Simulation-Based Decision Support System in Cost Estimation for Vegetable Grafting Propagation

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2\textsuperscript{nd} VEGETABLE GRAFTING SYMPOSIUM 2013, SAN DIEGO, CA
Outline

- Challenges for grafting propagation
- Simulation-based decision support system
- Experiments
- Conclusions
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Grafting Propagation

Scions production

- Seeding
  - Germination & Grow-on
  - Sorting
  - Grow-on
  - Grafting
  - Healing
  - Grow-on
  - Cold storage

Rootstock production

- Seeding
  - Germination & Grow-on
  - Sorting
  - Grow-on
- Environment & disease control
- Automation level
- Workforce scheduling
- Cold storage design
Grafting Automation Levels\[1\]

- Manual grafting
- Semi-automated grafting
- Fully-automated grafting

Grafted Seedling Cost Composition[2,3]

Grafted seedling cost

Labor cost
- Salary rate
  - No. of grafting workers
  - No. of sorter operators
  - No. of substrate mixer operators
  - No. of miscellaneous workers

Material cost
- Fertilizer cost
  - Substrate cost
    - No. of seeder operators
  - Razor cost
    - Clip cost
      - Tray replacement cost

Germination chamber cost
- Sorter cost
  - Tray cost
  - Headhouse cost
    - Cold storage cost
    - Greenhouse construction cost
  - Grafting robot cost
    - Grafting robot operating cost
    - Seeder cost
      - Headhouse operating cost
        - Healing chamber operating cost
          - Heating chamber operating cost
            - Greenhouse heating cost
              - Greenhouse operating cost
        - Grafting robot operating cost

Mixer cost
- Sorter operating cost
  - Mixer operating cost

Clip cost
- Substrate cost

Capital expenses

Utility cost

Major Challenges and Proposed Solutions

- **Challenge**
  - High demand fluctuation → high labor cost

- **Problems**
  - Selection of grafting technologies
  - Cold storage design
  - Workforce scheduling

- **Simulation-based decision support system**
  - Use user defined input and time-dependent input
  - Optimize weekly workforce schedule and cold storage design
  - Output monthly performance
Outline

- Challenges for grafting propagation
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Overview of Proposed Framework

1. Fetch default input
2. Optimize workforce/cold storage schedule
3. Read simulation inputs
4. Output simulation results
5. Generate report

Optimization Model

Simulator

User Interface

Input Database

Output Database

USER (grafting propagator)
User Interface

- **Main Features:**
  - Define *crop type*, *annual production*, *grafting technology*, *equipment model* and *utility prices*
  - Generate/adjust *demand patterns*
  - Set *bounds of decision variables* for optimization
  - View *simulation outputs*
User Interface Demo
Overview of Proposed Framework

1. Fetch default input

2. Optimize workforce/cold storage schedule

3. Read simulation inputs

4. Output simulation results

5. Generate report

Input database

Output database

User Interface

- USER (Seedling propagator)

Optimization Model

Simulator

Output Reporter

Computer Integrated Manufacturing & Simulation Lab
Department of Systems and Industrial Engineering
Workforce & Cold Storage Scheduling

Indices:

- $t$: week index, $t=1,2,…,T$
- $j$: weeks in cold storage, $j=1,2,…,J$

Parameters:

- $T$: number of weeks in the planning horizon
- $J$: maximum weeks in cold storage
- $d_t$: grafting quantity originally scheduled in week $t$ (plants/week)
- $c_w$: skilled worker regular time salary ($/hour$)
- $c_o$: skilled worker overtime salary ($/hour$)
- $c_h$: unskilled worker salary ($/hour$)
- $c_i$: inventory (cold storage) holding cost($/plant \cdot hour$)
- $k_w$: skilled worker capacity (hours/plant)
- $k_h$: unskilled worker capacity (hours/plant)
Decision variables:

- $W$: available regular working hours for skilled workers (hours/week)
- $O_t$: overtime scheduled for skilled workers in week $t$ (hours)
- $U_t$: undertime for skilled workers in week $t$ (hours)
- $H_t$: unskilled worker working hours in week $t$ (hours)
- $Q_{tj}$: number of plants grafted in week $t$ and stored until week $t+j$

Min $Z = \sum_{t=1}^{T} (c_w W + c_o O_t + 7 \times 24 \times \sum_{j=1}^{J} j c_i Q_{tj} / k_t + c_h H_t)$ \hspace{1cm} (1)

s.t

$W + O_t + \sum_{j=1}^{J} Q_{t-j} + H_t - U_t = \sum_{j=1}^{J} Q_{tj} + k_t d_t \ \forall t$ \hspace{1cm} (2)

$O_t \leq 0.25W \ \forall t$ \hspace{1cm} (3)

$O_t \times U_t = 0 \ \forall t$ \hspace{1cm} (4)

$(0.25W - O_t) H_t = 0 \ \forall t$ \hspace{1cm} (5)

$\sum_{j=1}^{J} Q_{t-j} < k_t d_t \ \forall t$ \hspace{1cm} (6)

$k_t = (W + H_t) / (W / k_w + H_t / k_h) \ \forall t$ \hspace{1cm} (7)
Overview of Proposed Framework

1. Fetch default input

2. Optimize workforce/cold storage schedule

3. Read simulation inputs

4. Output simulation results

5. Generate report

User Interface

1. Define user inputs

Optimization Model

Simulator

USER
(Seedling propagator)

Output database

Output Reporter

Input database
Propagation Operation Simulation Model

☐ Main Features:

☐ Incorporated various processes in the propagation such as seeding, germination, grow-on, sorting, grafting, healing and cold storage

☐ Incorporated manual/semi-automated/fully-automated grafting

☐ Collected daily cost data and monthly output

☐ Stochastic data: grafting speed, success rate, machine Mean Time Between Failure (MTBF) and Mean Time Between Recovery (MTBR)
Propagation Operation Simulation Model
Grafting Department
Propagation Operation Simulation Model
Greenhouse Module
Outline

- Challenges for grafting propagation
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Experiments

- Demand peak reduction (workforce scheduling & cold storage design)
- Monthly variable cost
- Manual grafting vs. automated grafting
- High volume grafting vs. low volume grafting
Demand Peak Reduction

Grafting schedule

Plants in CS

- Before reduction
- After reduction
- Skilled worker available capacity
Feasibility of Using Cold Storage

Operational costs (grafting labor cost + inventory cost)

Cold storage operation cost rate ($/week.plant)

Using Cold Storage: 0.0066 ($/week.plant)

Itemized costs

Cost items

- Skilled worker cost: 0.0129 ($/plant) vs. 0.0128 ($/plant)
- Unskilled worker cost: 0.0181 ($/plant) vs. 0.0192 ($/plant)
- Cold storage cost: 0.0066 ($/week.plant) vs. 0.0000 ($/week.plant)
Monthly Variable Cost

Location: Fort Myers, FL

Monthly Utility Cost

- Average
- Simulation

Month

$0.040 - 0.056$
Monthly Variable Cost

Monthly Labor Cost

Month

0 2 4 6 8 10 12

$
# Manual Grafting vs. Automated Grafting (Parameters)

<table>
<thead>
<tr>
<th></th>
<th>Skilled worker grafting speed (plants/hour)</th>
<th>Skilled worker salary rate ($/hour)</th>
<th>Unskilled worker grafting speed (plants/hour)</th>
<th>Unskilled worker salary rate ($/hour)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Skilled worker</strong></td>
<td>300</td>
<td>7.97-13.47</td>
<td>200</td>
<td>5.5-12</td>
</tr>
<tr>
<td><strong>Grafting robot</strong></td>
<td>Grafting robot capacity (plants/hour)</td>
<td>Grafting robot electricity consumption rate (kw)</td>
<td>Grafting robot price ($)</td>
<td>Basic time unit</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>3.35</td>
<td>195150</td>
<td>Week</td>
</tr>
</tbody>
</table>
Manual Grafting vs. Automated Grafting

Optimal weekly skilled worker working hours

\[ Y = -22.7318X + 893.3851 \]

Unskilled worker salary: $6.14/hour

Optimal grafting labor cost ($/plant)

\[ Y = 0.002002X + 0.68449 \]

Unskilled worker salary: $6.14/hour
Manual Grafting vs. Automated Grafting

Optimal grafting operational cost*

Unskilled worker salary: 6.14 $/hour

*Operational cost includes labor cost and robot operational cost (only for automated grafting)
Manual Grafting vs. Automated Grafting

Manual and automated grafting operational cost* (consider payout period)

*Operational cost includes labor cost and robot operational cost (only for automated grafting)
### High Volume vs. Low Volume

<table>
<thead>
<tr>
<th>Location</th>
<th>Unskilled worker salary ($/hr)</th>
<th>Skilled worker salary ($/hr)</th>
<th>Electricity price ($/kwh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minneapolis, MN</td>
<td>6.15</td>
<td>7.38</td>
<td>0.0826</td>
</tr>
<tr>
<td>Charlotte, NC</td>
<td>7.25</td>
<td>8.7</td>
<td>0.0838</td>
</tr>
<tr>
<td>Tucson, AZ</td>
<td>7.65</td>
<td>9.18</td>
<td>0.0862</td>
</tr>
<tr>
<td>Charleston, SC</td>
<td>7.25</td>
<td>8.7</td>
<td>0.0928</td>
</tr>
<tr>
<td>Fort Myers, FL</td>
<td>7.67</td>
<td>9.21</td>
<td>0.094</td>
</tr>
<tr>
<td>Seattle, WA</td>
<td>9.04</td>
<td>10.85</td>
<td>0.0773</td>
</tr>
<tr>
<td>Bellingham, WA</td>
<td>9.04</td>
<td>10.85</td>
<td>0.0773</td>
</tr>
<tr>
<td>LA, CA</td>
<td>8</td>
<td>9.6</td>
<td>0.1196</td>
</tr>
<tr>
<td>Salinas, CA</td>
<td>8</td>
<td>9.6</td>
<td>0.1196</td>
</tr>
<tr>
<td>Hilo, HI</td>
<td>7.25</td>
<td>8.7</td>
<td>0.3402</td>
</tr>
</tbody>
</table>

Other major location dependent parameters include: degree day and monthly gas price


High Volume vs. Low Volume

Grafted seedling cost for low volume (1 million plants) production

<table>
<thead>
<tr>
<th>Location</th>
<th>Material cost</th>
<th>Labor cost</th>
<th>Utility cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minneapolis, MN</td>
<td>0.0894</td>
<td>0.0192</td>
<td>0.0180</td>
</tr>
<tr>
<td>Charlotte, NC</td>
<td>0.1024</td>
<td>0.0392</td>
<td>0.0182</td>
</tr>
<tr>
<td>Tucson, AZ</td>
<td>0.0926</td>
<td>0.0244</td>
<td>0.0189</td>
</tr>
<tr>
<td>Charleston, SC</td>
<td>0.0953</td>
<td>0.0229</td>
<td>0.0184</td>
</tr>
<tr>
<td>Fort Myers, FL</td>
<td>0.0940</td>
<td>0.0246</td>
<td>0.0174</td>
</tr>
<tr>
<td>Seattle, WA</td>
<td>0.0851</td>
<td>0.0248</td>
<td>0.0177</td>
</tr>
<tr>
<td>Bellingham, WA</td>
<td>0.0844</td>
<td>0.0287</td>
<td>0.0179</td>
</tr>
<tr>
<td>LA, CA</td>
<td>0.1226</td>
<td>0.0250</td>
<td>0.0175</td>
</tr>
<tr>
<td>Salinas, CA</td>
<td>0.1201</td>
<td>0.0393</td>
<td>0.0178</td>
</tr>
<tr>
<td>Hilo, HI</td>
<td>0.2359</td>
<td>0.0395</td>
<td>0.0178</td>
</tr>
</tbody>
</table>
## High Volume vs. Low Volume

### Grafted seedling cost for high volume (100 million plants) production

<table>
<thead>
<tr>
<th>Location</th>
<th>Material cost</th>
<th>Labor cost</th>
<th>Utility cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minneapolis, MN</td>
<td>0.0547</td>
<td>0.0182</td>
<td>0.0178</td>
</tr>
<tr>
<td>Charlotte, NC</td>
<td>0.0525</td>
<td>0.0216</td>
<td>0.0178</td>
</tr>
<tr>
<td>Tucson, AZ</td>
<td>0.0569</td>
<td>0.0231</td>
<td>0.0178</td>
</tr>
<tr>
<td>Charleston, SC</td>
<td>0.0613</td>
<td>0.0215</td>
<td>0.0178</td>
</tr>
<tr>
<td>Fort Myers, FL</td>
<td>0.0601</td>
<td>0.0231</td>
<td>0.0178</td>
</tr>
<tr>
<td>Seattle, WA</td>
<td>0.0467</td>
<td>0.0274</td>
<td>0.0192</td>
</tr>
<tr>
<td>Bellingham, WA</td>
<td>0.0480</td>
<td>0.0272</td>
<td>0.0185</td>
</tr>
<tr>
<td>LA, CA</td>
<td>0.0741</td>
<td>0.0237</td>
<td>0.0182</td>
</tr>
<tr>
<td>Salinas, CA</td>
<td>0.0739</td>
<td>0.0244</td>
<td>0.0178</td>
</tr>
<tr>
<td>Hilo, HI</td>
<td>0.2214</td>
<td>0.0199</td>
<td>0.0166</td>
</tr>
</tbody>
</table>

*Locations indicate different production sites across the United States, including Minneapolis, Charlotte, Tucson, Charleston, Fort Myers, Seattle, Bellingham, Los Angeles, Salinas, and Hilo.*
Conclusions

- Proposed a simulation-based decision support system for grafting propagation
  - Grafting workforce scheduling
  - Cold storage design
  - Cost effectiveness analysis
- Demonstrated the proposed system using a realistic case study
- Future research extension: supply chain coordination strategy for demand peak reduction
QUESTIONS?