Quantitative Models for the Circular Economy

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Outline

1. Modelling closed loop supply chain
   - Closed Loop Network architecture
   - Industrial Cases
   - Model building

2. Lot Sizing Models: implications of closing the loop
   - Inventory Policy Models
   - Dynamic Lot Sizing Models

3. Dynamic Lot Sizing Models: partial investigations
   - A first model: Reuse and Remanufacturing
   - additional criteria investigations
   - Model1: Static Analysis

4. Conclusion and Further investigations
Modelling choices

Network Modelling

Interdependencies among supply chain parts and value drivers

- Forward and Reverse Operations: Which one to focus on?
- Demand structure and returns modelling: Quality issues.
- The set of relevant economic parameters.
Modelling closed loop supply chain
Lot Sizing Models: implications of closing the loop
Dynamic Lot Sizing Models: partial investigations
Conclusion and Further investigations

Closed Loop Network architecture
Industrial Cases
Model building

Figure: Functional Diagram (Ellen Mc Arthur Foundation)
The Circular Economy: Industrial Applications

- Coca Cola, Grigny Factory.
  PET Bottles recovery for production, Investment: 17 M euros
The Circular Economy: Industrial Applications

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- Michelin, Transportation Compagnies Service.
  Recovery of Tires and Refurbishing
The Circular Economy: Industrial Applications

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- Castorama; Veolia, Partnership. Wood recovery by Veolia, Kitchen board remanufacturing
The Circular Economy: Industrial Applications

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- Michelin, Transportation Compagnies Service.
  Recovery of Tires and Refurbishing
- Renault, Vehicle repairing and Recycling.
  Car modules for repair and use of 29% of recycled Metals.
- Castorama; Veolia, Partnership.
  Wood recovery by Veolia, Kitchen board remanufacturing
- Kalundborg; Le Havre, Eco-Industrial Parks.
  Cascading valorisation of waste as inputs
Model Design Variables

Product Design

Design to fit with Circularity needs

- Modularity and disassembly.
- Bill of Materials: technical coefficients.
- Product state is changing over the chain and cycles.
Model design variables

Mathematical formulation

How to represent such a system

- Exogeneous parameters: Structuring the problem.
- Decision variables: Directly acting for managing the chain.
- Status variables: Ensure consistency and realism.
Model Design

New Business Models

Sustainability must be addressed by criteria and constraints

- Economic side: Financial requirements.
- Environmental side: Polluting emissions, resources depletion.
- Social side: Workforce well being, localization of activities.
Inventory Policy Models: New Design Variables

- Product return patterns.
- Collection operations.
- Component inventories.
- Remanufactured product inventories.
- Recovery operations.
Example

Saadany, Jaber (2010): A production-remanufacture model with returns subassemblies managed differently (Int. J. Production Economics)
Decision variables:
Remanufacturing and production binaries; reuse ratio

\[ H_1 = h_r \frac{DT_r^2}{2} + h_p \frac{DT_p^2}{2} = h_r \frac{D\beta_x^2 T^2}{2} + h_p \frac{D(1-\beta_x)^2 T^2}{2} \]

\[ = \frac{DT^2}{2} (h_r \beta_x^2 + h_p (1-\beta_x)^2) \]

Figure: Objective Function

Here, extreme policies are tested
Dynamic Lot Sizing Models: new patterns

- Product return patterns.
- Component management.
- Remanufacturing.
- Recovery and disposal operations.
Example

Pan and Al (2008):
Capacitated dynamic lot sizing problems in CLSC
(European Journal of Operational Research)

Fig. 1. The closed-loop supply chain with production, disposal and remanufacturing.
Decision variables:

Remanufacturing and production; inventory levels; disposal

\[
\begin{align*}
\text{min} & \quad \sum_{t=1}^{T} (g_t(y_t) + e_t(z_t) + \theta_t(I_t^r) + \phi_t(I_t^s)) \\
\text{subject to} & \quad I_t^r = I_{t-1}^r + R_t - y_t \quad \forall t, \\
& \quad I_t^s = I_{t-1}^s + y_t + z_t - D_t \quad \forall t, \\
& \quad y_t \leq C_t^r \quad \forall t, \\
& \quad z_t \leq C_t^p \quad \forall t, \\
& \quad I_t^r, I_t^s, y_t, z_t \in R^+ \quad \forall t.
\end{align*}
\]

**Figure:** The Mathematical Programm

Aim: Introduce capacity constraints and derive implications for different specifications under several scenarios
Our Focus: Development of Quantitative Models for CLSC

- An investigation Tool.
  Raising trade-offs, structuring CLSC analysis
- Normative assessment.
  Adressing trade-offs, provide recommendations
- Need to develop innovative models.
  network configuration, criterias, constraints
We must target a **focal firm** to name the recovery operations. Scales are related to a final product (different representations).
Model1: Reuse and Remanufacturing

- Our focus: Level 1 and 0 for a vertically integrated firm: B2C framework with segmentation, Profit Maximization.
Model1: Reuse and Remanufacturing

NIVEAU 2: SOURCING

Procurement

\( X_{a,2}(t) \)

[Modules Inventory]

\( X_{c,2} \)

Reuse and Remanufacturing

\( X_{c,2}(t) \)

NIVEAU 1: PRODUCTION

Production

\( X_{a,1}(t) \)

\( X_{a,0}(t) \)

\( X_{a,1}(t) \)

NIVEAU 0: DISTRIBUTION

[Finished Products Inventory]

\( X_{c,0}(t) \)

\( X_{c,1} \)

\( d_a(t) \)

\( d_b(t) \)

\( d_c(t) \)

Collection Center

\( r_i'(t) \)

Waste

\( X_{w}(t) \)

NIVEAU 0: DISTRIBUTION

Mgmt

\( X_{w}(t) \)

\( R_{i}(t) \)
Modelling closed loop supply chain
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Model 1: Reuse and Remanufacturing

Objective Function: PROFIT MAXIMIZATION

\[
\max \sum_{t=1}^{T} \sum_{i=1}^{L} \sum_{m} X_{m0}(t) p_m(t) - (s_{mi}(t) S_{mi}(t) + c_{mi}(t) X_{mi}(t) + c_w(t) X_w(t) + h_{mi} l_{mi}(t) + h_{ri} l_{ri}(t))
\]

\(t \in \{0, T\}\) the time periods
\(i \in \{1, L\}\) the supply chain levels (where 0 stands for the distribution) where: the returns of level \(i\) are usable at \(j \geq i\) value recovery options
\(m \in \{a; c\}\) the new or used status of items where: "a" stands for the new items and "c" for the used ones (red flows)
Model 1: Reuse and Remanufacturing

Model Parameters:
- $d_a(t)$, demand for new product
- $d_b(t)$, demand accepting both products
- $d_c(t)$, demand for used product
- $p_a(t)$, market price for new product
- $p_c(t)$, market price for used product
Model1: Reuse and Remanufacturing

Model Parameters:

$Cap_{mi}(t)$, Capacity for activities

$s_{mi}(t)$, set-up cost for activity in level i

$c_{mi}(t)$, item of level i unit cost

$c_w(t)$, waste disposal unit cost

$h_{mi}(t)$, item of level i inventory unit cost

$h_{ri}(t)$, returned products of level i inventory unit cost

$r'_i(t)$, amount of returns of items of level i in t
Model 1: Reuse and Remanufacturing

Decision Variables:
- $R_i(t)$, quantity of returned item of least reusable level "i" sorted
- $X_{mi}(t)$, quantity of servicable items of "i" level
- $X_w(t)$, quantity of disposed items (wasted)

Status Variables:
- $l_{mi}(t)$, Inventory for item of level i
- $l_{ri}(t)$, Inventory for returned item of level i
- $S_{mi}(t)$, Boolean indicating if activity is performed in t
- $X'_{ci}(t)$, quantity of used items allocated from $R_j$. 
Model 1: Reuse and Remanufacturing

Demand Constraints:

\[ X_{a0}(t) \leq d_a(t) + d_b(t) \quad \forall t \]  \hspace{1cm} (2)

\[ X_{c0}(t) \leq d_c(t) + d_b(t) \quad \forall t \]  \hspace{1cm} (3)

\[ X_{a0}(t) + X_{c0}(t) \leq d_a(t) + d_b(t) + d_c(t) \quad \forall t \]  \hspace{1cm} (4)
Model 1: Reuse and Remanufacturing

Capacity Constraint and Set up trigerring:

$$X_{mi}(t) \leq S_{mi}(t)Cap_{mi}(t) \quad \forall t, m, (i \neq 0)$$  \hspace{1cm} (5)

Recovery Decisions Constraints:

$$\sum_{j=1}^{i} R_j(t) \geq \sum_{j=1}^{i} X'_{c,j}(t) \quad \forall t, 0 < i < L$$  \hspace{1cm} (6)

$$\sum_{j=1}^{L} R_j(t) = \sum_{j=1}^{L} (X'_{c,j}(t)) + X_w(t) \quad \forall t$$  \hspace{1cm} (7)
Model 1: Reuse and Remanufacturing

Inventories Dynamics:

\[ I_{ri}(t) = I_{ri}(t-1) + r_i'(t) - R_i(t) \quad \forall t, i \quad (8) \]
\[ I_{m0}(t) = I_{m0}(t-1) + X_{m1}(t) - X_{m0}(t) \quad \forall t, m \quad (9) \]
\[ I_{ci}(t) = I_{ci}(t-1) + X_{ci}'(t) - X_{ci}(t) \quad \forall t, \forall (i \neq 0) \quad (10) \]
\[ I_{ai}(t) = I_{ai}(t-1) + X_{a(i+1)}(t) + X_{c(i+1)}(t) - X_{ai}(t) \quad \forall t, \forall (i \neq 0) \quad (11) \]

Variables Sets:

\[ S_{mi}(t) \in \{0, 1\} \quad (12) \]
\[ X_{mi}(t), X_{w}(t), X_{ci}'(t), R_i(t), l_{mi}(t), I_{ri}(t) \in \mathbb{R}^+ \quad (13) \]
Some Simulations (X-Press)
Economic Sustainability: Financial issues

- No Bankruptcy: loss compensation by gain

\[
\sum_{t=1}^{k} \pi(t) \geq 0 \quad (14)
\]

- No persistent losses: no more than \((\tau - 1)\) consecutive periods

\[
\sum_{t=1}^{\tau} \gamma(t) + \sum_{t=(\tau + 1)}^{k} (\gamma(t) - \gamma(t-\tau)) \leq (\tau - 1) \quad s.t: \quad M \gamma(t) \geq -\pi(t) \quad (15)
\]

- Loss occurrence limitation: mitigating losses frequency

\[
Objective: \quad MAX(\Pi) - \Gamma \sum_{t=1}^{T} \gamma(t) \quad s.t: \quad M \gamma(t) \geq -\pi(t) \quad (16)
\]
Social Sustainability: Workforce well-being

- Workload balance:

\[ \text{Objective} : \max (\Pi) - \omega \dot{W} \quad \text{s.t.} \quad \dot{W} \geq W(t) \forall t \quad (17) \]

- Workload volatility

\[ \text{Objective} : \max (\Pi) - \Theta \sum_{t=1}^{T} \Delta(t) \quad \text{s.t.} \quad W(t+1) - W(t) = \Delta(t) \quad (18) \]

- Compensation scheme for over the limit worked hours

\[ \text{Objective} : \max (\Pi) - \omega \sum_{t=1}^{T} \theta(t) \quad \text{s.t.} \quad M \theta(t) \geq (W - W_{\text{max}}) \quad (19) \]
Some Simulations with Workforce Consideration

Figure: Workload volatility mitigation
Environmental Sustainability: Waste and pollutions

- Natural capital regeneration: ecosystem services

\[
\sum_{t=1}^{k} \sum_{\text{activities}} E(t,\text{act}) \leq \epsilon \quad (20)
\]

- Pollution mitigation
  Include unitary, fixed costs for emissions.

- Additional constraints
  on emissions in periods or over the planning horizon, Cumulative Waste Constraint.
Static Analysis

Single Period Trade-offs

Investigate decisions in a period about circular schemes relevance

- Parameters configuration
- Priority rules for optimality
- Issues related to capacities
Static Analysis

The methodology is based on:

- Cases discussion: Parameters for resources and costs
- Optimization: Allocations orientation
- Determination of values: min/ Max operators
Static Analysis: Elements of interest

- for activities Mark-up:

Procurement: \( m_P = p_a(X_{P,a} + X_{P,b}) - c_P X_P - c_{a,1} X_P - c_{a,0} X_P \)

Reuse: \( m_{RU} = p_c(X_{RU,c} + X_{RU,b}) - c_{RU} X_{RU} - c_{c,0} X_{RU} \)

reman: \( m_{rm} = p_a(X_{rm,a} + X_{rm,b}) - c_{rm} X_{rm} - c_{a,1} X_{rm} - c_{a,0} X_{rm} \)

- for resources from returns:

\( r' \leq (d_b + d_c) \), few returns available

\( r' \leq (d_a + d_b + d_c) \), not enough for all

\( r' \geq (d_a + d_b + d_c) \), large enough for all
Static Analysis: problem setting

MAXIMIZE PROFIT

Under Demand/Supply decomposition constraints:

\[ X_P = X_{P,a} + X_{P,b} \]
\[ X_{RU} = X_{RU,c} + X_{RU,b} \]
\[ X_{rm} = X_{rm,a} + X_{rm,b} \]
\[ d_a \geq X_{P,a} + X_{rm,a} \]
\[ d_b \geq X_{P,b} + X_{rm,b} + X_{RU,b} \]
\[ d_c \geq X_{RU,c} \]
\[ d_c + d_b \geq X_{RU} \]
\[ d_a + d_b \geq X_P + X_{rm} \]
\[ d_a + d_b + d_c \geq X_P + X_{rm} + X_{RU} \]

Meaning: Lost sales are allowed and market is segmented

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Quantitative Models for the Circular Economy
How and Why to analyse the single period system behavior? Parameters drive the resolution path, tricky configurations addressed. Optimizing the Demand-Activities-Resources channels:

- Intensively:
  The Mark-up defines priorities for resource allocation.
- Extensively:
  Lost sales must be avoided (carefully analyse $d_c$ status).
- Leakages:
  Disposal is neutral because of the assumed mark-up rankings.
Static Analysis: Outcomes without Capacities

Table: Case 1-1: $r' \leq (d_b + d_c)$

<table>
<thead>
<tr>
<th>$m_{RU} &gt; m_{rm} &gt; m_P$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X_{RU,c} = \min{r'; d_c}$</td>
</tr>
<tr>
<td>$X_{RU,b} = \max{r' - d_c; 0}$</td>
</tr>
<tr>
<td>$X_{rm,a} = 0$</td>
</tr>
<tr>
<td>$X_{rm,b} = 0$</td>
</tr>
<tr>
<td>$X_{Pa} = d_a$</td>
</tr>
<tr>
<td>$X_{P,b} = d_b + \min{d_c - r'; 0}$</td>
</tr>
<tr>
<td>$W = 0$</td>
</tr>
</tbody>
</table>
Static Analysis: Outcomes with Capacities

Table: Case 1;1: \( r' \leq (d_b + d_c) \)

<table>
<thead>
<tr>
<th>( m_{RU} )</th>
<th>( m_{rm} )</th>
<th>( m_P )</th>
</tr>
</thead>
</table>

\[
X_{RU} = \min\{r'; K_{RU}\} \\
X_{rm} = \max\{0; \min\{K_{rm}; r' - K_{RU}\}\} \\
X_P = d_a + d_b - \max\{0; X_{RU} - d_c\} - X_{rm} \\
W = \max\{r' - (K_{rm} + K_{RU}); 0\}
\]
Static Analysis: Profit Diagrams

- infinite capacities, $m_{Ru} > m_{Rm} > m_P$. 

![Diagram showing profit diagrams with marks for $r'$, demand, $d_c$, $d_b$, $d_a$, $m_P$, $m_{Rm}$, and $m_{Ru}$]
finite capacities, $m_{Ru} > m_{Rm} > m_P$. 

\begin{align*}
\text{Static Analysis: Profit Diagrams} \\
\text{finite capacities, } m_{Ru} > m_{Rm} > m_P. 
\end{align*}
finite capacities, \( m_{Rm} > m_{Ru} + m_P \).
Static Analysis: Profit Diagrams

- finite capacities, $m_{Rm} < m_{Ru} + m_P$.
Static Analysis: Profit Diagrams

- Lost sales plays an important role (High opportunity cost)
Conclusion and further investigations

- "Green" and "Social" Criteria.
  Energy, Disposal, WorkForce:
  Need to refine objective functions and constraints

- Dynamics Analysis.
  Inventories, demands and cost structure evolutions:
  How to manage inter-temporal channels activities

- Optimization Mechanism for Dynamic Lot Sizing Problem.
  Which characterizes an optimal plan?:
  Necessary conditions, dynamic interactions
Conclusion and further investigations

- Adressing model relevance.
  Economic conditions:
  Do not focus on irrelevant cases

- Enlight regulatory issues.
  Endogeneizing mark-up:
  Regulator objectives, incentive schemes

- Returns modelling and industrial collaborations.
  Consumers implication, bargaining over incremental value:
  Techno-economic models for business development
Some references

- Saadany, Jaber, 2010: A production-remanufacture model with returns subassemblies managed differently
- Pineyro, Viera, 2013: The economic lot sizing problem with remanufacturing and one way substitution
- Ramezani and Al, 2014: CLSC network design: a financial approach
- Pan and Al, 2008: Dynamic lot sizing problems in CLSC
Modelling closed loop supply chain
Lot Sizing Models: implications of closing the loop
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Thank you for your attention!