenhouse	**$C0_{sc5}$**	**$C11_{sc5}$**	**$C8759_{sc5}$**				
Primary energy consumption [kWh/m^2]	517.4	508.4	485.8	349.9				
Primary energy consumption [€/m^2]	14.7	14.5	13.8	10.0				
Primary energy **reduction** [%]	**-**	**2**	**6**	**32**				

Whereas the optimized static greenhouse showed only a minor improvement in performance, the two CAGS concept greenhouses demonstrated the potential to significantly increase net profit and to save a significant amount of energy. The figures for each greenhouse concept are as follows:

- The CAGS concept greenhouse in SC1 increased net profit by 31 % ~ 35 %, and reduced the primary energy consumption by 41 % ~ 61 %;

- The CAGS concept greenhouse in SC2 increased net profit by 4% ~ 7%, and reduced primary energy consumption by 8% ~ 25%;
- The CAGS concept greenhouse in SC3 reduced primary energy consumption by 12% ~ 29%;
- The CAGS concept greenhouse in SC4 reduced primary energy consumption by 20% ~ 34%;
- The CAGS concept greenhouse in SC5 reduced primary energy consumption 6% ~ 32%.

It is observed that the CAGS concept greenhouse with higher adaptation frequencies achieved a higher net profit increase and higher energy savings. In the case study, the hourly adaptive greenhouse performed better than the monthly adaptive greenhouse. This is because variation of shell properties during day and night results in high energy saving mainly due to the influence of the solar radiation.

The CAGS concept greenhouses that show the greatest energy savings are those with high energy demands resulting from low performance of both the greenhouse shells and systems, such as SC1. In fact, these greenhouses enjoy greater benefits precisely because they are provided with energy saving by greater control of the greenhouse shells. For example, the CAGS concept greenhouse in SC2, only heated with high performance HP systems, achieves 8% ~ 25% of primary energy savings by shell adaptation, while the CAGS concept in SC1, requiring high energy consumption for operation, achieves the much higher 41 % ~ 61 %;

Separate control of PAR and NIR shows great energy saving potential in the optimized static greenhouse and in the CAGS concept greenhouse, particularly where energy consumption is high. Both the optimized static greenhouse and CAGS concept greenhouses in SC1 and SC2 produce more tomatoes than the reference greenhouse, which results from improvements due to high PAR transmittance and better control of greenhouse environment.

Control of thermal properties (U-value, inside and outside emissivity) leads to high energy saving in winter for SC1 and SC2; however, it was not greatly effective in the three greenhouse concepts (SC3, SC4 and SC5) for flowers due to the use of CHP. When it comes to high adaptation frequency, the control of thermal properties is only effective at night time.

Since temperature is highly relevant to the quality of flowers, the study introduced temperature constraints to avoid high and low greenhouse temperatures. This constraint retains a favorable greenhouse temperature for flowers, but since it adopts a less optimal set of shell properties, it limits the possibility for the CAGS concept greenhouse to save energy. In addition, the tight heating and cooling air temperature set-point results in high energy demand. Analysis of the results shows that only the hourly adaptive greenhouse achieved significant energy saving under the operation of SC3, SC4 and SC5. These results indicate a clear finding: high adaptive shell control is appropriate for the cultivation of flowers, but static and low adaptive shell controls are unsuitable.

To conclude, the CAGS concept greenhouse achieved a large increase in net profit and energy saving in five system concepts. However, the performance of the CAGS concept greenhouse varied depending on greenhouse system and operation; the use of high performance systems and the temperature constraints decreased the advantage of CAGS concept greenhouses.

It is important to note that the testing done up to this point has simulated the most common growing season, summer. This season is the most popular for growers since the weather is most favorable for crop production in summer, and energy prices are considerably higher in winter, which affects the crop's profitability. However, growers are under great pressure from global competition, which means that it would be highly beneficial to develop growing systems that can produce profitable crops at other times of the year. In the next chapter, this study investigates the performance of the CAGS concept greenhouse with a range of different cultivation scenarios to determine to what extent crops can be produced profitably in different periods of the year.

7 Case study III: Testing Climate Adaptive Greenhouse Shells with different cultivation scenarios

In The Netherlands, the winter weather provides only low amounts of SW radiation. In addition, energy prices are generally much higher during winter months. These factors combined have such a serious impact on the profitability of the crop that under current conditions some farmers consider not growing during winter months to be the most cost-effective decision.

The potential of the CAGS concept to reduce energy use and increase net profit was demonstrated for the typical summer growing scenario in the case studies presented in the previous chapter. The case studies reported in this chapter aim to determine whether CAGS concept greenhouses can be applied to allow growers to produce crops profitably throughout the year.

To achieve success in these case studies, the CAGS concept greenhouses will need to operate with low heating energy consumption and provide high shortwave radiation. Doing so would allow growers to generate significantly more net profit than is possible with current greenhouse designs and may make growing crops in winter a profitable exercise.

The previous two case studies clearly demonstrated that the CAGS concept greenhouse has great potential to save heating energy. Thus, adding additional lighting to the CAGS concept greenhouse seems a promising solution to dealing with the deficit of SW radiation in shifting growth and harvest seasons.

This chapter investigates the potential of the CAGS concept greenhouse with different cultivation scenarios covering different growing seasons. In total, three greenhouse concepts are tested in four different cultivation scenarios. The tomato is used for all scenarios in order to keep the crop variable stable and focus to be placed on the performance indicators and to allow comparison between conditions. The following section describes the cultivation scenarios and greenhouse concepts in detail. The chapter concludes with a discussion of the results from the case study.

7.1 Cultivation scenarios

The tests reported in this chapter cover three system concepts in four different cultivation scenarios. The study includes the typical Venlo-type greenhouse. The other two greenhouse concepts tested here are the CAGS concept greenhouse with monthly adaptation and the CAGS concept greenhouse with hourly adaptation. These two CAGS concepts were adopted for use here because the results in the previous chapters showed that these two concepts had the greatest potential for saving energy and realizing an increase in net profit.

The four cultivation scenarios that are used are shown in Figure 7.1. One of these scenarios represents a reference cultivation scenario of the typical Venlo-type greenhouse. In order to be able to generate results throughout the year, the research shifted each subsequent scenario by three months from the date of planting of the previous scenario. The dates of planting (DOP) of the scenarios is as follows: reference scenario (R) is January 15, scenario 1 (S1) is April 15, scenario 2 (S2) is July 15 and scenario 3 (S3) is October 15.

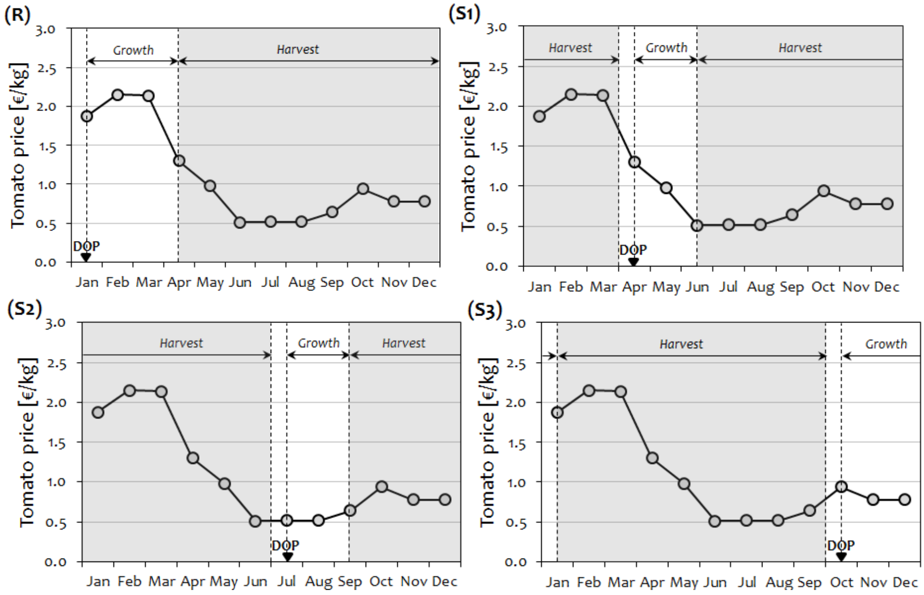

Figure 7.1 *Monthly tomato price and three cultivation scenarios: (R) planting tomato on 15/Jan and starting harvest from 15/Apr, (S1) planting tomato on 15/Apr and starting harvest from 15/Jun, (S2) planting tomato on 15/Jul and starting harvest from 15/Sep, (S3) planting tomato on 15/Oct and starting harvest from 15/Jan*

Since the amount of shortwave radiation varies over the year, the onset of harvest from DOP is faster in summer than in winter. Thus, this case study assumes that the period of growth is three months for R and S3 and two months for S1 and S2. The 15-day gap between the end of harvest and the new DOP represents the period when old tomatoes are removed and preparation takes place for planting.

Since Dutch weather conditions require the use of an hourly temperature set-point for tomato cultivation, a change of temperature set-point is also necessary. Fortunately, experts in the field of agriculture in The Netherlands from the University of Wageningen were able to provide this information in the form of a temperature set-point profile. In what follows, each scenario is described in more detail.

7.2 Potential of Climate Adaptive Greenhouse Shell concept

Each concept is described in general terms below. Full specifications of each concept will be provided in the appendices. Accompanying the description of each concept is a graph that shows the amount of tomato crop produced, the amount of energy used and the amount of net profit generated. These factors were chosen because they will ultimately be used to judge the success of the CAGS concept greenhouses. Organising the results in this way also aids easy comparison of results of the different greenhouse designs. The results will be discussed in section 7.3.

7.2.1 Typical Venlo-type greenhouse

The greenhouse is heated with a boiler and cooled by natural ventilation. Indoor humidity is controlled by both natural and mechanical ventilation. CO_2 is only supplied during day time to meet a set concentration point, usually of 800ppm, but this value may change due to air change from ventilation. In order to supply additional shortwave radiation in winter, artificial lighting is applied. For the full specifications, please see appendix A.

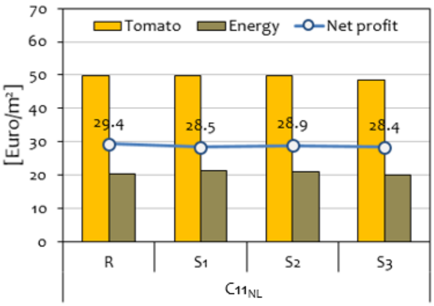

Figure 7.2 *Potential of the monthly adaptation with different cultivation scenarios for typical Venlo-type Dutch greenhouse concept*

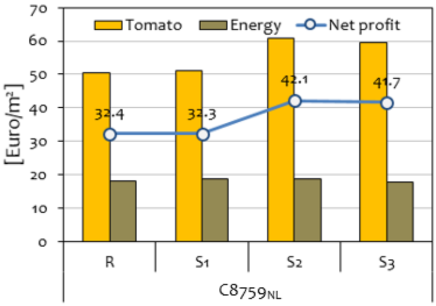

Figure 7.3 *Potential of the hourly adaptation with different cultivation scenarios for typical Venlo-type Dutch greenhouse concept*

Table 7.1 *Total tomato production, energy consumption and net profit depending on the scenarios and the adaptation frequencies for the typical Venlo-type Dutch greenhouse concept*

	C11$_{NL}$				C8759$_{NL}$			
	R	S1	S2	S3	R	S1	S2	S3
Production [kg/m²]	73.5	63.2	49.4	56.3	74.4	68.1	70.5	77.5
Primary energy [kWh/m²]	716.0	747.2	739.3	704.6	638.5	663.4	659.2	623.6
Production [€/m²]	49.7	49.7	49.9	48.4	50.5	51.1	60.9	59.4
Primary energy [€/m²]	20.4	21.2	21.0	20.0	18.2	18.9	18.7	17.7
Net profit [€/m²]	29.4	28.5	28.9	28.4	32.4	32.3	42.1	41.7
Net profit increase [%]	-	-3	-2	-3	-	10	44	42

7.2.2 System concept 1: closed greenhouse for tomato

SC1 is a closed greenhouse concept with active heating provided by gas boiler, active cooling by heat pump and dehumidification by active condensation. Since air change by ventilation is not used, the greenhouse maintains a high CO_2 concentration, which results in high crop production. In order to supply additional SW radiation in winter, artificial lighting is applied. For the full specifications, please see appendix A.

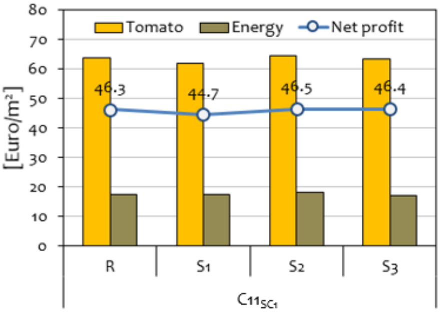

Figure 7.4 *Potential of the monthly adaptation with different cultivation scenarios for system concept 1*

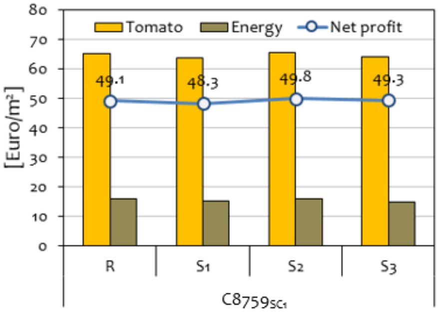

Figure 7.5 *Potential of the hourly adaptation with different cultivation scenarios for system concept 1*

Table 7.2 *Total tomato production, energy consumption and net profit depending on the scenarios and the adaptation frequencies for system concept 1*

	C11$_{SC1}$				C8759$_{SC1}$			
	R	S1	S2	S3	R	S1	S2	S3
Production [kg/m²]	97.1	87.1	73.5	83.4	102.9	91.2	74.0	85.9
Primary energy [kWh/m²]	613.7	608.8	637.4	596.9	556.2	536.7	557.7	522.2
Production [€/m²]	63.7	62.0	64.6	63.4	65.0	63.5	65.6	64.2
Primary energy [€/m²]	17.5	17.3	18.1	17.0	15.8	15.3	15.9	14.8
Net profit [€/m²]	46.3	44.7	46.5	46.4	49.1	48.3	49.8	49.3
Net profit increase [%]	-	-3	0	0	-	-2	1	0

7.2.3 System concept 2: high performance heating for tomato

SC2 is a typical Venlo-type greenhouse with high performance heating systems with natural (for cooling and dehumidification) and mechanical (for dehumidification) ventilation. In order to supply additional SW radiation in winter, artificial lighting is applied. For the full specifications, please see appendix A.

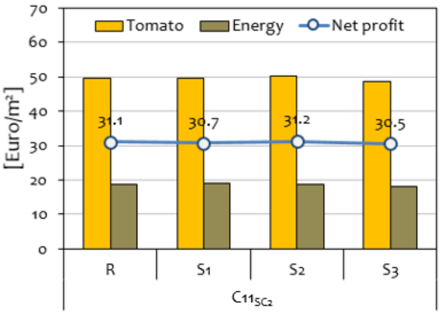

***Figure* 7.6** *Potential of the monthly adaptation with different cultivation scenarios for system concept 2*

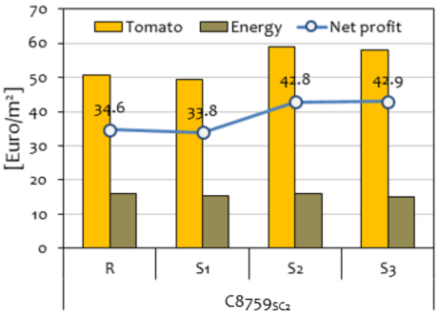

***Figure* 7.7** *Potential of the hourly adaptation with different cultivation scenarios for system concept 2*

***Table* 7.3** *Total tomato production, energy consumption and net profit depending on the scenarios and the adaptation frequencies for system concept 2*

	$C11_{SC2}$				$C8759_{SC2}$			
	R	S1	S2	S3	R	S1	S2	S3
Production [kg/m^2]	73.2	62.8	49.2	55.9	73.6	65.9	67.8	75.6
Primary energy [kWh/m^2]	653.7	665.8	663.0	633.8	567.0	544.8	566.5	528.0
Production [€/m^2]	49.7	49.6	50.1	48.5	50.8	49.3	58.9	57.9
Primary energy [€/m^2]	18.6	18.9	18.9	18.0	16.1	15.5	16.1	15.0
Net profit [€/m^2]	31.1	30.7	31.2	30.5	34.6	33.8	42.8	42.9
Net profit increase [%]	-	-1	0	-2	-	-2	23	24

7.3 Discussion

The aim of the case studies presented in this chapter was to determine if the CAGS concept greenhouse could provide the means to reduce energy use and increase net profit during non-favorable growing seasons in The Netherlands. To conduct this test, four different growing scenarios were included to reflect the full range of growing conditions in The Netherlands throughout the year. Three greenhouse concepts were tested in these scenarios, one typical greenhouse concept and two CAGS concepts.

Judging the performance of a greenhouse is a matter of determining how much crop has been produced, in this case tomato, how much energy has been used to produce it, and finally how much profit is left once the energy usage is deducted from the value of the produced crop. The graphs provided alongside the descriptions of the concepts provide an overview of this information. In what follows, a more detailed discussion of the results is presented. Since net profit is the ultimate determinant of success, the discussion of the results will be organized around this criterion. However, the discussion will also mention findings concerning production and energy use where relevant.

In the typical Venlo-type greenhouse concept ($C11_{NL}$), none of the cultivation scenarios with monthly adaptation generated more net profit than $C11_{NL}R$. The greenhouse $C11_{NL}R$ produced more tomatoes in kilograms due to abundant solar radiation, and despite the low tomato price in summer, it returned higher net profit than the others scenarios ($C11_{NL}S1$, $C11_{NL}S2$ and $C11_{NL}S3$). Monthly adaptation led to only minor differences in primary energy consumption (plus or minus 4%). In contrast, the two CAGS concept greenhouses with hourly adaptation frequency achieved significant increases in net profit. $C8759_{NL}S1$ showed no increase in profit, $C8759_{NL}S2$ and $C8759_{NL}S3$ generated an increase in net profit of 44% and 42% respectively. This huge increase in net profit comes from a significant increase in winter tomato production and change of energy consumption is minor.

To sum up, neither the hourly or monthly adaptation scenarios led to significant changes in energy consumption. The main finding here is that only cultivation scenarios that include winter tomato harvest and use high adaptation frequency are highly effective in terms of increasing both tomato production and net profit.

In system concept 1 (SC1), the change of cultivation scenario does not provide any benefit in terms of energy saving, increasing tomato production and ultimately increasing net profit. Although the quantity of tomato varied depending on the cultivation scenarios, the total production of tomatoes in euro showed little or no difference (less than 3%). The few percent of energy saving was achieved only with hourly adaptation frequency: 3 % in $C8759_{SC1}S1$ and 6% in $C8759_{SC1}S3$; however, this is achieved by sacrificing tomato production and thus net profit. In these two scenarios net profit is similar to $C8759_{SC1}R$. Thus, change of cultivation scenario in SC1 is ineffective for both low and high adaptation frequency.

In system concept 2 (SC2), the operation of the tested greenhouse is the same as the typical Venlo-type greenhouse, except for the performance of the heating systems. Since it is barely affected by changing the cultivation scenario, energy consumption is not an influential performance indicator for net profit. Here, the overall trend of energy saving, tomato production and net profit is similar to the typical Venlo-type greenhouse.

None of the cultivation scenarios with monthly adaptation generated more net profit than $C11_{SC2}R$. All cultivation scenarios ($C8759_{SC3}S1$, $C8759_{SC3}S2$ and $C8759_{SC3}S3$) show a few percent difference in energy saving and tomato production. Like the typical Venlo-type greenhouse, only two scenarios ($C8759_{SC2}S2$ and $C8759_{SC2}S3$) with hourly adaptation frequency generated an increase in net profit by 23% and 24% respectively. Thus, change of cultivation scenario with high adaptation frequency is effective in terms of increasing net profit.

To sum up, the performance of CAGS concept greenhouse varies depending on cultivation scenario and system concept. Since the scenarios tested here needed to cover different growing seasons, the temperature set-point was different for each cultivation scenario. However, the effect of these different set points on total energy consumption was negligible. Therefore, in all cases, the performance of the system had little influence on total energy consumption. Under the tomato price used for this test, none of the cultivation scenarios using low adaptation frequency generated meaningful benefits. However, benefits were seen in the case of high adaptation frequency concepts including winter cultivation.

7.4 Conclusion

The case studies reported in this chapter aimed to determine whether CAGS concept greenhouses can be applied to allow growers to produce crops profitably throughout the year. In order to reach this aim, a number of case studies were conducted that included different greenhouse concepts and growing scenarios representing different growing seasons throughout the year. To successfully achieve the aim, the CAGS concept greenhouses will need to demonstrate the ability to generate an increase in net profit in the scenarios tested in comparison to the reference case, a typical Venlo-type greenhouse.

As explained earlier, net profit is calculated by subtracting the cost of energy use from the sale price of the produced tomatoes. In these case studies the tomato price is calculated based on information provided by Wageningen University on monthly tomato prices in the Netherlands in the period of 2007 – 2009. Thus, reducing energy use and increasing tomato production are the two key drivers of profit increase. To test how best to manage these two drivers, the case studies compared the performance of hourly adaptation and monthly adaptation frequencies.

The results provide a clear picture of which concepts performed best in which scenarios. The main conclusions to be drawn here are as follows. CAGS concept greenhouses using monthly adaptation do not result in significant increases in net profit. However, CAGS concept greenhouses using hourly adaptation provide much greater opportunities to increase tomato production in winter than the monthly adaptation. This increase in tomato production is large enough to generate significant increases in net profit compared to the reference case. Ultimately, the amount of tomatoes produced during winter in the hourly adaption CAGS concept greenhouses was sufficient to realise a real world profit, even based on the historical tomato prices used. Since prices of tomato may well rise further in the future, these CAGS concepts may turn out to be considerably more profitable than is now the case.

8 Conclusion and future research

8.1 Conclusion

The horticulture and agricultural sectors in The Netherlands have come under increasing pressure in recent times from two key factors. First, as heavy energy users, they face increasingly stringent targets and legislation governing energy use and CO_2 reduction. Second, they face growing competition in the international markets in which they operate, and many of their competitors have climate conditions that are much more favourable for growing crops at lower cost than is traditionally possible in The Netherlands.

In response to these problems, the current research aimed to develop an innovative greenhouse concept that is capable of outperforming the commonly used greenhouses in the agricultural sector in The Netherlands. To be more precise, the proposed greenhouse concept should provide improved performance in two key areas: reducing energy use and increasing crop production. Ideally, the greenhouse concept should also aid production increase by providing the means to produce a profitable crop throughout different periods of the year, thereby extending the traditional, profitable growing seasons in The Netherlands.

In order to determine how best to develop the innovative greenhouse concept, a preliminary review of existing greenhouse technologies was performed. This review, presented in chapter 2, provides an overview of promising greenhouse shells and energy efficient greenhouse concepts currently being used or under development. Based on the findings from the literature review, the study proposed the Climate Adaptive Greenhouse Shells (CAGS) concept greenhouse as a new and innovative greenhouse concept.

As its title suggests, the innovative aspect of the CAGS concept greenhouse is its ability to manage and operate with 'adaptability'. To be more precise, the shell of the greenhouse is capable of adapting to climate conditions in order to maintain the best possible conditions for crop growing. While some limited examples of adaptability were identified in the review, it is clear that much greater adaptability is required to achieve meaningful improvements to the current greenhouse designs.

Since the proposed concept is based on new or non-existent technologies, the study computationally investigated the performance and feasibility of the CAGS concept greenhouse. In Chapter 3, the study searched for a greenhouse performance simulation (GPS) tool that could be used for the performance assessment of the CAGS concept greenhouse. It turned out that no existing tool alone had sufficient capabilities to manage the adaptability required for the CAGS concept. Therefore, the study developed codes in ESP-r for GPS with the required capabilities.

In Chapter 4, the study searched for a simulation approach to implement the CAGS concept greenhouse. Based on previous approaches, the study developed a simulation-based multi-objective dynamic optimization methodology. In order to implement this methodology, the ESP-r was coupled with Matlab and co-simulated using BCVTB as middleware.

Chapter 4 represented the end of the development of the CAGS design concept and the methodology and simulation approach required to test it. In order to test the performance of the CAGS concept greenhouse, a number of case studies were conducted, which are reported on in chapters 5 through 7.

In Chapter 5, the study demonstrates the potential of the CAGS concept with a typical Venlo-type greenhouse growing a tomato crop. Two performance indicators and decision making criteria are first defined, and the five design parameters are then determined by sensitivity analysis. The performance assessment of the CAGS concept greenhouses focuses on the potential of energy saving, crop production and finally net profit. The investigation is performed with an optimized static greenhouse, monthly adaptation and hourly adaptation. The performance of each concept is compared to the reference greenhouse to determine its potential.

In Chapter 6, this study extends the investigation of the performance of the CAGS concept by testing different system concepts for three crops. To do so, five system concepts were first defined and the study then investigated and compared the performance of an optimized static greenhouse and two CAGS concept greenhouses.

In Chapter 7, the study investigates the performance of the CAGS concept greenhouse with four different cultivation scenarios to determine to what extent crops can be produced profitably in different periods of the year. The investigation focused on three system concepts: one typical Venlo-type greenhouse, and two CAGS concept greenhouses, one with monthly and one with hourly adaptation.

The three case studies that were conducted allowed for a broad test of the performance of the CAGS concept greenhouse in a number of conditions and scenarios. The testing carried out needed to determine how the different CAGS concepts affected both the management of energy use and the overall production of the crop, not only in the summer season, but also at different times throughout the year. The results of the case studies are described in turn below.

In case study I, it was important to determine which greenhouse properties should be controlled for the CAGS concept greenhouse. To this end, the Venlo-type greenhouse was subjected to a sensitivity analysis covering year, month and hour, which revealed that the most sensitive properties in terms of energy consumption are U-value, inside emissivity, outside emissivity and solar transmittance for energy consumption. The solar radiation is split into PAR and NIR transmittance for the implementation of CAGS concept greenhouse.

Next, the comparative performance of the CAGS concept greenhouse was investigated. It is important to note here that the CAGS concept greenhouse differs from the typical Venlo-type greenhouse in the following key aspects: the CAGS greenhouse concept varies in regard to five thermal and optical properties, which are selected for the CAGS concept by sensitivity analysis.

The comparative performance of the different greenhouse concepts is conducted via a calculation of net profit generated. Here, the net profit of an optimized static greenhouse and two CAGS concept greenhouses (monthly and hourly adaptation) are investigated and compared to a reference greenhouse (a typical Venlo-type greenhouse). The results show that the design optimization and the two CAGS concepts generated an increase in net profit (= crop production in euro – primary energy consumption in euro) of 7% ~ 20 % compared to the reference greenhouse. Monthly and hourly adaptation showed little crop production increase, but did demonstrate considerable primary energy saving of 23% and 37% respectively. The CAGS concept with the higher adaptation frequency demonstrated greater potential in terms of primary energy saving and thus net profit increase.

Next, an in-depth analysis is performed of the CAGS simulation results. The results show that optical properties (PAR and NIR transmittance) are the most influential variables in the design optimization and in the CAGS concept with monthly adaptation frequency. U-value and PAR transmittance in day time and U-value and inside emissivity at night time are the most influential variables in the CAGS concept with hourly adaptation.

In case study II, the performance of the CAGS concept is investigated further by testing five system concepts for three crops: tomato, phalaenopsis and chrysanthemum. The testing here revealed that applying the CAGS concept to greenhouses with high energy demands resulting from low performance of both the greenhouse shell and systems, such as a closed greenhouse with boiler, generate the greatest energy savings. The tests also demonstrated that providing separate control of PAR and NIR can lead to significant energy reduction, which was clearly demonstrated in the optimized static greenhouse and in the monthly adaptation, whose energy consumption is high, for all system concepts.

Both the monthly adaptation and the optimized static greenhouse produced more tomatoes than the reference greenhouse, which is explained by the increase gained in PAR transmittance. Control of thermal properties led to high energy saving in winter for greenhouses using low performance heating systems; however, it was not effective in the three greenhouses growing flowers due to high performance heating from the use of CHP. In contrast, when it comes to hourly adaptation, the hourly control of thermal properties is effective at night time for flowers. Due to the use of temperature constraint for quality control of flowers, high adaptive shell control is appropriate for the cultivation of flowers, but static and low adaptive shell controls are unsuitable.

In case study III, the potential of the CAGS concept greenhouse is investigated with different cultivation scenarios covering different growing seasons. In total, three greenhouses growing tomato crops are tested in four different cultivation scenarios. The performance of CAGS concept greenhouses varied depending on cultivation scenario and system concept. The results show that none of the cultivation scenarios with monthly adaptation generated meaningful benefits. However, benefits were seen in the case of hourly adaptation during winter cultivation.

In conclusion, the simulation results of the case studies demonstrate that the CAGS greenhouse concept has great potential in terms of reducing primary energy use (CO_2 reduction), increasing production and thus increasing net profit. However, it must be noted that the potential of CAGS concept greenhouse is dependent on adaptation frequency, the installed systems and the greenhouse's operation.

8.2 Limitations of the current research & future research

While the main problem addressed in this research, not only how to increase profitability of greenhouse crop production but also how to decrease energy consumption (CO_2 emission), may seem simple at face value, providing a reasonable answer to the question is a complex task. In terms of the current research, the complexity can be divided into two areas. First, to conduct a truly definitive test, a large number of variables and performance indicators would need to be managed simultaneously. Second, as any proposed solution in this type of research will necessarily be a theoretical solution, in this case a design concept, the testing of the solution is somewhat problematic. Since no physical tests could be conducted on a real building in the real world, the design concept presented in this work had to be tested by other means, in this case computational simulation. While computational simulation has proven itself to be a robust method capable of providing reliable results, the field of greenhouse performance simulation is still burgeoning and it will be some time before it reaches full maturity. Therefore, it was not possible to find an off-the-shelf simulation tool capable of managing the adaptability and flexibility required to test the CAGS concept. This meant that the current research had to divide its efforts between modifying a simulation tool for the GPS and testing methodology, and developing and testing the design concepts themselves. Managing the burden of these two tasks within the parameters of a PhD project resulted in the need to make important decisions about what could be realistically done within the available time. In what follows, the most significant limitations of the current research are discussed and proposals are offered on how future research may address these limitations.

Since no off-the-shelf simulation tools were available, a key assumption needed to be made: namely, that the use of ESP-r for GPS simulation would be valid. The tool used in the current research operated by means of inter-model comparison between a building performance simulation tool (BPS) and an existing GPS tool, KASPRO. The items used for inter-model comparison are indoor air temperature and solar radiation only. Therefore, additional validation tests are necessary for better quality assurance of the simulation results on energy consumption, crop production, humidity, air temperature, and so on. In addition, the further improvement of simplifications used in this research, such as constant CO_2 level, simplified crop model, use of conversion factor for calculation from DM to FM, humidification efficiency and efficiency of air change by ventilation, would be beneficial for achieving more accurate calculations and broader applications.

Another area of potential improvement is decision making. The decision making used in this study is very simple. For instance, the study did not consider investment cost of the greenhouse, maintenance cost, etc. in calculation of the net profit. Therefore, the optimization results might not be fully applicable for all current greenhouse designs and operations. In addition, as Vanthoor (2012) concluded, selection of performance indicator for decision making can affect the optimization and design. Thus, further consideration of decision making criteria would be advisable in future studies including pay-back period and the return on investment cost.

This study takes the adaptation of climate condition into account at current timeslot. In order to achieve a better CAGS concept greenhouse, better greenhouse shell controls, such as Model Predictive Control (MPC), are desirable. MPC might provide better optimized solutions by considering future timeslots in the optimization process, which includes future climate conditions and the thermal storage of the greenhouse floor.

In an attempt to capture promising solutions and to avoid missing optimal solutions, this study employs a sufficiently large search space, which results in large computational cost. However, as yet, there is no specific way to reduce the search space without losing the reliability of the optimization result. Therefore, as Nguyen (2014) indicated, it is necessary to improve efficiency of the search space by reducing the number of calculations.

While adaptation was the key innovation in the CAGS concept design and the main driver of improved performance in comparison to the reference case, the current study was limited to two adaptation frequencies only: monthly and hourly adaptation. Including more adaptation frequencies such as week, day and minute, would provide a much more detailed picture of the potential of the CAGS concept greenhouse to reduce energy use, increase crop production and generate increased net profit.

The profit generated in the case studies was based on historical average tomato prices and gas prices from 2007 to 2009. As the price of tomato and gas is likely varied in the future, the variation of net profit increase generated by the CAGS concept may be higher in reality than appears at present. This profit may also be increased further as new energy-saving technologies become available that can be controlled by the CAGS system.

The computational simulation approach used in this research provided a number of positive results regarding the performance of CAGS concept greenhouses. At this stage, it could be argued that the CAGS concept has been theoretically shown to have great potential. Ultimately, in order to verify the potential of CAGS, replication studies of the CAGS concept greenhouses should be performed in the real world.

The effect of the continuously changing weather conditions is mitigated and the utilization of it is maximized by employing the CAGS concept. Nevertheless, there are still high heat loss in winter and high heat gain in summer by ventilation for dehumidification. Since the humidity control is important for crop growth and production, the dehumidification by ventilation is unavoidable. In order for the greenhouse to be more energy efficient, a CAGS concept incorporating a heat exchanger for dehumidification could be promising for future applications.

Despite the limitations mentioned above, the research has generated a number of positive results and has opened up promising directions for future research. First and foremost, the CAGS concept greenhouses clearly demonstrated that they could outperform the type of greenhouse that is typically used for agricultural and horticultural purposes in The Netherlands. The CAGS concept greenhouses generate a significant increase in net profit throughout the year by greatly reducing energy use. In addition, the CAGS concept greenhouses generated profit during winter, a time when it is much harder to generate profit because of increased heating costs and a lack of PAR radiation.

The positive results in this study provide inspiration on how to develop the greenhouse shell for future greenhouse. In addition, the newly developed, flexible GPS tool can be used for the investigation of other innovative greenhouse design concepts. Similarly, the newly developed simulation-based dynamic optimization and co-simulation technique can be utilized for further study into the optimization or investigation into the adaptability of other building types.

To conclude, the results of this research are not only of benefit to the academic domain. The results are of great importance to agricultural and horticultural growers in The Netherlands who must find new ways to reduce their energy use and resulting CO_2 emissions and survive in increasingly competitive international markets. The current research shows these growers that significant reductions in energy use are achievable, and that significant increases in net profit are also possible. In addition, the research demonstrates that it is possible to produce crops during the winter at profit, which can greatly strengthen the competitive position of the Dutch grower.

Appendix A: System concepts

A.1 Typical Venlo-type greenhouse for three crops

Size	Tomato	100 m (L) * 100 m (W) * 6 m (H)			
	Phalaenopsis	100 m (L) * 100 m (W) * 6 m (H)			
	Chrysanthemum	100 m (L) * 100 m (W) * 4.5 m (H)			
Opening area	Tomato	size	2.5 m (L) * 1.3 m (W) = 3.25 m^2		
		Fraction$^{(1)}$	0.0417		
	Phalaenopsis	size	2.5 m (L) * 2.0 m (W) = 5.0 m^2		
		Fraction$^{(1)}$	0.0556		
	Chrysanthemum	size	2.5 m (L) * 1.45 m (W) = 3.625 m^2		
		Fraction$^{(1)}$	0.0417		
Optical properties of shell	Transmittance		0.85		
	Absorptance		0.04		
	Reflectance		0.11		
Thermal properties			Shell (Glass)	Floor (White plastic)	Soil
	Thickness [mm]		4	25	
	Conductivity [W/(m-K)]		1.05	0.50	0.85
	Density [kg/m^3]		2600	1050	1640
	Specific heat [J/(kg-K)]		840	837	879
	Emissivity		0.84	0.6	-
	Solar absorptance		0.03	0.25 Chrysanthemum (soil): 0.50	-

(1) Number of openings per m^2 of greenhouse area

A.2 System concept: typical Venlo-type greenhouse (Tomato)

<table>
<tr><td>Temperature set-point</td><td colspan="7">Hourly heating and cooling temperature set-point that Dutch growers use.</td></tr>
<tr><td>Heating</td><td colspan="7">Overall AFUE: 0.9 (Boiler)</td></tr>
<tr><td>Cooling</td><td colspan="7">Natural ventilation</td></tr>
<tr><td rowspan="19">Screen control (on/off)</td><td></td><td colspan="3">Transparent screen</td><td colspan="3">Aluminized screen</td></tr>
<tr><td>τ PAR</td><td colspan="3">0.8</td><td colspan="3">0.0</td></tr>
<tr><td>τ NIR</td><td colspan="3">0.8</td><td colspan="3">0.0</td></tr>
<tr><td>ε</td><td colspan="3">0.5</td><td colspan="3">0.1</td></tr>
<tr><td></td><td>From</td><td>To</td><td>Set-point</td><td>From</td><td>To</td><td>Set-point</td></tr>
<tr><td rowspan="7">Set-point of global solar radiation [W/m²] (close when solar radiation is below set-point)</td><td>12/Jan</td><td>22/Jan</td><td>300</td><td>12/Jan</td><td>18/Jan</td><td>10</td></tr>
<tr><td>23/Jan</td><td>25/Jan</td><td>50</td><td>19/Jan</td><td>29/Mar</td><td>20</td></tr>
<tr><td>26/Jan</td><td>8/Feb</td><td>100</td><td>30/Mar</td><td>11/Nov</td><td>0</td></tr>
<tr><td>9/Feb</td><td>1/Mar</td><td>120</td><td>12/Nov</td><td>11/Jan</td><td>20</td></tr>
<tr><td>2/Mar</td><td>15/May</td><td>100</td><td></td><td></td><td></td></tr>
<tr><td>16/May</td><td>26/Sep</td><td>20</td><td></td><td></td><td></td></tr>
<tr><td>27/Sep</td><td>11/Jan</td><td>75</td><td></td><td></td><td></td></tr>
<tr><td rowspan="7">Set-point of air temperature [°C] (close when solar radiation is below set-point)</td><td>12/Jan</td><td>27/Apr</td><td>10</td><td>12/Jan</td><td>29/Mar</td><td>11</td></tr>
<tr><td>28/Apr</td><td>14/May</td><td>0</td><td>30/Mar</td><td>12/Apr</td><td>9</td></tr>
<tr><td>15/May</td><td>31/Oct</td><td>12</td><td>13/Apr</td><td>30/Apr</td><td>8</td></tr>
<tr><td>1/Nov</td><td>11/Jan</td><td>14</td><td>1/May</td><td>31/May</td><td>0</td></tr>
<tr><td></td><td></td><td></td><td>1/Jun</td><td>22/Oct</td><td>7</td></tr>
<tr><td></td><td></td><td></td><td>23/Oct</td><td>11/Nov</td><td>10</td></tr>
<tr><td></td><td></td><td></td><td>12/Nov</td><td>11/Jan</td><td>12</td></tr>
<tr><td>Dehumidification</td><td colspan="7">Control set-point: 85%
If (screens are open)
If (ventilation need < 10 m³/m²/hr)
Mechanical ventilation
else if (10 m³/m²/hr < ventilation need < 30 m³/m²/hr)
Both mechanical and natural ventilation (ŋ=0.5)
else if (ventilation need > 30 m³/m²/hr)
Natural ventilation (ŋ=0.5)
else
No ventilation
end if
else (screens are closed)
If (RH inside> 85%)
Mechanical ventilation
else
No ventilation
end if
end if</td></tr>
<tr><td>CO_2 concentration</td><td colspan="7">Dosing CO_2 until 800 ppm during daytime
CO_2 concentration is depending on ventilation
No control and dosing CO_2 during night time</td></tr>
<tr><td>Artificial lighting (for case study III)</td><td colspan="7">On until total 796 Wh PAR/m² /day
- No use after sunset until it pass 8 hours (max 16 hr/day)
- Light power: 110 W/m² (44 W PAR/m²)</td></tr>
</table>

A.3 System concept 1: Closed greenhouse (Tomato)

Temperature set-point	Hourly heating and cooling temperature set-point that Dutch growers use.						
Heating	Overall AFUE: 0.9 (Boiler)						
Cooling	Overall SEER: 3 (Heat pump)						
Screen control (on/off)		Transparent screen			Aluminized screen		
	τ PAR	0.8			0.0		
	τ NIR	0.8			0.0		
	ε	0.5			0.1		
		From	To	Set-point	From	To	Set-point
	Set-point of global solar radiation [W/m^2] (close when solar radiation is below set-point)	12/Jan	22/Jan	300	12/Jan	18/Jan	10
		23/Jan	25/Jan	50	19/Jan	29/Mar	20
		26/Jan	8/Feb	100	30/Mar	11/Nov	0
		9/Feb	1/Mar	120	12/Nov	11/Jan	20
		2/Mar	15/May	100			
		16/May	26/Sep	20			
		27/Sep	11/Jan	75			
	Set-point of air temperature [°C] (close when solar radiation is below set-point)	12/Jan	27/Apr	10	12/Jan	29/Mar	11
		28/Apr	14/May	0	30/Mar	12/Apr	9
		15/May	31/Oct	12	13/Apr	30/Apr	8
		1/Nov	11/Jan	14	1/May	31/May	0
					1/Jun	22/Oct	7
					23/Oct	11/Nov	10
					12/Nov	11/Jan	12
Dehumidification	Control set-point: 85% By active condensation Overall SEER:4 (Heat pump with aquifer)						
CO_2 concentration	Dosing CO_2 until 800 ppm during daytime CO_2 concentration is depending on ventilation No control and dosing CO_2 during night time						
Artificial lighting (for case study III)	On until total 796 Wh PAR/m^2 /day - No use after sunset until it pass 8 hours (max 16 hr/day) - Light power: 110 W/m^2 (44 W PAR/m^2)						

A.4 System concept 2: High performance heating (Tomato)

Temperature set-point	Hourly heating and cooling temperature set-point that Dutch growers use.						
Heating	Overall HSPF: 4 (Heat pump with aquifer)						
Cooling	Natural ventilation						
Screen control (on/off)		Transparent screen			Aluminized screen		
	τ PAR	0.8			0.0		
	τ NIR	0.8			0.0		
	ε	0.5			0.1		
		From	To	Set-point	From	To	Set-point
	Set-point of global solar radiation [W/m^2] (close when solar radiation is below set-point)	12/Jan	22/Jan	300	12/Jan	18/Jan	10
		23/Jan	25/Jan	50	19/Jan	29/Mar	20
		26/Jan	8/Feb	100	30/Mar	11/Nov	0
		9/Feb	1/Mar	120	12/Nov	11/Jan	20
		2/Mar	15/May	100			
		16/May	26/Sep	20			
		27/Sep	11/Jan	75			
	Set-point of air temperature [°C] (close when solar radiation is below set-point)	12/Jan	27/Apr	10	12/Jan	29/Mar	11
		28/Apr	14/May	0	30/Mar	12/Apr	9
		15/May	31/Oct	12	13/Apr	30/Apr	8
		1/Nov	11/Jan	14	1/May	31/May	0
					1/Jun	22/Oct	7
					23/Oct	11/Nov	10
					12/Nov	11/Jan	12
Dehumidification	Control set-point: 85%						

```
If (ventilation need < $10\ m^3/m^2/hr$)
    Mechanical ventilation
else if ($10\ m^3/m^2/hr$ < ventilation need < $30\ m^3/m^2/hr$)
    Both mechanical and natural ventilation ($\eta=0.5$)
else if (ventilation need > $30\ m^3/m^2/hr$)
    Natural ventilation ($\eta=0.5$)
else
    No ventilation
end if
```

CO$_2$ concentration	Dosing CO$_2$ until 800 ppm during daytime CO$_2$ concentration is depending on ventilation No control and dosing CO$_2$ during night time
Artificial lighting (for case study III)	On until total 796 Wh PAR/m^2 /day - No use after sunset until it pass 8 hours (max 16 hr/day) - Light power: 110 W/m^2 (44 W PAR/m^2)

A.5 System concept 3: Propagation area (Phalaenopsis)

	System concepts
Temperature set-point	Heating: 28 °C Cooling: 29 °C
Shading control	Control period: 16. Feb ~ 30. Oct Control point: if outside solar radiation > 300 W/m^2 (Inside solar radiation is around 150 W/m^2) Optical properties of shading screen: - PAR transmittance: 0.8 - NIR transmittance: 0.8 - Emissivity: 0.5
Artificial lighting	On If outside radiation < 100 W/m^2 until total 485 Wh PAR/m^2 /day - No use after sunset until it pass 8 hours (max 16 h/day) - Light power: 44 W/m^2 (14.08 W PAR/m^2) - No lighting period: 01. May ~ 01. Sep
Electricity production	CHP - Generate electricity with 45% of efficiency - Run for lighting and heating
Dehumidification	Natural ventilation - Ventilation efficiency: 0.5 (50% of mixed air) Control set-point: 70%
Humidification	High pressure fogging system When RH is below 55%, supply up to 100 g/m^2/hr of water
Irrigation	Supply 12 l/m^2 of water once a four days at 6 AM (0.7 l /m^2 of water evaporate and rest of water (11.3 l /m^2) is removed by drain. It takes 6 hours to dry up.)
Cooling	Natural ventilation
Heating	Controllable heat additions in order: surplus heat of CHP unit (During electricity production) HP additional heating with overall HSPF = 4 (primary overall HSPF = 1.7), with heat extraction from aquifer

A.6 System concept 4: Cooling and ripening area (Phalaenopsis)

	System concepts
Temperature set-point	Heating: 19 °C Cooling: 20 °C
Shading control	Control period: 16. Feb ~ 30. Oct Control point: if outside solar radiation > 200 W/m^2 Optical properties of shading screen: PAR transmittance: 0.8 NIR transmittance: 0.8 Emissivity: 0.5
Artificial lighting	On If outside radiation < 100 W/m^2 until total 625 Wh PAR/m^2 /day - Light power: 55 W/m2 (17.6 W PAR/m^2) - Not use after sunset until it pass 8 hours (max 16 hr/day) - No lighting period: 15. May ~ 15. Aug Electricity from CHP (45% of efficiency)
Electricity production	CHP - Generate electricity with 45% of efficiency - Run for lighting, cooling (when PV is not enough) and heating PV panel - 10% of total greenhouse area
Dehumidification	Natural ventilation - Ventilation efficiency(η): 0.5 (50% efficiency) Control set-point: 70%
Humidification	High pressure fogging system When RH is below 55%, supply up to 100 g/m^2/hr of water
Irrigation	Supply 12 l/m^2 of water once a four days at 6 AM (0.7 l/m^2 of water evaporate and rest of water (11.3 l/m^2) is removed by drain. It takes 6 hours to dry up.)

Cooling	if (outside temperature Te < 15°C) then
	Natural ventilation
	else (outside temperature Te > 15°C)
	Mechanical ventilation
	Fan capacity: 50 m^3/m^2 /hr
	Fan power: 60 W/m^2
	end if

Heating	Controllable heat additions in order: surplus heat of CHP unit (During electricity production) HP additional heating with overall HSPF = 4 (primary overall HSPF = 1.7), with heat extraction from aquifer

A.7 System concept 5: Long and short day (Chrysanthemum)

		System concepts
Long-day (14 days)	Temperature set-point	Daytime Nighttime Heating: 17 °C 19 °C Cooling: 19 °C 21 °C
	Artificial lighting	On if outside radiation < 200W/m^2 until total 1000Wh PAR/(m^2 ·day) - No use after sunset until 4 hours pass (max20 h/day) - Light power: 65 W/m^2 (20.8 W PAR/m^2) Electricity from CHP (45% of efficiency)
	Electricity production	Generate electricity with 45% of efficiency form CHP
	Dehumidification	Natural ventilation - Ventilation efficiency(ŋ): 0.5 (50% of mixed air) Set-point: 90%
	Humidification	Irrigation : Supply 4 l/m2 of water once a four days at 6 AM (0.5 l/m^2) of water evaporate and rest of water (3.5 l/m^2) is absorbed in soil. It takes 6 hours to dry up.)
	Cooling	Natural ventilation
	Heating	Controllable heat additions in order: surplus heat of CHP unit (During electricity production) HP additional heating with overall HSPF = 4, with heat extraction from size-unlimited aquifer
Short-day (61 days)	Temperature set-point	Daytime Nighttime Heating: 17.5 °C 18.5 °C Cooling: 19.5 °C 20.5 °C
	Darkening screen control	Darkening greenhouse from 18:00PM to 5:30 AM - PAR transmittance: 0.0 - NIR transmittance: 0.0 - Emissivity: 0.1
	Artificial lighting	On If outside radiation < 200 W/m^2 until total 1000 Wh PAR/(m^2 ·day) - Light power: 65 W/m2 (20.8 W PAR/m^2) - No lighting period: 15. May ~ 15.Aug Electricity from CHP (45% of efficiency)
	Electricity production	CHP - Generate electricity with 45% of efficiency - Run for lighting and heating
	Dehumidification	Natural ventilation - Ventilation efficiency .(ŋ): 0.5 (50% of mixed air) Set-point: 90%
	Humidification	Irrigation Supply 4 l/m^2 of water once a four days at 6 AM 1 l/m^2 of water evaporate and rest of water (3 l/m^2) is absorbed in soil. It takes 6 hours to dry up.
	Cooling	Natural ventilation
	Heating	Controllable heat additions in order: surplus heat of CHP unit (During electricity production) HP additional heating with overall HSPF = 4 (primary overall HSPF = 1.7), with heat extraction from size-unlimited aquifer

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Curriculum Vitae

Chul-sung Lee was born on the 3rd of September 1982 in Hongcheon-gun, South Korea. He moved to Daejeon in March 2001 to begin his study at the Department of Architectural Engineering in Hanbat National University. By February 2008, he completed his two-year military service and obtained a bachelor's degree.

In February 2010, Chul-sung graduated from Hanbat National University with a M.Eng. in Architectural Engineering. His master project computationally investigated the potential of transparent Building Integrated Photovoltaic (BIPV) windows system in an office building application. After graduation, he worked for a year in an energy consulting company as a researcher.

In March 2011, he began his PhD project on climate adaptive greenhouse shells under the supervision of Professor Jan Hensen at the Department of the Built environment in Eindhoven University of Technology. The PhD project is connected to the Long Term Energy Research Strategy (EOS-LT) project, Climate Adaptive Glastuinbouw: Inverse Modelling (CAGIM), funded by Rijksdienst voor Ondernemend Nederland (RVO).

Publication list

Conference papers (peer reviewed)

Lee, C., Costola, D., Loonen, R.C.G.M. & Hensen, J.L.M. 2013. ” Energy saving potential of long-term climate adaptative greenhouse shells”, Proceedings of Building Simulation 2013: 13th Conference of the International Building Performance Simulation Association IBPSA, 26-28 August, Chambery, pp. 954 – 961.

Lee, C., Costola, D., Swinkels, G. L. A. M. & Hensen, J.L.M. 2012. “On the use of building energy simulation programs in the performance assessment of agricultural greenhouses”, ASim, Proceedings of the 1st Asia Conference of the International Building Performance Simulation Association, 25-27 November, Shanghai, IBPSA-Asia, pp. 1-8.

Acknowledgements

From the beginning, doing a PhD project was a challenging task. Every result described in this thesis was accomplished with the help and support of supervisors and collaborators. I am grateful to everyone for all the contribution during four years.

First of all, I would like to express my sincerest appreciation to Jan Hensen for accepting me into his group. Jan is resourceful and quick thinker, and has broad range of perspectives on the research. His supervision greatly helped me complete this thesis.

I am very grateful to three daily supervisors of my PhD project: Marija Trcka, Daniel Cóstola, and Pieter-jan Hoes. Marija guided me during the first year of the research. She help me strengthen the basis of PhD project. Daniel guided me during the second and third year of the research. He suggested the research direction and greatly help me narrow down the research works. Pieter-jan guided me during last year of the research. He contributed to organizing thesis structure and reviewed the thesis. Again, thank you all for invaluable assistance for the project! I am also indebted to the member of doctorial committee, Eldert van Henten, Per Heiselberg, Bert Blocken, Laure Itard, for their valuable comments.

I would like to thank dozens of people I met at the unit BPS: Alessia, Ana Paula, Azzedine, Daniela, Giovanni, Hamid, Ignacio, Isabella, John, Katarina, Luyi, Marcel, Meng, Mike, Massimo, Mohammad, Petr, Qimiao, Rajesh, Rebeca, Rizki, Sanket and Votech. They provided a friendly and cooperative atmosphere at work and also useful feedback and insightful comments on my work. A special acknowledgement goes to Pieter-jan and Roel. Thank you for amazing help in implementation of dynamic optimization and sharing knowledge on the climate adaptive building shell concept. Without their efforts, my work would have undoubtedly been more difficult.

I also thank to all CAGIM project members. I want to especially thank Frank Kempkes for providing and sharing the knowledge on the plant behaviour and greenhouse control.

Finally, I would like to acknowledge my family who supported me during the time in the Netherlands. I want to thank Jung-min for constant love and support and my two lovely kids, Dong-geun and Ain, for giving me much happiness.

Chul-sung Lee

December 2016

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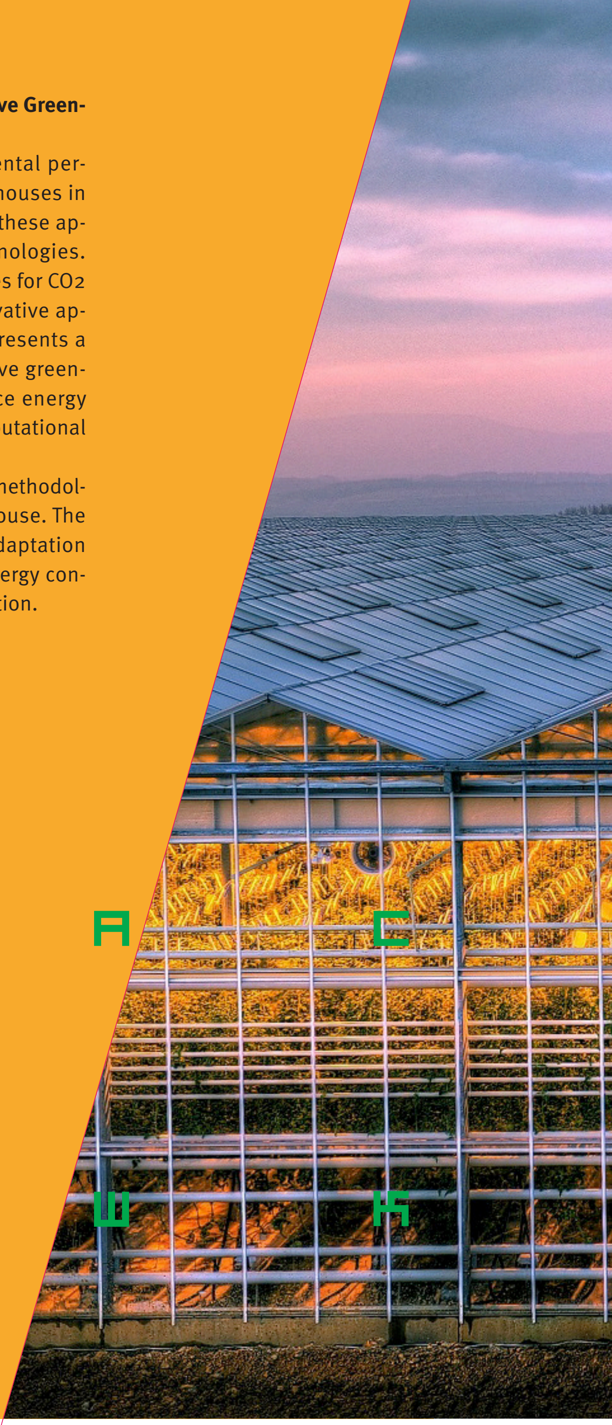
Simulation-based Performance Assessment of Climate Adaptive Greenhouse Shells

Some attempts have been made to improve the environmental performance and reduce the energy needs of commercial greenhouses in the Netherlands. However, while they do represent progress, these approaches are largely based on existing ‘energy-saving’ technologies. Thus, there is still a need to improve greenhouse performances for CO2 reduction and crop production increase. To do so, truly innovative approaches are required. The current research develops and presents a new, innovative greenhouse concept entitled climate adaptive greenhouse shells (CAGS), and investigates its potential to reduce energy use while also increasing crop yields through the use of computational greenhouse performance simulation (GPS).

The main objective of this research is to develop a simulation methodology for performance assessment of the CAGS concept greenhouse. The research aims to explore the potential of greenhouse shell adaptation through case studies, which focus not only on minimizing energy consumption (CO2 emission) but also on maximizing crop production.



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