Guiding Innovations and Value-Chain Improvements Using Life-Cycle Design for Sustainable Circular Economy

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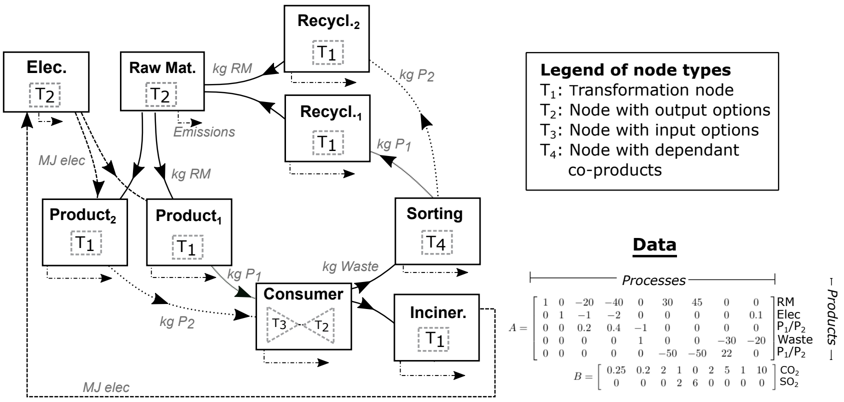
Abstract

While the current linear state of the economy has led to large scale natural-resource exploitation and pollution, circular economy can also lead to unexpected harm to environmental sustainability. Thus, there is a need to design product value-chains to achieve a Sustainable and Circular Economy (SCE). Previous work has focused on developing a systems engineering framework using life-cycle assessment with 'superstructure' network optimization to find optimal value-chain pathways while considering product life-cycles. However, the role of innovations in the form of novel technologies, societal action and new policy action has become increasingly crucial to establish SCE. In this work, we propose a sensitivity optimization framework to find the most attractive innovation directions within the value-chain using parameter perturbations as additional decision variables over pathway choice. The objectives include maximizing circularity and minimizing carbon dioxide emissions. We quantify the trade-off between these objectives and determine win-win innovative solutions using pareto and perturbation fronts. The method is demonstrated for an illustrative example, and its applicability to real value-chain networks has been probed.

Keywords: Life-cycle design, Sustainable and circular economy, Multi-objective optimization, Innovation modeling

1. Introduction

The current 'linear' state of the economy is contributing to many man-made disasters like climate change, plastic oceanic gyres, resource scarcities, harmful algal blooms in lakes, etc. While 'circular economy' is expected to bring about reduction in waste and pollution, it may not always be aligned with sustainability requirements such as curtailing climate change and respecting nature's carrying capacity. Progress toward a Sustainable Circular Economy (SCE) is crucial to mitigate large-scale exploitation of natural resources and pile-up of man-made materials like plastics in the environment. For achieving a SCE there is a need to holistically design entire value-chains of products and services while considering the environmental, economic, and social implications of potential alternatives. The field of Process Systems Engineering (PSE) has the potential to contribute towards establishing SCE for material life-cycles provided it expands its system boundary to account for the life cycle, economy, and ecosystems (Bakshi, 2019). This work is aimed at expanding PSE models and methods toward Sustainable Engineering to find optimal value-chain reforms and discover most attractive innovation directions.



$$A = \left[\begin{array}{ccccccccc|l} 1 & 0 & -20 & -40 & 0 & 30 & 45 & 0 & 0 & \text{RM} \\ 0 & 1 & -1 & -2 & 0 & 0 & 0 & 0 & 0.1 & \text{Elec} \\ 0 & 0 & 0.2 & 0.4 & -1 & 0 & 0 & 0 & 0 & \text{P}_1/\text{P}_2 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & -30 & -20 & \text{Waste} \\ 0 & 0 & 0 & 0 & 0 & -50 & -50 & 22 & 0 & \text{P}_1/\text{P}_2 \end{array}\right]$$

$$B = \left[\begin{array}{ccccccccc|l} 0.25 & 0.2 & 2 & 1 & 0 & 2 & 5 & 1 & 10 & \text{CO}_2 \\ 0 & 0 & 0 & 2 & 6 & 0 & 0 & 0 & 0 & \text{SO}_2 \end{array}\right]$$

Figure 1: Illustrative example of a typical circular value-chain network

We construct the connection between SCE and PSE using the framework of life-cycle assessment (LCA), which focuses on calculating net environmental impact of 'singular' product value-chains, while considering entire life-cycles of the product - right from natural resource extraction to disposal. The computational structure of LCA involves solving a linear programming (LP) problem on life-cycle inventory data of value-chains (Heijungs and Suh, 2002). In our previous work (Thakker and Bakshi, 2021a), we have developed the SCE design framework which uses optimization to evaluate multiple alternative value-chains by creating a 'superstructure' network of alternatives. In this work, we expand the scope of design to identify the optimal perturbations in technology efficiencies, supply chains, policies and behavior that can be brought about by innovations. These perturbations do not consider systemic disruptions to value-chains that can be brought about by innovations, which need to be modeled as separate processes in the superstructure network. Sections 2 and 3 of this paper are devoted to finding SCE optimal value-chain pathways from the illustrative example network in figure 1 using previous work. Section 4 then describes the novel sensitvity optimization framework developed for innovation guidance, which is followed by insights on potential applications of the framework in conclusions.

2. Life Cycle Assessment (LCA) framework

LCA is used to find the impact of catering to a particular demand of a product, from the processes in its entire life cycle. The input, output and emissions data for each process is found from national averages, and are included within columns of the technology and intervention matrices (A and B). These matrices are available from national agencies and commercial organizations. LCA method consists of the equations, $As = f$, $g = Bs$ which ensures flow conservation of all products (rows), while meeting the final demand 'f', specified for the LCA study. 's' is the scaling vector, which represents the scale of operation of each process in A to meet the demand. 'g' is a vector of total resource use and emissions for meeting the demand, and is found by scaling the interventions B with the same 's'. One short-coming of LCA is that it requires separate analysis for each alternative value-chain pathway, which is rectified using the SCE design method described below.

3. SCE Design Framework

In our previous work (Thakker and Bakshi, 2021a), we have developed a multi-objective superstructure optimization method to find optimal value-chain pathways for SCE objectives, and develop pareto fronts to quantify trade-offs between these objectives.

3.1. Node-alphabet representation of superstructure networks

The framework is generally applicable to any circular system owing to the node-alphabet representation. Nodes in a typical life-cycle network are classified into 4 types (T_{1-4}) according to the substitutability of inputs and outputs, and whether the streams undergo transformations. Any SCE network may be represented as a combination of these node types, as shown for the illustrative example in figure 1.

3.2. Illustrative example

This paper describes the foundational work and methodological developments using an illustrative example, shown in figure 1. This example involves finding the optimal-value chain to meet a consumer demand from one of the two-products (P_1 & P_2), which are sent either to segregation (and recycling) or to incineration. The goal is to find optimal pathways to meet SCE requirements. This illustration is chosen since the network is representative of typical product life-cycles, e.g. plastic containers, semi-conductors, laptops, etc., thereby highlighting the wide applicability of this work to relevant SCE problems.

3.3. Constraints

The decision variables of the SCE design problem are the scaling factors 's' denoting the pathway selection, i.e. s_j is 0 if value-chain process j is inactive. Since the technology matrix A represents a 'superstructure' network of alternatives, A is a rectangular matrix (not full rank) and pathways design for an arbitrary objective $Z(s)$ is possible. However, optimizing value-chains requires flow conservation with the life-cycle which is established by specifying the LCA equations as constraints on the decision variables.

$$\begin{aligned} &\min_s z := Z(s) \\ &\text{Subject to:} \quad As = f \\ &\qquad\qquad\qquad g = Bs \end{aligned} \tag{1}$$

In addition, the network needs to be scaled to meet consumer demand, which is added as a constraint on the life-cycle flows (Hs). Furthermore, governing equations such as material, energy and component balances are specified as balance constraints ($\mathcal{F}_B$). Node efficiencies are also specified as constraints ($\mathcal{F}_n$) for each node based on its type (T_{1-4}).

$$Hs \geq u \tag{2}$$

$$\mathcal{F}_B(s) \leq 0 \tag{3}$$

$$\mathcal{F}_n(s) \leq 0 \tag{4}$$

Finally, non-negative scaling ($s \geq 0$) and the net-zero final demand of intermediate flows ($f_i = 0$) are ensured using variable bounds. All these constraints yield a feasible design space of pathway choices and technology options in a non-linear problem (NLP), which is optimized for various SCE objectives and to characterize the trade-offs between them.

3.4. Objectives and Pareto-front generation

SCE objectives must comprise of Environmental, Economic and Circularity aspects. The emission and effluent flows are captured within the g vector and can be used as environmental objectives. In the illustrative example, there are two emission flows, i.e. carbon dioxide (CO_2) and sulfur dioxide (SO_2), which need to be minimized. However, real life-cycle inventory data contains hundreds of emission flows, which can be aggregated into midpoint indicators such as global warming, acidification and eutrophication potential.

The economic objective can be formulated as life cycle cost (LCC), which would consider the cost of directly and indirectly used natural resources. For simplicity, this objective has been excluded from the illustrative example. Within the circularity domain, we formulate a novel metric θ using life-cycle flows of the network to quantify the circularity of the network. It is calculated as the ratio of the value of circular flows within the system to the value of manufactured products ($M.s$). Circular flows comprise of recycling, refurbishment, down-cycling and up-cycling in the technological system ($C \in A$) and valuable effluents such as compost g_c to the environment. The general expression for θ is as follows,

$$\theta = \frac{\Sigma\gamma_i C.s + \Sigma\gamma_k g_c}{\Sigma\gamma_i M.s} \quad i \in \text{products},\ k \in \text{emissions},\ C \in A_{\text{circular}},\ M \in A_{\text{manufacturing}} \tag{5}$$

γ denotes the value function, typically in monetary, exergetic or physical units, and it determines the nature of the circularity metric, θ. In this example, we consider monetary circularity with both recycled raw material and electricity generating monetary value. Since we consider multiple objectives of SCE, there are bound to be trade-offs and win-win solutions. These are quantified using pareto optimal solutions, found using the ϵ-constraint method. The pareto-optimal solutions form a front which represent the best possible solutions without bias to any one of the three objective domains. The points lying above the front are sub-optimal and the ones lying below are infeasible. Thus, pareto front generation provides quantification and visualization of trade-offs.

3.5. SCE designs for the illustrative example

The SCE design solutions for the illustrative example are shown on the extremities of the black solid line pareto front in figure 2. The P_1-C-S-R_1 pathway corresponds to minimum CO_2 emissions, whereas the P_2-C-S-R_2 pathway has maximum circularity. ϵ-constraint is used to find points on the pareto front (solid line) which correspond to impartial compromise solutions between the objectives. The objective space below the front is sub-optimal, whereas the space above corresponds to win-win solutions which can only be achieved by innovations and pathways outside the superstructure network.

4. Sensitivity optimization for innovation discovery

It is crucial to identify the most attractive directions for innovations in the value-chain to improve SCE objectives. This is achieved by modifying the SCE design framework to

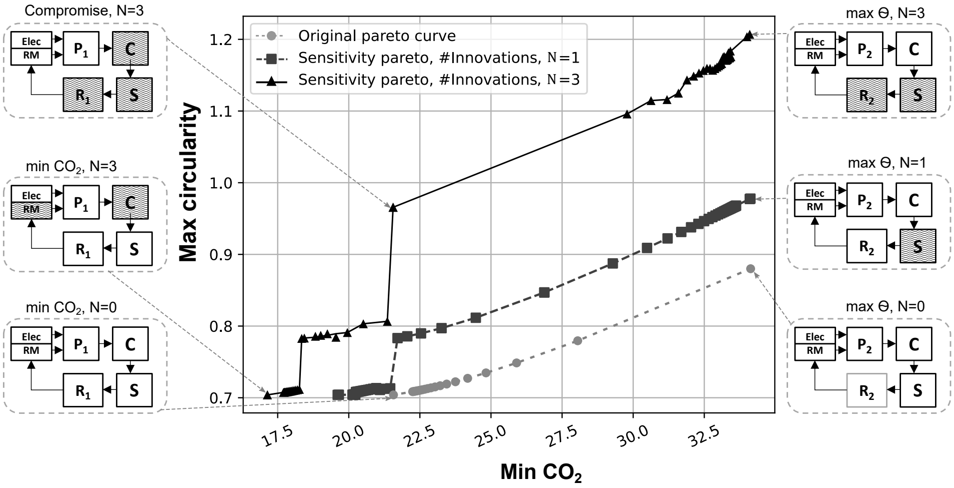


Figure 2: Pareto and Perturbation fronts for SCE design of network in figure 1.

include additional decision variables corresponding to the sensitivity of the parameters in the technology matrix(A). Each element in A (a_{ij}) represents a particular property of a life-cycle activity (j). We introduce binary variables y_{1ij} and y_{2ij} to assume the value '1' if a_{ij} can be increased or decreased (respectively), by a factor of $\Gamma \in [0, 1]$. These perturbations to a_{ij} are assumed to be brought about by innovations, better technologies, or improved policy, and the number of such permitted perturbations (N) are set by the user of the framework. Flow conservation and material-energy balances need to hold despite these perturbations, which is done by changing the original design formulation to the following.

$$
\begin{aligned}
&\min z := \text{kgCO}_2,\ \text{kgSO}_2\\
&\max_{s, y_1, y_2}\ z := \text{Circularity } (\theta)\\
&\text{Subject to:} \quad A \odot (1 + \Gamma y_1 - \Gamma y_2) s_j = f\\
&\qquad\qquad\quad y = y_1 + y_2\\
&\qquad\qquad\quad \sum_i \sum_j y_{ij} \leq N,\ \text{\# of permitted perturbations}\\
&\qquad\qquad\quad G(s) \geq 0,\ \text{other constraints on } s\\
&\qquad\qquad\quad y_1,\ y_2, y \in \mathbb{Z}^{i \times j};\ \Gamma \in [0, 1];\ s \geq 0
\end{aligned}
\tag{6}
$$

Here, '$\odot$' represents element-wise multiplication, and (y_1, y_2) are binary variables to identify the optimal innovative perturbations in the positive and negative directions. The resulting optimization is a MINLP that finds best value-chain pathways and most attractive perturbations within a user-defined range (Γ=0.1). The pareto fronts for SCE objectives using this formulation are referred to as 'perturbation fronts'. These fronts provide win-win solutions over the original pareto front, and greater win-win is obtained when more innovation perturbations (N) are allowed. For the illustrative example, two perturbation fronts are developed; with $N = 1$ (dashed line), $N = 3$ (dotted line), as shown in figure 2.

While the value-chain pathways on the extremes are identical to the original pareto front, the perturbed value-chain activities (shaded boxes) vary. For instance, minimum CO_2 emissions demand innovations to focus on manufacturing and consumer use, whereas highest circularity requires them to perturb sorting and recycling of P_2. A 'compromise' solution on the perturbation front is found (top left pathway in figure 2), which improves both objectives from the original SCE design. This solution says that innovations must be focused towards improving efficiencies and yields of sorting and recycling, while also increasing consumer re-use. Through this illustrative example, we prove the utility of the method to guide value-chain reforms and innovations for any SCE network of relevance.

5. Conclusions

In this work, we have expanded the previously developed SCE design framework (Thakker and Bakshi, 2021a) to include sensitivity optimization for finding most attractive innovation directions, along with pathway design of value-chains. The new modeling framework is demonstrated upon an illustrative example, to find the optimal perturbations in technology and societal parameters that can lead to win-win solutions from circularity and CO_2 emissions viewpoint. Pareto front generation allows quantification of trade-offs and selection of pareto-optimal solutions, which can inform new research directions based on a reasonable 'compromise' between SCE objectives. Future work will pertain to application of this methodology to a real-life value-chains of products, such as plastic-containers, windmills, etc. While the general applicability of the framework is established in section 3.1., the tractability of sensitivity optimization for large value-chain network is currently being explored using a case study on plastic grocery bags. In addition, it may be needed to introduce a physico-chemical transformation network using a multi-scale approach (Thakker and Bakshi, 2021b) to provide a realistic constraints on allowable perturbations.

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