

A System-Dynamics Based Approach for Modeling Circular Economy Networks: Application to the Polyethylene Terephthalate (PET) Supply Chain

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ABSTRACT

The transition to a circular economy (CE) requires agents in circular supply chain (SC) networks to take a variety of different initiatives, many of which are dynamic in nature. We use a system dynamics (SD)-based approach to develop a generic framework for dynamic modeling of CE networks and propose a prototypical circular SC network by combining dynamic models for five actors: a manufacturer, consumer, material recovery facility (MRF), recycling facility, and the Earth. We apply this framework to the supply chain for Polyethylene Terephthalate (PET) plastic packaging by considering different scenarios over a 65-year time horizon in the US. We include both “slow-down-the-loop” initiatives (i.e., those that extend product use time through demand reduction or reuse) and “close-the-loop” initiatives (i.e., those that reintroduce product to the supply chain through recycling) by the consumer, as well as sorting and recycling capacity expansion. We find that, given the current recycling infrastructure in the U.S., “slow-down-the-loop” initiatives are more effective than “close-the-loop” initiatives for improving circularity and minimizing environmental impact. However, combining the two initiatives eliminates the need for capacity expansion and leads to the highest circularity in the shortest amount of time.

Keywords: Dynamic Modelling, Circular Economy, Plastic recycling

INTRODUCTION

The current “take-make-use-dispose” paradigm of the current extractive “linear economy” has led to unnecessary waste, pollution, and extraction of natural resources. The “circular economy” (or CE) paradigm aims to eliminate waste, pollution, and resource extraction through restorative circular flows [1].

Circular *initiatives* are actions that an *actor* (e.g. a firm or consumer) in a supply chain (SC) network can take to improve their level of “circularity.” Initiatives can be categorized into those that “slow down the loop” by using products for longer, “narrow the loop” by using fewer resources per product, or “close the loop” by reintroducing the product to the SC through recycling [2].

Since most frameworks for studying CE networks operate at steady state and do not include the time dimension, they cannot consider the time-delayed effects of CE initiatives on upstream and downstream actors or

time-dependent initiatives such as those that extend product use time. Thus, dynamic models that incorporate the time dimension are needed to model CE networks.

The use of system dynamics (SD), a framework that, in addition to stocks and flows, incorporates auxiliary variables, coflows, and nonlinear feedback mechanisms [3], would enable a more detailed understanding of what external driving forces are needed to enable these changes and any possible unintended consequences of CE initiatives. Previous studies have already begun to use SD to study various aspects of CE transitions [4-7]. However, none of these studies are systematic in nature or provide clear mathematical models of CE initiatives at the actor level.

The main objective of this work is to develop a modular SD-based framework that can be used to study the effects of CE initiatives taken by different actors. First, we develop a dynamic model for a generalized actor and propose a systematic method for quantifying material

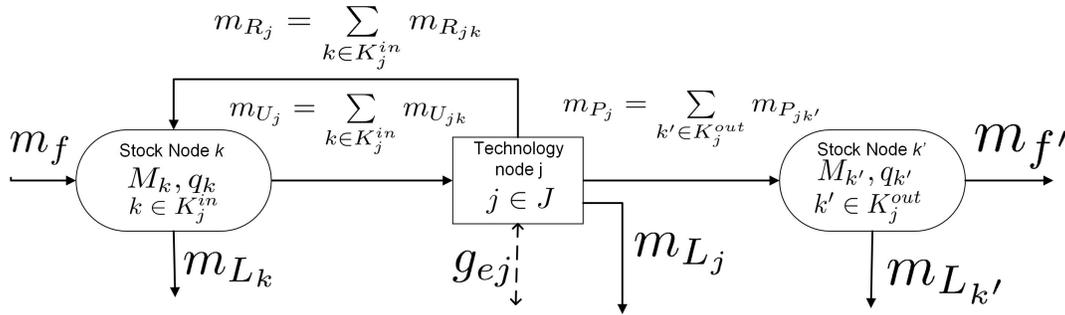


Figure 1: Stock-and-flow diagram for a generalized actor in a circular SC network, including technology node $j \in J$ and stock nodes $k \in K$. m_{L_k} is the rate of disposal from stock node k , $m_{U_{jk}}$ is the rate of usage of material from stock node k , $m_{P_{jk'}}$ is the rate of production of output k' , and $m_{R_{jk}}$ is the rate of recirculation of input k . Environmental impact flows (g_{ej}) and denoted by the dashed arrow.

quality loss. Then, we combine different actors in a prototypical circular SC to form a synthetic “block” network and formulate a dynamic model governing the network on multiple time scales. Finally, we apply this framework to compare the long-term effects of different CE initiatives on the PET plastic packaging SC.

GENERIC MODEL FOR AN ACTOR

The stock-and-flow diagram for a generalized actor is shown in **Figure 1**. Each actor exchanges material with other actors, performs a composition transformation on the material via a *technology node*, and stores material as inventory in one or more *stock nodes*. Let F be the set of material flows J be the set of technology nodes, K be the set of stock nodes, K_j^{in} (and K_j^{out}) be the sets of stock nodes that feed into (and are fed to) by node $j \in J$, F_j^{in} (and F_j^{out}) be the sets of flows entering (and exiting) node j , F_k^{in} (and F_k^{out}) be the sets of material flows entering (and exiting) stock k , E be the set of environmental impact flows (e.g., natural resource inputs and pollution), g_{ej} be the rate at which technology node j contributes to environmental impact e , M_k be the quantity of material stored in stock node k at a given time, m_f be the material flow rate of flow f , and q_k (and q_f) be the material qualities of stock node k and flow f . Material quality is modeled as a coflow and discussed below.

Using this notation, the material balances on stock node k and technology node j are given by **Equations 1–2**. The total rates of material input and production of technology node j are denoted by m_{U_j} and m_{P_j} , which are related by the process yield η_j (**Equation 3**). The remainder of the input is either discarded at a rate of m_{L_j} or recirculated at a rate of m_{R_j} .

$$\frac{dM_k}{dt} = \sum_{f \in F_k^{in}} (m_f) - \sum_{f' \in F_k^{out}} (m_{f'}) \quad \forall k \in K \quad (1)$$

$$m_{U_j} = m_{P_j} + m_{L_j} + m_{R_j} \quad \forall j \in J \quad (2)$$

$$m_{P_j} = \eta_j m_{U_j} \quad \forall j \in J \quad (3)$$

Material stocks (or flows) may also have some quality attributes, such as desirable physical properties, and they are modeled using the co-flow structure [3]. We normalize quality to be between zero and one, with virgin material having a quality of one and increasing quality being more desirable. We assume quality follows a linear mixing rule; that is, the quality of a mixture of two streams is given by the mass flow-weighted average of their qualities. The quality of stock node k is governed by **Equation 4**, while **Equation 5** specifies that technology node j reduces material quality by some constant factor (ω_j).

$$\frac{dq_k}{dt} = \frac{1}{M_k} \sum_{f \in F_k^{in}} m_f [q_f - q_k] \quad \forall k \in K \quad (4)$$

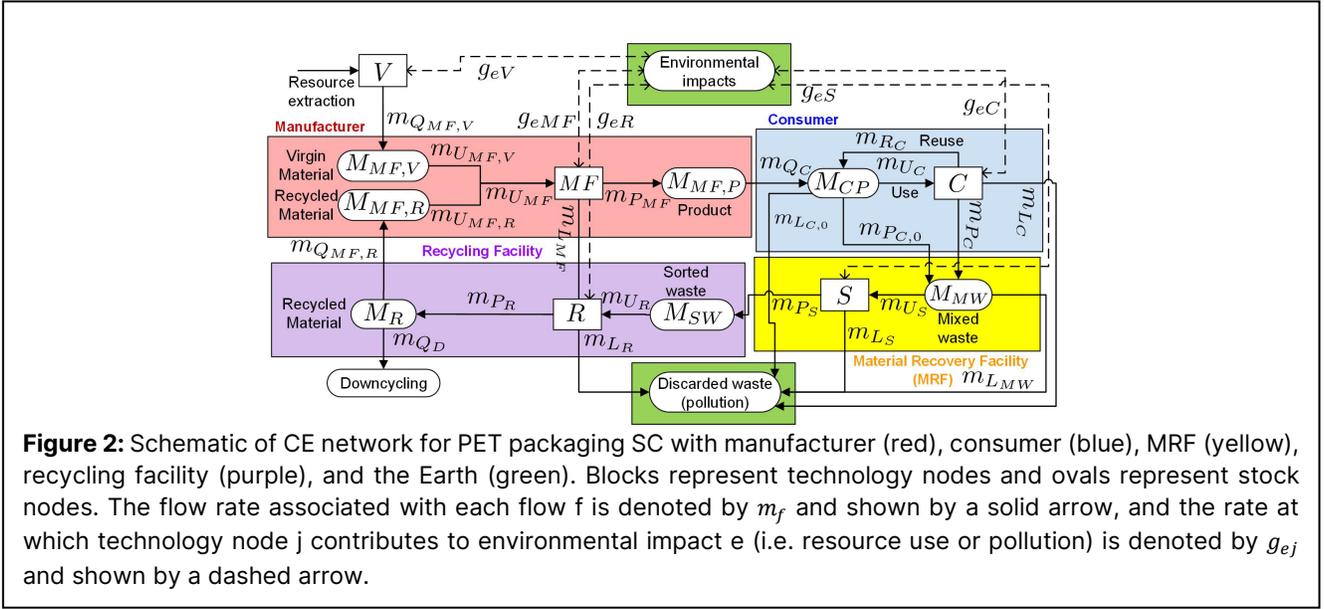
$$q_{P_j} = \omega_j q_{U_j} \quad \forall j \in J \quad (5)$$

We assume m_{U_j} , the rate of material input to technology node j , is limited by some maximum processing capacity ($Capacity_j$). If the rate of material influx exceeds the maximum capacity or downstream demand for material produced by the node, any excess inventory may be discarded at a rate of m_{L_k} .

To adjust to increased (or decreased) demand or inflow, an actor may expand the capacity of a technology node. However, capacity expansion requires planning and construction, leading to a time delay (θ_j) between the time that capacity expansion is initiated and completed. The time scale (τ) on which capacity expansion occurs is much longer than the time scale (t) on which production does. If $Inst_j(\tau)$ is the rate of initiation of capacity expansion at time τ , the installed capacity of technology node j and the quantity of capacity currently under construction (Con_j) are governed by **Equations 6 and 7**.

$$\frac{dCapacity_j}{dt} = Inst_j(\tau - \theta_j) \quad \forall j \in J \quad (6)$$

$$\frac{dCon_j}{dt} = Inst_j(\tau) - Inst_j(\tau - \theta_j) \quad \forall j \in J \quad (7)$$



We assume capacity expansion is governed by a proportional control-like policy (**Equation 8**). That is, the rate of initiation of capacity expansion is proportional to the difference between $m_{j,in}$, the total inlet flow rate to stock nodes that feed into node j from outside the system boundary of the actor and the current capacity plus the capacity currently under construction (**Equation 9**):

$$Inst_j(\tau) = \max\{0, \kappa_j [m_{j,in} - Capacity_j(\tau) - Con_j(\tau)]\} \quad (8)$$

$$m_{j,in} = \sum_{f \in F_k^{in}} \sum_{k \in K_j^{in}} (m_f) - m_{R_j} \quad (9)$$

Here κ_j is a proportional control parameter, which we assume is inversely proportional to construction time θ_j required to install new capacity: $\kappa_j = 1/\theta_j$.

SYNTHETIC CIRCULAR SUPPLY CHAIN NETWORK

Figure 2 shows a stock-and-flow diagram for a synthetic CE network including a manufacturer, who produces a product from raw material, a consumer who uses product and generates waste material, a material recovery facility (MRF) who collects and sorts mixed post-consumer waste into purified waste streams, a recycling facility who converts these purified waste streams into useful products, and the Earth, who supplies virgin material and is a sink for disposed waste.

The manufacturing process (technology node MF) requires a single input, which may be sourced from virgin material extracted and produced via technology node V or recycled material produced via technology node R . The manufacturing process requires a minimum quality of q_{min} . We assume none of the actors recirculate processing waste except for the consumer, who recirculates product for reuse at a rate of m_{R_C} . The fraction of end-of-

life product recycled by the consumer is given by the “recycle rate” r_C . The recycling facility produces recycled material at a rate of m_{P_R} , which reduces quality by a constant factor of ω_R . Any unpurchased recycled material is downcycled at a rate of m_{Q_D} .

Sustainability Assessment

To quantify absolute environmental sustainability, or the extent to which the environmental impact of a CE network exceeds the restorative capacity of the Earth [8], we use the planetary boundaries (PBs) framework [9], which proposes a “safe operating space” for humanity by defining threshold values (i.e., planetary boundaries) for different “control variables” describing human impacts on nine “Earth-system processes” beyond which there is increasing risk of environmental destabilization.

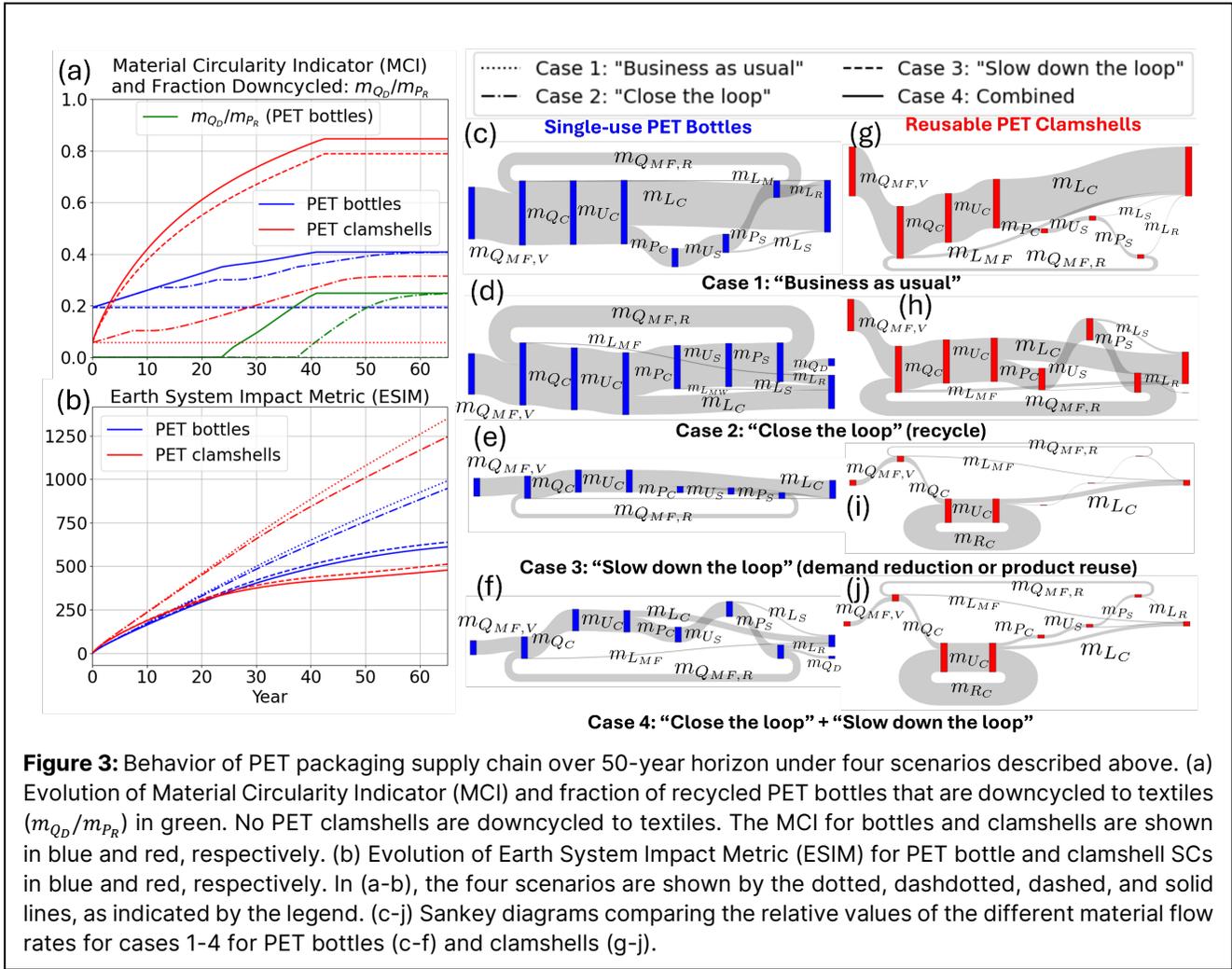
The Earth system impact metric (ESIM) measures the aggregated impact of a network on multiple Earth-system processes while accounting for current levels of global PB transgression [10]. For the sake of space, details on the calculation of the ESIM are not shown here and are left for a full journal publication.

Circularity Assessment

The circularity of a CE network is quantified using the Material Circularity Indicator (MCI) proposed by the Ellen MacArthur Foundation [1, 11]. The MCI is given by **Equation 15** and is a function of the Linear Flow Index (LFI), or the fraction of material flowing in a linear fashion (**Equation 16**), and the product utility $\bar{\chi}$ (the mean utility, or number of uses) relative to the industry average (χ_{av}). Here $m_{L_{tot}}$ is the total rate of discarded waste.

$$MCI = 1 - \frac{LFI}{\bar{\chi}/\chi_{av}} \quad (15)$$

$$LFI = \frac{m_{Q_{MV}} + m_{L_{tot}}}{2m_{U_M}} \quad (16)$$



CASE STUDY: PET SUPPLY CHAIN

We apply the generic model described above to the supply chain for single-use polyethylene terephthalate (PET) bottles and reusable PET clamshell packaging (a type of thermoform) in the U.S. We choose PET since it is relatively easy to recycle yet suffers from low recycling rates in the U.S., representing an opportunity for improved circularity [12]. In addition, a wide variety of circular pathways can be applied to PET, including reuse or repurposing of packaging [13], downcycling to textiles [14], and conversion to pyrolysis oil [15].

Given the current recycling infrastructure in the U.S., we assume the recycling facility uses mechanical recycling; the maximum capacities of the MRF and recycling facility are based on current recycling infrastructure in the U.S. [19]. Since most recyclers only accept PET bales with up to 10% thermoform content, we assume the maximum capacity for clamshell recycling is 10% of total recycling capacity [20]. As a measure of PET material quality, we use the intrinsic viscosity (IV) of the polymer melt,

which determines what applications it can be used for [14] and is reduced by mechanical recycling [16].

RESULTS AND DISCUSSION

The dynamic model for the PET SC network was implemented in Python using the JITCDDE package [17] and simulated for a 65-year time horizon, from 2022 to 2087, with parameters initialized at their current baseline values. We consider four scenarios: case 1 ("business as usual"), with recycling rates remaining at their current levels of 9% and 29% for clamshells and bottles and with no consumer reuse, case 2 ("close-the-loop" initiatives), or a recycle rate increase of 1% per year for 41 years, case 3 ("slow-down-the-loop" initiatives), or an increase in the fraction of clamshells reused of 2% per year until reaching 85% and a decrease in bottle demand of 1% per year, and case 4 (a combination of "close-the-loop" and "slow-down-the-loop" initiatives). For simplicity, we consider the SCs for PET clamshells and bottles separately. The behavior of the PET bottle and clamshell SC over the 50-year horizon for the four scenarios described above

is shown in **Figure 3**. Panels (a-b) show the temporal evolution of the Material Circularity Indicator (MCI), Earth System Impact Metric (ESIM), and fraction of recycled PET that is downcycled to textiles (m_{Q_D}/m_{P_R}) over the simulation. Sankey diagrams with line widths proportional to the final values of the different material flow rates are shown in panels (c-f) and (g-j) for bottles and clamshells, respectively. Case 1 (“Business as usual”) results in both the lowest circularity and highest environmental impacts, while case 3 (“slow-down-the-loop”) is significantly more effective than case 2 (“close-the-loop”) for both increasing circularity and lowering environmental impact.

This is illustrated by the Sankey diagrams. Product reuse (i) results in significantly more circular flow than increased clamshell recycling (h), and demand reduction (e) reduces the amount of linear flow more than increased bottle recycling (d). The difference in environmental impact between cases 2 and 3 is even greater since product reuse is less resource-intensive than recycling and preserves the value of the product, not just its material. Additionally, due to quality loss, a product can be reused far more times than it can be recycled.

For PET bottles, although both cases 2 and 4 achieve the highest final circularity (MCI), the MCI increases faster in case 4 due to the time delay associated with capacity expansion in case 2. Nonetheless, it is important to note that since the LFI is normalized by total product flow, the MCI is insensitive to demand reduction, unless such a reduction is reflected by an increase in product utility (as with product reuse). These results demonstrate that more holistic circularity indicators are needed to account for “slow-down-the-loop” and “narrow-the-loop” initiatives such as a reduction in consumer demand or the mass per unit of product.

However, due to quality loss, mechanically recycled PET must be blended with virgin PET to meet the minimum intrinsic viscosity requirements of the manufacturing process, which puts an upper bound on the fraction of product that can be sourced from mechanically recycled PET. As a result, once the bottle recycles rate exceeds a threshold of around 50%, the manufacturer does not purchase any additional recycled PET, and it must be downcycled to textiles. This was not observed in the PET clamshell results since the minimum quality requirement for clamshell manufacturing is lower than for bottles, although it would be observed for a recycle rate above 85%. Mitigating this effect would require more costly and resource-intensive chemical recycling techniques that produce virgin-grade PET resin [18].

CONCLUSIONS

Here, we developed a generic framework for dynamic modeling of circular economy networks, which can be used to better understand the effects of circular

initiatives taken by individual actors in a supply chain on upstream and downstream actors, including the Earth. We start by developing a dynamic model for a generic actor and then combine different actors into a synthetic CE network. We use the planetary boundaries framework to quantify the absolute environmental sustainability of the network. We apply this framework to study the supply chain for PET clamshells and bottles in the U.S. by comparing the effects of different initiatives.

We find that “slow-down-the-loop” initiatives like consumer reuse and demand reduction are more effective than “close-the-loop” initiatives like recycling. Additionally, increased recycling associated with the “close-the-loop” scenario requires recycling capacity expansion and an associated time delayed circularity increase. However, when combined with “slow-down-the-loop” initiatives, the need for capacity expansion, and thus the time delay, is reduced or eliminated.

However, even with increased consumer reuse, recycling, and capacity expansion, closed-loop circularity is still limited by the quality loss associated with the mechanical recycling process widespread in the U.S. Thus, although “slow-down-the-loop” initiatives are more promising short-term solutions, investments in chemical or solvent-based recycling technologies that reduce or eliminate quality loss are needed in the long term to maximize circularity.

Since the framework is modular, it can easily be extended to other supply chain structures by constructing alternative networks to the one considered here. For example, such a network could include multiple product manufacturers and recyclers or additional actors such as a government agency, who regulates the network, a “repairer,” who extends product lifetime by making repairs, and a “refurbisher,” who converts end-of-life products to alternative applications through refurbishment.

In future work, we aim to extend the framework to combine the supply chains for multiple PET products, including bottles, clamshells, and textiles. We hope this framework will enable the identification of which initiatives favor win-win scenarios by maximizing circularity while balancing trade-offs among different actors' objectives and avoiding burden-shifting.

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