Plant Production Management System for PFAL (plant factory with artificial lighting)

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• **Introduction** — essential resources for plant production -
• **Current status of PFALs in Japan** and issues to be solves
• **Structure of PFAL (plant production system)**
Essential resources (left) in plant production system & produce obtained from the system (right)

**Essential Resources**
- Light
- Water \( (\text{H}_2\text{O}) \)
- \( \text{CO}_2 \)
- Inorganic fertilizers
- Seeds/transplants
- Heat (Temperature)

**Plant production system**

**Produce**
- \( \text{H}_2\text{O}, \text{O}_2 \)
- Plants with
  - Primary & secondary metabolites & water
  - Max. value & Min. plant residue

Other important resource: Labor
Most fresh garbage in the city can be converted into essential resources for plant production.
Annual production capacity is 100-200 times higher in the PFAL than in the open-field.

Yearly production capacity
2,500 lettuce heads/m²
Sales: 2,500 US$/m²
The number of PFALs has been increasing in Japan. Why?
Production costs by components

Consumables 3%, Seeds 2%, Repair 2%
Supplies 1%, Water 1%, Land rental 1%,
Miscellaneous 1%, Land rental 1%

- Electricity 28%
- Labor 26%
- Depreciation 23%
- Packing, shipping, transportation 12%
- Consumables 3%, Seeds 2%, Repair 2%
- Supplies 1%, Water 1%, Land rental 1%
- Miscellaneous 1%, Land rental 1%
Structure of PFAL-D&M (plant factory with artificial lighting - design and management) system

- **PFAL-D (Design)**
  - Requirements, constraints & specifications
  - Building & infrastructure
  - Measurement & control system
  - Facilities & equipment
  - Lighting system
  - Air conditioning
  - Culture bed
  - Equipment layout

- **PFAL-M (Management)**
  - Plan & finance
  - Marketing
  - Production management (PM)
  - Development & renovation
  - PM-Data (data acquisition, analysis, visualization & diagnosis for recommendation)
  - PPM-Control (plant production control)

**Level 1**

**Level 2**

**Level 3**

**Level 4**
Structure of PFAL-D&M system in the cloud and PFAL

Cloud service

PFAL-M (Management)

PFAL-D (Design)

Internet

Data uploader

Controller

Sensor

Web browser

Design

Web browser
PFAL-D&M is used via Internet. Type A: Installed at an existing PFAL, Type B: Installed at a newly built PFAL.

PFAL measurement & control system

Wireless LAN

PFAL-M-PM-Data-acquisition & upload

Cloud
PFAL-D&M system except for ‘data acquisition & upload’ of PFAL-M-PM unit

Internet

PFAL-M-PM-Data-acquisition & upload with PFAL measurement & control
**Structure of PFAL-D (Design) system**

- **PFAL-D (Design) subsystem**
  - Requirements, constraints and specifications
  - Building & infrastructure
  - Facilities & equipment
  - Measurement & control

- Level 3
  - Culture racks/beds/panels
  - Delivery of electricity, water & CO₂
  - Lighting system (LS)
  - Air conditioning
  - Salinity, sterilization
  - Equipment layout & traffic line
  - Tea room, etc. for welfare

Level 2                                               Level 3                                               Level 4
Parameters used to simulate the light environment using PFAL-D-LS (design of lighting system)

- Luminous intensity distribution curve of lamps
- Optical properties of reflectors, culture panels & plant canopy
- 3-Dimensional structure of culture shelf, culture bed & plant canopy
- Temperature dependencies of photosynthetic photon flux efficiency ($\mu$mol/s), wattage & life span of lamps
- Type, size and shape and layout of lamps
- Sink/release of thermal energy generated by lamps
Data collected by PFAL-M-PM Data acquisition part

- Electricity consumption rates by components
- Water, CO₂ & fertilizer consumption rates
- Consumption rates of various supplies
- Environmental factors in the culture room
- Plant growth rate, daily yields & sales figures
- Wastes (plant residue, used supports & supplies)
- Photosynthesis, respiration & water uptake rates
- Human jobs, working status of machine & equipment
- 2-D Images by visible light & thermal radiation cameras
Resource Use Efficiency (RUE) = P/R

Resource: electricity, light, water, CO₂, fertilizer
Seeds/cuttings, human power, PFAL building
Resource use efficiencies (RUE) to be displayed on the screen

- **Electricity**
  - Lamps
  - Air conditioners
  - COP (CO₃ coefficient of performance)
  - % cooling load to cooling capacity

- **Water for nutrient solution, washing/cleaning, hot water shower**
  - Transpired water by plants & % recycled water in the PFAL

- **CO₂ for enrichment**
  - CO₂ supplied, absorbed by plants, released to the outside

- **Fertilizer**
  - Supplied, absorbed, drained amounts of fertilizers

- **Seeds & supports**
  - % germinated, transplanted, harvested & shipped plants

- **Human resource**
  - Working hours, jobs done, health care

- **Human resource**

- **Level 6**
- **Level 7**
- **Level 8**
- **Level 9**
Tabulated list of variables on electricity consumption and light environment together with their attributes ①～⑭ stored in PFAL-M


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Tabulated list of variables on electricity consumption and light environment together with their attributes ①～⑭ stored in PFAL-M

<table>
<thead>
<tr>
<th>Variables</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light</td>
<td>Electricity consumption</td>
</tr>
</tbody>
</table>

250 equations in this table with respect to PARL.

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The variables on CO₂, water, heat energy, plant growth, etc. are also stored in the same way.

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Electricity consumption

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The variables on CO₂, water, heat energy, plant growth, etc. are also stored in the same way.
A part of the structure map in PFAL-D&M showing how to obtain the index value from the measured value, constant value, set point value and equation.
A logical structure of the equations stored in PFAL D&M. Equations are logically connected as shown. The variables in the circle show the indices such as CO₂ and water use efficiencies and rates of photosynthesis and CO₂ supply.
An output example of PFAL-D for light environment improvement by use of light a reflector

<table>
<thead>
<tr>
<th></th>
<th>Without reflector</th>
<th>With reflector</th>
<th>Effect of reflector</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Average (A)</strong></td>
<td>146 μmol m⁻² s⁻¹</td>
<td>202 μmol m⁻² s⁻¹</td>
<td>38% up</td>
</tr>
<tr>
<td><strong>Highest (H)</strong></td>
<td>181 μmol m⁻² s⁻¹</td>
<td>227 μmol m⁻² s⁻¹</td>
<td>25% up</td>
</tr>
<tr>
<td><strong>Lowest (L)</strong></td>
<td>58 μmol m⁻² s⁻¹</td>
<td>76 μmol m⁻² s⁻¹</td>
<td>31% up</td>
</tr>
</tbody>
</table>
A simulated result using PFAL-D of 3 dimensional PPFD distribution on crisp head lettuce plants planted on the culture panels
Daily changes in electricity consumption by lamp groups A and B, and COP (coefficient of performance) of air conditioners in a PFAL. Lamps of each tier are turned on together for 16 continuous hours a day, but shifting the light period.
COPs of air conditioners in August as affected by air temperature difference between inside and outside. The dashed line indicates the maximum possible COP at the cooling load of around 70% of the cooling capacity.

August 2013 (in the suburb of Tokyo, Japan)

Room air temperature is around 22 deg. C

Electricity cost for air conditioning is halve when COP is doubled.

Air temperature difference (outside – inside) (deg.)

Expected improved COP line

COP
Diurnal courses of power consumptions of air conditioners (AC). From 1:00 to 17:00, all ACs were turned on, but 4 ACs only were turned on after 17:00. In either case, air temperature was controlled at the set point of 22. Average COP of ACs in operation was 20-25% higher after 17:00 than before 17:00.
Visualized daily report of power consumptions by components on the computer display screen for the PFAL manager as a daily report.

- **Menu bar**
- **Equipment type & data**
- **Current time, date & year**
- **Alert & Message**
- **Percent power consumption by components**
- **Measured numerical data**
- **Current power consumption (kW)**
- **Layout of culture room**
- **Power consumption integral (kWh)**
- **Predicted % power consumption this month by components**
- **Time course of power consumption by components**
Radar chart showing the overall performance of electricity. Each axis is automatically scaled.
An example of three dimensional air temperature distribution in the culture room with 9 rows & 10 tiers in the PFAL.
Plant growth curve expressed as logistic growth equation. Stage 1: from seeding to 1st transplanting; Stage 2: from 1st to 2nd transplanting; Stage 3: from 2nd transplanting to harvesting.

\[ S(t) = \frac{S_{\text{max}}}{1 + ke^{-rt}} \]
Projected leaf areas as affected by the days after seeding of 1st and 2nd transplanting

<table>
<thead>
<tr>
<th>Line</th>
<th>1st</th>
<th>2nd</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>9</td>
<td>22</td>
</tr>
<tr>
<td>B</td>
<td>10</td>
<td>25</td>
</tr>
<tr>
<td>C</td>
<td>15</td>
<td>30</td>
</tr>
<tr>
<td>D</td>
<td>20</td>
<td>40</td>
</tr>
</tbody>
</table>
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Conclusion

• A design and operation tool for PFAL was developed as a cloud computing service.

• By improving the design and operation of current PFAL, it is expected that:
  - Electricity costs is halved.
  - 3-D distributions of light and temperature distributions are significantly improved.
  - Labor cost is saved and productivity is improved.
Daily electricity charge of ‘ad valorem’ as affected by lighting time scheduling pattern in Tokyo. (1 US$ = 120 Yen as of 2013)
An example of monthly electricity charge for a PFAL in Japan, producing about 100,000 leaf lettuce heads per month. Percent base charge is lowest (12%) in summer and highest in winter (16%) with average of 16%. In Japan, monthly basic charge is determined by the maximum 30-minute power consumption (kW) during the past one year.

1,200,000 JPY is approximately 10,000 US$. 

![Graph showing monthly electricity charges](image-url)
Averaged COP of 7 air conditioners as affected by the ratio of actual cooling load to full cooling capacity. Total electricity consumption of 7 air conditioners at full cooling capacity is 58.6 kW (Sekiyama and Kozai, 2015).

\[ y = -14.1 x^2 + 21.6 x - 3.09 \]
Fig. 22.21  Three dimensional air temperature distributions in the culture room of PFAL. U, M and L denote the upper, middle and low shelves. For row numbers, floor layout and heights of shelves, see Fig. 22.21.