An analytics solution for harvesting operations in an oil palm plantation

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Agenda

- Introduction
- Project stages
- Results
Agenda

Introduction

- Motivation
- Context
- Problem definition
- Literature review
Motivation

Palm oil

Economic:
- By 2015, valued at USD 66 billion (global)
- Major job provider in Colombia (140,000)*

**Motivation**

Economic:
- By 2015, valued at USD 66 billion (global)
- Major job provider in Colombia (140,000)*

Palm oil market

Motivation

Palm oil

Higher productivity in:
• Malaysia – 26%
• Indonesia – 23%

Economic:
- By 2015, valued at USD 66 billion (global)
- Major job provider in Colombia (140,000)*

Palm oil market

Motivation

Palm oil

Main uses:

- Alimentary: cooking oil, margarine and ice cream
- Non-alimentary: biodiesel, soap and cosmetics
Motivation

Palm oil

Main uses:

- Alimentary: cooking oil, margarine and ice cream
- Non-alimentary: biodiesel, soap and cosmetics

Environmental issues:

- Deforestation in Southeast Asia
- Plantations in flooded savannas as in Colombian Orinoquia have less impact in the ecosystem
Agenda

Introduction

- Motivation
- Context
- Problem definition
- Literature review
Context
Context
Context - La Ilusión plantation

- 2,090 hectares
Context - La Ilusión plantation

- 2,090 hectares
- 87 land plots
  - Sowing years 2009, 2010 y 2011
- 200 workers (direct and outsourced)
- 100 km of cableway
  - 8 aerial tractors
Context - La Ilusión plantation

- Planting, fertilization and maintenance
- Harvest
- Transport
- Oil extraction
Context - La Ilusión plantation

- Planting, fertilization and maintenance
- Harvest
- Transport
- Oil extraction
Context - La Ilusión plantation

Planting, fertilization and maintenance → Harvest → Transport → Oil extraction

8 days, 20 days

Buffalo
Mechanized

Harvest crew

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Context - La Ilusión plantation

Planting, fertilization and maintenance → Harvest → Transport → Oil extraction

- 30 containers per trip
- 150 kg per container
- 3 - 4.5 tons per trip

8 aerial tractors
Context - La Ilusión plantation

Planting, fertilization and maintenance → Harvest → Transport → Oil extraction

Cableway network
- Main cable
- Secondary cables
- Tertiary cables
- Stockpiling center
Business problem

Average harvest cycle length: 19.6 days
How to visit the plantation to reduce the harvest cycle length?
Business problem

How to visit the plantation to reduce the harvest cycle length?

- Reduce costs
- Optimize resource allocation
- Reduce uncertainty in task scheduling

8 days to 20 days
Agenda

Introduction

- Motivation
- Context
- Problem definition
- Literature review
Literature review

**Oil palm**

**Harvest**
- Durán, Sierra & García (2004). Extraction potential.
- Mosquera et al. (2008). Harvest comparison, individual or group.

**Transport**
- Fontanilla et al. (2010). Comparison between FFB evacuation systems.

**Supply chain**
- Corley & Tinker (2016). The Oil Palm.
- Murphy (2014). Oil palm crop challenges.

**General analysis**

- Euler, Hoffmann, Fathoni, & Schwarze (2016). Exploring yield gaps in oil palm production systems.

**Linear optimization**

- Fontanilla (2012). Stockpilling center location model for an oil palm plantation.

**Other**

## Literature review

### Harvest


### Transport

- Caixeta-Filho (2006). Orange harvesting scheduling management: A case study. MIP optimal harvest for juice extraction and acidity level.

### Supply chain

- van der Vorst et al. (2009). Simulation modeling for food supply chain redesign.
- Amorim et al. (2012). Multi-objective integrated production and distribution planning of perishable products.
Agenda

Introduction

Project stages

Results
Project stages

Resource allocation model \( W \)

Transport allocation model \( D \)

Harvest cycle model \( Q \)

Ripeness cost function

Yield forecast

Parameter estimation

Discrete-event simulation \( W \)

Q: Quarterly
W: Weekly
D: Daily

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Project stages

- Resource allocation model (W: Weekly)
- Transport allocation model (D: Daily)
- Harvest cycle model (Q: Quarterly)

Q: Quarterly
W: Weekly
D: Daily
Project stages

Resource allocation model

Transport allocation model

Harvest cycle model

What day and how much fruit should be collected for each land plot?

Strategical

Q: Quarterly
W: Weekly
D: Daily
Project stages

Resource allocation model

How to allocate harvest crews throughout the plantation?

Transport allocation model

What day and how much fruit should be collected for each land plot?

Harvest cycle model

Tactical

Strategical

Q: Quarterly
W: Weekly
D: Daily
**Project stages**

**Resource allocation model**

How to allocate harvest crews throughout the plantation?

**Transport allocation model**

What are the aerial tractor routes for fruit evacuation?

**Harvest cycle model**

What day and how much fruit should be collected for each land plot?

**Operational**

**Tactical**

**Strategical**

Q: Quarterly
W: Weekly
D: Daily
Project stages

- **Resource allocation model**
  - Amount (kg) of fresh fruit to be harvested each day
- **Transport allocation model**
  - Amount (kg) of fresh fruit to pick in each land plot each day
- **Harvest cycle model**
  - Ripeness cost function
  - Yield forecast
  - Parameter estimation

- **Discrete-event simulation**

**Feasible? Add constraints**

**Q: Quarterly**
**W: Weekly**
**D: Daily**

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We assign a penalization for not visiting the palm on time.

**FFB state**

<table>
<thead>
<tr>
<th></th>
<th><strong>Unripe</strong></th>
<th><strong>Ripe</strong></th>
<th><strong>Overripe</strong></th>
<th><strong>Rotten</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of days</td>
<td>&lt; 8 days</td>
<td>8-12 days</td>
<td>12-17 days</td>
<td>&gt;17-20 days</td>
</tr>
<tr>
<td>State</td>
<td>Unripe</td>
<td>Ripe</td>
<td>Overripe</td>
<td>Rotten</td>
</tr>
<tr>
<td>Fruitlets</td>
<td>No fruitlets detachment</td>
<td>&lt; 50% fruitlets detachment</td>
<td>&gt;50% fruitlets detachment</td>
<td>Dehydrated bunch</td>
</tr>
</tbody>
</table>

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Ripeness cost function

Oil yield loss

Higher harvesting time
Project stages

- **Resource allocation model** (W)
- **Transport allocation model** (D)
- **Harvest cycle model** (Q)
- **Ripeness cost function**
- **Yield forecast**
- **Parameter estimation**
- **Discrete-event simulation** (W)
- **Feasible?** Add constraints
- **Amount (kg) of fresh fruit to be harvested each day**
- **Amount (kg) of fresh fruit to pick in each land plot each day**
- **Aerial tractor order**

Q: Quarterly  
W: Weekly  
D: Daily
Yield forecast

Methodology

1. Time series fitting and forecast

Forecast for average yield zone 9 for short harvest cycle lengths
Yield forecast

Methodology

2. Variability for each land plot

Forecast for average yield zone 9 for short harvest cycle lengths

\[ \ln(\hat{y}_{9, Q2}), \sigma_{2010} \]

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Yield forecast

Methodology

2. Variability for each land plot

Forecast for average yield zone 9 for short harvest cycle lengths

\[ y'_{52} \]
Yield forecast

1. Quarterly average per zone (Holt-Winters) captures seasonality and long-term trend
2. Monte Carlo simulation (particular value per land plot)
3. Increase in production due to accumulation (harvest cycle length)
   - Polynomial regression

\[ f(x) = y_52' (1 + \hat{\beta}_2 x^2 + \hat{\beta}_3 x^3) \]
Project stages

- Resource allocation model
  - Feasible?
  - Add constraints
  - Amount (kg) of fresh fruit to be harvested each day

- Transport allocation model
  - Feasible?
  - Add constraints
  - Amount (kg) of fresh fruit to pick in each land plot each day

- Harvest cycle model
  - Ripeness cost function
  - Yield forecast
  - Parameter estimation

- Discrete-event simulation

- Aerial tractor order

Q: Quarterly
W: Weekly
D: Daily
Harvest cycle model

- **When and how much fruit to collect from each land plot?**
- Planning horizon: 3 months

- **Objective:** Reduce harvest cycle length
- **Subject to:**
  - Transport capacity
  - Daily labor time
  - Daily production capacity
Harvest cycle model

Aim

Land plot 1

Days

1  2  3  4  5  6  7  8  9  10
X  X  X  X  X

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Harvest cycle model

Aim

Land plot 1

Days

1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10
---|---|---|---|---|---|---|---|---|---
X | X | X | X | X | X | X | X | X | X
Harvest cycle model

Aim

Land plot 1

Days

1 2 3 4 5 6 7 8 9 10

X X X X X

X X X

X X X

X X X

X X X

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Harvest cycle model

**Aim**

- **Land plot 1**
  - Days: 1, 3, 4, 5, 10
- **Land plot 2**
  - Days: 1, 3, 4, 9
- **Land plot 3**
  - Days: 1, 3, 4, 7, 9
Harvest cycle model

Column generation

Visit pattern

Auxiliary problem
Harvest cycle model

Column generation

Master problem
\( x^H_p \geq 0 \)

Auxiliary problem

\( \mathbb{w}^T \)

\( \mathbb{a}_s \)

\( r_s > 0 \)

\( x^H_p \in \{0, 1\} \)

End
Harvest cycle model

Mathematical model

Objective function

\[
\max \sum_{i \in I} \sum_{j \in J} \sum_{\ell \in L} y_{ij\ell}^H (g \cdot \delta_{ij\ell} - \zeta_{ij\ell}) - w^T a_s \]

\[r_S\]
Harvest cycle model

Mathematical model

Objective function

$$\max \sum_{i \in T} \sum_{j \in T} \sum_{l \in L} y_{ijl}^H (g \cdot \delta_{ijl} - \zeta_{ijl}) - w^T a_s$$

Pattern usefulness

Auxiliary problem

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Harvest cycle model

Mathematical model

Objective function

\[
\max \sum_{i \in T} \sum_{j \in T} \sum_{t \in L} y_{ijt}^H (g \cdot \delta_{ijt} - \varsigma_{ijt}) - w^T a_s
\]

Problem linking
Harvest cycle model

Mathematical model

Objective function

\[
\max \sum_{i \in T} \sum_{j \in T} \sum_{\ell \in L} y_{ij\ell}^H (g \cdot \delta_{ij\ell} - \zeta_{ij\ell}) - w^T a_s
\]

Problem linking

\[w^T: \text{dual variables from master problem constraints}\]

\[
a_s = \begin{bmatrix}
\sum_{j \in T} y_{sj\ell}^H \\
\sum_{j \in T} \sum_{\ell \in L} \frac{y_{ij\ell}^H \delta_{ij\ell}}{k} t_{\ell} \\
\sum_{j \in T} \sum_{\ell \in L} y_{ij\ell}^H \delta_{ij\ell}
\end{bmatrix}
\]

Pattern type

\[
\forall \ell \in \mathcal{L},
\]

Utilization of aerial tractors

\[
\forall i \in T,
\]

Amount of fruit collected

\[
\forall i \in T,
\]
Harvest cycle model

Mathematical model

Days

Land plots

|L| 0  1  2  3  4  5  6  7  8  9

S

\( e \)

Q
Harvest cycle model

Mathematical model

Land plots

|\mathcal{L}|$

Days

\begin{align*}
  1,0 & \rightarrow 1,1 \\
  1,1 & \rightarrow 1,2 \\
  1,2 & \rightarrow 1,3 \\
  1,3 & \rightarrow 1,4 \\
  1,4 & \rightarrow 1,5 \\
  1,5 & \rightarrow 1,6 \\
  1,6 & \rightarrow 1,7 \\
  1,7 & \rightarrow 1,8 \\
  1,8 & \rightarrow 1,9 \\
  1,9 & \rightarrow 2,0 \\
  2,0 & \rightarrow 2,1 \\
  2,1 & \rightarrow 2,2 \\
  2,2 & \rightarrow 2,3 \\
  2,3 & \rightarrow 2,4 \\
  2,4 & \rightarrow 2,5 \\
  2,5 & \rightarrow 2,6 \\
  2,6 & \rightarrow 2,7 \\
  2,7 & \rightarrow 2,8 \\
  2,8 & \rightarrow 2,9 \\
  2,9 & \rightarrow 1,0
\end{align*}
Harvest cycle model

Mathematical model

\[
\begin{align*}
&\text{Land plots} \\
&\text{Days} \\
&\text{Auxiliary problem}
\end{align*}
\]
Harvest cycle model

Column generation

- Master problem
- Pattern selection for each land plot

<table>
<thead>
<tr>
<th>Days</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Days 1</td>
<td>X</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Days 2</td>
<td></td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Days 3</td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Days 4</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Project stages

- Resource allocation model
- Transport allocation model
- Harvest cycle model
- Discrete-event simulation

- Amount (kg) of fresh fruit to be harvested each day
- Amount (kg) of fresh fruit to pick in each land plot each day

- Feasible? Add constraints
- Feasible? Add constraints

- Ripeness cost function
- Yield forecast

- Parameter estimation

- Q: Quarterly
  W: Weekly
  D: Daily

- Aerial tractor order

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Resource allocation model

- **How to arrange the land plots programmed in a timetable?**
  - Planning horizon: 1 week

- **Objective:** Minimize yield loss (earliness)

- **Subject to:**
  - Available personnel
  - Harvesting time for each land plot
  - Deadline per land plot
## Resource allocation model

### Aim

<table>
<thead>
<tr>
<th>Time interval</th>
<th>Day</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Start</td>
<td>End</td>
<td>M</td>
</tr>
<tr>
<td>06:00</td>
<td>07:00</td>
<td></td>
</tr>
<tr>
<td>07:00</td>
<td>08:00</td>
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<tr>
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<td>09:00</td>
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<td>10:00</td>
<td>11:00</td>
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<tr>
<td>14:00</td>
<td>15:00</td>
<td></td>
</tr>
<tr>
<td>15:00</td>
<td>16:00</td>
<td></td>
</tr>
</tbody>
</table>

Legend:
- Land plot 1
- Land plot 2
- Land plot 3
- Land plot 4
- Land plot 5
- Land plot 6
- Land plot 7
- Land plot 8
- Land plot 9
- Rest/travel time
## Resource allocation model

### Aim

<table>
<thead>
<tr>
<th>Harvest crew 1</th>
<th>Time interval</th>
<th>Day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start</td>
<td>End</td>
<td>M</td>
</tr>
<tr>
<td>06:00</td>
<td>07:00</td>
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<td>15:00</td>
<td></td>
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<tr>
<td>15:00</td>
<td>16:00</td>
<td></td>
</tr>
</tbody>
</table>

### Harvest crew 2

<table>
<thead>
<tr>
<th>Time interval</th>
<th>Day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start</td>
<td>End</td>
</tr>
<tr>
<td>06:00</td>
<td>07:00</td>
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<tr>
<td>07:00</td>
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<td>11:00</td>
<td>12:00</td>
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<tr>
<td>13:00</td>
<td>14:00</td>
</tr>
<tr>
<td>14:00</td>
<td>15:00</td>
</tr>
<tr>
<td>15:00</td>
<td>16:00</td>
</tr>
</tbody>
</table>

Legend:
- Land plot 1
- Land plot 2
- Land plot 3
- Land plot 4
- Land plot 5
- Land plot 6
- Land plot 7
- Land plot 8
- Land plot 9
- Rest/travel time
Resource allocation model

Scheduling
Machine-oriented

Harvest crews

Land plots to harvest

M1
L2
L3

M2
L1
L5

M3
L28

M4
L14
L18

M5
L21
L20

0 5 10 15 20 25
time
Resource allocation model

Optimization

Network structure

Sequence

Land plots

\[ s^* \rightarrow 1,1 \rightarrow 1,2 \rightarrow 1,3 \rightarrow \ldots \rightarrow 1,|\mathcal{L}| \]

\[ e^* \rightarrow 2,1 \rightarrow 2,2 \rightarrow 2,3 \rightarrow \ldots \rightarrow 2,|\mathcal{L}| \]

\[ \vdots \rightarrow \vdots \rightarrow \vdots \rightarrow \vdots \rightarrow \vdots \]

\[ |\mathcal{M}| \rightarrow |\mathcal{M}|,1 \rightarrow |\mathcal{M}|,2 \rightarrow |\mathcal{M}|,3 \rightarrow \ldots \rightarrow |\mathcal{M}|,|\mathcal{L}| \]

Arcs \( A_1 \) - Red
Arcs \( A_2 \) - Black
Arcs \( A_3 \) - Cyan

\[ s^* \rightarrow e^* \]

\( s^* \) and \( e^* \) represent the start and end nodes of the network, respectively.
Resource allocation model

Network structure

Sequence (example)

Optimization

Harvest crews

Land plots

$\begin{align*}
\mathcal{M} & : \{1, 2, 3, \ldots, |\mathcal{M}|\} \\
\mathcal{L} & : \{1, 2, 3, \ldots, |\mathcal{L}|\}
\end{align*}$

Network structure

Sequence (example)

$\begin{align*}
\mathcal{M} & : \{M_1, M_2, M_3, \ldots, M_{|\mathcal{M}|}\} \\
\mathcal{L} & : \{L_1, L_2, L_3, \ldots, L_{|\mathcal{L}|}\}
\end{align*}$

Harvest crews

Land plots

$\begin{align*}
1, 1 & \leftrightarrow 1, 2 \\
1, 2 & \leftrightarrow 1, 3 \\
1, 3 & \leftrightarrow 2, 1 \\
2, 1 & \leftrightarrow 2, 3 \\
2, 3 & \leftrightarrow 3, 1 \\
3, 1 & \leftrightarrow \ldots
\end{align*}$

Arcs $A_1$

Arcs $A_2$

Arcs $A_3$
Resource allocation model

Mathematical model

\begin{align*}
M_1 & \rightarrow \quad t_2^s \quad L_2 \quad t_2^c \quad L_3 \\
0 & \rightarrow \quad 5 \quad 10 \quad 15 \quad 20 \quad 25 \\
\text{time} & \\
\end{align*}
Mathematical model

Resource allocation model

Project stages

Results
Resource allocation model

Mathematical model
Project stages

Resource allocation model

Feasible? Add constraints

Amount (kg) of fresh fruit to be harvested each day

Harvest cycle model

Ripeness cost function

Yield forecast

Parameter estimation

Discrete-event simulation

Transport allocation model

Feasible? Add constraints

Amount (kg) of fresh fruit to pick in each land plot each day

Aerial tractor order

Quarterly (Q)

Weekly (W)

Daily (D)

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Transport allocation model

- Which should be the daily routes for the aerial tractors?
- Planning horizon: one day

- **Objective:** Collect all the estimated production
- **Subject to:**
  - Maximum pulling capacity
  - Daily operational time
Transport allocation model

- Calculate number of trips per land plot
- Create route for unattended demand
- Assign routes to every aerial tractor
Transport allocation model

Calculate number of trips per land plot

Create route for unattended demand

Assign routes to every aerial tractor

<table>
<thead>
<tr>
<th>Land plot</th>
<th>Demand (kg)</th>
<th>Number of trips</th>
<th>Unattended demand (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>12,300</td>
<td>2.7</td>
<td>3,300</td>
</tr>
<tr>
<td>L8</td>
<td>8,500</td>
<td>1.9</td>
<td>4,000</td>
</tr>
<tr>
<td>L2</td>
<td>10,200</td>
<td>2.3</td>
<td>1,200</td>
</tr>
</tbody>
</table>

4,500 Kg

http://copa.uniandes.edu.co/
Transport allocation model

<table>
<thead>
<tr>
<th>Land plot</th>
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<th>Number of trips</th>
<th>Unattended demand (kg)</th>
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<tr>
<td>L1</td>
<td>12,300</td>
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<td>3,300</td>
</tr>
<tr>
<td>L8</td>
<td>8,500</td>
<td>1.9</td>
<td>4,000</td>
</tr>
<tr>
<td>L2</td>
<td>10,200</td>
<td>2.3</td>
<td>1,200</td>
</tr>
</tbody>
</table>

Calculate number of trips per land plot

Create route for unattended demand

Assign routes to every aerial tractor

4,500 Kg
Transport allocation model

- Calculate number of trips per land plot
- Create route for unattended demand
- Assign routes to every aerial tractor

Route A: L8, 3 times
Route B: L1, 2 times
Route C: L1, L2
Transport allocation model
Transport allocation model

- Calculate number of trips per land plot
- Create route for unattended demand
- Assign routes to every aerial tractor

Route A

Rowe A:

SPC
AA AB 14A 11A 8A 8A 11A 14A AB AA

L8

http://copia.uniandes.edu.co/
Transport allocation model

- Calculate number of trips per land plot
- Create route for unattended demand
- Assign routes to every aerial tractor

Route - A
Route - B
Route - C
On hold
Transport allocation model

- Calculate number of trips per land plot
- Create route for unattended demand
- Assign routes to every aerial tractor
- Local search with swap moves
- Discrete-event simulation

- Route-A
- Route-B
- Route-C

On hold
Transport allocation model

- Calculate number of trips per land plot
- Create route for unattended demand
- Assign routes to every aerial tractor

New sequence
Discrete-event simulation
Local search with swap moves
Time calculation

Route-A
Route-B
Route-C
On hold

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Project stages

Resource allocation model

Transport allocation model

Feasible?
Add constraints

Harvest cycle model

Ripeness cost function

Yield forecast

Parameter estimation

Amount (kg) of fresh fruit to be harvested each day

Amount (kg) of fresh fruit to pick in each land plot each day

Discrete-event simulation

Q: Quarterly
W: Weekly
D: Daily

Aerial tractor order

Feasible?
Add constraints

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Discrete-event simulation
Discrete-event simulation
Discrete-event simulation

- Node types
  - Intersection
  - Land plot

FFB: Fresh fruit bunches
Discrete-event simulation

- Node types
  - Intersection
  - Land plot

General modeling

FFB: Fresh fruit bunches

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Discrete-event simulation

- Node types
  - Intersection
  - Land plot
  - Aerial tractor
  - Transits through the network

FFB: Fresh fruit bunches
Discrete-event simulation

- Node types
  - Intersection
  - Land plot
- Aerial tractor
  - Transits through the network
- Stockpiling center

FFB: Fresh fruit bunches

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Discrete-event simulation

- Node types
  - Intersection
  - Land plot
- Aerial tractor
  - Transits through the network
- Stockpiling center
- Entities
  - Represent containers of FFB
  - Transported by aerial tractors

FFB: Fresh fruit bunches

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Discrete-event simulation

**Uncertainty**

- **Aerial tractors**
  - Loading time
  - Unloading time (workers in SPC)
  - Time between failures
  - Repair Time

**Scenarios**

- Number of aerial tractors

FFB: Fresh Fruit Bunches
Project stages

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Amount (kg) of fresh fruit to be harvested each day

Feasible? Add constraints

Feasible? Add constraints

Amount (kg) of fresh fruit to pick in each land plot each day

Q: Quarterly
W: Weekly
D: Daily

http://copa.uniandes.edu.co/
Discrete-event simulation

Inputs

Harvest cycle model

Days

1 2 3 4 5 6 7

Land plots

X X ...
...
X X
X X

Modeling logic
## Discrete-event simulation

### Inputs

#### Harvest cycle model

<table>
<thead>
<tr>
<th>Days</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land plots</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>

### Results

<table>
<thead>
<tr>
<th>Land plot</th>
<th>Day 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>15 ton</td>
</tr>
<tr>
<td>L2</td>
<td>-</td>
</tr>
<tr>
<td>...</td>
<td>-</td>
</tr>
<tr>
<td>...</td>
<td>2.5 ton</td>
</tr>
<tr>
<td>LX</td>
<td>-</td>
</tr>
<tr>
<td>..</td>
<td>-</td>
</tr>
<tr>
<td>...</td>
<td>20 ton</td>
</tr>
<tr>
<td>L86</td>
<td>-</td>
</tr>
<tr>
<td>L87</td>
<td>10 ton</td>
</tr>
</tbody>
</table>

---

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Discrete-event simulation

Containers (daily)

Modeling logic
Discrete-event simulation

- Containers in land plots
- Number of trips
- Route to land plot
Discrete-event simulation

- Containers in land plots
- Number of trips
- Route to land plot
  - Shortest path between SPC and land plot
  - How to avoid collisions?

Modeling logic

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Discrete-event simulation

- Containers in land plots
- Number of trips
- Route to land plot
  - Shortest path between SPC and land plot
  - How to avoid collisions?
Discrete-event simulation

- Containers in land plots
- Number of trips
- Route to land plot
  - Shortest path between SPC and land plot
  - How to avoid collisions?
Discrete-event simulation

- Branch system
  - Branch: subset of nodes and paths
Discrete-event simulation

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  - Branch: subset of nodes and paths
Discrete-event simulation

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  - Branch: subset of nodes and paths
Discrete-event simulation

- Branch system
  - Branch: subset of nodes and paths
Discrete-event simulation

- **Branch system**
  - Branch: subset of nodes and paths

- **Assumptions**
  - Only one aerial tractor per branch
  - Aerial tractors may park in the origin of a branch
  - Aerial tractors parked do not block the path
Discrete-event simulation

- **Branch system**
  - Branch: subset of nodes and paths

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  - Only one aerial tractor per branch
  - Aerial tractors may park in the origin of a branch
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Discrete-event simulation

- Branch system
  - Branch: subset of nodes and paths

- Assumptions
  - Only one aerial tractor per branch
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Discrete-event simulation

- Containers in land plots
- Number of trips
- Route to land plot

Results
- Containers in land plots
- Number of trips
- Route to land plot
Agenda

- Introduction
- Project stages
- Results
Results

Resource allocation model

Transport allocation model

Amount (kg) of fresh fruit to be harvested each day

Feasible? Add constraints

Feasible? Add constraints

Harvest cycle model

Ripeness cost function

Yield forecast

Parameter estimation

Discrete-event simulation

Aerial tractor order

Q: Quarterly
W: Weekly
D: Daily

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Results

Average harvest cycle length: 8.3 days
Results

Tons collected per day

- **FFB (ton)**
  - 0
  - 50
  - 100
  - 150
  - 200
  - 20
  - 40
  - 60
  - 80

- **8 tractors**

http://copa.uniandes.edu.co/
Results

Average harvest cycle length: 10.9 days

Land plots

Day in the quarter

8 tractors

Average harvest cycle length: 10.9 days (days)
Results

Tons collected per day

- FFB (ton)

- Day

- 8 tractors

http://copa.uniandes.edu.co/
Results

Resource allocation model

Transport allocation model

Feasible? Add constraints

Feasible? Add constraints

Amount (kg) of fresh fruit to be harvested each day

Amount (kg) of fresh fruit to pick in each land plot each day

Harvest cycle model

Ripeness cost function

Yield forecast

Parameter estimation

Discrete-event simulation

Q: Quarterly
W: Weekly
D: Daily

http://copa.uniandes.edu.co/
Results

\[
\min \sum_{j \in J} w_j t_j^e
\]
Results

\[ \min \sum_{j \in J} t_j^e \]

Earliness (hours)
Results

\[ \min \sum_{j \in J} w_j t_j^e \]

\[ \min \sum_{j \in J} t_j^e \]

Utilization

Harvest crew

0% 10% 20% 30% 40% 50% 60% 70% 80% 90% 100%
Project stages

Resource allocation model  

Feasible?  
Add constraints  

Amount (kg) of fresh fruit to be harvested each day  

Transport allocation model  

Feasible?  
Add constraints  

Amount (kg) of fresh fruit to pick in each land plot each day  

Harvest cycle model  

Ripeness cost function  

Yield forecast  

Parameter estimation  

Discrete-event simulation  

Q: Quarterly  
W: Weekly  
D: Daily  

Q: Quarterly  
W: Weekly  
D: Daily  

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Results - transport

Tons collected

(i) day 1
SPC
1.72
44.48 (tons)

(ii) day 3
SPC
0.75
46.64 (tons)

(iii) day 7
SPC
1.57
25.74 (tons)
Aerial tractor 1
Aerial tractor 2
Aerial tractor 3
Aerial tractor 4
Aerial tractor 5
Aerial tractor 6
Aerial tractor 7
Aerial tractor 8

Results - transport

8 tractors

1st trip for aerial tractor
2nd trip for aerial tractor
3rd trip for aerial tractor
4th trip for aerial tractor
Results - transport

Routes for aerial tractor 6

- L 40
- L 35
- L 62
- L 74
- L 59

Projected FFB (ton)

Land plots visited:

- SPC

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**Project stages**

- **Resource allocation model**
  - Feasible?
  - Add constraints
  - Amount (kg) of fresh fruit to be harvested each day

- **Transport allocation model**
  - Feasible?
  - Add constraints
  - Amount (kg) of fresh fruit to pick in each land plot each day

- **Harvest cycle model**
  - Ripeness cost function
  - Yield forecast
  - Parameter estimation

- **Discrete-event simulation**

---

Q: Quarterly
W: Weekly
D: Daily
Results – uncertainty

- 10 hours
- 60 containers/hour

Amount of aerial tractors

- Working day
- Containers/hour
Results – uncertainty

- 10 hours
- 60 containers/hour

<table>
<thead>
<tr>
<th>Change</th>
<th>Amount of aerial tractors</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>5</td>
</tr>
<tr>
<td>5%</td>
<td>6</td>
</tr>
<tr>
<td>10%</td>
<td>7</td>
</tr>
<tr>
<td>15%</td>
<td>8</td>
</tr>
<tr>
<td>20%</td>
<td>9</td>
</tr>
<tr>
<td>25%</td>
<td>10</td>
</tr>
<tr>
<td>30%</td>
<td>11</td>
</tr>
</tbody>
</table>

Working day
Containers/hour
Results – uncertainty

- 10 hours
- 60 containers/hour

Change

Amount of aerial tractors

- Working day
- Containers/hour

http://copia.uniandes.edu.co/
Results – uncertainty

- 10 hours
- 60 containers/hour

Change:
- Amount of aerial tractors

- Working day
- Containers/hour

http://copa.uniandes.edu.co/
Results – uncertainty

Utilization

Amount of aerial tractors

Change

Amount of aerial tractors

- Working day
- Containers/hour

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Conclusions

- We showed the potential of reducing the harvest cycle length from 19.6 days to 8.3 days.

- We highlighted the benefits of combining harvest and transport planning.

- We measured the impact on the fruit evacuation metrics under failure scenarios.

- We delivered results in a visual interactive interface to facilitate decision-making at the plantation.
Thank you!

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Future work

- Implement the planning in the plantation.
- Adjust parameters if necessary.
- Incorporate other activities from the plantation.
- Integrate the models in a single computational tool that enables parameter modifications, model execution and result visualization.