CHEMICAL ENGINEERING TRANSACTIONS

VOL. 114, 2024

A publication of
AIDIC
The Italian Association
of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Petar S. Varbanov, Min Zeng, Yee Van Fan, Xuechao Wang

ISBN 979-12-81206-12-0; **ISSN** 2283-9216

DOI: 10.3303/CET24114057

A System Dynamics Model for Analyzing the Circular Economy Rebound

Cristina Beatrice Mallari, Richard Li, Jayne Lois San Juan*

Department of Industrial and Systems Engineering, De La Salle University, 2401 Taft Avenue, 1004 Manila, Philippines
jayne.sanjuan@dlsu.edu.ph

As the traditional linear economy becomes increasingly unsustainable, circular systems offer a compelling alternative, promoting the regeneration of materials and minimization of waste. Recently, however, the rebound effect has emerged as a critical constraint in the successful implementation of such strategies. The circular economy rebound occurs when efforts to enhance resource efficiency inadvertently stimulate higher levels of consumption or production. To address research gaps, this study proposes a system dynamics model to investigate the underlying drivers and dynamics of the rebound effect within circular economy systems. A hypothetical scenario was modeled, and the results support the premise that the circular economy rebound can exist under conditions of circularity. At the end of the simulation, a rebound equivalent to 2,443.73 kg-CO_2 was observed, denoting that only 32.82 % of the potential environmental savings were realized. This highlights the critical need to re-evaluate the assumptions within circular economy frameworks. Sensitivity analysis was also conducted to explore the impact of fluctuations in key variables on the rebound dynamics. Overall, the study contributes to a deeper understanding of the complexities surrounding circular economies and provides valuable insights for stakeholders seeking to navigate the transition toward a more sustainable economic model.

1. Introduction

The circular economy (CE) has recently gained momentum as societies strive to reduce the stress on natural resources and curb pollution from industrial activities. This paradigm shift aims to decouple economic growth from resource consumption by emphasizing recovery strategies. Although it is a promising solution to the world's looming sustainability problem, the movement toward a circular model is not without challenges. Most notably, the emergence of rebound effects presents a significant barrier that may undermine the benefits of circularity.

Thiesen et al. (2008) formally define the rebound effect as the occurrence in which efficiency improvements, often spurred by technological advancements, result in reduced costs, creating more opportunities to consume more of the improved product. It conveys that "sustainable" initiatives may have secondary effects leading to a reduction in environmental impact that is lower than expected. In the context of a CE, rebound occurs when the implementation of circular strategies, designed to enhance resource efficiency unintentionally leads to increased consumption and production due to reasons like lowered costs and improved accessibility.

Despite increasing evidence of the rebound effect under CE settings (Makov and Font Vivanco, 2018), studies that introduce quantitative models to describe such rebound effect cases and directly address the phenomenon's impact are still limited. Recent literature adopts a more generalized and qualitative perspective on modeling the dynamics of the rebound effect. For instance, Freeman (2018) developed a conceptual model to investigate the historical implications of the rebound effect in socio-technical systems. Guzzo et al. (2024) provided further detail by constructing causal loop diagrams (CLDs) that illustrate the structure of 26 rebound mechanisms. Within the CE domain specifically, Bassi et al. (2021) also investigated the relationship of CE strategies with territorial dynamics and sustainable development using CLDs.

While qualitative frameworks contribute to a general understanding of the CE rebound, decision-makers require a balanced approach to accurately assess the magnitude of the rebound effect under different scenarios and formulate data-driven policy interventions. In this regard, the present study aims to (1) develop a system dynamics (SD) model that quantitatively simulates the rebound effect within CE environments and (2) generate actionable insights about the phenomenon based on the simulation results.

Paper Received: 1 May 2024; Revised: 16 October 2024; Accepted: 26 November 2024
Please cite this article as: Mallari C.B., Li R., San Juan J.L., 2024, A System Dynamics Model for Analyzing the Circular Economy Rebound, Chemical Engineering Transactions, 114, 337-342 DOI:10.3303/CET24114057

2. System Overview

The CE system under analysis consists of two main segments: the producer and the consumers. The producer represents any manufacturing company practicing circular activities, e.g., recycling, reuse, remanufacturing, and refurbishing. The consumers, on the other hand, constitute the end-users of the producer's outputs, influencing demand patterns and participating in the reverse flow by returning used products. As shown in the CLD in Figure 1, the system is divided into two markets: primary and secondary. The primary market is used to describe how supply and demand interact for primary products, i.e., goods that were produced using virgin raw materials. The secondary market is its equivalent for secondary products, which are goods produced using product return materials and are the output of the recovery process.

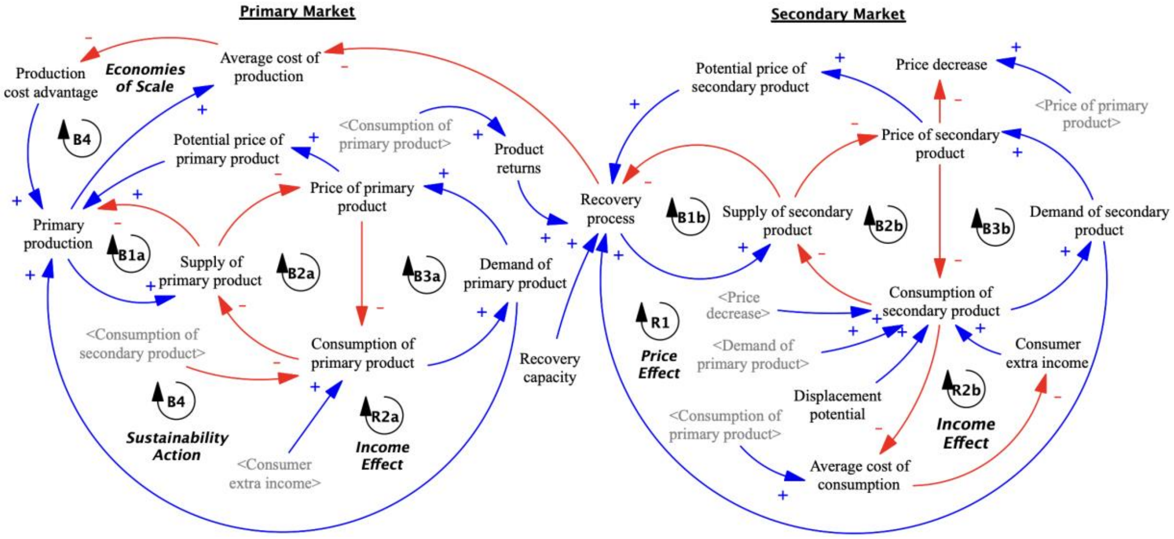


Figure 1: Causal loop diagram for the circular economy system

Several feedback loops simultaneously act on the system's variables. The basic market dynamics captured in the model focus on natural supply constraints (B1) and mechanisms to achieve market equilibrium (B2, B3). These dynamics are assumed to be present in both primary and secondary markets. The fundamental concept of circularity is encapsulated in the B4 balancing loop, which indicates that any increase in the consumption of the primary product is regulated by displacement forces fueled by the introduction of a secondary product. However, this can be opposed by rebound effects. Three types of CE rebound are considered, namely the price effect, income effect, and economies of scale, which were adopted from the study of Guzzo et al. (2024). The price effect (R1) is the mechanism by which the consumption of the secondary product increases disproportionately because consumers are motivated by the price discount stemming from the lower cost of recovery relative to raw production. The income effect (R2) induces a similar response but pertains to how lower prices generally provide consumers with more income to spend on either product. Economies of scale (B4) occur when the adoption of circular practices leads to increased efficiency in production processes, resulting in lower unit costs that can incentivize producers to expand their output.

3. Model Development

From the CLD, an equivalent stock-flow model was developed in the Vensim simulation software. SD models simulate the behavior of complex systems over time, incorporating feedback delays, non-linear relationships, and other complexities of the real world. They consist of stocks and flows, stocks representing the accumulations of resources or entities and flows being the rates of transfer between these stocks.

As illustrated in Figure 2, the stocks of the model include variables like the supply of products and product returns, demand in each market, and prices. Inflows to the supply of primary and secondary goods come from the production and recovery processes respectively, whereas outflows result from consumption. The model's parameters were selected by calibration with the goal of generating natural fluctuations in price and supply.

The rebound effect mechanisms were incorporated into the model by adding relevant relationships. The price effect was modeled by including a price decrease variable representing the price reduction for the secondary product and is a multiplier to the secondary consumption flow. The income effect and economies of scale were modeled by adding stock variables denoting the average cost of consumption and unit cost of production, respectively. These denote information delays for both the consumer and producer on the cost of their respective economic activities, in which lower costs encourage more consumption, production, and product recovery.

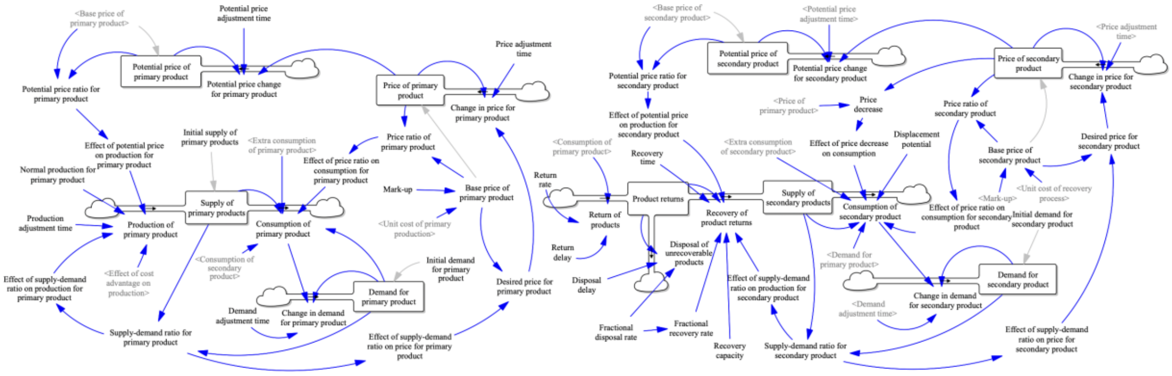


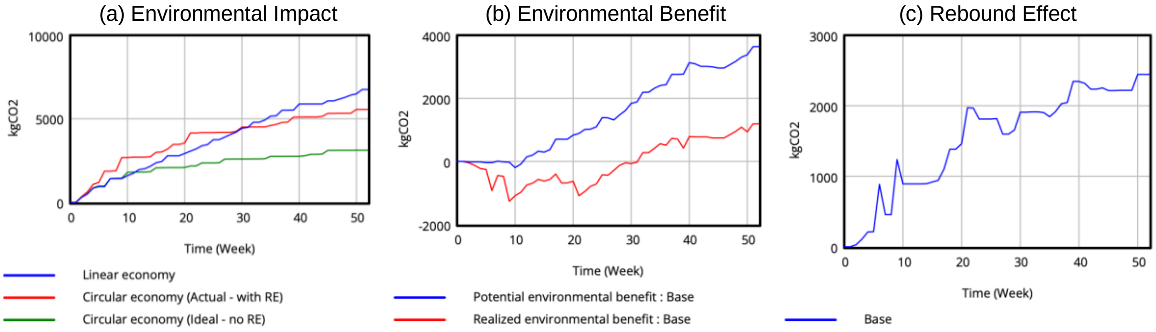
Figure 2: Stock flow diagram for the circular economy system

To assess the system's performance, two quantitative indicators are used: cumulative environmental impact and rebound effect. Cumulative environmental impact refers to the greenhouse gas emissions associated with the end-to-end production or recovery process and is measured in kg of CO_2 produced. To calculate the rebound effect, cumulative environmental impact is first obtained for three scenarios: (1) the present system (i.e., CE with rebound effects), (2) the linear economy (i.e., no secondary market), and (3) the ideal CE system (i.e., CE with no rebound effects). The potential environmental benefit of CE is the difference in impact between the linear and ideal CE scenarios, whereas the realized benefit is that between the linear and realistic CE scenarios. As expressed in Eq(1), the rebound effect is defined as the amount by which the realized benefit fails to meet the potential benefit, adopting the approach of Zink and Geyer (2017).

$$\text{Rebound effect}(t) = \text{Potential benefit}(t) - \text{Realized benefit}(t) \qquad (1)$$

4. Simulation Results

Key outputs of the base simulation are displayed in Figure 3. Overall, the results support the argument that the rebound effect is a significant possibility within circular economies. As illustrated, the environmental benefit of implementing a CE becomes largely sub-optimal when rebound effects are considered. Interestingly, up until the approximately week 30 of the 52-week or one-year study period, the linear economy performs even better than its circular equivalent, indicating that during the initial phases, it may take some time for the returns of CE practices to fully materialize. This behavior can be attributed to the delays in the complementary activities between the primary and secondary markets, such as product return delays and product recovery time. Nonetheless, even after the transition period, the present system fails to meet the potential savings in environmental impact of the ideal CE system, yielding a positive value for the rebound effect throughout the time horizon. After one year of operation, the total environmental benefit lost is worth 2,443.73 kg-CO_2, indicating that only 32.82 % of the potential benefit materialized. It is also worth noting that the magnitude of the rebound effect increases over time, which is most likely due to the reinforcing nature of most rebound mechanisms.


(a) Environmental Impact

(b) Environmental Benefit

(c) Rebound Effect

Figure 3: Simulation results of the base model

To validate the drivers of the observed rebound effect, the direct causes of the production and consumption rates that are associated with the rebound are investigated. The results are summarized in Figure 4. As it appears, all three rebound mechanisms modeled work in action under the base scenario. For one, the cost advantage of production stemming from economies of scale exceeds the base value of 1 for several weeks in the year, indicating that production was multiplied up to twice the intended amount. Similarly, consumers were motivated to purchase more of the secondary product with the price decrease multiplier being greater than 1 for several periods. The effect of the income mechanism is captured in the extra consumption variables, which are added (rather than multiplied) to the two consumption outflows. As shown, its impact is present for both markets but experiences a delay, which may be due to the gradual decrease in the average cost of consumption and external parameters like the consumers' average disposable income.

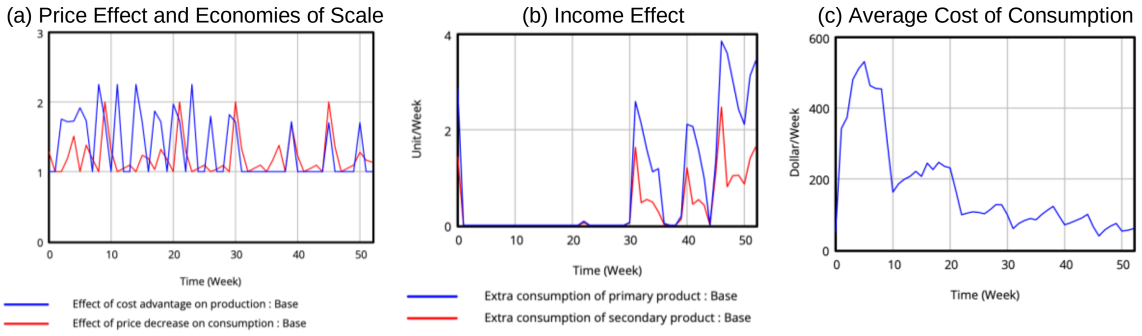


Figure 4: Evidence of the CE rebound mechanisms in action

To further understand the CE rebound dynamics, a sensitivity analysis was performed on four parameters: (1) displacement potential, (2) willingness to consume more, (3) willingness to produce more, and (4) recovery capacity. This process involves analyzing how the system responds to changes in the value of the parameters. Given that only one parameter is manipulated at each time, it is important to interpret the results of the analysis with caution and consider the possibility of variable interactions.

4.1 Sensitivity to displacement potential

Displacement potential is a variable conveying the percentage of primary consumption that is displaced by secondary consumption, or in alternative terms, the substitutability of the primary and secondary products. A displacement potential of 1 indicates that the supposed consumption of primary goods is fully replaced by the consumption of the secondary product, theoretically reducing the system's total environmental impact. Several studies argue that this is one of the most critical variables to consider when addressing the rebound effect as low displacement implies that recovered products cannot effectively compete in the same market as new products, and may only increase overall consumption (Zink and Geyer, 2017). Partially, this argument is validated by the results of the sensitivity analysis, which shows that the cumulative environmental impact and rebound effect may decrease, as the displacement potential increases. However, despite already testing the extreme values, the difference in the three scenarios' environmental performance does not seem to be as large relative to that for economic return—especially in the case of having zero displacement potential. This suggests that the dynamic rebound mechanisms based on feedback loops are more strongly driving the system.

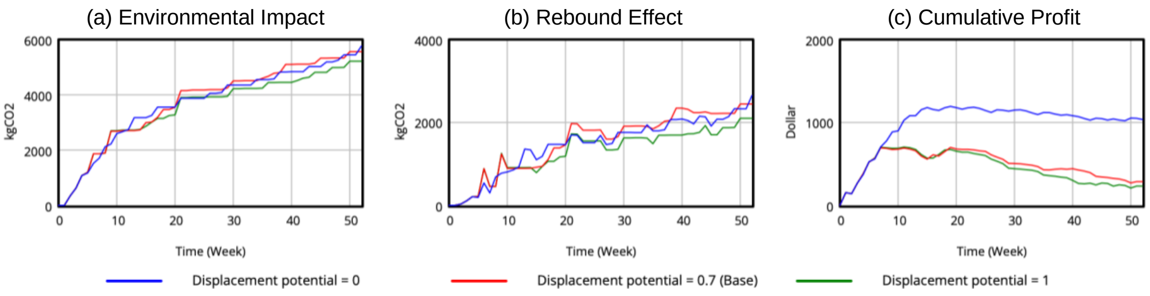


Figure 5: Sensitivity analysis on displacement potential

4.2 Sensitivity to willingness to consume more

Willingness to consume more is the parameter assumed to drive the income effect feedback loop. The variable has a dimensionless value ranging from 0 to 1, with 1 denoting the situation in which consumers are, on average, willing to spend all of their excess income to purchase more of the business's products, and 0 being the opposite where they simply choose to keep all cost savings. For this analysis, three levels of this variable are tested: 0.2, 0.4 (base model), and 0.8. Overall, the SD model is able to demonstrate the potential impact of the CE income effect. As presented in Figure 6, having consumers who are more willing to spend their extra income has been shown to result in increased total consumption and a higher cumulative impact on the environment. The magnitude of the rebound effect also appears to increase along with the willingness to consume more products. In terms of economic performance, profits are more promising, which is expected given that it entails a significantly higher sales volume for the same amount of fixed cost. In this light, policymakers and businesses must carefully navigate trade-offs between economic growth and environmental sustainability.

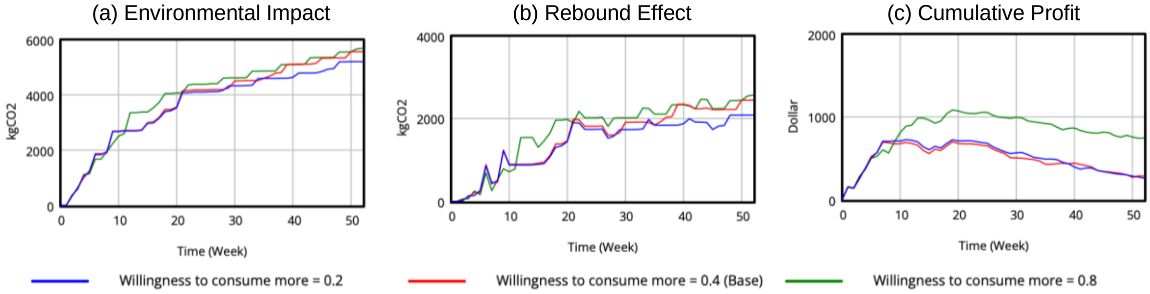


Figure 6: Sensitivity analysis on the willingness to consume more

4.3 Sensitivity to willingness to produce more

Similar to willingness to consume more, willingness to produce more reflects the degree to which the business is inclined to boost its primary production in response to cost advantages brought about by more resource-efficient processes. This parameter, along with the cost advantage variable, serves as a multiplier to the production rate that flows into the supply of primary products. To illustrate, when the cost advantage is 0.3 (i.e., the average unit cost of production is 30 % lower than how it would have been in a linear model) and the willingness to produce more is 0.5, then weekly production is multiplied by (1+0.3) * (1+0.5) = 2.34. Figure 7 displays the performance of the system under the base and extreme scenarios. Generally, the results are consistent with the logical hypothesis that when the producer is extremely willing to increase their production to take advantage of economies of scale, then the economic profits are maximized at the expense of environmental performance. On the other hand, when they are not willing to produce further, such as in the case of more constrained businesses, then environmental impacts may be reduced as production remains more constrained.

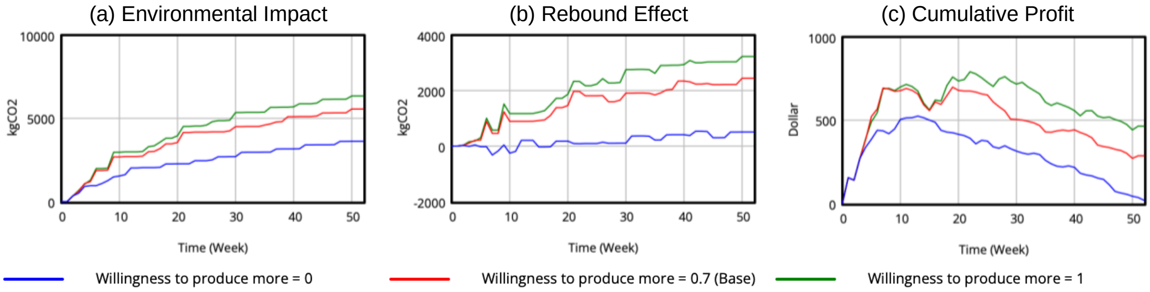


Figure 7: Sensitivity analysis on the willingness to produce more

4.4 Sensitivity to recovery capacity

Recovery capacity refers to the number of units that the producer's recovery facility can recover per week, and it effectively limits the conversion of product returns into saleable products. Along with variables like the potential price, supply, demand, and availability of the product returns, recovery capacity is one of the variables driving the rate of the recovery process. Three scenarios were considered in this analysis: low capacity (5 units/week), medium capacity (20 units/week, which is the case for the base model), and high capacity (35 units/week). The performances of these scenarios are compared in Figure 8. The results reveal that increasing the system’s recovery capacity, despite strengthening its circularity, does not necessarily improve environmental performance. As shown in the figure, the high-capacity case yields the highest environmental impact among all. Theoretically, this scenario should be beneficial as it provides the system with the most opportunities to restore end-of-life products. However, as can be observed in the graph of the rebound effect, these benefits have been strongly counteracted by the rebound mechanisms. The graph also suggests that recovery capacity may have a positive relationship with the magnitude of the rebound effect. In terms of profit, the low-capacity case resulted in the best performance, which may be due to the decrease in the weekly fixed cost for recovery processes.

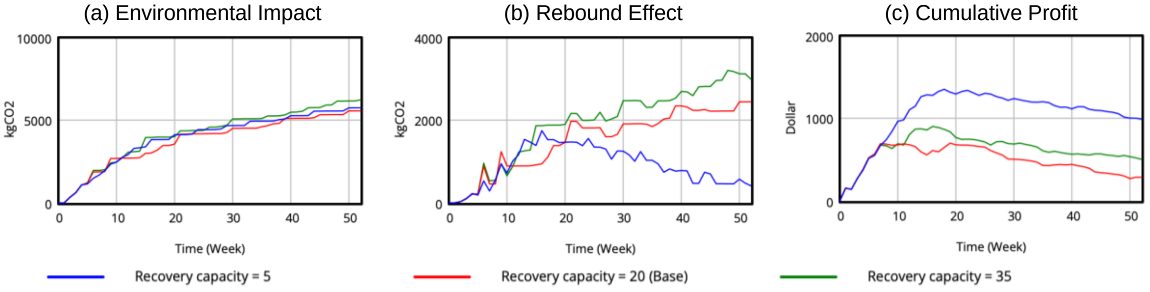


Figure 8: Sensitivity analysis on recovery capacity

5. Conclusions

While the circularity concept presents a promising avenue for addressing environmental challenges, the rebound effect underscores the complexity of its implementation. The present study introduces an SD model for analyzing the dynamics of CE environments, particularly focusing on the rebound effect. The model developed provides a comprehensive view of circular systems, including elements like the natural interplay between market variables and the consequences of circular interventions. The results of the simulation confirm that circular systems do potentially experience rebound effects. For the hypothetical case, 2,443.73 kg-CO_2 worth of carbon emission savings was lost, indicating that only 32.82 % of the potential benefit was realized due to price discounts, income savings, and economies of scale. This highlights the need for decision-makers to carefully consider the systemic implications of circular interventions and adopt an integrated and holistic approach to sustainability. The analysis of multiple scenarios also reveals that variables like the displacement potential, willingness of consumers to spend their excess income, willingness of producers to leverage cost savings, and recovery capacity can have a significant influence on the magnitude and pattern of the rebound effect. However, their impact is not as straightforward as driving performance in one direction. Rather, the rebound effect is a highly complex phenomenon influenced by the interaction of feedback loops and parameter combinations. The study's analysis of only a few hypothetical cases may limit the generalizability of the findings.

Initial policy recommendations to minimize the rebound include designing secondary products that have a good displacement potential and regulating society’s willingness to consume and produce more products. Future works must investigate possible patterns and thresholds within the variable interactions to anticipate the rebound effect's dynamics more accurately and develop optimal policies and regulatory frameworks. The model may also be extended to account for strategies based on narrowing loops in addition to slowing down and closing them.

References

Bassi A.M., Bianchi M., Guzzetti M., Pallaske G., Tapia C., 2021, Improving the understanding of circular economy potential at territorial level using systems thinking. Sustainable Production and Consumption, 27, 128–140.

Freeman R., 2018, A Theory on the Future of the Rebound Effect in a Resource-Constrained World. Frontiers in Energy Research, 6, 81.

Guzzo D., Walrave B., Videira N., Oliveira I.C., Pigosso, D.C.A., 2024, Towards a systemic view on rebound effects: Modelling the feedback loops of rebound mechanisms. Ecological Economics, 217, 108050.

Makov T., Font Vivanco D., 2018, Does the Circular Economy Grow the Pie? The Case of Rebound Effects From Smartphone Reuse. Frontiers in Energy Research, 6, 39.

Thiesen J., Christensen T.S., Kristensen T.G., Andersen R.D., Brunoe B., Gregersen T.K., Thrane M., Weidema B.P., 2008, Rebound effects of price differences. The International Journal of Life Cycle Assessment, 13(2), 104–114.

Zink T., Geyer R., 2017, Circular Economy Rebound. Journal of Industrial Ecology, 21(3), 593–602.