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# Enhancing Consumer Engagement in Plastic Waste Reduction: A Stackelberg Game

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## ABSTRACT

Circular economy is recognized as one of the most effective strategies for promoting plastic sustainability. However, its implementation requires to enhance consumer engagement, which remains a primary target of regulatory initiatives designed to promote plastic circular economy. To ensure sustained consumer participation, it is essential to evaluate and optimize various incentives, including regulatory policies, voluntary programs, and market-related mechanisms. This study applies Stackelberg Game Approach to quantitatively capture the strategic interactions between the authorities (as the leader) and consumers (as followers). The model incorporates key consumer behaviors, i.e., "use less," "use longer," and "recycling", to reflect their role in advancing plastic circular economy goals. By integrating factors such as governmental utility (gains of benefits), consumer utility (welfare), and plastic waste reduction, the model identifies the optimal intensities of various public initiatives, which represent the quantitative levels of policy intervention necessary to maximize desired outcomes. A case study based on EU-27 data demonstrates the model's applicability, revealing optimal intensities of 0.91, 0.41 and 0.8 for regulatory, voluntary, and market-related initiatives. At these optimal intensities, regulatory measures achieve the highest governmental utility (benefits) and plastic waste reduction, while market-related mechanisms yield more favorable outcomes for consumer welfare. The findings highlight the need for a balanced policy mix that effectively aligns government objectives with consumer incentives.

**Keywords**: Circular Economy, Plastic Waste Reduction, Government initiatives Consumer behavior, Stackelberg Game

## INTRODUCTION

The conventional plastic consumption model, characterized by a linear "use-and-dispose" pattern, is gradually being replaced by a more sustainable approach known as the plastic circular economy [1]. This model emphasizes behaviors such as "use less", "use longer", and "recycling", which collectively aim to minimize plastic waste and maximize resource efficiency [2]. Howe-er, the transition to a circular economy presents significant challenges, particularly in influencing and sustaining changes in consumer behavior.

Governments play a pivotal role in this transition by implementing a range of initiatives designed to either incentivize or regulate consumer behavior. These measures include regulatory policies, voluntary programs, and market-related mechanisms such as taxes or subsidies [3]. While these initiatives are essential, their effectiveness largely depends on how consumers respond [4], making the dynamic interaction between government interventions and consumer behaviors a key issue.

Previous research has extensively explored this relationship, primarily through qualitative methods, such as consumer surveys and behavioral assessments [5]. Although these studies provided valuable insights into

consumer preferences and policy acceptance, they often lack quantitative evaluation of how different policy intensities affect consumer behavior and plastic waste reduction. Most existing literature tends to focus on broad initiative evaluations, such as the overall impact of policies on waste reduction, rather than exploring the strategic interactions between policymakers and consumers in a structured, decision-theoretic manner [5].

To address this gap, this study employs a Stackelberg game model, a well-established framework for analyzing hierarchical decision-making processes where one player (the leader) makes decisions anticipating the responses of another player (the follower) [6]. In the context of the plastic circular economy, the government acts as the leader, setting initiatives to influence consumer behaviors, while consumers act as followers, adjusting their actions to maximize their utility in response to these initiatives. This approach allows for the quantitative evaluation of interactions between the government and consumers, providing insights into how different measure intensities affect not only plastic waste reduction but also the benefits of both parties.

The contributions of this work are outlined as follows,

1) The establishment of a Stackelberg Game model to quantitatively capture the interaction between the government and consumers, addressing the lack of quantitative focus in the existing literature.

2) Assessment of the interactions between government initiatives, i.e., regulatory, voluntary, and market-related, and consumer behaviors such as "use less," "use longer," and "recycling," providing a quantitative evaluation of how these factors influence the plastic circular economy.

3) Optimization of the intensities of various government initiatives, considering the balance between government utility, consumer welfare, and plastic waste reduction, providing a decision- making framework for government initiatives.

The remainder of this work is organized as follows: Section 2 proposes the developed Stackelberg game model for capturing the interactions between government and consumer. Section 3 introduces a numerical case study based on the EU-27. The numerical results are presented and discussed in Section 4. This work is concluded in Section 5. All symbols used in this work are illustrated in Table 1.

**Table 1:** Symbols.

| | |
|---|---|
| **Sets** | |
| $I$ | Types of government initiatives and/or policies implemented to promote a circular economy in plastics |
| $J$ | Types of consumer behaviors relevant to fostering a circular economy for plastics |
| **Indices** | |
| $i$ | Index for initiatives aimed at promoting the circular use of plastics, $i$ = {Regulatory measure, Voluntary measure, Market-based measure} |
| $j$ | Index for consumer behavior supporting the adoption of a circular economy for plastics, $j$ = {Reduce plastic use (Use less), Extend plastic product lifespan (Use longer), Recycling plastics} |
| **Parameters** | |
| $\alpha_i$ | Consumer sensitivity or resistance to $i$-th government initiative. ($\alpha_i \leq 0$) |
| $B$ | The total budget for voluntary measures, measured in € |
| $C_c$ | The cost of carbon price for consumer (€/kg) |
| $C_d$ | The charges of consumer plastic disposal, i.e., landfill (€/kg) |
| $C_e$ | The cost of government education investment (€/kg) |
| $C_r$ | The cost of consumer plastic recycling (€/kg) |
| $C_v$ | The cost of plastic virgin raw material consumption (€/kg) |
| $C_w$ | The cost of plastic waste management (€/kg) |
| $F_r$ | The consumer refundable fees of plastic recycling (€/kg) |
| $P_p$ | The price of plastics (€/kg) |
| $P_s$ | The prices of plastic substitutes (€/kg) |
| $T_c$ | The tax paid by consumer on plastic consumption (€/kg) |
| $W_0$ | The total amount of plastic waste generated (kg) |
| **Decision Variables** | |
| $\delta_{ij}$ | The impact of the $i$-th government initiative on the $j$-th consumer behaviour, where a value of 0 indicates no impact and a value of 1 indicates full impact. |
| $S_i$ | Government measure intensity, where $S_i \in [0,1]$. |
| **Functions** | |
| $R(S_i)$ | The response rate of the consumer behavior under the $i$-th government initiative and/or policy |
| $U_{ci}$ | Consumer utility under the $i$-th government initiative (€) |
| $U_{gi}$ | Government utility under the $i$-th government initiative (€) |
| $W_{di}$ | Reduction in plastic waste achieved under the $i$-th government initiative (kg) |

## STACKELBERG GAME MODEL

The Stackelberg Model is a framework designed to

describe strategic decision-making processes between hierarchical players under conditions of incomplete information [7]. In this work, the two-stage framework of government and consumer is illustrated in Figure 1. In the first stage, the government acts as the leader, selecting a measure from set $I$ and anticipates the corresponding consumer response. In the second stage, consumers, as followers, adjust their behaviors by choosing a strategy from set $J$ based on the selected government measure $i$ to maximise their benefits in response to these initiatives, primarily through actions such as using less, extending plastic product lifespan (use longer), and promoting plastic recycling.

Note that stage 2 captures the aggregated response of a heterogeneous consumer population, considering variations in overall consumer behavior under different government interventions. $\delta_{ij}$ is introduced to represent the impact of various government initiatives on corresponding consumer behaviours, while it equals 0 if there is no impact on consumer behaviours, as shown in Table 2. For instance, if the government adopts a regulatory measure, the consumer's strategy set includes only "Use less", while there is no impact on "Use longer" and "Recycling".

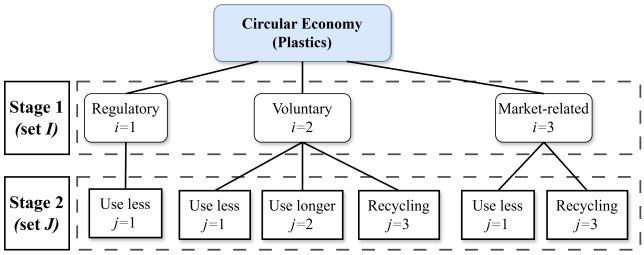


**Figure 1.** Two-stage Stackelberg Game model for plastic circular economy.

**Table 2:** The impact of government initiatives on consumer behaviors.

| | Regulatory | Voluntary | Market-based |
|---|---|---|---|
| Use less | $\delta_{11}=1$ | $\delta_{21}=1/3$ | $\delta_{31}=2/3$ |
| Use longer | $\delta_{12}=0$ | $\delta_{22}=1/3$ | $\delta_{32}=0$ |
| Recycling | $\delta_{13}=0$ | $\delta_{23}=1/3$ | $\delta_{33}=1/3$ |

Building upon the two-stage Stackelberg framework, the mathematical models are elaborated. As followers, consumers adjust their behaviors in response to the government's initiatives based on the intensity of initiative implementation, denoted by $S_i$. These intensities correspond to specific policy measures, such as the extent of regulatory enforcement, financial support for voluntary programs, and subsidies or market-based instruments promoting recycling. While consumers generally exhibit certain responsiveness (i.e., $R(S_i)$ ) to different government measures, new initiatives often trigger resistance [8]. This resistance constrains the sensitivity of consumer responses, causing the reaction function to exhibit saturation effects rather than continuous linear growth as the intensity of the government's measures increases. The parameter $\alpha_i$ is introduced to represent the resistance constrains, as shown in Eq. (1).

$$R(S_i)=\frac{\alpha_i {S_i}^3}{1+\alpha_i(S_i+{S_i}^2)} \quad (1)$$

The total reduction in plastic waste under the $i$-th government initiative, i.e., $W_{di}$, is determined by the combined effects of consumer responses to the employed government initiative. Specifically, it is the weighted sum of the impacts of each consumer behaviours, multiplied by the initial amount of plastic waste $W_0$. This relationship is expressed in Eq. (2) as follows:

$$W_{di}=\sum_{j=1}^{3}\delta_{ij}R(S_i)W_0 \quad (2)$$

The $i$-th government's utility function, $U_{gi}$, as shown in Eq. (3), consists of two main components: (1) the benefits derived from the implementation of measures, such as the reduction in waste disposal costs and the avoidance of raw material consumption due to waste reduction, tax revenue generated by market-related measures, and charges collected from the disposed plastic waste; and (2) the costs associated with the implementation of these measures, including the costs from the introduction of substitutes, the costs of voluntary measures, and the recycling deposits to be refunded to consumers. It is noted that only under market-related measures does the 'use less' behavior of consumers get influenced by the tax, $T_c$.

$$U_{gi}=(C_w+C_v)W_{di}-\left(P_p-P_s\right)\delta_{i1}R(S_i)W_0-\delta_{i2}S_iC_eW_0-F_r\delta_{i3}R(S_i)W_0+T_c\delta_{31}R(S_3)W_0+(W_0-W_{di})C_d \quad (3)$$

The function of consumer welfare under the $i$-th government initiative, $U_{ci}$, as shown in Eq. (4), also consists of two components: (1) the benefit component, which includes the reduction in carbon costs due to decreased plastic waste and the net benefit from plastic recycling (recycling revenue minus recycling costs); and (2) the cost component, which includes the additional expenses required for using plastic substitutes and the charges incurred for disposing of plastic waste.

$$U_{ci}=C_cW_{di}-(P_s-P_p)\delta_{i1}R(S_i)W_0+(F_r-C_r)\delta_{i3}R(S_i)W_0-(W_0-W_{di})C_d \quad (4)$$

The model's constraints are shown in Eqs. (5)–(8). The intensity of government measures ($S_i$) and the range of the consumer response function $R(S_i)$ are both within [0,1] (see Eqs. (5) and (6) ). The reduction in waste $W_{di}$ under the $i$-th government initiative should not exceed the total amount of waste $W_0$ (see Eq. (7) ). Voluntary measures, such as education, are primarily aimed at all

plastic waste, and their total cost should equal the total budget allocated for voluntary measures, as shown in Eq. (8).

$$0 \le S_i \le 1, \forall i \in \{1,2,3\} \quad (5)$$

$$0 \le R(S_i) \le 1, \forall i \in \{1,2,3\} \quad (6)$$

$$W_{di} \le W_0 \quad (7)$$

$$C_e \times W_0 = B \quad (8)$$

## CASE STUDY

A case study based on the EU-27 is conducted using the proposed Stackelberg model to quantitatively assess the interactions between government initiatives and consumer behaviors, aiming to promote a circular economy for plastic sectors. The case study utilizes data from official EU reports, industry surveys, and relevant literature data to numerical analyze the effects of varying intensities of regulatory, voluntary, and market-based interventions on consumer responses. This allows for an assessment of how various measure intensities and consumer reactions influence both government and consumer welfare, as well as the effectiveness of the strategies for plastic circular economy. All relevant parameters, including their descriptions, numerical values and data sources, are presented in Table 3.

**Table 3:** Collected data for proposed Stackelberg Game model in the EU-27.

| Parameters | Description | Values | Ref. |
|---|---|---|---|
| $\alpha_1$ | Consumer sensitivity to regulatory initiative. | -1.125 | [9] [10] [11] |
| $\alpha_2$ | Consumer sensitivity to voluntary initiative. | -3 | |
| $\alpha_3$ | Consumer sensitivity to market-related initiative. | -1.33 | |
| $B$ | The total budget for voluntary measures. | 13,850,000 € | [12] |
| $C_c$ | The cost of carbon price for consumer. | 0.16 €/kg | [13] |
| $C_d$ | The charges of consumer plastic disposal. | 0.8 €/kg | [14] |
| $C_e$ | The cost of government education investment. | 0.0021 €/kg | [15] |
| $C_r$ | The cost of consumer plastic recycling. | 0.73 €/kg | [16] |
| $C_v$ | The cost of plastic virgin raw material consumption. | 2.7€/kg | [17] |
| $C_w$ | The cost of plastic waste management. | 0.116 €/kg | [18] |
| $F_r$ | The consumer refundable fees of plastic recycling. | 1.2 €/kg | [19] |
| $P_p$ | The price of plastics. | 1.154 €/kg | [20] |
| $P_s$ | The prices of plastic substitutes. | 1.546 €/kg | [21] |
| $T_c$ | The tax paid by consumer on plastic consumption. | 0.8035 €/kg | [22] |
| $W_0$ | The total amount of plastic waste generated | 32·109 kg | [23] |

The collected numerical values are substituted into Eqs. (1)-(4) and calculated using backward induction. The specific steps are as follows:

**(1)** Under the given government $i$-th strategy, the objective of consumer is to maximize their benefits:

$$\max U_{ci} \quad (9)$$

This involves determining the optimal consumer response that yields the highest benefits based on the given government initiative.

**(2)** Take the first derivative of $U_{ci}$ with respect to $S_i$ and set it equal to zero to identify the optimal policy intensity that maximizes consumer's benefits:

$$\frac{dU_{ci}}{dS_i} = 0 \quad (10)$$

This condition helps determine the critical points where consumer utility reaches its maximum under the given government initiative.

**(3)** Substitute the optimal $S_i$, constrained by Eq. (5) within the range [0,1], into the government utility function $U_{gi}$ (Eq. (3)), the consumer utility function $U_{ci}$ (Eq. (4)), and the plastic waste reduction equation $W_{di}$ (Eq. (2)). This allows for the calculation of maximum benefits for government and consumer, and the plastic waste reduction under the optimal policy intensity $S_i$.

## RESULTS AND DISSCUSSION

The case study is conducted using the proposed Stackelberg Game model, calculated in Mathematica 14.0 software [24]. Figure 2 presents the optimal benefits for both the government and consumer, and plastic waste reduction under the optimal government strategy intensity.

As shown in Figure 2, the government initiative intensities are as follows: regulatory measure: 0.91, voluntary measure: 0.41, and market-related measures: 0.8, For each optimal strategy intensity, the government utility (represented by the blue bars in Figure 2) and waste reduction (represented by the green bars in Figure 2) resulting from the regulatory measure outperform those of the voluntary and market-related measures. This suggests that, within the context of the given case study, regulatory measures are the most effective in maximizing

government utility and reducing plastic waste, provided that the intensity reaches 0.91. These findings underscore the importance of carefully calibrating the strength of government interventions when formulating policies aimed at advancing a circular economy in the plastic sector [25].

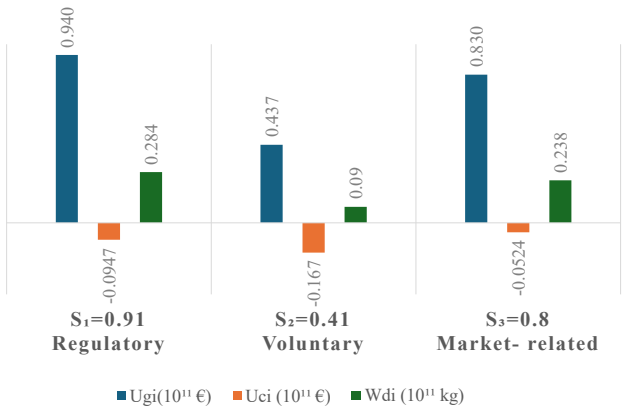


**Figure 2.** The results under different initiative intensities for government utility ($U_{gi}$), consumer utility ($U_{ci}$), and plastic waste reduction ($W_{di}$): S1: Regulatory intensity; S2: Voluntary intensity; S3: Market-related intensity.

With the optimal intensities for government interventions, all consumer utilities are negative (represented by the orange bars in Figure. 2), whereas market-related measures, at an intensity of 0.8, exhibit the highest consumer utility. This suggests that while regulatory measures may achieve significant government utility and plastic waste reduction, they come at the expense of consumer welfare. On the other hand, market-related measures seem to strike a better balance, offering more favorable outcomes for consumers [3]. This indicates that when designing effective policies, it is crucial to consider not only the environmental and economic goals of the government but also the potential impacts on consumer behavior and utility. Striking this balance can help ensure more sustainable and effective strategies for promoting a circular economy in the plastic sector.

## CONCLUSION

This study develops a Stackelberg game model to quantitatively capture the interactions between the government (as the leader) and consumers (as the followers) in promoting the circular economy of plastics. By considering both the benefits and costs of the government and consumer within the plastic circular economy, a case study of the EU-27 is implemented. The optimal intensities of various government initiatives are captured: regulatory measures at 0.91, voluntary measures at 0.41, and recycling measures at 0.8.

The proposed Stackelberg Game model provides valuable insights into the strategic decision-making process between government interventions and consumer behaviour. By utilising this framework, policymakers can better assess the potential outcomes of different intervention strategies and determine the most effective measure intensities to promote sustainability in the plastic sector. The model highlights the trade-offs between government utility, consumer welfare, and environmental goals, offering a more comprehensive approach to policy design in the context of a circular economy in plastic sector.

The limitation of this study lies in not considering the combined effects of the various government initiatives, as well as the detailed consumer responses to each measure. Future research will address this by incorporating the synergistic impacts of the three initiatives and refining the model to capture more nuanced consumer behavior in response to government initiatives.

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