Systematic design of greenhouse crop production systems

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Abstract. Protected cultivation systems are used throughout the world as a powerful instrument to produce crops. They protect the crops from unfavorable outdoor climate conditions and pests and offer the opportunity to modify the indoor climate to create an environment that is optimal for crop growth and production, both in terms of quality and quantity. Designing protected cultivation systems is a multi-factorial optimization problem. During this process, choices have to be made with respect to construction, cladding material, climate conditioning equipment, energy sources and management, growing substrates, water and nutrient supply, internal logistics and labour, to mention a few. All of these choices mutually influence each other and are influenced by local boundary conditions like climate, economics, market, legislation and availability of resources. This paper presents the outlines of a systematic design methodology to design protected cultivation systems including several design examples of modern greenhouses production systems.

Introduction

Today protected cultivation systems are used throughout the whole world for crop production. Areas with protected cultivation are still growing. Driving forces range from improved food production with higher production levels, extended growing seasons, decreased water use compared to open field production and/or diminished risks of crop failure by for instance storm, rain or hail and pests, to better quality and safer food products and a growing demand for convenience products like specialties, flowers and potted plants in Western-Europe.

A quick scan of protected cultivation systems used throughout the world reveals that, just like happens in nature, influenced by local conditions a wide range of protected cultivation systems has evolved. They range from low-tech, low-cost plastic tunnels to high-tech expensive glasshouses used in Western-Europe and North-America. Greenhouses differ in size, shape and materials used, ranging from single span structures covered with plastic to multi-span greenhouses with glass covers. Instrumentation ranges from unheated greenhouses with natural ventilation to production systems with computer controlled heating, cooling, (de)humidification, CO_2-supply and artificial light. High-tech fully closed greenhouses are already installed in the

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Netherlands. Crops are grown in soil, but also in artificial substrates with water and nutrient supply using drip irrigation and closed water circuits with drain water treatment. Manual labor is commonly used throughout the world, but in high-tech greenhouses the first robots have recently been introduced to replace human labor. There is a need to adapt a greenhouse design to the local climatic and socio-economic conditions and the availability of resources and legislation. For that a systematic design methodology is needed.

Hanan (1998) and Van Heurn and Van der Post (2004) have identified some factors that determine the particular choice of the protected cultivation system used. A combination and extension of their lists of factors:

1. Market size and regional physical and social infrastructure which determines the opportunity to sell products as well as the costs associated with transportation,
2. Local climate which determines crop production and thus the need for climate conditioning and associated costs for equipment and energy. It also determines the greenhouse construction dependent of, for example, wind forces, snow and hail.
3. Availability, type and costs of fuels and electric power to be used for operating and climate conditioning of the greenhouse,
4. Availability and quality of water,
5. Soil quality in terms of drainage, the level of the water table, risk of flooding and topography,
6. Availability and cost of land, present and future urbanisation of the area, the presence of (polluting) industries and zoning restrictions,
7. Availability of capital,
8. The availability and cost of labour as well as the level of education,
9. The availability of materials, equipment and service level that determines the structures and instrumentation of the protected cultivation systems,
10. Legislation in terms of food safety, residuals of chemicals, the use and emission of chemicals to soil, water and air.

With these observations in mind, this paper addresses the question of how to design a protected cultivation system that best satisfies the local conditions in the region considered. Definitely, this question is not raised for the first time. An abundance of literature exists in which various design issues have been tackled, related to greenhouse structure and greenhouse covering materials (*e.g.* Von Elsner *et al.*, 2000a,b), to optimize the greenhouse design to one specific location or to one single construction parameter (e.g. Hemming *et al.*, 2004; Impron et al., 2007; Zaragoza et al., 2007), to optimize climate conditioning (*e.g.* Garcia *et al.*, 1998), greenhouse climate control (*e.g.* Bakker *et al.*, 1995) or substrates and nutrition control (*e.g.* Gieling, 2001), to mention just a few examples. But in most of these studies greenhouse design is approached as a single factorial problem, which means that only one issue is being considered which may lead to a sub-optimal design. From the list stated above it will be clear that the design of protected cultivation systems in fact is a multi-factorial design and optimization problem (van Henten *et al.*, 2006).

Developing and implementing a systems design approach as presented in this paper was, first of all, motivated by the fact that greenhouse production systems in the Netherlands are already highly optimized for the current conditions, but further improvement in greenhouse design is needed due to the strong dynamic changes in the major factors as listed above such as energy costs, labor costs and environmental impact. Secondly, this research was motivated by the fact that there is a growing and flourishing industry producing greenhouse constructions,

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cladding materials, climate conditioning equipment and other infrastructure throughout the whole world. Sometimes these systems perform sub-optimal because they are not sufficiently adapted to the conditions in all regions of the world where they are applied. For example, recently a new greenhouse project to grow strawberries at Curacao was stopped because of an underestimation of the effects of heat loads and insufficient insulating properties of the greenhouse. This resulted in too high cooling costs. The systematic design approach aims at resolving problems of regional adaptation.

In this paper, the outlines of this approach to designing protected cultivation systems are sketched. Several examples will be given, ranging from greenhouses for the various climatic zones in Mexico to the design of high-tech minimum fossil energy greenhouses in the Netherlands.

A systematic greenhouse design procedure

Designing protected cultivation systems is a multi-factorial optimization problem. During this process, choices have to be made with respect to construction, cladding material, climate conditioning equipment, energy sources, energy management, growing substrates, water and nutrient supply, internal logistics and labour, to mention a few. All of these choices mutually influence each other and are influenced by local boundary conditions like climate, economics, market, legislation and availability of resources.

For the evaluation of various designs of greenhouse systems, several decision support systems have been developed such as KASPRO (de Zwart, 1996), SERRISTE in France (Tchamitchian *et al.*, 2006) or HORTEX (Rath, 1992) or GTa-Tools (Van ’t Ooster, 2006). These systems support either designers or growers with reliable and quick assessment of energy conservation measures in greenhouse cultivation. Rapid changes in technology and energy costs require a dynamic and flexible approach in which one can select a wide range of components (e.g. greenhouse dimensions, heating systems, covering materials, lighting, conversion- and storage systems) together with energy prices and settings for operational control. The output shows the energetic and economic effects of both the strategic and the operational choices. All in all, these software tools are basically developed to evaluate predefined designs of protected cultivation systems. To push the multi-factorial design of protected cultivations systems one step further, a more general and wider applicable design method is suggested here. It is based on systematic design procedures that have been described by for instance Van den Kroonenberg and Siers (1999) and Cross (2001). The design procedure roughly contains the following steps (Van den Kroonenberg and Siers (1999)):

0. Definition of the design objective.
1. In a brief of requirements the specifications and design objectives are stipulated. Here one may think of for instance costs, performance in terms of energy use, emission levels, labour requirements etc.
2. A systems analysis will reveal the functions needed such as heating, cooling, water and nutrient supply, internal transport.
3. Derivation of alternative working principles for each function which yields a so-called morphological diagram. For example, in case of cooling we may consider natural ventilation, forced ventilation, fog systems and pad-and-fan cooling as design alternatives. Similar alternative working principles have to be described during this phase for other functions.
4. Concept development stage. During this stage, the different functions, or more specifically working principles in the morphological diagram, are combined into a conceptual design that

should at least satisfy the functional requirements stated in the design specifications. Several different concepts can be designed at this stage. Bear in mind that nothing has been built yet. All these analyses are performed as a desktop study.

5. Design evaluation and bottle-neck assessment. During this stage the various conceptual designs are evaluated in view of the design requirements stated above. Design evaluation is based on expert assessment but also on quantitative simulation using mathematical models. Also bottle-necks and contradictions in the design can be identified. One or two conceptual designs are chosen.
6. For the conceptual design(s) chosen, each working principle has to be worked out in more detail. Solutions for a bottle-neck function and design contradictions have to be found.
7. The design prototype is built and tested in view of the design requirements.

The advantages of such a design procedure can be summarized as follows. It prevents jumping too quickly to a solution while not having looked into the overall design problem seriously. It offers the opportunity for a multi-disciplinary approach to systems design. It prevents trial and error. The knowledge of the designer stays in the company and is not lost when the designer leaves the company. It produces a good overview of the design requirements and reduces the chance of overlooking some essential design requirements. Bottle-necks and design contradictions are identified at an early stage. It offers insight into design alternatives. It offers a basis for sound and objective decisions during the design procedure. By producing insight, stake-holders and decision makers can contribute to the process and are more easily convinced of the correctness of the design. Clearly, such a design method guides the engineer in the design process, but it does not guarantee success. In depth assessment of promising concepts with adequate models and decision support systems helps to increase the success rate.

Example 1: Minimum fossil energy greenhouse systems

The design procedure is best illustrated with an example. In this paper, the development of a conceptual design of a greenhouse for Dutch circumstances that was required to use no fossil energy sources for heating, a minimum fossil energy greenhouse (Van ’t Ooster *et al.*, 2007a), is used as example. This example only covers the first five steps of the design procedure. Due to the limited printing space, this example will only be described in qualitative terms.

Step 0. The design objective

This design study was motivated by the fact that the Dutch horticultural industry has committed itself to improving the energy efficiency by 65% in the year 2010 compared with consumption levels of 1980 (Bot, 2001). Also, the Dutch government has signed the Kyoto treaty stating that CO_2 emission levels should be reduced by 6% in the period 2006-2010 compared with emission levels in 1990 (Van der Knijff and Benninga, 2003). Designing a minimum fossil energy greenhouse aims at tackling both objectives.

Step 1. Brief of requirements

As a first step in the development of the conceptual design a brief of requirements was produced. This brief included amongst other the following objectives:

1. The greenhouse must have a size of 4 ha and produce at least 50 kg/m^2 of tomatoes,
2. Relative humidity must lie between 60 and 85%. The temperature must stay under 27 ^oC. The CO_2 concentration must stay between 360 and 1000 ppm,

3. The greenhouse construction must satisfy the NEN3859 construction standard.
4. Energy storage systems must have a zero net energy budget,
5. Energy sources must be sustainable but if fossil energy is needed it must be compensated by the production of an equal amount of sustainable energy surplus.
6. The vents must be closed as much as possible (to prevent losses of energy and harvest energy in the warm season),
7. CO_2-emissions must be reduced to 65% of current values,
8. The system must be economically feasible,
9. Investment must have a pay-back time of less than 6 years,
10. With this greenhouse production system, production must be economically competitive with standard production systems.

Step 2. Definition of required functions

To satisfy these requirements, the required functions were listed as shown in the morphological chart in Figure 1. This figure shows functions along the vertical axis. Functions included energy production, energy storage, heating, cooling and dehumidification of the greenhouse air, CO_2-enrichment, prevention of energy losses through the greenhouse cover as well as shading of sunlight. These functions are considered to be the minimum set of functions to operate a minimum-fossil energy greenhouse. In this example, internal transport, labour, cultivation systems etc. are assumed to be fixed. Also the greenhouse construction is of a standard Venlo-type and not subject to design optimization.

Step 3. Definition of working principles

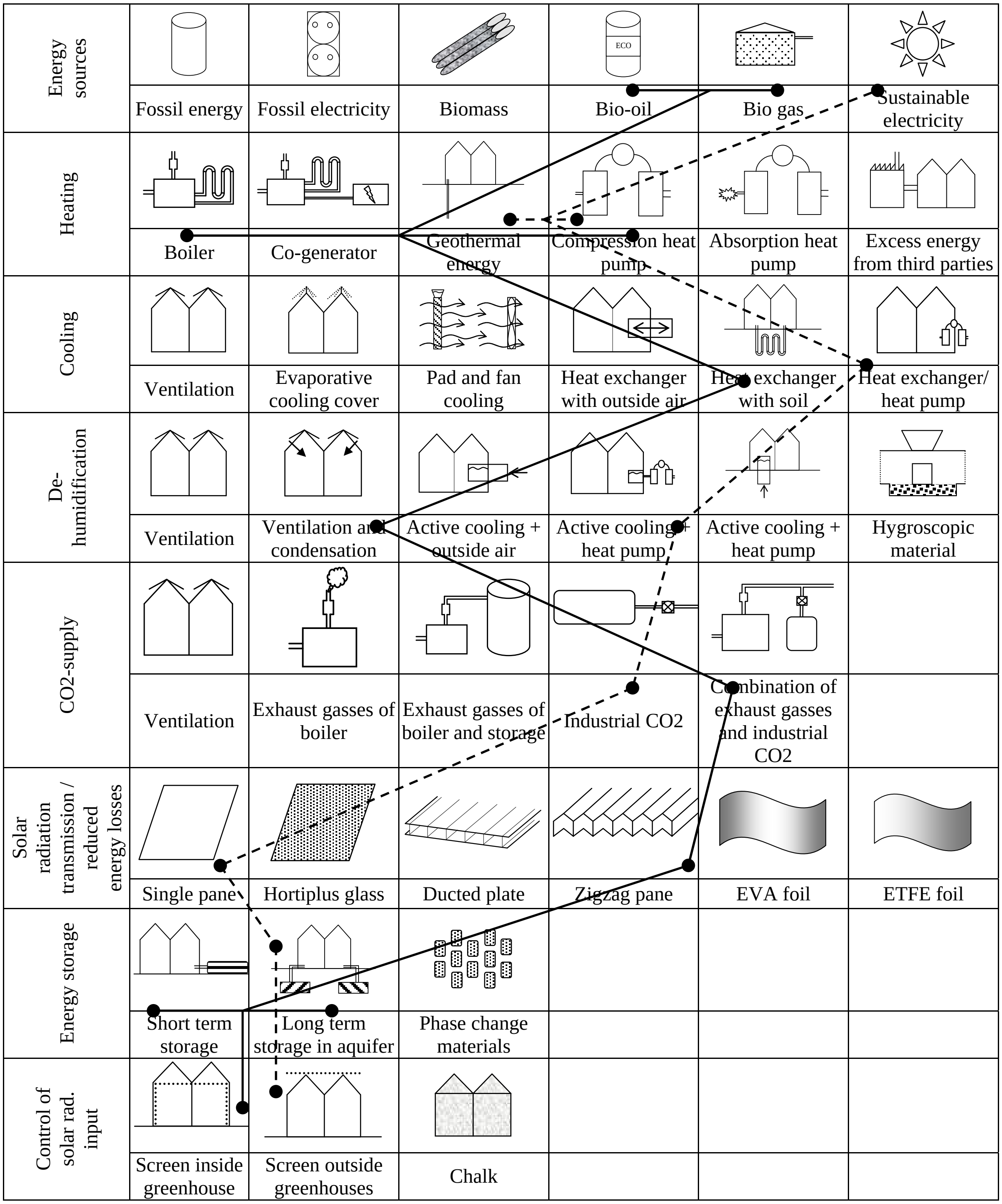
For each of these functions alternative working principles were derived as shown in Figure 1 along the horizontal direction for each function. For example, cooling could be achieved with natural ventilation, water cooling of the greenhouse cover, fog system in the greenhouse, pad-and-fan cooling and heat exchangers with outdoor air or soil.

Step 4. Derivation of conceptual designs

Conceptual designs were developed by combining functions, as illustrated by the two lines in Figure 1. All in all, 9 different promising designs were derived by experts, of which two are shown in the figure. It is worth mentioning that in each function two or more working principles can be combined. Also, the final number of 9 designs is rather arbitrarily. In fact, the number of designs that can be derived is not limited but increases the effort needed for the remaining design steps. A quick-scan for best solutions is relevant.

Concept 1 was constructed as follows. So-called green electricity produced by sustainable energy sources like wind mills, was used as external energy source. Geothermal energy combined with an electrically driven compression heat pump in combination with long term heat storage in an aquifer, was used for heating the greenhouse. For cooling the greenhouse air, a heat exchanger with heat pump in combination with a long term cold storage in an aquifer in the soil, was used. Industrial carbon dioxide was used for enriching the greenhouse air. The greenhouse cover consisted of a single cover and solar radiation energy input to the greenhouse was controlled with a screen outside the greenhouse.

Concept 2 used bio-oil and bio-gas as external energy sources. The greenhouse air was heated by a boiler in combination with a gas fired compression heat pump. Cooling was achieved by a heat exchanger in the soil. Dehumidification of the greenhouse air was achieved by natural ventilation together with a heat exchanger collecting sensible heat from the ventilation air. Carbon dioxide enrichment consisted of an optimized combination of exhaust gasses from the boiler and industrial CO_2. The greenhouse cover was made of a double layer ZigZag® polycarbonate. Energy was stored in short and long term storages. Solar radiation levels inside the greenhouse were controlled with a screen inside the greenhouse.



Energy sources	Fossil energy	Fossil electricity	Biomass	Bio-oil	Bio gas	Sustainable electricity
Heating	Boiler	Co-generator	Geothermal energy	Compression heat pump	Absorption heat pump	Excess energy from third parties
Cooling	Ventilation	Evaporative cooling cover	Pad and fan cooling	Heat exchanger with outside air	Heat exchanger with soil	Heat exchanger/ heat pump
De-humidification	Ventilation	Ventilation and condensation	Active cooling + outside air	Active cooling + heat pump	Active cooling + heat pump	Hygroscopic material
CO2-supply	Ventilation	Exhaust gasses of boiler	Exhaust gasses of boiler and storage	Industrial CO2	Combination of exhaust gasses and industrial CO2	
Solar radiation transmission / reduced energy losses	Single pane	Hortiplus glass	Ducted plate	Zigzag pane	EVA foil	ETFE foil
Energy storage	Short term storage	Long term storage in aquifer	Phase change materials			
Control of solar rad. input	Screen inside greenhouse	Screen outside greenhouses	Chalk			

Figure 1. A morphological diagram; concept 1 (dashed line) and concept 2 (solid line) of a minimum fossil energy greenhouse (van Henten et al. 2006)

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Step 5. Evaluation of conceptual designs

The nine designs were evaluated by experts as a quick scan in view of a set of criteria including: the expected production level, the input of fossil fuels, the production of energy, the efficiency of CO_2-enrichment, the ability to operate independent of outdoor weather conditions, humidity control, effectiveness of short and long term energy storage, light transmission of the cover, insulation of the cover, labour conditions inside the greenhouse, operating costs for heating, cooling, dehumidification, short and long term energy storage and CO_2 enrichment as well as the costs of the greenhouse cladding material.

With each criterion a weighing factor was associated. The weighing factor expressed the relative importance of the individual criterion. Also the weighing factor expressed availability of knowledge about the criterion. If a criterion was very difficult to assess and not too important it received a low weighing factor and vice-versa. The experts were asked to evaluate each criterion on a scale of 1 to 4. Using this procedure, concept 1 was chosen as most promising out of nine. This design was implemented in a simulation model and evaluated through simulations. The simulations revealed that under Dutch circumstances a considerable reduction in the use of fossil energy could be achieved up to 97.5%. Still, this concept required a small amount of fossil energy to cover peak loads. Also short term energy storage is mandatory for covering peak loads in the energy consumption. Because the design hardly used any fossil energy sources, the emission of CO_2 was also strongly reduced compared with standard horticultural practice. Finally, the simulations showed that natural ventilation or other cooling sources than cold water from the aquifer are needed to cover the cool load of the greenhouse in the summer period.

Example 2: Energy delivering greenhouse systems

Other examples of modern greenhouse systems designed by this systematic design procedure can be given, such as the energy-delivering greenhouse and the electricity-producing greenhouse (Bakker *et al.*, 2007). These concepts are based on closing the greenhouse. Main paradigm shift in these systems is that cooling and dehumidification no longer relies on natural ventilation through ventilation windows resulting in generally a higher CO_2-concentration which favors crop yield. In closed greenhouses cooling and dehumidification is achieved using air conditioning equipment.

With completely closed energy-delivering greenhouses (e.g. Opdam, 2005) the next step in the integral design is to extract the total heat surplus during the summer and reuse this during the winter for heating the greenhouse itself and e.g. neighbouring greenhouses or buildings. For this purpose energy is stored in an aquifer. Therefore the performance of the greenhouse as a solar collector is maximized by further reduction of the heat loss and maximizing the heat collection by very efficient heat exchangers as shown in Figure 2 (Bakker *et al.*, 2006). Simulations showed that with this system theoretically a year round heat production might be expected of about 800 $MJ.m^{-2}$, comparable to the equivalence of 25 m^3 natural gas per m^2 (De Zwart en Campen, 2005). The first trials in a commercial scale greenhouse, however, show that this heat production will be hard to achieve since the output is restricted by the growers temperature band widths to minimise detrimental effects on his crop (De Zwart en Van Noort, 2007). Another disadvantage of these systems is the low temperature level of energy delivered by the system (water at 40 ^{o}C).

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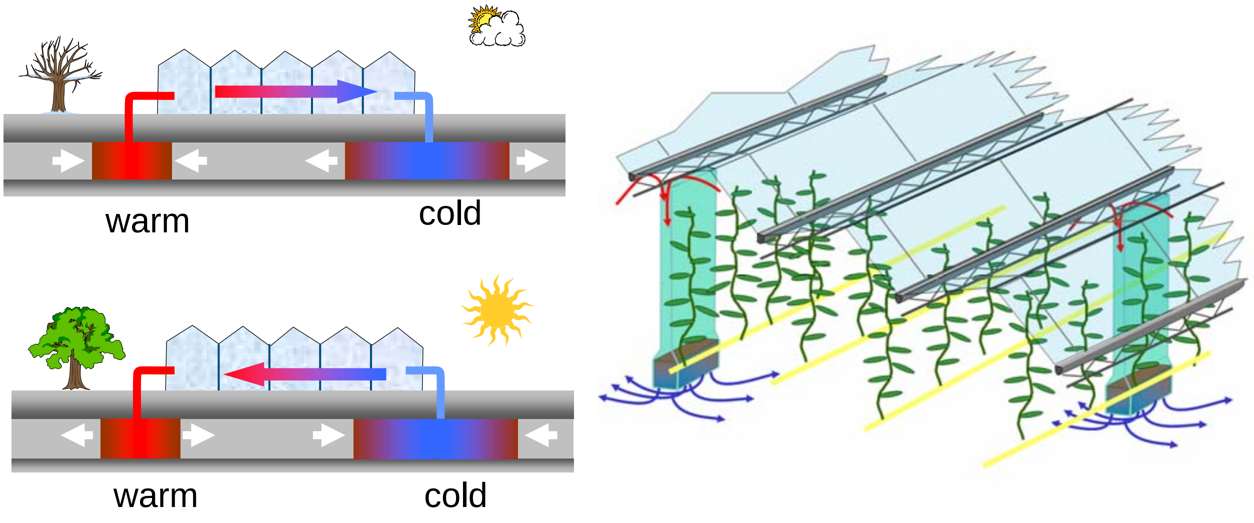

Figure 2. Principle of a heat storage and heat pump system (left) and an efficient heat exchanging system near the crop (right) that uses the greenhouse as a solar energy collector. The energy-delivering greenhouse concept for The Netherlands (De Zwart en Van Noort, 2007)

In an attempt to combine greenhouse production with electricity production instead of warm water production, Sonneveld *et al*. (2006 and 2007) described a system with a parabolic greenhouse cover that reflects near infra-red radiation (NIR) (Figure 3). This cover reflects and focuses the NIR radiation on a specific PV cell or solar collector to generate either electricity or steam. So far the results however, show that the electric power which may be generated, is not enough to power the necessary heat pump capacity to keep the greenhouse completely closed. On the other hand, the reduced heat load in the greenhouse, by the NIR reflecting cover, significantly reduces the required cooling power, which in combination with the limited electricity generated, still may have significant impact on the energy efficiency of this system.

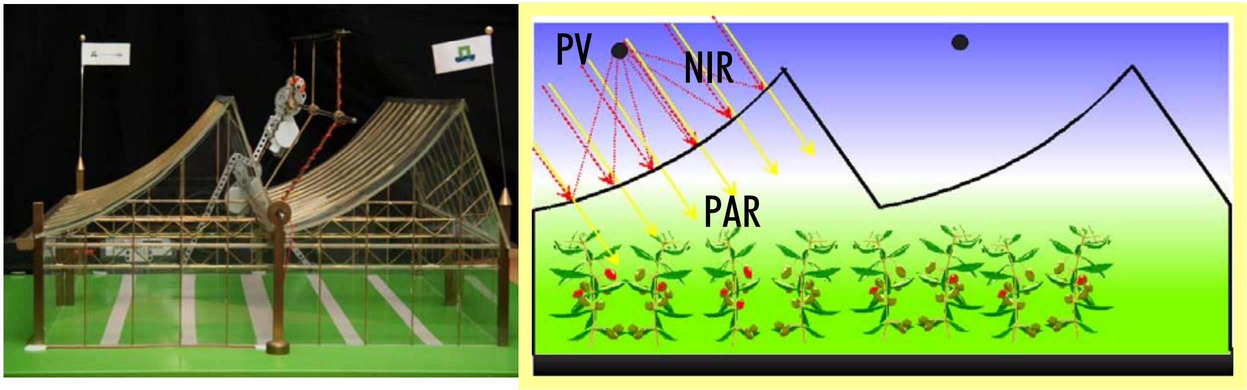

Figure 3. Principle of a selective mirror to separate the useful solar radiation for plant growth (PAR) and near-infrared part of the solar radiation (NIR), which is used for electricity production by concentrating the NIR on photovoltaic cells on a arm outside the greenhouse roof (Sonneveld et al., 2006 and 2007)

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Example 3: Water-efficient greenhouse systems

Also for Southern latitudes in Europe some interesting research projects aim to design innovative and energy efficient greenhouses that incorporate high levels of technology and that intend to adapt the concept of closed or semi-closed greenhouse for these regions. In the Watergy project, a completely closed greenhouse was developed aiming at complete recirculation of water based on an innovative heat exchanger (Buchholz *et al.*, 2005). See figure 4. The actual prototype showed promising results, but like for the Northern Latitudes, the economic feasibility of complete closed greenhouses still is the major bottle neck.

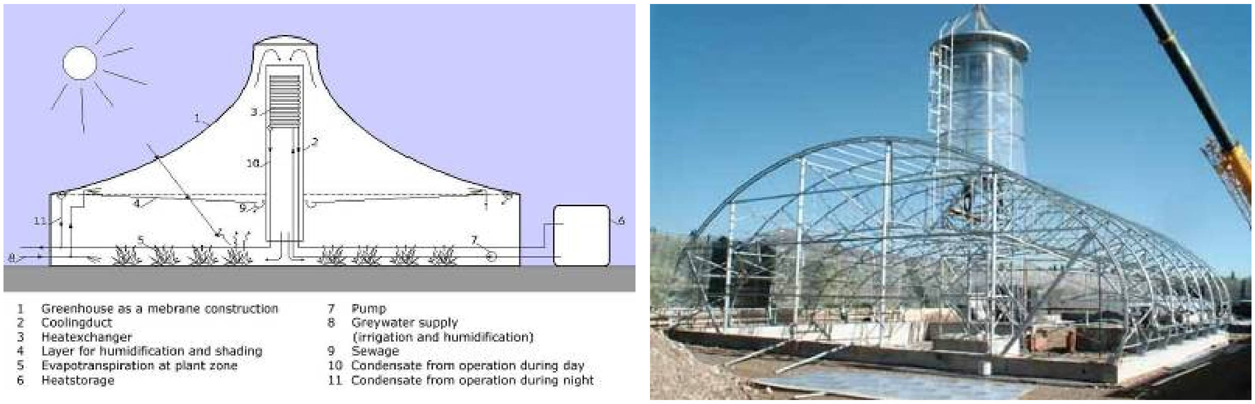

Figure 4. Principle of a greenhouse systems to maximize energy and water use efficiency for Spain (Buchholz et al., 2005)

Example 4: Greenhouse systems for different climate zones in Mexico

The greenhouse area in Mexico is increasing rapidly the last years. The main greenhouse production areas in Mexico are located along the North Pacific coast, in the Mexican states of Sinaloa and Baja California respectively, along the west coast in the state of Jalisco and in the centre of Mexico. Distributed over the country, Mexico contains widely differing climatic regions including an arid climate in the North East, humid tropic climate along the Caribbean Gulf coast and temperate climate on the central plains. In this example, the objective was to determine the feasibility of using cooling systems under desert, humid tropic and temperate Mexican weather conditions.

Though some of the larger growers are experimenting with shades or passively ventilated greenhouses, heat stress prevents tomato production from reaching the levels obtained in the United States and Western Europe. But, the technology levels used and yields obtained in the coastal areas are improving, and more growers are moving into higher technology systems to improve yield, quality and marketing. There are some companies in the North of Mexico that use active cooling systems like pad and fan, but an economical justification of using these systems is not publicly known.

Using a systematic design procedure, this research aimed at generating concepts of cooled greenhouses for the three climate regions. Using simulations, the greenhouse concepts were evaluated in view of the design requirements (van ’t Ooster *et al.*, 2007b).

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Simulation evaluation of greenhouse designs for various climates

To generate concepts of cooled greenhouses a systematic design method was employed. First a brief of requirements was defined. High on the requirements list ranked:

1. adequate growing conditions with air temperature not exceeding 42°C and daily mean not exceeding 26°C,
2. crop production above 40 kg.m^{-2}, at an average practical production of 15.6 kg.m^{-2},
3. efficient use of best available resources and
4. adequate ventilation at all times with effective cooling when needed.

A systems analysis revealed the most relevant functions to realise the above mentioned requirements. They included ventilation, shading, cooling, de-humidification, heating, indoor climate protection and shading. For each function, alternative working principles were generated, leading to a morphological chart. This chart is shown in Fig. 5. In this research, three experts were asked to generate two concepts of a cooled greenhouse for each of the three climate zones considered. Using a predefined set of weight factors on the design requirements, designs were ranked and finally, one concept was produced for each climate zone. These concepts are shown in Fig. 5 as connected lines through the morphological chart. Each of the selected concepts was evaluated by means of simulation using the greenhouse simulation package GTa-tools (van ’t Ooster, 2007).

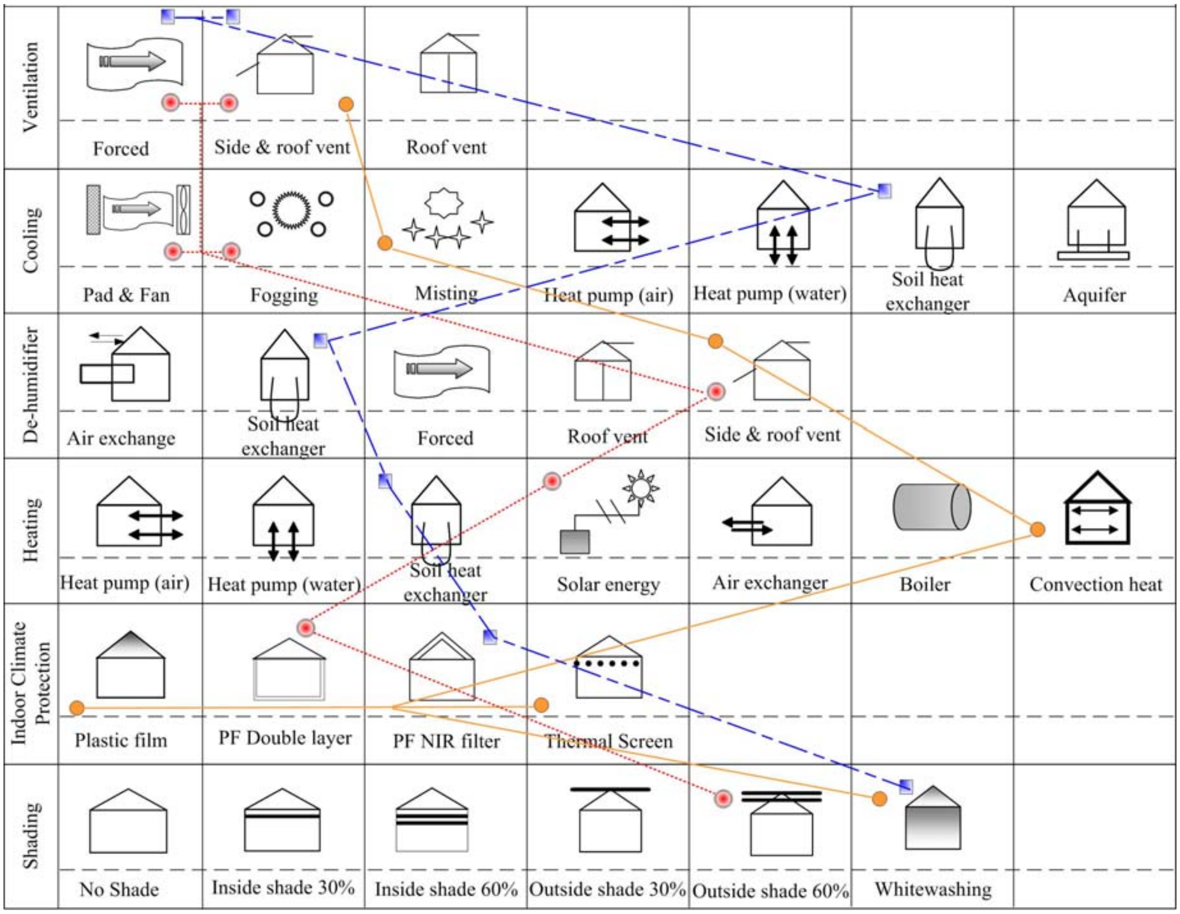

Fig. 5. The morphological chart with the concepts of the cooled greenhouse systems for each of the three climate zones in Mexico: Mexicali – desert climate (◉), Merida – humid tropic climate (■), Huejutla – temperate climate (●).

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1. Desert Climate. The arid region, city of Mexicali, has extreme weather conditions. It has a yearly radiation of 7488 MJ and a yearly average temperature of 24°C. The temperatures in the city that can be as high as 45°C and as low as 4°C. In order to explore possibilities of management we developed 2 different climate control schemes by fixing the set points where pad and fan and fogging are activated at different temperatures. These two strategies had a set point at 27°C for pad and fan and at 30°C for the fogging system and set points at 30°C and 35°C, respectively. The shade screen is active at natural radiation above $650W.m^{-2}$ outside. During cold nights target temperature for heating is 18°C.

2. Humid Tropical Climate. For the humid tropical region, city of Merida, the weather conditions are also extreme, 7105 MJ annually incident solar radiation, a high relative humidity and a 26°C average air temperature. In Merida there are no temperatures below 11°C. Only one climate strategy was developed for Merida. The set point at which the cooling system started was at 30°C, just above 29°C where heat stress is intensified and working conditions can be kept normal. The procedure followed was the same as with the arid climate but instead of using the pad and fan air cooling in the calculations, a soil water heat exchanger was implemented at a forced air exchange rate of $0.0275m^3.m^{-2}.s^{-1}$. The result was used in the same way as with the pad and fan cooling.

3. Temperate Climate. The Mexican temperate region, example is city of Huejutla, receives 6000 MJ per year solar radiation. It has an average temperature of 23°C and maximum and minimum temperatures of 40 and 0°C, respectively. Two climate control strategy were chosen; set points for cooling were fixed at 27°C and at 30°C. The simulation procedure was the same as for the arid climate but not using the pad and fan module.

Assuming heat stress occurs beyond a temperature of 26^oC and given the fact that without active cooling at outdoor temperature levels higher than 26^oC will normally result in equal or higher indoor temperatures, a frequency distribution of the outdoor temperature gives a first insight into the cooling demand. Fig. 6 shows the amount of hours with outdoor temperature exceeding 26^oC. Though the trends are clearly different, to prevent heat stress, the cooling demand is high for all three climate regions considered.

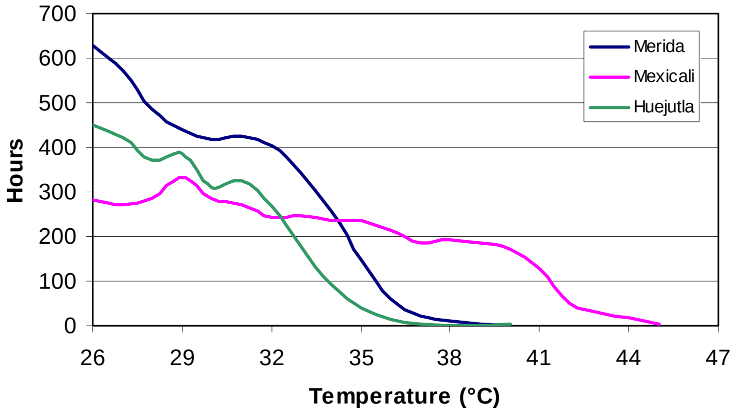

Fig. 6. Frequency distribution of outdoor temperatures in open air above the heat stress limit by region. Total hours T_e>26°C: Merida 4213h (22463Dh), Mexicali: 3865h (32279Dh), Huejutla: 2873h (13925Dh).

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In all cases a non-actively cooled greenhouse was used as a reference. Then, the simulation evaluation revealed that none of the treatments was able to realise optimum plant growth all year, but strong improvements over the control situation were realised in the range of a 25-34% decrease in degree-hours cooling demand, except for the humid region where only 7% decrease in cooling demand was predicted. For Huejutla and Mexicali the best treatments show improved temperature conditions even compared to outdoor climate, however the cooling target of daily mean temperature not exceeding 26°C proved to be unrealistic. Keeping in mind that humidity levels exceeding 95% make crops susceptible to fungal diseases, the simulations showed that humidity levels below 95% are easily obtained under arid conditions. In the temperate climate region, humidity performance is poor. Due to a high humidity content of the air in the humid tropical region, relative humidity levels of the active cooling strategy yield higher indoor relative humidity levels, despite the water removal. Table 1 lists the net income expressed in USD.m^{-2} for the three climate regions. In every case but the humid tropical conditions, profit was obtained in case of use of active cooling systems even though a considerable use of water for cooling decreased the water use efficiency. Looking at the profit and yield values for all cases considered, the results suggest that investing in cooling systems is a good decision, allowing production off-season giving the growers the possibility to become a year round supplier of fresh produce for the US market.

This design study clearly indicates that at potential yields cooling is feasible in desert and moderate climate regions of Mexico but in humid tropic climate regions feasibility is a problem. Initiating the cooling at lower temperatures resulted in higher yield despite of higher operation time and less water use efficiency. Application of design methodology and design evaluation with help of simulation greatly contributed to pointing out effective and non-effective solutions to reduce heat stress in hot climates. For a more detailed analysis, this research indicated that more detailed knowledge is required on crop growth at high radiation and high temperatures with emphasis on continued effects of heat stress.

Table 1. Net profit caused by cooling in USD/m^2 defined as difference with reference.

	Temperate		Humid tropical	Arid	
	Fog 27	Fog 30	HE 30	P&F 27, Fog 30	P&F 30, Fog 35
Marginal Yield	$18.54	$16.48	$28.66	$18.34	$13.10
Marginal Cost	$3.12	$2.99	$35.84	$7.94	$8.57
Net Profit	$15.42	$13.49	$-7.18	$10.40	$4.53

Conclusion

In this paper, a systematic design procedure was presented and illustrated on various examples of the design of protected cultivation systems. This approach was motivated by the complexity, multi-disciplinarily and multi-factorial characteristics of the design process. Besides handling complexity, in practice, this approach has shown various advantages. It prevents jumping too quickly to a solution while not having looked into the overall design problem seriously. It offers the opportunity for a multi-disciplinary approach to systems design. It prevents trial and error. The knowledge of the designer stays in the company and is not lost when the designer leaves the company. It produces a good overview of the design requirements and reduces the chance of overlooking some essential design requirements. Bottle-necks and design contradictions are identified at an early stage. It offers insight into design alternatives. It offers a

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basis for sound and objective decisions during the design procedure. By producing insight, stakeholders and decision makers can contribute to and get convinced of the correctness of the design. Clearly, such a design method guides the engineer in the design process, but it does not guarantee success. To attain robustness and improve the chance of success, further development of the procedure and of tools for objective assessment is still required.

The approach was illustrated with various examples ranging from the design of actively cooled protected cultivations systems for different climatic regions in Mexico to high-tech energy producing greenhouse in The Netherlands.

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Biography

Dr. rer. hort. Silke Hemming (3 June 1970) received her M.Sc. degree in 1996 and her Ph.D. degree in 1998 with summa cum laude in Horticultural Sciences at Hannover University, Germany. Since 1999 she is a Scientist in the research group Wageningen UR Greenhouse Horticulture. Since February 2007 she is the team leader of the Greenhouse Technology Research Group. With greenhouse crop production as the main application field, her research interests are greenhouse design, integrated production systems, greenhouse climate and energy management, optimum use of natural and artificial light.

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Ir. Bram Vanthoor (7 November 1980) received his M.Sc. degree in 2005 in Agricultural Engineering at Wageningen University, The Netherlands. Since 2006 he is a PhD student in the research group Wageningen UR Greenhouse Horticulture. The aim of the project is to develop a generic method to design greenhouses which are adapted to their local conditions. Besides his focus on international greenhouse design, his research interests are greenhouse climate modelling, crop modelling and combined design and control optimization of bio-systems.

Dr.ir. Sjaak (J. C.) Bakker (6 March 1957) received his M.Sc. at the University of Wageningen in 1982 with degrees in greenhouse engineering and systems technology and control. In 1991 he received his PhD with honours in Greenhouse Horticulture for his thesis: Analysis of humidity effects on growth and production of greenhouse vegetable crops. In 1994 he became head of the climate technology department at Wageningen UR. From 1999 until 2006 he was manager of the R&D department of Priva Hortimation, a leading company in greenhouse environmental control. Afterwards he returned to Wageningen UR and is since 2006 business unit manager of the research group Greenhouse Horticulture, a group of about 100 scientists.

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