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Modeling Post-disruption Equilibrium for Circular Supply Chains and New Measures for Resilience

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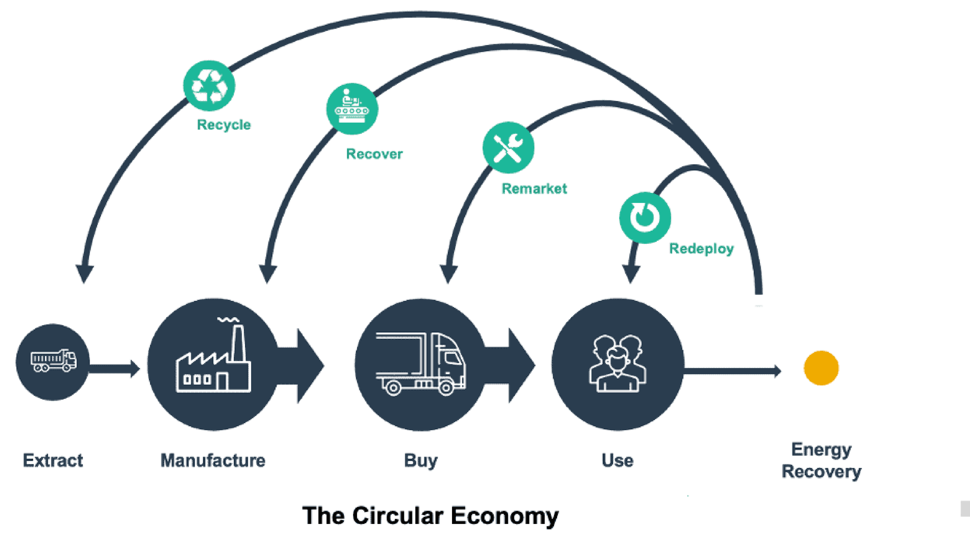
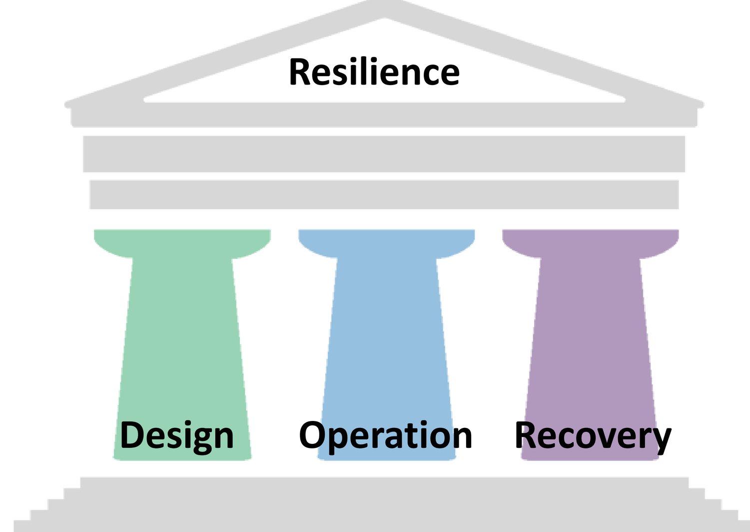
Background and Objectives





Source: Inbound Logistics (url: https://www.inboundlogistics.com/articles/the-road-to-the-circular-economy/)

- **Circular economy** is a sustainable economic paradigm that aims at prolonging the resource value as long as feasible.
- The connection between **circular supply chains (CSC)** and **resilience** not clear.

- **Material Handling in CSC**
  - ➢ Various stages of the CSC require material handling processes (collecting, sorting, washing, shredding, transporting).
  - ➢ These processes contribute to enhancing sustainability, but also can act as additional sources of disruption in the system.

- **Objectives:**

1. Present a framework for better analyzing the resilience of Circular supply chains in the face of disruptions.
2. Present an algorithm for computing the new equilibrium state of CSC after a disruption.
3. Provide a measure that quantifies the benefits of CSC when compared to linear supply chains

Methodology

- **Circular supply chain dynamics**

$$S_i = S_i' \le \bar{P}_i \qquad \forall i \in \mathcal{S} \qquad (1)$$
➡ Source supply constraint

$$R_i^m = \sum_{k\in\mathcal{P}(m)\cap\hat{\mathcal{N}}(i)} R_{k,i} \qquad \forall i \in \mathcal{V}/\mathcal{S} \qquad (2)$$
➡ Inflow of materials

$$S_i' \le \min\{\alpha_i^m R_i^m \mid m \in \mathcal{M}(i)\} \qquad \forall i \in \mathcal{V}/\mathcal{S} \qquad (3)$$
➡ Production using materials

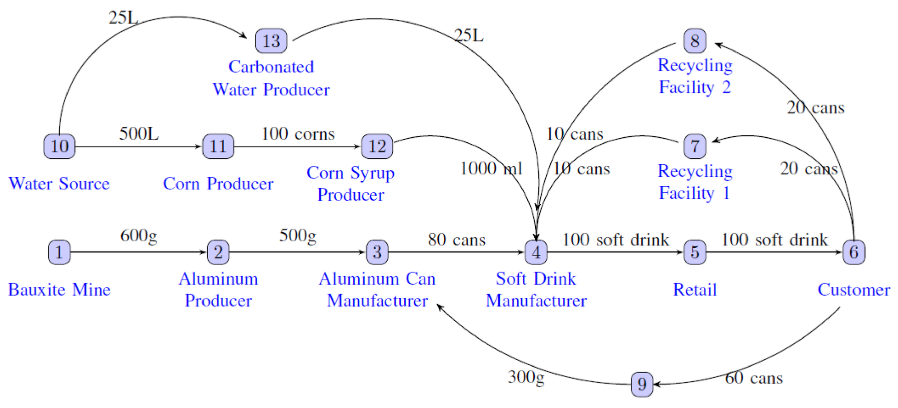
$$S_i \le \min\{S_i', \bar{P}_i\} \qquad \forall i \in \mathcal{V}/\mathcal{S} \qquad (4)$$
➡ Production capacity constraint

$$S_{i,j} = \beta_{i,j} S_i \qquad \forall j \in \check{\mathcal{N}}(i), \forall i \in \mathcal{V} \qquad (5)$$
➡ Distribution of products

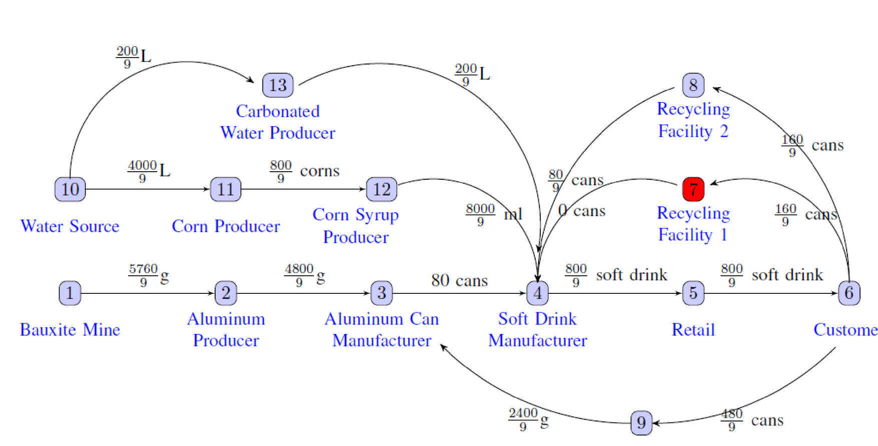
$$R_{i,j} = \min\{S_{i,j}, W_{i,j}\} \qquad \forall (i,j) \in \mathcal{E} \qquad (6)$$
➡ Transportation capacity constraint

- **Equilibrium-state conditions**

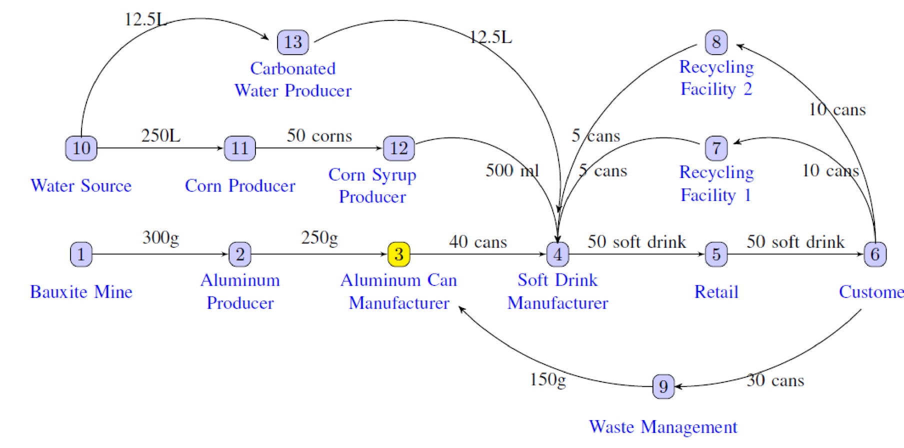
$$\alpha_i^m R_i^m = \alpha_i^{m'} R_i^{m'} \qquad \forall m, m' \in \mathcal{M}(i) \qquad (7)$$
➡ No surplus material flows



(a) Equilibrium state of CSC under normal conditions. System meets the full demand (100 soft drinks).



(c) Equilibrium state of CSC after full disruption in node 7. System meets 88% demand (88 soft drinks).

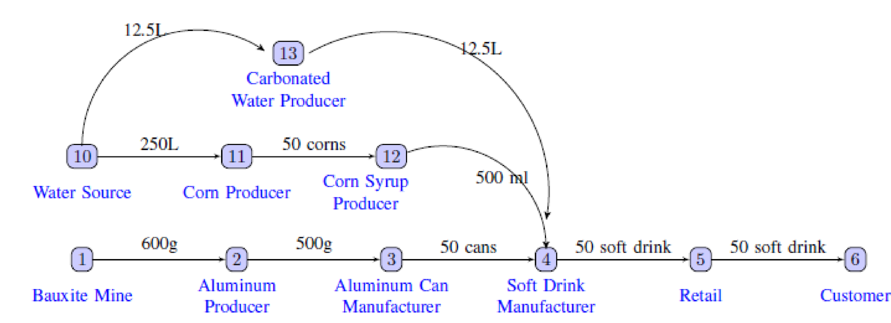


(b) Equilibrium state of CSC after partial disruption in node 3. System meets 50% demand (50 soft drinks).

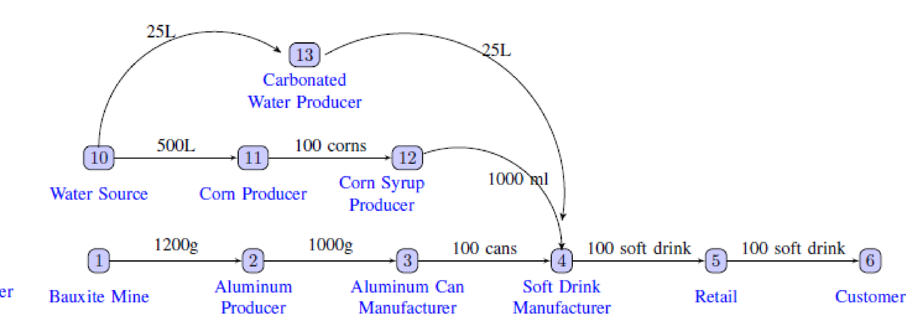
- The three diagrams show the pre-disruption and post-disruption equilibrium states of the circular supply chain.
- **Overall resilience of supply chain**

$$Z(\mathcal{D}) = \sum_{d\in\mathcal{D}} p_d Z_d + p_{\text{base}}$$

Results



Linear supply chain 1



Linear supply chain 2

- **Computation of satisfied demand after various disruptions**
  - ➢ New equilibrium states after disruption are computed by solving an optimization problem reflecting the updated constraints.
  - ➢ Tables compare CSC, LSC1, LSC2

(a) Circular supply chain

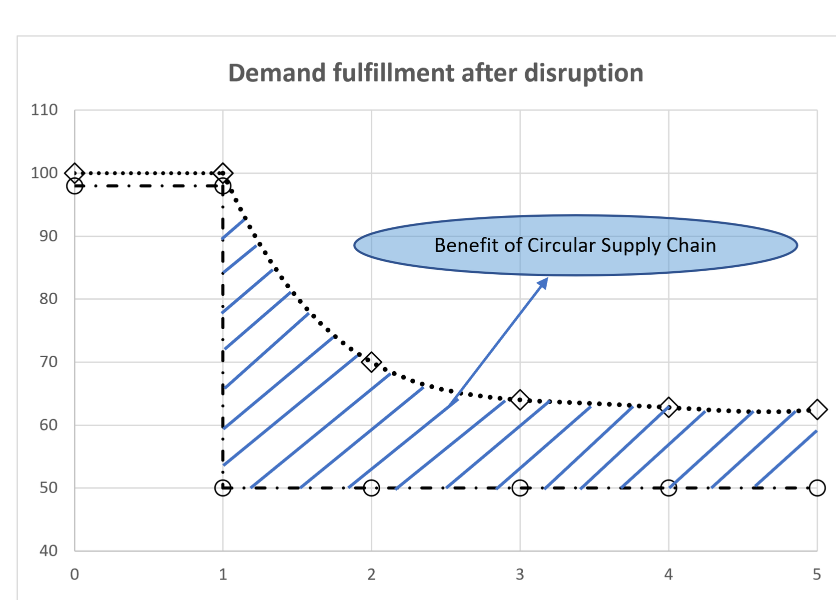
	Index	Original capacity	Satisfied Demand ($\tilde{D}$) 80%	60%	40%	20%	0%
Nodes	1	600g	80	60	40	20	0
	2	500g	80	60	40	20	0
	3	80 cans	80	60	40	20	0
	4	100 drinks	80	60	40	20	0
	5	100 drinks	80	60	40	20	0
	6	100 drinks	90	80	70	60	50
	7	10 cans	96.7	93.3	90	86.7	83.3
	8	10 cans	96.7	93.3	90	86.7	83.3
	9	300g	92.5	85	77.5	70	62.5
	10	525L	80	60	40	20	0
	11	100 corns	80	60	40	20	0
	12	1000mL	80	60	40	20	0
	13	25L	80	60	40	20	0
Arcs	(1,2)	600g	80	60	40	20	0
	(2,3)	500g	80	60	40	20	0
	(3,4)	80 cans	80	60	40	20	0
	(4,5)	100 drinks	80	60	40	20	0
	(5,6)	100 drinks	80	60	40	20	0
	(6,7)	20 cans	96.7	93.3	90	86.7	83.3
	(7,4)	10 cans	96.7	93.3	90	86.7	83.3
	(6,8)	20 cans	96.7	93.3	90	86.7	83.3
	(8,4)	10 cans	96.7	93.3	90	86.7	83.3
	(6,9)	60 cans	92.5	85	77.5	70	62.5
	(9,3)	300g	92.5	85	77.5	70	62.5
	(10,13)	25L	80	60	40	20	0
	(13,4)	25L	80	60	40	20	0
	(10,11)	500L	80	60	40	20	0
	(11,12)	100 corns	80	60	40	20	0
	(12,4)	1000mL	80	60	40	20	0

(b) Linear supply chain 1

	Index	Original capacity	Satisfied Demand ($\tilde{D}$) 80%	60%	40%	20%	0%
Nodes	1	600g	40	30	20	10	0
	2	500g	40	30	20	10	0
	3	80 cans	50	48	32	16	0
	4	100 drinks	50	50	40	20	0
	5	100 drinks	50	50	40	20	0
	6	100 drinks	50	50	50	50	50
	7	525 L	50	50	40	20	0
	8	100 corns	50	50	40	20	0
	9	1000mL	50	50	40	20	0
	10	25L	50	50	40	20	0
Arcs	(1,2)	600g	40	30	20	10	0
	(2,3)	500g	40	30	20	10	0
	(3,4)	80 cans	50	48	32	16	0
	(4,5)	100 drinks	50	50	40	20	0
	(5,6)	100 drinks	50	50	40	20	0
	(6,7)	25L	50	50	40	20	0
	(7,4)	25L	50	50	40	20	0
	(6,8)	500L	50	50	40	20	0
	(8,4)	100corns	50	50	40	20	0
	(6,9)	1000mL	50	50	40	20	0

(c) Linear supply chain 2

	Index	Original capacity	Satisfied Demand ($\tilde{D}$) 80%	60%	40%	20%	0%
Nodes	1	1200g	80	60	40	20	0
	2	1000g	80	60	40	20	0
	3	100 cans	80	60	40	20	0
	4	100 drinks	80	60	40	20	0
	5	100 drinks	80	60	40	20	0
	6	100 drinks	100	100	100	100	100
	7	525 L	80	60	40	20	0
	8	100 corns	80	60	40	20	0
	9	1000mL	80	60	40	20	0
	10	25L	80	60	40	20	0
Arcs	(1,2)	1200g	80	60	40	20	0
	(2,3)	1000g	80	60	40	20	0
	(3,4)	100 cans	80	60	40	20	0
	(4,5)	100 drinks	80	60	40	20	0
	(5,6)	100 drinks	80	60	40	20	0
	(6,7)	25L	80	60	40	20	0
	(7,4)	25L	80	60	40	20	0
	(6,8)	500L	80	60	40	20	0
	(8,4)	100corns	80	60	40	20	0
	(6,9)	1000mL	80	60	40	20	0



- **Transient Resilience Measure**
  - ➢ Circular supply chain: disruption is buffered by circular flows and the satisfied demand decreases slowly.
  - ➢ Linear supply chain: disruption causes immediate decrease in satisfied demand.

Conclusion

Despite the increasing interest in CSCs, caution is needed when analyzing its benefits over LSC. Material handling processes must be designed and operated in a way such that the positive effects of the CSC (e.g., prolonging resource value, reducing waste) outweigh the negative effects (e.g., increased components in the supply chain, increased vulnerability to disruptions).

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