The Adaptive Greenhouse – an Integrated Systems Approach to Developing Protected Cultivation 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. A quick scan of protected cultivation systems presently in use reveals that various types of protected cultivation systems have evolved in time. These cultivation systems differ for instance in terms of construction and cover materials used, the presence and use of different types of climate conditioning equipment, soil or soilless cultivation and nutrition. These differences are determined by the local climate, the availability of water, soil and water quality, the availability of capital, labor and materials and local legislation, to mention a few. 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. This is a multi-factorial design and optimization problem. This research aims at developing a generic design tool, using available knowledge for instance contained in heuristic and mathematical models. In this paper, the outlines of a systematic design procedure to design protected cultivation systems are sketched. The design of a minimum fossil energy greenhouse is used as example to illustrate the approach.

INTRODUCTION

As illustrated by Stanghellini (1987), going back 2000 years in the literature, it can be discovered that the Romans already recognized the benefits of protecting crops from unfavorable outdoor climate conditions by means of light transmitting shelters to facilitate the cultivation of exotic crops during winter and spring. Later on, people became aware of the fact that crop productivity could be improved by actively modifying the climate inside these shelters by means of heating, humidification and carbon dioxide enrichment. Throughout time, technology evolved and 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 in less developed countries, 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, a wide range of protected cultivation systems has evolved. They range from low-tech, low-cost plastic tunnels to high-tech expensive glass-houses used in Western-Europe and North-America. Greenhouses differ in size, shape and materials used, ranging from quonset type single span structures covered with plastic to multi-span greenhouses with glass covers. Instrumentation ranges from unheated greenhouses to production systems with computer controlled heating, natural ventilation, CO_2-supply and artificial light. Full scale experiments with fully closed greenhouses are ongoing in the Netherlands. Crops are grown in soil, but also in artificial substrates with water and nutrient supply using drip irrigation. Manual labour is commonly used throughout the world, but in high-tech greenhouses the first robots have recently been introduced to replace human labour.

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 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 and it 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 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), climate conditioning (e.g. Garcia et al., 1998), greenhouse climate control (e.g. Bakker et al., 1995), 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. 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, and it is this design problem that is being tackled in this research. The aim is to develop a generic integrated design tool or Decision Support System (DSS) which produces conceptual designs of protected cultivation systems for various regions throughout the world. These conceptual designs will be based on available knowledge for instance contained in heuristic rules, mathematical models, experts minds and databases. This design tool is coined 'the adaptive greenhouse' because all protected cultivation systems from low-tech to high-tech are considered to be based on the same generic components, such as construction, cover material, equipment, etc., but the particular choice of cultivation system is, so to say, adapted to the local conditions in the region.

This research 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 and labor costs. Secondly, this research is motivated by the fact that there is a growing and flourishing industry producing greenhouse constructions, 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. This research aims at resolving this problem.

In this paper, the outlines of this approach to designing protected cultivation systems are sketched. An example of the design of a minimum-fossil energy greenhouse, i.e. a greenhouse design that minimizes fossil energy consumption for heating under Dutch circumstances is used to illustrate the design approach.

A SYSTEMATIC DESIGN PROCEDURE

Solving a multi-factorial design and optimization problem is a challenge, to say the least. While designing a protected cultivation system, choices have to be made with respect to construction, cladding material, climate conditioning equipment, energy sources, 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. To increase the chance of an effective design result, methodological design procedures have been developed such as advocated by van den Kroonenberg and Siers (1999) and Cross (2001). But there are more examples of such procedures. The design procedure described by van den Kroonenberg and Siers (1999) roughly contains the following steps:

0. Definition of the design objective.
1. In a brief of requirements the specifications and design objectives have to be 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. 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, 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.

Although this will not be clear at first glance, the above design procedure may and in most cases will have an iterative nature. During steps 3 and 4, it may become apparent that functions have been overlooked. Then, the best thing to do is to revert to step 2 or even to step 1 because this design flaw may originate from improper definition of the requirements and specifications. Iteration is possible from each step including 6. Once the system is built, reverting to earlier steps will become increasingly costly and more difficult. It is important to stress that until step 7, no structures are being built. Step 6 may include building small sized functional models of a particular working principle. But realization of the whole design will take place in step 7. The analyses up to step 6 are performed on paper or with a computer using design software, analysis software, simulation models, CAD and knowledge from experts and databases.

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 more easily be 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.

AN EXAMPLE – DESIGN OF A MINIMUM FOSSIL ENERGY GREENHOUSE

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, 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 should have a size of 4 ha and produce at least 50 kg/m^2 of tomatoes,
2. Relative humidity should lie between 60 and 85%. The temperature should stay under 27°C. The CO_2 concentration should stay between 360 and 1000 ppm,
3. The greenhouse construction should satisfy the NEN3859 construction norm,
4. Energy storage systems should have a net zero energy budget,
5. Energy sources should be sustainable but if fossil energy is needed it should be compensated by the production of an equal amount of sustainable energy surplus,
6. The vents should be closed as much as possible (to prevent losses of energy and harvest energy in the warm season),
7. CO_2-emissions should be reduced to 65% of current values,
8. The system should be economically feasible,
9. Investment should have a pay-back time of less than 6 years,
10. With this greenhouse production system, production should be economically competitive with standard production systems.

Step 2. Definition of Required Functions

To satisfy these requirements, functions were derived and for each function, working principles were defined. These are illustrated in Fig. 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 Fig. 1 along the horizontal direction for each function. The resulting diagram is called a morphological chart. 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 Fig. 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. Geo-thermal 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, 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.

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 10.

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 considerably 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.

DISCUSSION

The systematic design procedure was found to be a powerful instrument. But the design study on the minimum fossil energy greenhouse revealed that especially the evaluation of the different conceptual designs by experts is a difficult step in the design process. Experts may and in most cases will have different viewpoints upon concepts depending on their background, which may result in the fact that none of the designs is uniformly identified as the best solution. This point requires attention in future research.

Finally, this particular design study mainly focused on energy production and energy consumption. For instance water and nutrient supply, labour and infrastructure were not considered in this short study.

CONCLUDING REMARKS

In this paper the outlines of an approach to integrated design of protected cultivation systems was presented. The approach was illustrated with an example. This example mainly focused on energy production and consumption under Dutch circumstances.

The Adaptive Greenhouse project started only very recently and therefore more definite results or directions are difficult to describe. Main challenges will lie in further development of the systematic design procedure as well as the development of the software components of the DSS in which a wide range of knowledge from very different resources have to be combined. This raises questions as to the particular nature and the availability of the required knowledge as well as to the combination of this knowledge into software using algorithms for rapid evaluation of various designs.

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Figures

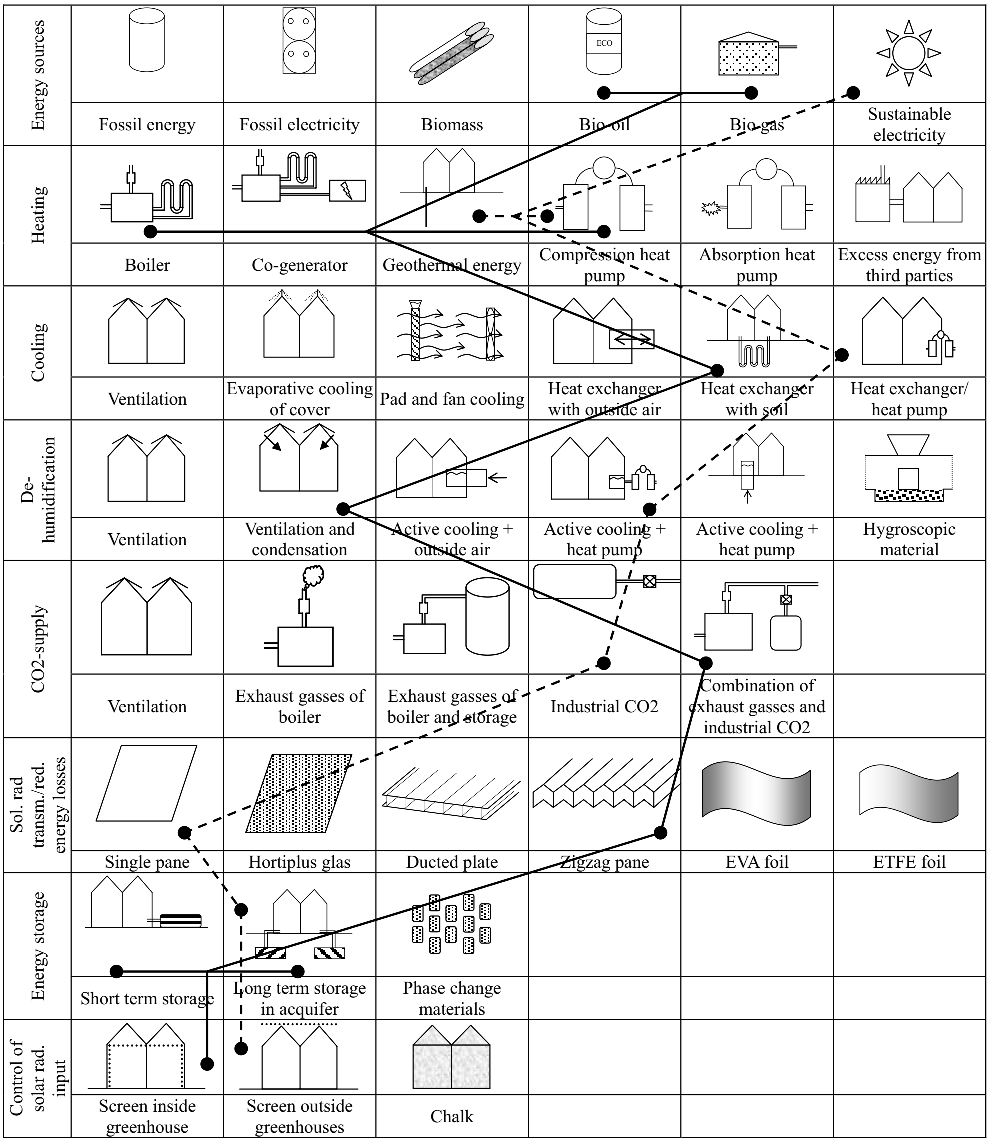

Fig. 1. A morphological diagram; concept 1 (dashed line) and concept 2 (solid line) of a minimum fossil energy greenhouse.