Quantitative Models for the Circular Economy

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Outline

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.

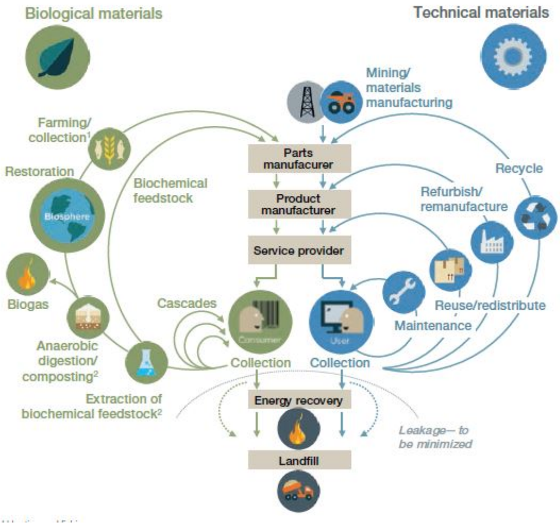

Figure : Functional Diagram (Ellen Mc Arthur Foundation)

The Circular Economy:Industrial Applications

- Coca Cola,Grigny Factory.
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- 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 adressed by criterias and constraints

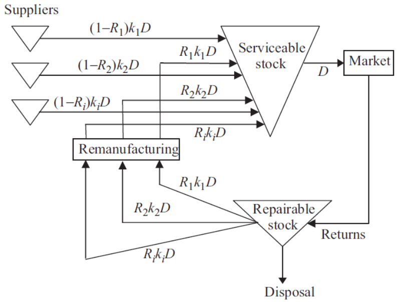
- Economic side : Financial requirements.
- Environmental side : Polluting emissions,resources depletion.
- Social side : Workforce well being, localization of activities.

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 AI (2008):
Capacitied dynamic lot sizing problems in CLSC
(European Journal of Operational Research)

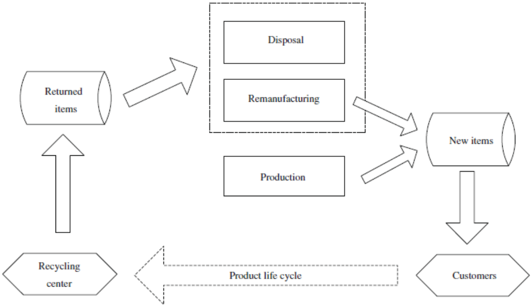


Fig. 1. The closed-loop supply chain with production, disposal and remanufacturing.

- Decision variables:
  Remanufacturing and production; inventory levels; disposal

$$\begin{aligned}
\min \quad & \sum_{t=1}^{T} (g_t(y_t) + e_t(z_t) + \theta_t(I_t^r) + \phi_t(I_t^s)) \\
\text{subject to} \quad & I_t^r = I_{t-1}^r + R_t - y_t \quad \forall t, \\
& I_t^s = I_{t-1}^s + y_t + z_t - D_t \quad \forall t, \\
& y_t \leqslant C^r \quad \forall t, \\
& z_t \leqslant C^p \quad \forall t, \\
& I_t^r, I_t^s, y_t, z_t \in R^+ \quad \forall t.
\end{aligned}$$

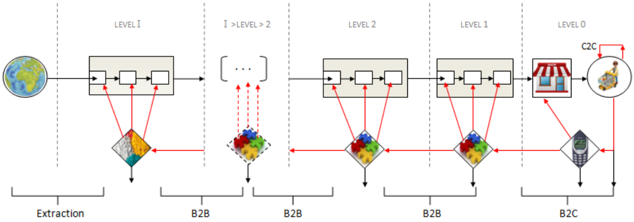
Figure : The Mathematical Programm

- Aim: Introduce capacity constraints and derive implications for different specifications under several scenarios

Our Focus: Development of Quantitative Models for CLSC

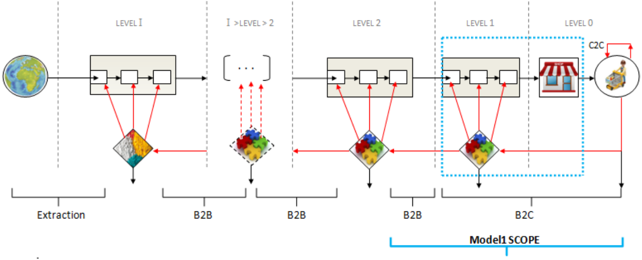
- An investigation Tool.
  Raising trade-offs,structuring CLSC analysis
- Normative assessment.
  Adressing trade-offs,provide recommandations
- Need to develop innovative models.
  network configuration,criterias,constraints

Generic model



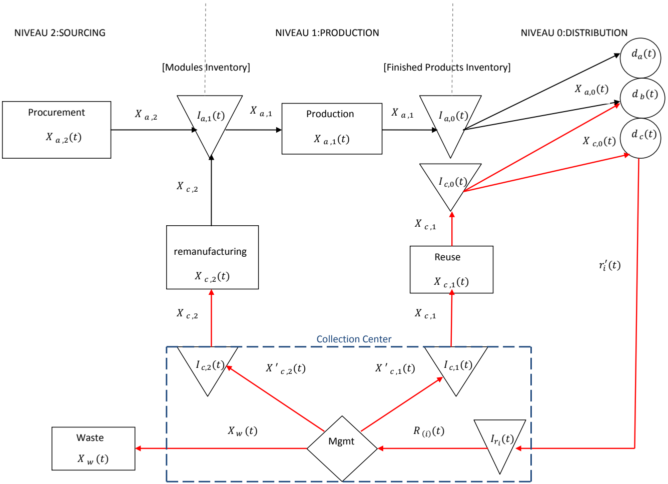
- We must target a focal firm to name the recovery operations. Scales are related to a final product(different representations).

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

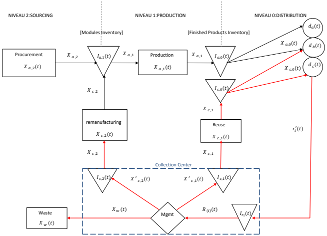


Model1: Reuse and Remanufacturing

Objective Function: PROFIT MAXIMIZATION

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

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 $\geqslant$ 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)



Model1: 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

Model1: Reuse and Remanufacturing

Decision Variables:

$R_i(t)$, quantity of returned item of least reusable level "i" sorted

$X_{mi}(t)$,quantity of serviciable items of "i" level

$X_w(t)$,quantity of disposed items(wasted)

Status Variables:

$I_{mi}(t)$, Inventory for item of level i

$I_{ri}(t)$, 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.

Model1: Reuse and Remanufacturing

Demand Constraints:

$$X_{a0}(t) \leq d_a(t) + d_b(t) \quad \forall t \tag{2}$$

$$X_{c0}(t) \leq d_c(t) + d_b(t) \quad \forall t \tag{3}$$

$$X_{a0}(t) + X_{c0}(t) \leq d_a(t) + d_b(t) + d_c(t) \quad \forall t \tag{4}$$

Model1: Reuse and Remanufacturing

Capacity Constraint and Set up trigerring:

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

Recovery Decisions Constraints:

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

$$\sum_{j=1}^{L} R_j(t) = \sum_{j=1}^{L} (X'_{c,j}(t)) + X_w(t) \qquad \forall t \tag{7}$$

Model1: Reuse and Remanufacturing

Inventories Dynamics:

$$I_{ri}(t) = I_{ri}(t-1) + r'_i(t) - R_i(t) \qquad \forall t, i \tag{8}$$

$$I_{m0}(t) = I_{m0}(t-1) + X_{m1}(t) - X_{m0}(t) \qquad \forall t, m \tag{9}$$

$$I_{ci}(t) = I_{ci}(t-1) + X'_{ci}(t) - X_{ci}(t) \qquad \forall t, \forall (i \neq 0) \tag{10}$$

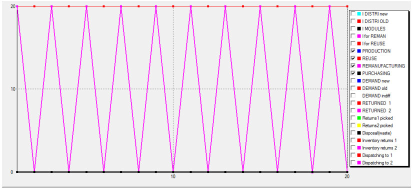
$$I_{ai}(t) = I_{ai}(t-1) + X_{a(i+1)}(t) + X_{c(i+1)}(t) - X_{ai}(t) \qquad \forall t, \forall (i \neq 0) \tag{11}$$

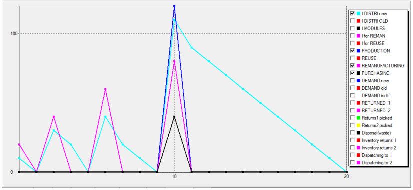
Variables Sets:

$$S_{mi}(t) \in \{0, 1\} \tag{12}$$

$$X_{mi}(t), X_w(t), X'_{ci}(t), R_i(t), I_{mi}(t), I_{ri}(t) \in \mathbb{R}^+ \tag{13}$$

Some Simulations (X-Press)





Economic Sustainability: Financial issues

- No Bankruptcy:loss compensation by gain

$$\sum_{t=1}^{k} \pi(t) \geqslant 0 \tag{14}$$

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

$$\sum_{t=1}^{\tau} \gamma(t) + \sum_{t=(\tau+1)}^{k} (\gamma(t) - \gamma(t-\tau)) \leqslant (\tau - 1) s.t : M\gamma(t) \geqslant -\pi(t) \tag{15}$$

- Loss occurence limitation: mitigating losses frequency

$$Objective : MAX(\Pi) - \Gamma \sum^{T} \gamma(t) s.t : M\gamma(t) \geqslant -\pi(t) \tag{16}$$

Social Sustainability: Workforce well-being

- Workload balance:

$$Objective : MAX(\Pi) - \omega \acute{W} s.t : \acute{W} \geqslant W(t) \forall t \tag{17}$$

- Workload volatitlity

$$Objective : MAX(\Pi) - \Theta \sum_{t=1}^{T} \Delta(t) s.t : W(t+1) - W(t) = \Delta(t) \tag{18}$$

- Compensation scheme for over the limit worked hours

$$Objective : MAX(\Pi) - \omega \sum_{t=1}^{T} \theta(t) s.t : M\theta(t) \geqslant (W - W max) \tag{19}$$

Some Simulations with Workforce Consideration

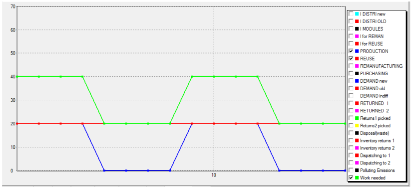
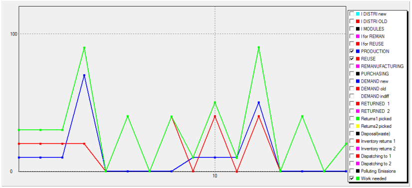


Figure : Workload volatility mitigation



Environmental Sustainability: Waste and pollutions

- Natural capital regeneration:ecosystem services

$$\sum_{t=1}^{k} \sum_{activities} E(t, act) \leqslant \epsilon \qquad (20)$$

- 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

Static Analysis: Approach

How and Why to analyse the single period system behavior?
Parameters drive the resolution path,tricky configurations adressed.
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: $r' \leq (d_b + d_c)$

$m_{RU} > m_{rm} > m_P$
$X_{RU,c} = min\{r'; d_c\}$ $X_{RU,b} = MAX\{r' - d_c; 0\}$
$X_{rm,a} = 0$ $X_{rm,b} = 0$
$X_{P,a} = d_a$ $X_{P,b} = d_b + min\{d_c - r'; 0\}$
$W = 0$

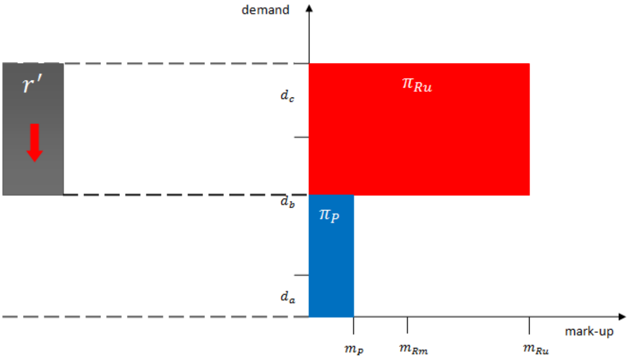
Static Analysis: Outcomes with Capacities

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

$m_{RU} > m_{rm} > m_P$
$X_{RU} = min\{r'; K_{RU}\}$ $X_{rm} = Max\{0; min\{K_{rm}; r' - K_{RU}\}\}$ $X_P = d_a + d_b - Max\{0; X_{RU} - d_c\} - X_{rm}$ $\mathrm{W} = Max\{r' - (K_{rm} + K_{RU}); 0\}$

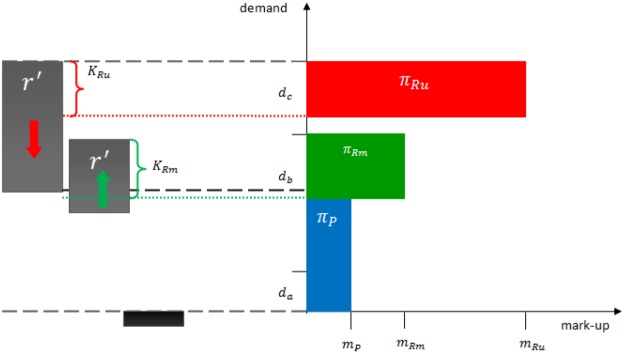
Static Analysis: Profit Diagrams

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



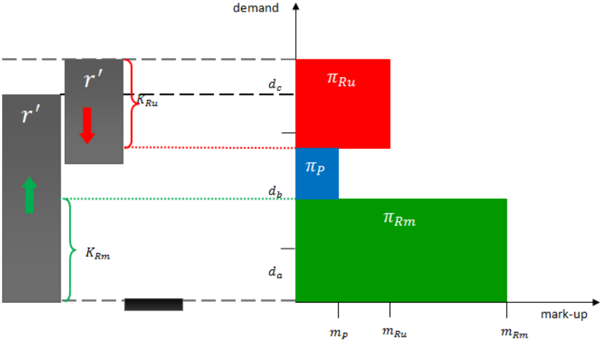
Static Analysis:Profit Diagrams

- finite capacites, $m_{Ru} > m_{Rm} > m_P$.



Static Analysis: Profit Diagrams

- finite capacites, $m_{Rm} > m_{Ru} + m_P$.



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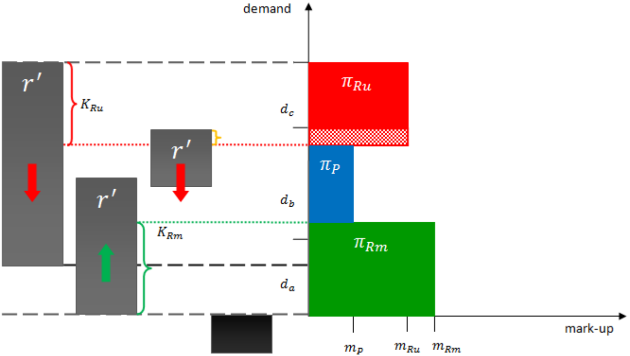
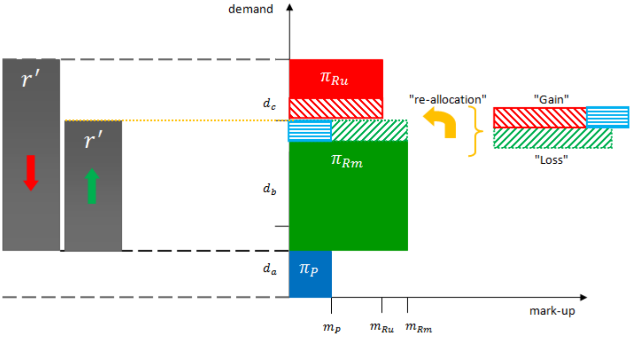


Static Analysis: Profit Diagrams

- 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 incemental value:
  Techno-economic models for business development

Some references

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Thank you for your attention !