The Design of Greenhouse in Sub-tropical areas - from Crop to Economics

Dr. B. Speetjens and Dr. S. Hemming
Wageningen UR Greenhouse Horticulture

Workshop of Greenhouse Horticulture 7th of November, Taichung, Taiwan

Content

- Why a systematic design approach?
- Theory of systematic design methodology
- Example of design of greenhouses for sub-tropical areas
- Conclusions
- Future perspectives

Systematic design of greenhouse crop production systems

![Graph showing sun radiation and mean temperature comparison between NL and Taiwan]

- Heating
- Cooling
- Lighting

- January
- July
Problem

- How to design a protected crop cultivation system that fits best in a certain region and that satisfies best a special objective?
- Single factorial problem → Multi-factorial design and optimization problem

Multi-factorial design

- Design factors for greenhouse crop production systems:
  - Market size and regional infrastructure
  - Local climate
  - Availability, type and costs of fuels and electric power
  - Availability and quality of water
  - Soil quality and topography
  - Availability and cost of land, zoning restrictions
  - Availability of capital
  - The availability and cost of labour and the level of education
  - The availability of materials, equipment and service level
  - Legislation in terms of food safety, residuals of chemicals, the use and emission of chemicals to soil, water and air

Modern greenhouse cultivation (Hanan, 1998 and Van Heurn and Van der Post, 2004)

Single factorial problem

- Which greenhouse construction?
- Which covering?
- Which energy source?
- Which cooling system?
- Which growing system?
- How to get light into the greenhouse?
- Manual labour or automation?
- ….

Design procedure

3. Alternative Working principles

1. Description of Requirements

4. Combination into Conceptual designs

5. Evaluation:
   - Experts
   - Model simulations
   - Practical experiments

2. Required functions
Design methodology

**Resources:**
- Land
- Energy
- Capital
- Labour
- Water
- Nutrients

**Climate:**
- Temperature
- Humidity
- Solar Radiation
- Wind

**Market:**
- Price of Products
- Quality of Products
- Legislation

---

Adaptive greenhouse model

**Adaptation greenhouse model**

Vanthoor, 2011

---

Design procedure

- **Advantages Design methodology:**
  - prevents jumping too quickly to a solution while not having looked into the overall design problem seriously
  - reduces the chance of overlooking some essential design requirements
  - prevents trial and error and offers insight into design alternatives
  - multi-disciplinary approach to systems design
  - bottle-necks and design contradictions are identified early
  - by producing insight, stake-holders and decision makers can contribute to the process and are more easily convinced of the correctness of the design
Example

- Systematic design of a sustainable greenhouse production system for vegetables in sub-tropical areas

Step 0. The design objective

- Sustainable greenhouse production system
- Suitable for sub-tropical areas
- Dedicated to production of tomato

Step 1. Description of requirements

- High production, must be higher than in today's systems
- High product quality, meet consumer demands
- Ideal greenhouse climate (temperature, humidity, light, CO₂)
- Maximise use of natural solar energy
- Low pesticide use, high food safety
- High water use efficiency, low nutrient losses
- Low maintenance need
- Economically competitive, fast return of investment

Step 2 to 4. Morphological chart

Step 2. Definition of required functions

Step 3. Definition of working principles

Step 4. Derivation of conceptual designs
Conceptual designs: Sustainable tomato greenhouse concept for sub-tropical areas

- Solar thermal heat collection
- Rain water collection
- Automatic irrigation/fertilization
- External shading screen
- High ventilation rate
- Diffuse non-thermic plastic film
- High-wire tomato crop
- Substrate cultivation
- Automatic irrigation/fertigation
- Solar thermal heat collection
- Pipe heating
- Drip irrigation, closed system
- Fogging
- Rain water collection
- Climate control

Step 5. Evaluation of conceptual designs
- Different designs selected by experts
- Evaluation by experts in a quick scan following different criteria including: expected production level, expected maintenance, expected operating and investment costs etc.
- Calculate technical performance by greenhouse model
- Calculate economical performance of different designs

Simulation models – technical performance

Simulation models – economical viability

De Zwart, 1996

<table>
<thead>
<tr>
<th>Variable costs</th>
<th>Annual investment costs (depreciation, maintenance, interest)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Net profit

Yield, quality, prices product
Step 6: Results

- Results of simulation models
- Results of expert views

**Taiwan climate – global radiation**

Typical:
- Yearround daily radiation sum of 10-20 MJ/m²
- Large difference in cloudiness per region

**Taiwan climate – temperatures**

Typical:
- Heating demand small

Challenge:
- High temperatures create need for efficient ventilation
- Extra cooling measures needed

**Taiwan climate – humidity**

Challenge:
- High humidity levels can cause diseases of crops and low quality of products
Light control – greenhouse covering

- Different types of greenhouse covering

<table>
<thead>
<tr>
<th>Material</th>
<th>EVA</th>
<th>EVA</th>
<th>PE</th>
<th>PE</th>
<th>Glass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermic</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>no</td>
<td>Yes</td>
</tr>
<tr>
<td>Diffuse</td>
<td>diffuse</td>
<td>clear</td>
<td>diffuse</td>
<td>clear</td>
<td>Clear</td>
</tr>
<tr>
<td>PAR transmission (perpendicular)</td>
<td>0.82</td>
<td>0.90</td>
<td>0.89</td>
<td>0.89</td>
<td>0.90</td>
</tr>
<tr>
<td>PAR transmission (hemispherical)</td>
<td>0.70</td>
<td>0.80</td>
<td>0.76</td>
<td>0.80</td>
<td>0.83</td>
</tr>
<tr>
<td>IR transmission</td>
<td>0.20</td>
<td>0.39</td>
<td>0.37</td>
<td>0.54</td>
<td>0</td>
</tr>
<tr>
<td>IR emission</td>
<td>0.77</td>
<td>0.58</td>
<td>0.60</td>
<td>0.43</td>
<td>0.80</td>
</tr>
<tr>
<td>Haze</td>
<td>High</td>
<td>low</td>
<td>high</td>
<td>low</td>
<td>Low</td>
</tr>
</tbody>
</table>

Covering with high transmission for heat radiation is advised (non-thermic) → lower night temperatures
Covering should be diffuse → higher crop production

Temperature control - heating

- Heating useful in winter → increase temperature, decrease humidity → higher production, higher quality
- Small capacities needed → solar energy & buffer?

Light control – supplementary light

- Only 3-5% production increase by supplementary lighting due to already high natural irradiation levels
Temperature control – natural ventilation

Natural ventilation decreases greenhouse maximum temperature
Ventilation area > 30% brings temperature inside close to outside

Effect of insect nets

<table>
<thead>
<tr>
<th>Window Fraction [m² window / m² greenhouse]</th>
<th>Number of hours warmer than [h]</th>
<th>Number of hours with relative humidity higher than [h]</th>
<th>Evapo-transp. [kg/m²/yr]</th>
<th>Crop production [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.07</td>
<td>T air&gt; 30°C</td>
<td>T air&gt; 35°C</td>
<td>RH&gt; 95%</td>
<td>RH&gt; 90%</td>
</tr>
<tr>
<td>1526</td>
<td>374</td>
<td>2197</td>
<td>5086</td>
<td>985</td>
</tr>
<tr>
<td>0.14</td>
<td>1231</td>
<td>157</td>
<td>2471</td>
<td>4906</td>
</tr>
<tr>
<td>0.27</td>
<td>1057</td>
<td>41</td>
<td>2570</td>
<td>4676</td>
</tr>
<tr>
<td>0.41</td>
<td>1004</td>
<td>18</td>
<td>2552</td>
<td>4522</td>
</tr>
<tr>
<td>0.54</td>
<td>977</td>
<td>9</td>
<td>2520</td>
<td>4400</td>
</tr>
<tr>
<td>1.1</td>
<td>943</td>
<td>1</td>
<td>2405</td>
<td>4176</td>
</tr>
</tbody>
</table>

Cooling – with water

Adiabatic cooling:
Evaporation of water decreases inside temperatures (and increases humidity)

BUT ventilation needed
NOT working at moments with too high humidity
Cooling - fogging

<table>
<thead>
<tr>
<th>Fogging capacity [g/m²/h]</th>
<th># hours on</th>
<th>Number of hours warmer than 30°C</th>
<th>Number of hours warmer than 35°C</th>
<th>Number of hours with relative humidity higher than 95 or 90%</th>
<th>Evapo-transp</th>
<th>Yearly fogging</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>t_air</td>
<td>t_crop</td>
<td>t_air</td>
<td>t_crop</td>
<td>t_crop</td>
</tr>
<tr>
<td>0</td>
<td>1174</td>
<td>1161</td>
<td>97</td>
<td>384</td>
<td>2639</td>
<td>868</td>
</tr>
<tr>
<td>75</td>
<td>2328</td>
<td>1060</td>
<td>35</td>
<td>344</td>
<td>2639</td>
<td>841</td>
</tr>
<tr>
<td>150</td>
<td>2339</td>
<td>971</td>
<td>16</td>
<td>316</td>
<td>2601</td>
<td>824</td>
</tr>
<tr>
<td>225</td>
<td>2345</td>
<td>903</td>
<td>3</td>
<td>289</td>
<td>2602</td>
<td>811</td>
</tr>
<tr>
<td>300</td>
<td>2343</td>
<td>840</td>
<td>0</td>
<td>259</td>
<td>2800</td>
<td>800</td>
</tr>
<tr>
<td>375</td>
<td>2345</td>
<td>799</td>
<td>0</td>
<td>241</td>
<td>2801</td>
<td>794</td>
</tr>
<tr>
<td>450</td>
<td>2347</td>
<td>784</td>
<td>0</td>
<td>230</td>
<td>2804</td>
<td>790</td>
</tr>
<tr>
<td>525</td>
<td>2347</td>
<td>764</td>
<td>0</td>
<td>225</td>
<td>2804</td>
<td>788</td>
</tr>
<tr>
<td>600</td>
<td>2347</td>
<td>757</td>
<td>0</td>
<td>217</td>
<td>2804</td>
<td>787</td>
</tr>
</tbody>
</table>

Temperature control – cooling with water

Cooling – pad & fan

| Temperature distribution bad with pad&fan | Also true for humidity | Energy consumption high |

1. 350 g fogging/m²/h 2.1 W/m²
   - Power rating of high pressure pump is 50kW/4ha
   - Energy consumption of reverse osmosis is 3kWh/m³ water produced
   - Energy consumption of the fans is 0.7 W/m³

2. 80 m³/m²/h pad&fan system 7.1 W/m²
   - The energy use of the fans is 6.9 W/m²
   - The energy use of the pump is 0.16 W/m³

Limit energy input by screening

- Screens reduce solar energy entering greenhouse → reduce air and crop temperatures

- BUT decrease crop production because of less light
Limit energy input by screening

<table>
<thead>
<tr>
<th>Screen control (W/m²), shading [%]</th>
<th># hours closed [h]</th>
<th># hours warmer than 30°C [h]</th>
<th># hours warmer than 35°C [h]</th>
<th>Biomass [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>No screen</td>
<td>0</td>
<td>864</td>
<td>1</td>
<td>100</td>
</tr>
<tr>
<td>500W/m², 30%</td>
<td>1504</td>
<td>1011</td>
<td>2</td>
<td>80</td>
</tr>
<tr>
<td>600W/m², 30%</td>
<td>1042</td>
<td>976</td>
<td>3</td>
<td>86</td>
</tr>
<tr>
<td>700W/m², 30%</td>
<td>538</td>
<td>933</td>
<td>4</td>
<td>91</td>
</tr>
<tr>
<td><strong>Inside screen:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>500W/m², 20%</td>
<td>1504</td>
<td>985</td>
<td>2</td>
<td>86</td>
</tr>
<tr>
<td>600W/m², 20%</td>
<td>1042</td>
<td>937</td>
<td>1</td>
<td>92</td>
</tr>
<tr>
<td>700W/m², 20%</td>
<td>538</td>
<td>891</td>
<td>0</td>
<td>97</td>
</tr>
<tr>
<td>Exterior screen:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>500W/m², 30%</td>
<td>1504</td>
<td>923</td>
<td>0</td>
<td>89</td>
</tr>
<tr>
<td>600W/m², 30%</td>
<td>1042</td>
<td>888</td>
<td>0</td>
<td>94</td>
</tr>
<tr>
<td>700W/m², 30%</td>
<td>538</td>
<td>868</td>
<td>0</td>
<td>97</td>
</tr>
<tr>
<td>500W/m², 40%</td>
<td>1504</td>
<td>867</td>
<td>0</td>
<td>90</td>
</tr>
<tr>
<td>600W/m², 40%</td>
<td>1042</td>
<td>859</td>
<td>0</td>
<td>94</td>
</tr>
<tr>
<td>700W/m², 40%</td>
<td>538</td>
<td>853</td>
<td>0</td>
<td>97</td>
</tr>
</tbody>
</table>

Effect of CO₂

- CO₂ increases production
- BUT CO₂ losses due to high ventilation rate are high in Taiwan
- Closed greenhouses with active cooling give high controllability

Possibilities of dehumidification

- Possibilities of decreasing humidity in greenhouse with natural ventilation:
  - Create air movement → avoid condensation on crop → use fans, sleeves above or under crop
  - Water system avoiding high evaporation → drip irrigation
  - Heating & ventilation → dry air
Closed greenhouse – real control

Active cooling is able to reduce greenhouse and crop temperatures → Better quality
Active cooling is able to lower humidity levels → Better quality
Advantage: CO₂ level high → Production increases
Disadvantage energy consumption high → 2800kWh/m²/year for cooling, 1100kWh/m²/year for heating → use heat pump: 930kWh/m²/year electricity needed with COP of 3

Water saving by soilless culture

→ Independent from soil quality
→ No soil-born diseases
→ High water use efficiency
→ Saving nutrients, saving costs
→ Better control, higher production

Water use efficiency
Water treatment

Tap water

Rain water storage 200 m³

Treated drain 2 m³

Fogging system

Filter/de-mineralisation

Untreated drain water tank

Sewage

Treated drain water tank

Fogging water

Fertigation unit

Fertigation water

To/from greenhouse

Fertigation water tank

Fertigation unit

Clean water tank

Acid solution

Clean water

B solution

Desinfection

Drain from greenhouse

Untreated drain water tank

Sand filter

UV disinfection unit

Treated drain water tank

Fertigation unit

Rainwater collection

Rainwater collection

usefull → good quality, cheap
Need for integrated pest control

- Hygienic conditions
- Good crop quality by controlled environment and modern crop management
- Integrated pest and disease control
- Biological control

→ less pesticides
→ healthy vegetables

Economic viability

### Assumptions

<table>
<thead>
<tr>
<th>Investments are per m² greenhouse ground area</th>
<th>TND/m²</th>
<th>Interest rate /% /year</th>
<th>Maintenance /% /year</th>
<th>Depreciation /% /year</th>
<th>Annual costs TND/m²/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Price for cherry tomatoes [TND/kg]</td>
<td>120.0</td>
<td>6.5</td>
<td>7</td>
<td>0.5</td>
<td>16.34</td>
</tr>
<tr>
<td>Diesel [TND/liter]</td>
<td>29.50</td>
<td>6.5</td>
<td>7</td>
<td>0.5</td>
<td>24.11</td>
</tr>
<tr>
<td>Electricity [TND/kWh]</td>
<td>3.00</td>
<td>6.5</td>
<td>7</td>
<td>0.5</td>
<td>2.25</td>
</tr>
<tr>
<td>CO₂/pure [TND/kg]</td>
<td>27.50</td>
<td>6.5</td>
<td>7</td>
<td>0.5</td>
<td>18.33</td>
</tr>
<tr>
<td>Ground water [TND/m³] (plant feed water)</td>
<td>10.00</td>
<td>6.5</td>
<td>7</td>
<td>0.5</td>
<td>5.06</td>
</tr>
<tr>
<td>Plant material [TND/plant]</td>
<td>11.75</td>
<td>6.5</td>
<td>7</td>
<td>0.5</td>
<td>3.82</td>
</tr>
<tr>
<td>Labor costs crop [TND/h]</td>
<td>170.0</td>
<td>6.5</td>
<td>7</td>
<td>0.5</td>
<td>12.67</td>
</tr>
<tr>
<td>Crop protection [TND/m²]</td>
<td>21.50</td>
<td>6.5</td>
<td>7</td>
<td>0.5</td>
<td>1.53</td>
</tr>
<tr>
<td>Crop nutrition closed cycle [TND/m²]</td>
<td>18.50</td>
<td>6.5</td>
<td>7</td>
<td>0.5</td>
<td>1.33</td>
</tr>
<tr>
<td>Crop nutrition open system [TND/m²]</td>
<td>48.50</td>
<td>6.5</td>
<td>7</td>
<td>0.5</td>
<td>3.63</td>
</tr>
<tr>
<td>Substrate [TND/m³]</td>
<td>48.50</td>
<td>6.5</td>
<td>7</td>
<td>0.5</td>
<td>3.63</td>
</tr>
<tr>
<td>Plastic film, wires, clips [TND/m²]</td>
<td>19.00</td>
<td>6.5</td>
<td>7</td>
<td>0.5</td>
<td>1.42</td>
</tr>
<tr>
<td>Packaging [TND/m²]</td>
<td>0.38</td>
<td>6.5</td>
<td>7</td>
<td>0.5</td>
<td>0.03</td>
</tr>
</tbody>
</table>

### Sensitivity

<table>
<thead>
<tr>
<th>Price change /%</th>
<th>Simple payback period [years]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low tech greenhouse</td>
<td></td>
</tr>
<tr>
<td>0.00</td>
<td>64.30</td>
</tr>
<tr>
<td>0.50</td>
<td>58.50</td>
</tr>
<tr>
<td>1.00</td>
<td>52.80</td>
</tr>
<tr>
<td>1.50</td>
<td>47.40</td>
</tr>
<tr>
<td>2.00</td>
<td>42.30</td>
</tr>
<tr>
<td>2.50</td>
<td>37.50</td>
</tr>
<tr>
<td>3.00</td>
<td>33.00</td>
</tr>
<tr>
<td>3.50</td>
<td>28.80</td>
</tr>
<tr>
<td>4.00</td>
<td>25.00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Price change /%</th>
<th>Simple payback period [years]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Closed greenhouse</td>
<td></td>
</tr>
<tr>
<td>0.00</td>
<td>57.50</td>
</tr>
<tr>
<td>0.50</td>
<td>52.50</td>
</tr>
<tr>
<td>1.00</td>
<td>48.00</td>
</tr>
<tr>
<td>1.50</td>
<td>43.80</td>
</tr>
<tr>
<td>2.00</td>
<td>40.00</td>
</tr>
<tr>
<td>2.50</td>
<td>36.60</td>
</tr>
<tr>
<td>3.00</td>
<td>33.60</td>
</tr>
<tr>
<td>3.50</td>
<td>30.80</td>
</tr>
<tr>
<td>4.00</td>
<td>28.20</td>
</tr>
</tbody>
</table>
Conclusion greenhouse system for vegetable production in sub-tropical areas

Low cost variant: mid-tech greenhouse
- High temperatures cause risk for fruit set and quality:
  ● High ventilation needed
  ● Adiabatic cooling by fogging (effect limited)
  ● Control radiation input by external screens (effect limited)
- High humidity levels cause risk for diseases and quality:
  ● Create air movement with fans, sleeves
  ● Add heating
- Computer control for climate, irrigation, fertigation
- Modern crop management needed
- Grower knowledge, skills needed

Highly controllable variant: high-tech greenhouse with active cooling and heat pump and CO₂ application
- Optimum temperature, humidity, CO₂ levels can be realised
- Tight for pests, low risk for diseases, healthy products
- Production doubled, product quality increased, year-round production, predictable
- Economic feasibility depending on prices for energy, CO₂ and vegetables
- Grower knowledge and skills on very high level needed

Simple greenhouse vs High tech greenhouse

Future perspectives
- Validate design models for subtropical climate
- Extend models: risks due to grower skills, risk due to technical failures, risk due to pest & diseases
- Build demo greenhouse
- Collect data and conduct experiments in sub-tropical conditions
非常感謝

Wageningen UR
Greenhouse
Horticulture

Thanks to our colleagues:
Eldert van Henten, Bert van 't Ooster, Bram Vanthoor, Feije de Zwart, Jouke Campen et al.