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Understanding decision-making in circular packaging ecosystems: An agent-based model of the Dutch beverage sector

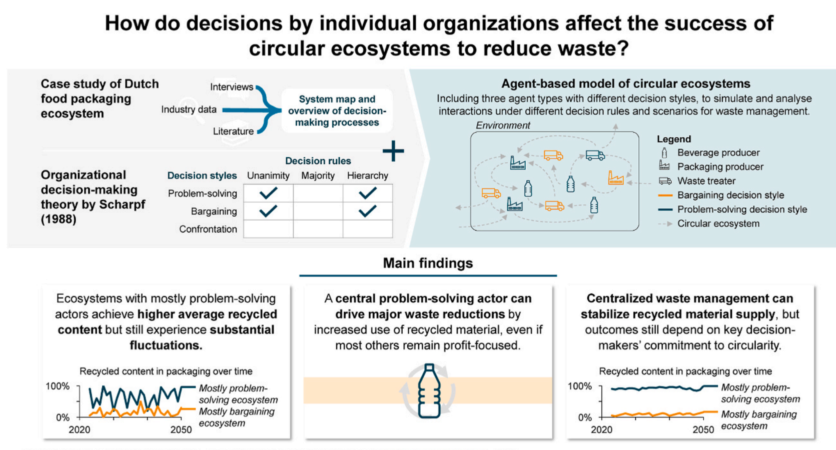
Annoek Reitsema [a,c], Eric Onderdelinden [a], Gijsbert Korevaar [b,d], Amineh Ghorbani [c,*]

[a] Deloitte Consultative Services, the Netherlands
[b] Energy and Industry Section, Engineering Systems and Services Department, Technology, Policy and Management Faculty, Delft University of Technology, Delft, the Netherlands
[c] System Engineering Section, Multi Actor Systems Department, Technology, Policy and Management Faculty, Delft University of Technology, Delft, the Netherlands
[d] Centre of Expertise HRTech, Rotterdam University of Applied Sciences, Rotterdam, the Netherlands

HIGHLIGHTS

- An agent-based model was developed to simulate the dynamics in circular ecosystems.
- The ABM was used to assess potential packaging waste reduction in these ecosystems.
- Results show reduction potential if just some actors choose circularity over profit.
- The decision-style of a central actor is pivotal in mainly profit-driven ecosystems.
- Centralized waste management can stabilize recycled material supply in ecosystems.

GRAPHICAL ABSTRACT



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ABSTRACT

Reducing packaging waste requires organizations to look beyond their own products, services, and business models. Collaboration in circular ecosystems may offer a promising approach. Material flows in circular ecosystems are affected by social, economic, and technical variables, including decision-making behaviour, material prices, and available technologies. The complexity of these interactions makes it challenging to assess the impact of strategic choices on circular ecosystems' effectiveness in reducing waste. Agent-based modelling (ABM) is a useful methodology for analysing dynamics within such complex systems. This study develops an ABM for a Dutch food packaging ecosystem and integrates organizational decision-making theory to account for actor behaviour, considering different decision-styles and rules. The ABM includes three types of agents representing beverage producers, packaging producers, and waste treaters, who can form circular ecosystems for closed-loop

* Corresponding author.
E-mail addresses: A.M.J.Reitsema@tudelft.nl (A. Reitsema), EOnderdelinden@deloitte.nl (E. Onderdelinden), G.Korevaar@tudelft.nl (G. Korevaar), A.Ghorbani@tudelft.nl (A. Ghorbani).

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recycling. Experimentation indicates that with just 10 % of organizations prioritizing circularity over maximizing individual profit, significant waste reduction is achievable, although the decision-style of the beverage producer is crucial in profit-driven ecosystems. Furthermore, centralized waste management could stabilize recycled material supply and mitigate fluctuations in recycled content. While the model is limited by deterministic agent behaviour and simplified decision-making processes, our findings demonstrate the value of ABM in understanding dynamics in circular ecosystems and provide insights for policymakers and industry stakeholders. Future research could explore alternative circular strategies with ABM, such as packaging reuse and material substitution, and the impact of modelling more nuanced decision-making behaviour on the model's scientific and practical value.

1. Introduction

Global economic growth has improved living conditions worldwide (Roser, 2020). However, it has also resulted in resource depletion and waste generation, largely due to the linear nature of most economies (Kaza et al., 2018; OECD, 2019; World bank, 2022). In a linear economy, products are produced, used, and disposed (Ellen MacArthur Foundation, 2023). Because of this linearity, waste generation is expected to grow to 3.4 billion tons worldwide by 2050 (Kaza et al., 2018).

The Circular Economy (CE) offers an alternative approach to overcoming the environmental problems related to waste (Geissdoerfer et al., 2017). Unlike a linear economy, the CE focuses on keeping resources in use for as long as possible. Strategies such as recycling, reusing, and remanufacturing aim to narrow, slow, and close material and energy flows, as well as regenerate resources (Bocken et al., 2016; Ghisellini et al., 2017; Geissdoerfer et al., 2017; Konietzko et al., 2020).

A fundamental requirement for establishing a CE is inter-organizational collaboration (Ghisellini et al., 2016; Nuβholz et al., 2019; Hileman et al., 2020; Jäger and Piscicelli, 2021). To enable collaboration, organizations can form business ecosystems in which they exchange information and knowledge (Graça and Camarinha-Matos, 2015; Moore, 1993). Collaboration in these business ecosystems can also provide useful resources, alliance partners, and market information (Zahra and Nambisan, 2012).

Building on this concept, a 'circular ecosystem' is a network of interconnected and diverse actors that cross industrial boundaries and collectively pursues a circular value proposition, creating potential economic and environmental sustainability (Trevisan et al., 2022). In circular ecosystems, organizations look beyond their own products, services, and business models to become more circular (Konietzko et al., 2020). The shift from linear to circular models affects all parts of the value chain, including production, distribution, consumption, and waste treatment (Kirchherr et al., 2017). As a result, many different types of actors are needed to support this transition (Tate et al., 2019). Most of these actors face the dilemma of being a first mover towards a circular model or to wait for others to act first.

The packaging ecosystem is especially important in efforts to improve circularity because it contributes significantly to waste generation. In Europe, packaging material accounts for 36 % of municipal solid waste (European Commission, 2022). While packaging is essential to protect products and reduce food waste (Humbert et al., 2009; Molina-Besch et al., 2019; Silvenius et al., 2011), it becomes waste once discarded and can harm the environment (Simon et al., 2016; Geyer et al., 2017; De Souza Machado et al., 2018; UNEP, 2021; Vethaak and Legler, 2021). Multiple CE strategies are available to minimize packaging waste, but the suitability of these strategies depends on the packaging requirements (Meherishi et al., 2019). Therefore, a combination of strategies is needed for a sustainable packaging system. There are various examples of circular ecosystems that aim to reduce packaging waste, such as glass recycling ecosystems (Hsieh et al., 2017), deposit-return systems on bottles (Zhou et al., 2020), reusable food packaging networks (Accorsi et al., 2022) and zero-packaging grocery stores (Beitzen-Heineke et al., 2017). However, the packaging industry often clings to end-of-the-pipe solutions, such as mixed-stream recycling, and is resistant to adopt more effective systemic changes to reduce waste, such as the deposit-return system for PET bottles (Hanemaaijer et al., 2023).

Understanding how decisions by individual organizations impact the overall success of circular ecosystems can help encourage the transition from traditional business models to circular ones (Asgari and Asgari, 2021). Recent research shows that agent-based modelling (ABM) is a useful tool for analysing the circularity transition, as it can capture the diversity and decision-making processes of the actors involved (Walzberg et al., 2023). However, to our knowledge, no previous study has used ABM to examine how organizational decision-making behaviour within circular ecosystems affects packaging waste reduction.

This study aims to fill this gap by developing an ABM that simulates the dynamics of a circular food packaging ecosystem. Our focus is to investigate how organizational decision-making shapes waste reduction outcomes. By integrating decision-making theory and a real-world case study, this research seeks to improve theoretical understanding and provide practical insights for organizations seeking to achieve circularity goals within ecosystems.

The paper is structured as follows: Section 2 starts with a literature review of circular ecosystems and organization decision-making behaviour, detailing the role of agent-based modelling to analyse both. Section 3 describes the methodology by introducing the case study, explaining the conceptualization and parametrization of the agent-based model, and describing the experimental design. Section 4 presents and analyses the results from the simulations. Section 5 discusses the validity and implications of the findings, acknowledges the limitations of the study, and suggests directions for future research, followed by the conclusion in Section 6.

2. Literature review

2.1. Analysing circular ecosystem dynamics with agent-based modelling

Previous research has identified multiple enabling factors for the transition to circular ecosystems (Ferrari et al., 2023; Gomes et al., 2024), variables influencing the dynamics of circular ecosystems (Barquete et al., 2022; Liu et al., 2022) and requirements for circular ecosystem management (Gomes et al., 2023; Marreiros-Barbosa et al., 2024). Circular ecosystems require a transformation of the business ecosystem (Asgari and Asgari, 2021; Gomes et al., 2024), ask for changes in infrastructure (Marques-McEwan et al., 2023) and consumer behaviour (Vidal-Ayuso et al., 2023; Corona et al., 2024), and can suffer from poor alignment among actors (Barquete et al., 2022), amongst other contextual factors (e.g. technological uncertainty) (Farahbakhsh et al., 2023).

Recent literature emphasizes the need for quantitative studies grounded in empirical data to better understand circular ecosystems (Trevisan et al., 2022). However, large in situ experiments in the packaging ecosystem are time-consuming and costly (Hanemaaijer et al., 2023) and may carry risks associated with incorrect decisions (Barquete et al., 2022). Agent-based modelling (ABM) offers a valuable solution to these challenges by allowing the simulation of actor behaviour in different scenarios to explore and analyse potential outcomes ex-ante while reducing costs and risks (Van Dam et al., 2013).

Several studies have used ABM to assess scenarios and conditions for the reduction of waste while considering individual actor behaviour. Meng et al. (2018) focused on changes in household recycling behaviour under different policies, Lieder et al. (2017) used ABM to study customer behaviour, assessing the acceptance of new circular business models, Koide et al. (2023) assessed product-level CE strategies considering consumer behaviour, and Farahbakhsh et al. (2023) used ABM to reveal variables affecting waste treaters' adoption of emerging technologies. Additionally, various studies assessed the interactions of producers who exchange resources in industrial symbiosis networks using ABM (e.g. Albino et al., 2016; Fraccascia et al., 2017; Ghali et al., 2017; Walzberg et al., 2020; Lange et al., 2021). However, none of these studies have taken an ecosystem approach that considers multiple different organizations and their decision-making behaviour.

2.2. Organizational decision-making theory

Within circular ecosystems, actors exhibit behaviour that both influences and is influenced by their objectives and interactions. While numerous studies have explored consumer behaviour in packaging waste reduction (e.g. Meng et al., 2018; Otto et al., 2021; Tong et al., 2018; Wikström et al., 2014), it should be recognized that most actors in this ecosystem are organizations. Therefore, this study will focus on organizational decision-making behaviour.

Organizations are composite actors when it comes to decision-making because their decisions are often collectively made by several people, such as a board of directors or C-level management (Scharpf, 1988a). This study uses the organizational decision-making theory by Scharpf (1988a) to conceptualize organizational decision-making, as it gives an institutional explanation for the paradox of the 'joint decision trap'. The joint decision trap refers to a situation in which organizations' individual decision-styles and decision-rules may lead to suboptimal outcomes in joint decision-making (Scharpf, 1988b). Various other frameworks have been used to conceptualize decision-making behaviour of organizations in an ABM, including inter-system control model (Sakaki, 2018), the multi-agent decision-making framework (Florez-Lozano et al., 2020) and the intra-group decision-making framework (Beal Cohen et al., 2021). For the analysis of organizational decision-making behaviour in a circular economy specifically, previous studies have used game theory (Abi Chahla and Zoughaib, 2019) and theory of planned behaviour (Lange et al., 2021). However, research by Eslamizadeh et al. (2022) shows the suitability of Scharpf's framework for conceptualizing inter-organizational decision-making behaviour in an ABM, hence the choice to use this theory for conceptualizing decision-making in this study's ABM.

3. Material and methods

This study follows an ABM-focused methodology (Van Dam et al., 2013). The first part of this section presents information on the selected Dutch food packaging ecosystem. The second part details the theoretical basis for the ABM. The third part explains the ABM conceptualization and implementation. The final part discusses experimentation and data analysis.

3.1. Case study: A Dutch food packaging ecosystem

This research develops an ABM of a circular food packaging ecosystem for a specific beverage producer and its ecosystem in the Netherlands to analyse the effect of organizational decision-making behaviour on circularity efforts. The Netherland has an active policy environment and is actively pursuing a transition to a CE. The country is currently implementing changes to improve circularity, making it a suitable case study for understanding the implications of transitioning to a CE and identifying potential improvements and effective policies (Brouwer et al., 2018; Çevikarslan et al., 2022). The case study provides a foundation to define the decision-making process of the actors in the ecosystem. Additionally, the Dutch waste management structure collects and reports annual data on waste amounts and recycling rates per packaging type, providing essential input data for this study. Overall, the Dutch food packaging ecosystem offers a representative case study that can generate insights that are applicable for other geographies with comparable ambitions, policies, recycling rates and governance structures. By integrating decision-making theory with a real-life case study, the research aims to enhance the realism of the ABM by more accurately reflecting decision-making processes and actor behaviour in an ecosystem.

The study focusses on the food packaging ecosystem of a prominent Dutch multinational, referred to as "beverage company" in this report for anonymity purposes. This case study was selected because beverages inherently require packaging, and this particular beverage is sold in various packaging (cans, PET bottles, glass bottles, cartons and bag-in-boxes). These packaging types are produced, used, collected, and treated in different ways, posing multiple opportunities to set up circular ecosystems. The beverage company uses PET bottles made of 100 % recycled material, although these bottles are currently not recycled into new PET bottles in the Netherlands, as they are not part of the deposit-return system according to the beverage producer. Glass bottles contain up to 95 % recycled content (KIDV, 2022a), but the current recycling rates at 79 % (Afvalfonds Verpakkingen, 2023). Aluminium is used in the cans and drink cartons, but only aluminium cans are currently recycled in the Netherlands (Afvalfonds Verpakkingen, 2023). Besides aluminium, the drink cartons contain paper and plastic. The paper could contain up to 87 % recycled content (Holwerda et al., 2019; Afvalfonds Verpakkingen, 2023), and the plastic could consist of 18 % recycled material as well (PRN, 2022), although current numbers might be lower for both (Tetra Pak, 2024). The beverage company's diversity in packaging formats and materials highlights the varying potential for improvements in the circularity of the packaging through circular ecosystems.

The beverage company is part of the larger Dutch food packaging ecosystem. This ecosystem, as in other countries, includes diverse actors with different objectives: some focus on product sales, some handle packaging waste, and others aim to protect the environment. Through system analysis, 19 distinct actor types were identified. There are various producers: material producers, packaging producers that manufacture packaging from virgin or recycled materials and beverage producers that pack their products in packaging. In the Netherlands, packaging producers and beverage producers packing their products must adhere to the extended producer responsibility (EPR). If a company markets at least 50,000 kg of packaging material, it must comply with the ERP and is legally obliged to pay a fee to cover the costs of waste collection, sorting and recycling of the packaging they sell (ILT, 2024). This waste treatment is executed via the Dutch waste management structure, which comprises organizations responsible for waste collection and the deposit-return system, as well as other organizations including a knowledge institute and a data monitoring organization. Furthermore, the Dutch food packaging ecosystems also involves other actors: outlets, consumers, governmental organizations, and other influential organizations such as universities and NGOs. Overall, the actors within the food packaging ecosystem interact through material, financial and information exchange to achieve their objectives (Kanda et al., 2021; Pietrulla, 2022; KIDV, 2022b). All actors in the Dutch food packaging system and their interactions are shown in Fig. 1.[1]

This case study of the beverage company, as part of the larger Dutch food packaging ecosystem, served as a tangible inventory, providing a practical foundation for the conceptualization of the ABM. The

[1] The case study data on the Dutch food packaging ecosystem and its actors represent the situation in 2023.

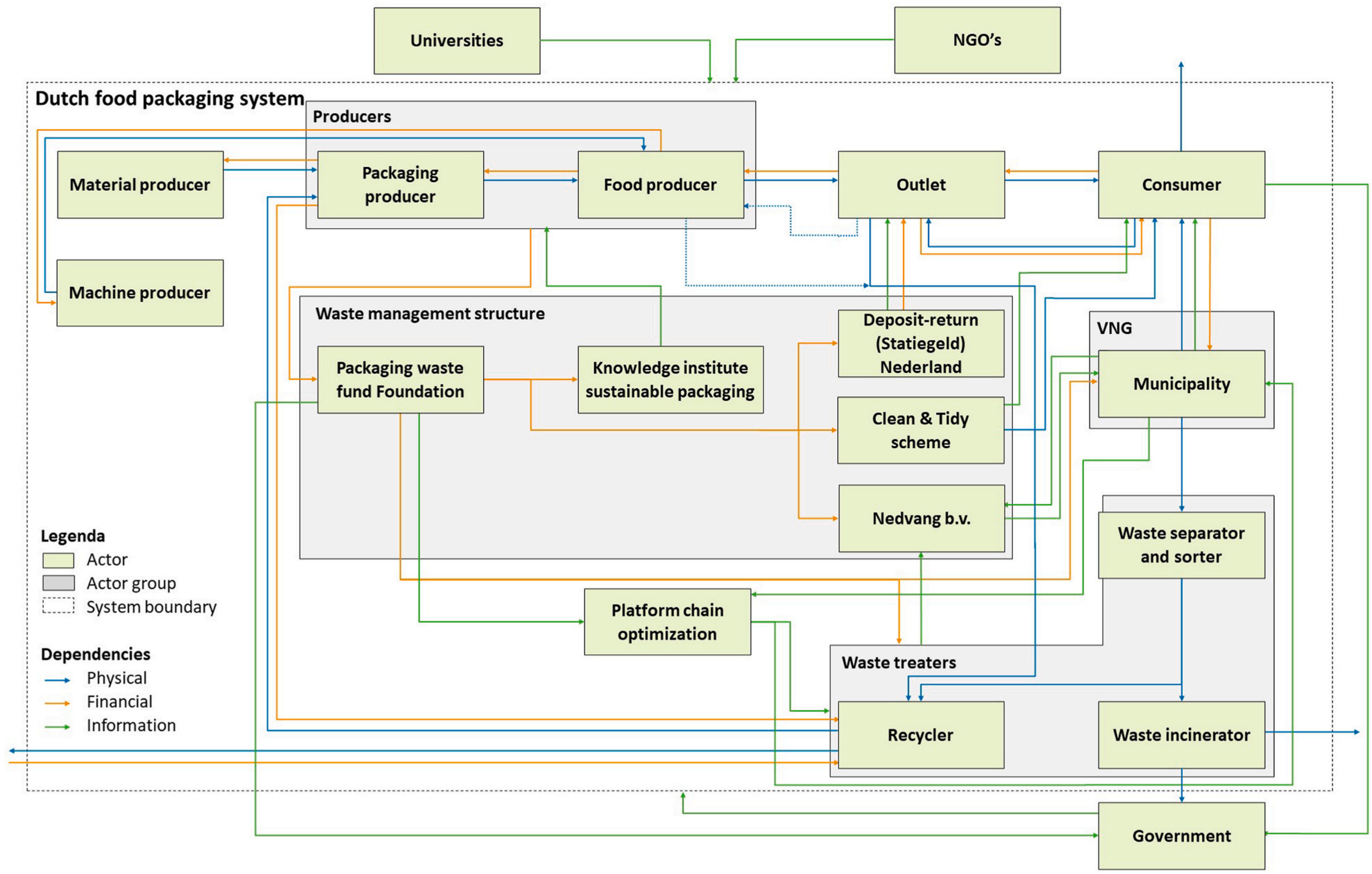

Fig. 1. Actors in the Dutch food packaging ecosystem and their material, financial and information dependencies.

packaging producers, beverage producers and waste treaters (as a composite of the waste treating actors) have been modelled as agents in the ABM, whereas the other actors have been represented via environment variables as shown in Section 3.2. This approach allows us to focus on impactful decision-makers within the ecosystem, providing clarity to the analysis and maintaining a manageable model complexity, while allowing for the analysis of other ecosystem actors' influence through environment variables.

3.2. Conceptualization of decision-making behaviour

As explained in Section 2.2, this study used the organizational decision-making framework by Scharpf (1988a) to characterize organizational behaviour in the Dutch food packaging ecosystem. Four combinations of the framework's decision-styles and decision-rules were used to characterize the behaviour of organizations (Fig. 2). Considering decision-styles (vertical axis), problem-solving and bargaining are the most probable styles for decision-making in a collaborative context. The problem-solving decision-style focuses on cooperation and pursuing common goals as a group, while the bargaining decision-style is driven by self-interest, being unconcerned about the outcome for others. In the confrontational decision-style, winning is the main driver, and collective gain is interpreted as no gain (Scharpf, 1988a). The establishment of a circular ecosystem requires collaboration; therefore, the confrontation decision-style is deemed unsuitable in a circular ecosystem. Regarding decision-rules (horizontal axis), the potential decision-rules in circular ecosystems are unanimity and hierarchy. The unanimity rule is considered the most likely decision-rule within an ecosystem, as decisions are made between private sector organizations. However, when the ecosystem is perceived as an organization of multiple organizations, the hierarchy decision-rule may apply, implying that certain organizations

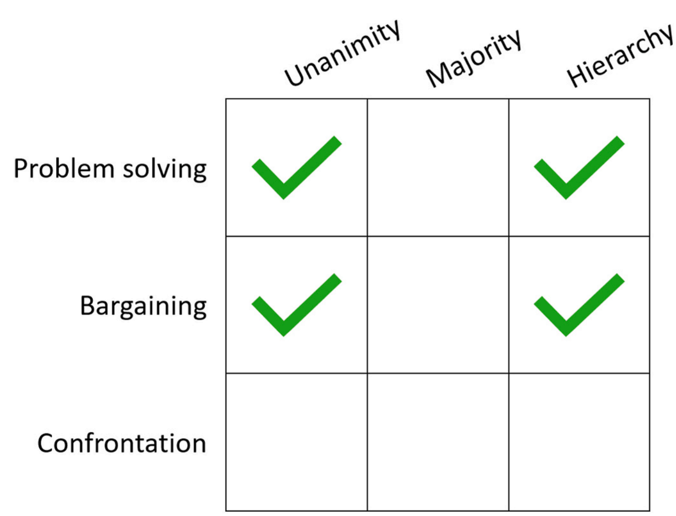

Fig. 2. Combinations of decision-rules and styles used to characterize organizations in the Dutch food packaging system (based on decision-making framework by Scharpf, 1988).

hold more power in decision-making than others. The majority decision-rule is less relevant in this study, as it is mainly used within the public sector, for example, in elections or voting on bills (Scharpf, 1988a). The four combinations of decision-styles and –rules shown in Fig. 2 were used for the conceptualization of behaviour in the ABM.

3.3. An agent-based model of a food packaging ecosystem

The results from the system analysis were used as the inventory to conceptualize the ABM of the beverage company's Dutch food packaging ecosystem (Reitsema, 2024). The conceptualization began with selecting three key actors in the ecosystem as agents: the beverage producer, packaging producers and waste treaters. These three agents make decisions that affect the circularity of the food packaging ecosystem and can collectively form closed-loop recycling circular ecosystems, meaning that packaging waste can be recycled into new packaging. By focusing on these three actors, the model captures dynamics crucial for understanding the ecosystem's circularity potential, while simplifying the complexity of including all possible actors. The processes the agents undergo were formulated based on information from literature, interviews with a Packaging Developer of the beverage company and a Business Analysts of the Dutch waste management structure, and quantitative sales data of the selected product. After model conceptualization and formalization, the ABM was implemented in NetLogo version 6.3.0 (Wilensky, 1999). An overview of the key modelling assumptions is provided in Appendix A. Correct implementation of the model was verified by performing various test runs and tracking agent behaviour.

3.3.1. Modelling concepts

3.3.1.1. Beverage producer agents. Although the beverage company is the producer of a single beverage, the company sells its product in various packaging formats, five of them being the most common (accounting for at least 1 % of the total weight of used packaging). Therefore, the beverage producer is divided into five agents to set up the ecosystem in the ABM, representing the production of cans, PET bottles, glass bottles, cartons, and bag-in-boxes. In other words, even though we are modelling only one beverage company, we assume that there are five different companies, each responsible for a certain packaging type. All five agents are referred to as beverage producers. Each beverage producer agent packs a certain product volume, constituting a portion of the total product volume. Consequently, the producer has a packaging demand based on the product volume, as well as the volume per packaging type, weight per packaging type and number of reuses per packaging type.

Each beverage producer agent requires a packaging supplier with a sufficient amount of the correct packaging type. The supplier selection process is simplified in the model, assuming only a one-year contract with the supplier, so beverage producers can seek a new packaging producer. In reality, contracts may have longer durations and complex renegotiation processes that are not captured in this model. The model also assumes that all packaging producers can supply the packaging type that fits the current production line, which simplifies real-world constraints such as production capacity limitations and technological compatibility. The choice for a packaging producer depends on the decision-style of the beverage producer agent: if the agent has a bargaining decision-style, it looks for a packaging producer agent with the best price and if the beverage producer agent has a problem-solving decision-style, it looks for a packaging producer agent with the highest overall recycled content.[2] In the model, the decision-style is assumed to be deterministic, meaning that a bargaining beverage producer always chooses the lowest-priced packaging, and a problem-solving beverage producer always opts for packaging with the highest recycled content. This deterministic approach does not account for potential variations in decision-making, due to e.g. external regulations or shifts in corporate strategy, which could introduce more dynamic behaviour in real-world scenarios. Fig. 3 demonstrates the processes of the beverage producer agents.

3.3.1.2. Packaging producer agents. Secondly, the packaging producer agents are conceptualized. The exact number of packaging producers per packaging type could not be established for our case, except for one packaging producer with an almost complete monopoly on drink cartons. For other packaging types, only information on the amount of waste per packaging type in the Netherlands is available (Afvalfonds Verpakkingen, 2023). Therefore, the model creates five hypothetical packaging producer agents for each remaining type, aiming to balance between a monopoly and numerous producers.[3] In the ABM, each packaging producer agent produces a randomly assigned portion of the total waste for that packaging type. Consequently, the packaging volume of a packaging producer agent varies per setup but remains constant throughout the simulation. Each packaging producer agent has a list of required materials for their packaging type, a list indicating the proportions of those materials in the packaging and a list specifying the maximum potential recycled content for each material.

The model assumes that each packaging producer agent calculates the demand for required materials annually. This material demand is divided into recycled material demand, based on the maximum potential recycled content, and the remaining material demand. If the packaging producer agent demands recycled material, it seeks a waste treater agent that can supply the correct material. If a packaging producer agent has a bargaining decision-style, it compares the lowest-priced recycled material with the virgin material price and buys the most affordable option. Conversely, a problem-solving packaging producer agent looks for the waste treater agent offering the most recycled material and buys it, regardless of price. This binary decision-making process does not account for hybrid strategies where companies balance cost and sustainability goals. If the recycled-material supply falls short of the packaging producer agent's demand, the agent recalculates the rest-material demand and buys that amount of virgin material. Afterwards, each packaging producer agent calculates the overall recycled content of the packaging based on the recycled content per material. Finally, the packaging producer agent determines the packaging price using the prices of recycled and virgin materials before selling the packaging to either the beverage company agent or another beverage producer outside the model, also referred to as the environment. The model assumes all produced packaging will be sold, either to the beverage producer agent or the environment. Market dynamics, including changes in demand, have not been considered in this ABM. Fig. 4 outlines the activities of the packaging producer agents.

3.3.1.3. Waste treater agents. Lastly, the ABM includes waste treater agents, collectively representing Dutch waste sorters, incinerators, and recyclers. Although specific numbers of waste treaters are inadequate for accurately representing the composite 'waste treater' agents, data on waste volumes per material type are available (Afvalfonds Verpakkingen, 2023). These serve as the basis for modelling the waste treater agents. Like the packaging producer agents, the model generates hypothetical waste treater agents for each material type, each responsible for handling a randomly assigned portion of the total Dutch waste volume for that material. The ABM includes three waste treater agents per material (based on statements of the waste management structure's Business Analyst that the number of sorters and recyclers in the Netherlands is limited). The waste treater agents collect and treat a randomly assigned waste volume that varies in each setup but remains

[2] The model assumes that all beverage producer agents have the same decision style, as they are part of the same organization. Therefore, if the decision style of the beverage producer agents is bargaining, all five agents will adopt this style. The model does not account for differences in decision-styles across departments within the organization.

[3] This modelling choice may impact outcomes, as a different number could reveal alternative patterns.

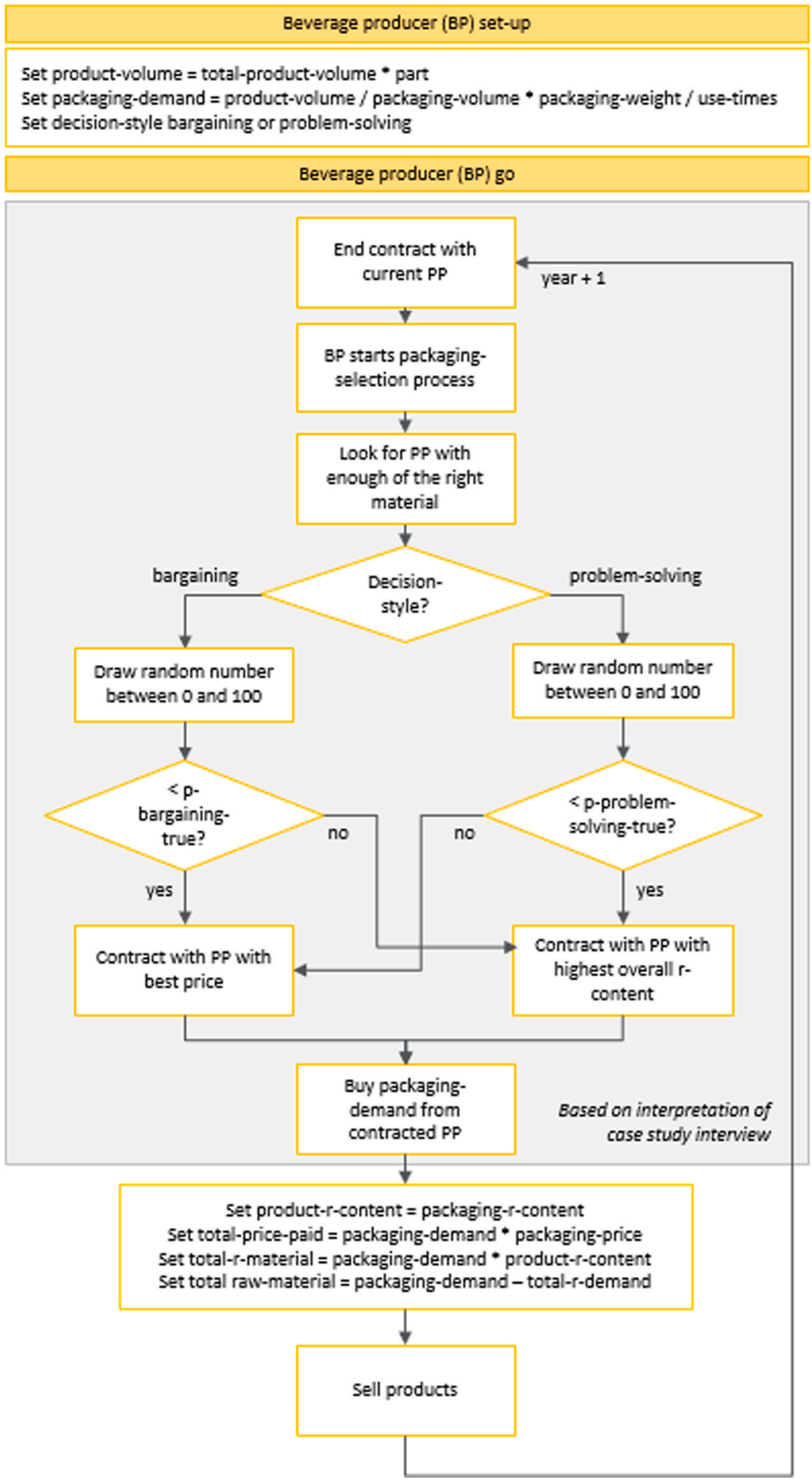

Fig. 3. Flowchart of the model concept of beverage producer agents' packaging selection process.

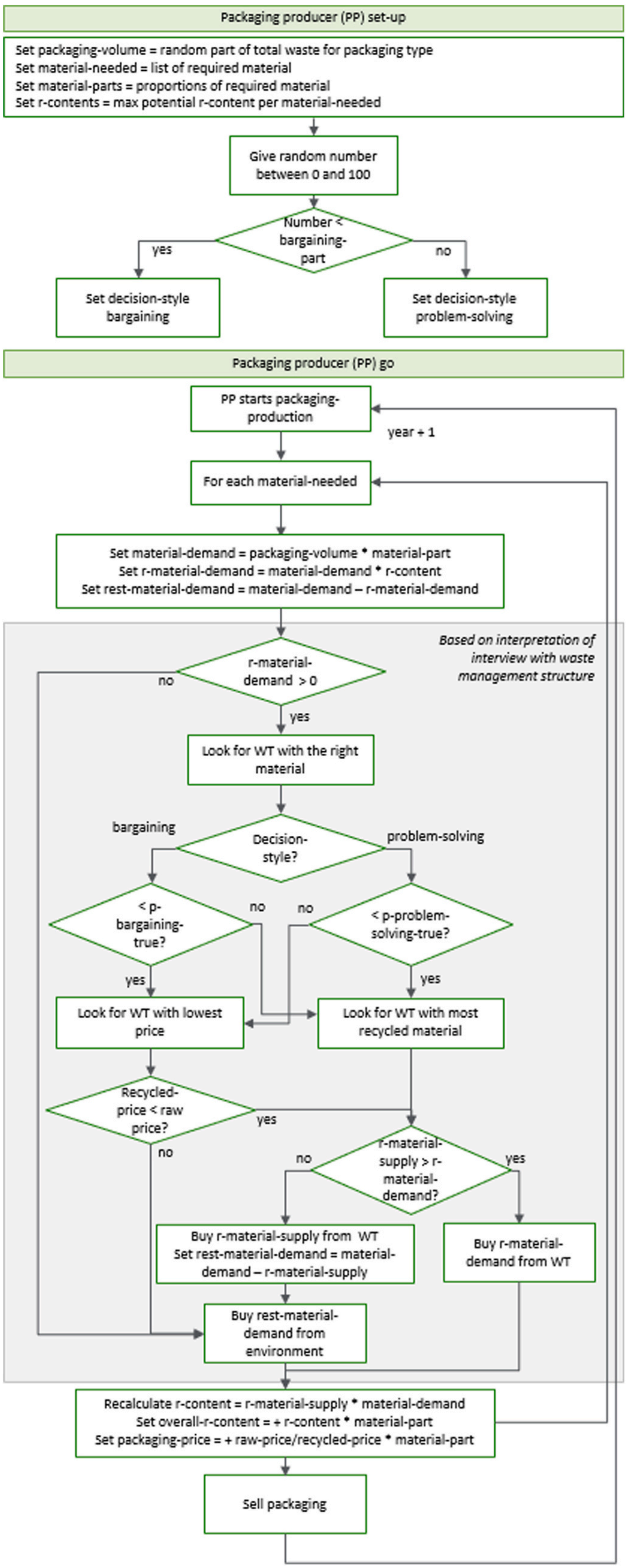

Fig. 4. Flowchart of the model concept of the packaging producers' material selection process.

constant during the simulation. Each waste treater agent is assigned a predefined starting price for the recycled material, which they use as the initial selling price.

In the ABM, the waste treater agent recycles a part of the collected waste at the year's start, determined by the current recycling rate for that specific material in the Netherlands. This recycling rate can fluctuate by up to 10 % higher or lower than the average recycling rate, varying annually. This modelling choice enables the consideration of recycling rate fluctuations but does not account for sudden disruptions. If a waste treater agent supplied a packaging producer agent in the previous year and has a bargaining decision-style, they raise their price for recycled material to maximize profit. Conversely, if the waste treater agent did not supply any packaging producer agent in the previous year and has a problem-solving decision-style, they lower the price of recycled material, preferring closed-loop recycling as the 'greater good'. For this adjusted price, the waste treater agent sells recycled material to packaging producer agents or to another party not included in the model, i.e., the environment. Similar to packaging producer agents, the model assumes all recycled material will be sold, either to a packaging producer agent or the environment. Fig. 5 shows the processes of the waste treater agents.

3.3.1.4. Environment. Other actors in the Dutch food packaging ecosystem are represented in the model through environment variables. The environment was structured by defining variables related to agent behaviour, Dutch waste, pricing, and innovation, along with performance metrics for analysing the potential of circular ecosystems to reduce packaging waste. The main aim of these performance metrics is to assess the impact of circular ecosystems on packaging waste generated by the beverage company, considering the types of materials used (raw, open-loop recycled, and closed-loop recycled materials), focusing on maximization of closed-loop recycling. Additionally, indicators were used to examine the potential of circular ecosystems to reduce packaging waste within the broader Dutch food packaging ecosystem, encompassing factors like raw material demand, waste volumes, and recycled material prices.

Fig. 6 outlines the model narrative.

3.3.2. Parameter setup and experimental design

3.3.2.1. Parameter setup. After conceptualization and implementation, the model was used to analyse the potential for reducing packaging waste (Reitsema, 2024). The model includes numerous input variables to ensure flexibility and enable diverse experimentation. For this study, the parameters were configured to represent the beverage company from the case study within the Dutch food packaging system (provided in Appendix A). The percentages of different packaging types as a portion of the total packaging are confidential industry data provided by the beverage producer under a non-disclosure agreement. The data reflects real-world sales volumes and packaging distributions, ensuring alignment with industry practices. To maintain confidentiality, the raw data was aggregated and anonymised to preserve the key statistical properties while preventing identification of the organization. Validation of the confidential data was conducted through consultation with industry experts and cross-referencing with publicly available market data, such as packaging market reports (Grand View Research, 2023), ensuring external validity.

3.3.2.2. Sensitivity analysis. After the parametrization, a one-factor-at-a-time (OFAT) sensitivity analysis was conducted to analyse the model's sensitivity towards decision-styles and -rules within the ecosystem. OFAT is a suitable method to gain insight into dynamics and patterns produced by the ABM (Ten Broeke et al., 2016). By systematically altering the decision-styles and -rules, the sensitivity analysis provides a nuanced understanding of how a shift from 'bargaining' to

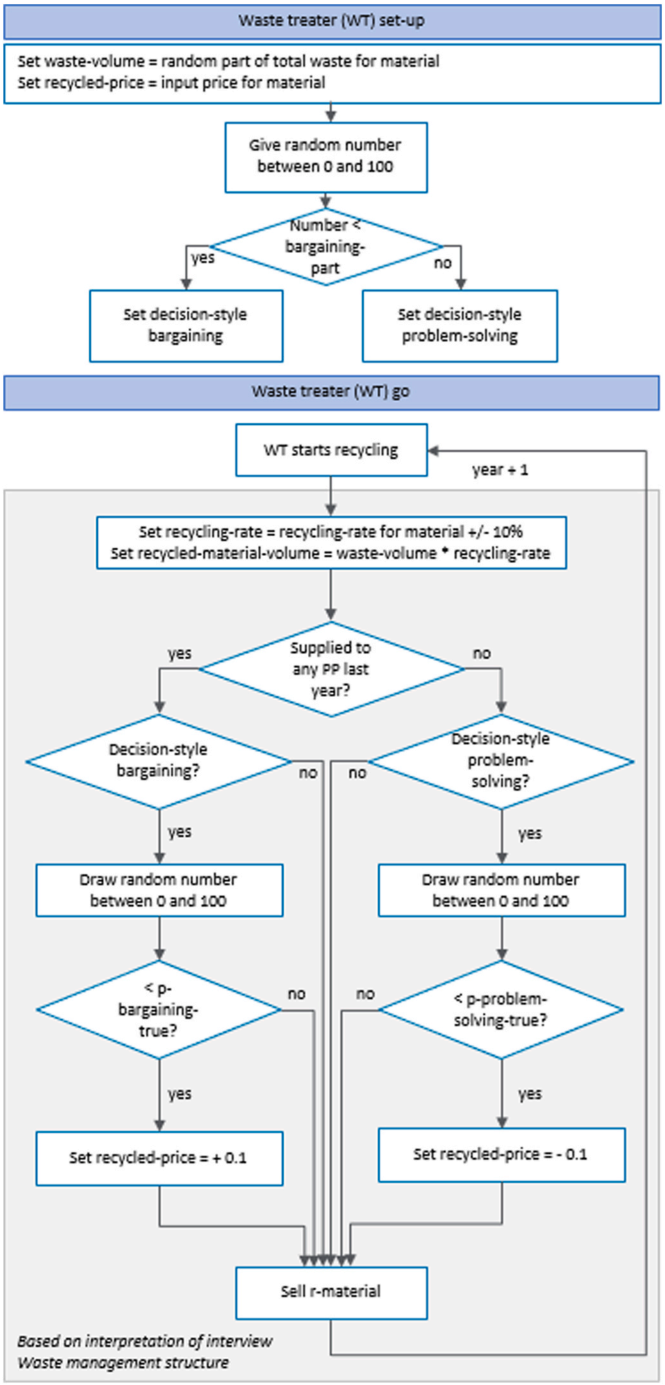

Fig. 5. Flowchart of the model concept of the waste treaters' waste selling process.

'problem-solving' decision-styles affects packaging waste management.

For the OFAT analysis, parameters were modified to examine the effect of three variables on packaging waste in the ecosystem: 1) the composition of decision-styles within the ecosystem, 2) the decision-style of the beverage producer and 3) the decision-rule employed within the ecosystem. The analysis started with an ecosystem comprising 100 % bargaining agents, followed by step-by-step decreases of 10 % until a final ecosystem of 0 % bargaining agents. The decision-styles were distributed randomly across the different types of agents. The second variable examines the decision-style of the beverage producer, which can be either bargaining or problem-solving. All beverage producer agents represent the production line of a specific beverage format; however, the five agents belong to the same company, meaning that these agents have the same decision-style. The third variable considers the decision-rule, which can be unanimity or hierarchy. By activating the hierarchy setting, the first-mover advantage is intentionally introduced. With this setting, the packaging producers perform their procedures in order of highest to lowest packaging volume, enabling an analysis of the effect of the hierarchy decision-rule in the circular ecosystem.

The setup of the sensitivity analysis is summarized in Table 1. The metrics show the settings for the variables *"fp-bargaining?"* and "*unanimity?*". For the *"bargaining-part"* variable, a step-by-step increase of 10 % was used, and for each step, ten runs were executed, resulting in 110 runs per scenario amounting to 440 runs in total. The number of repetitions was chosen based on preliminary convergence testing, where additional repetitions did not significantly alter the key outcome variables. The other input variables were set following the parameters described in Appendix A, ensuring consistency across all runs.

3.3.2.3. Experimental design. The experimentation in this study explored the practical implementation of waste management strategies and their interactions within broader ecosystem dynamics. The experiments were used to assess the effectiveness of different approaches in reducing packaging waste and identify potential implications. Five scenarios were tested, each representing a different waste management approach. This paper presents the results of two scenarios: centralized and decentralized waste management. The additional three scenarios explore the effects of reducing secondary material volume, increasing maximum potential recycled content and increasing recycling rates. The results from these additional scenarios are available in Appendix B.

Centralized waste management involves a single waste-treating

Table 1
Overview of the variable settings during the sensitivity analysis and the number of repetitions per setting.

		fp-bargaining?	
		TRUE	FALSE
unanimity?	TRUE	**Scenario 1** Bargaining-part 0 %, 10 % … 100 % *(n = 110)*	**Scenario 2** Bargaining-part 0 %, 10 % … 100 % *(n = 110)*
	FALSE	**Scenario 3** Bargaining-part 0 %, 10 % … 100 % *(n = 110)*	**Scenario 4** Bargaining-part 0 %, 10 % … 100 % *(n = 110)*

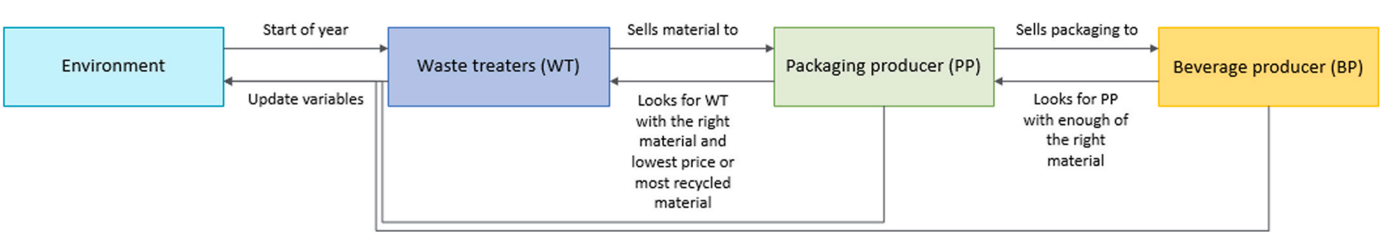

Fig. 6. Overview of the model narrative and the interactions between the model concepts.

organization managing waste processing and operating with the same decision-style, which can streamline processes but may lack flexibility. In contrast, decentralized waste management distributes waste treatment across multiple treaters, which can enhance adaptability and local optimization but may lead to inconsistencies. These two waste management strategies were compared to understand potential benefits and trade-offs.

During this experiment, the behavioural variables were fixed to represent 90 % bargaining agents, a problem-solving beverage producer and a unanimity decision-rule, which is on the conservative side and may best represent the status quo in the current packaging system (based on interviews with the Packaging Developer of the beverage company and the Business Analyst of the Dutch waste management structure). For the decentralized waste management scenario, input variables were set following the parameters described in Appendix A. The centralized waste management scenario is established by setting the number of waste treaters to one for each packaging material and giving all waste treaters the same decision-style. This experimental setup was used for ten repetitions in both scenarios to enable the identification of patterns. Again, ten repetitions were determined as sufficient based on convergence analysis, ensuring results were stable while keeping the computational requirements feasible.

3.3.2.4. Data analysis. For the sensitivity analysis and experiments, time series data was collected on the recycled content in the beverage producer's (combination of five producer agents) products. Within the runs, five packaging types are used, each with specific parameters for recycled content and the price paid per kilogram. For the sensitivity analysis, this results in a comprehensive dataset of 2200 rows containing the time series and for the experiments, this results in 50 time series per scenario. Furthermore, data was gathered on the raw, open-loop, and closed-loop recycled material used by the beverage producer in 2050, combining all packaging types.

The data from the simulations was collected and processed in Python 3.10. To visualize the data and identify patterns, graphs were created for the time series data of the recycled content for each material. The graphs of the recycled content time series were visually interpreted for pattern identification. Statistical analysis was conducted for the sensitivity analysis to compare the recycled content in 2050 for different setups and determine what compositions led to an increase. For this analysis, residuals were tested for normality using skewness and kurtosis analysis (Cain et al., 2017), followed by homogeneity of variances testing with Levene's or Brown-Forsythe tests (Garson, 2012), depending on the residual distribution. Since the assumption of equal variances was not met, Welch's ANOVA was used to test for significant differences in recycled content between groups. A Games-Howell post hoc test was then applied to determine which specific groups significantly differed.

4. Results

4.1. Sensitivity analysis: exploring the impact of decision-making styles on closed-loop recycling

4.1.1. Investigating recycled content variability in the beverage packaging ecosystem

Several observations stand out when looking at the time series data for recycled content per packaging in Fig. 7. The first noteworthy observation is the presence of spikes in the time series, which indicate fluctuations in the recycled content in packaging. The fluctuations are linked to the beverage producer's annual decision for a packaging producer and the packaging producer's annual decision for raw or recycled material. Cyclical supply-demand mismatches—driven by the timing of price adjustments, contract renewals, and agents' shifting

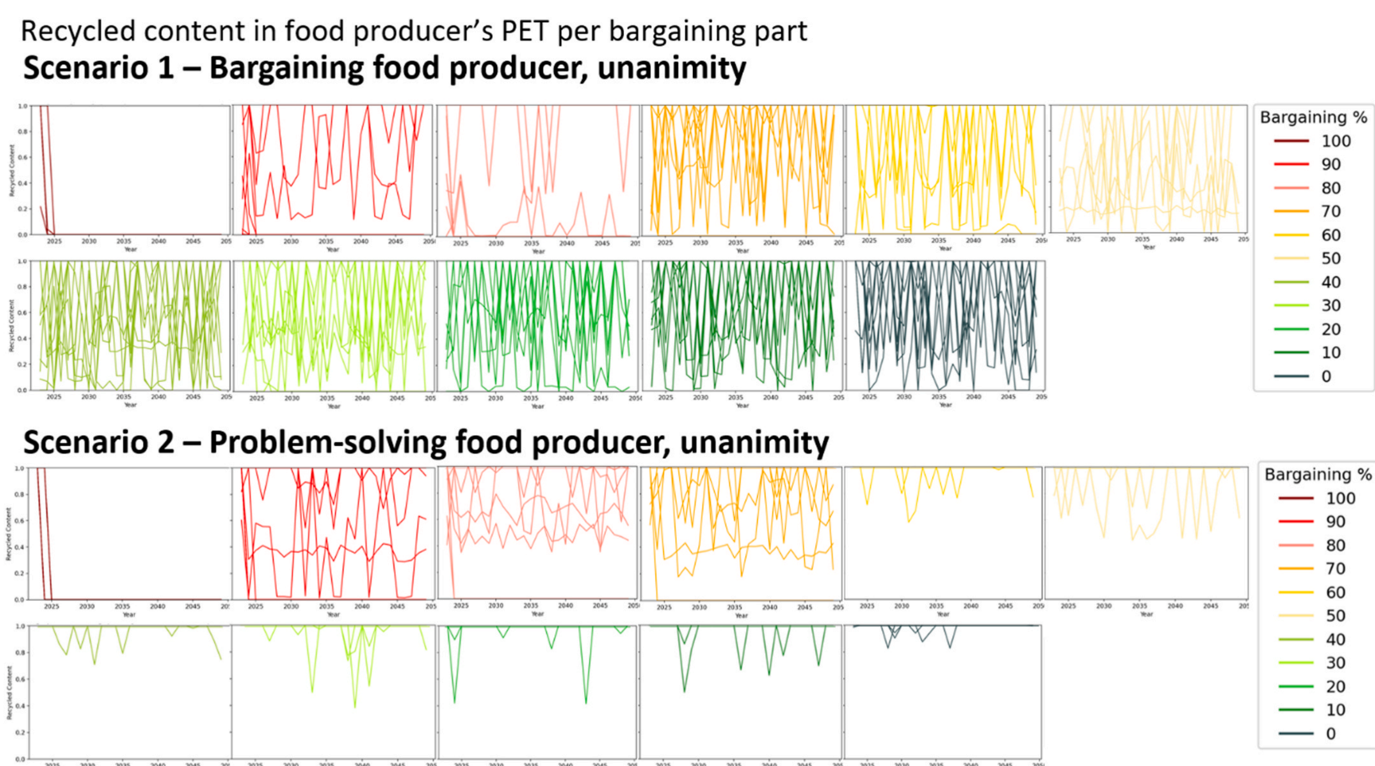

Fig. 7. Recycled content in PET bottles, represented by colour-coded graphs corresponding to different bargaining percentages within the ecosystem under the unanimity decision-rule. The upper graphs illustrate the recycled content time series in ecosystems with a bargaining beverage producer, revealing that the recycled content in PET bottles experiences greater fluctuations in ecosystems with a higher bargaining-part. The lower graphs present the time series for a problem-solving beverage producer, showing less fluctuations for the recycled content in PET bottles in ecosystems with a lower bargaining-part. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

preferences—exacerbate short-term changes in recycled content and create the observed spikey pattern. The spikes are especially prevalent in ecosystems where the beverage producer has a different decision-style than most of its ecosystem. There are multiple explanations for the presence of these spikes.

First, the spikes in the time series data appear in ecosystems with a bargaining beverage producer agent and a low value for the bargaining-part variable, indicating a larger proportion of problem-solving agents. In such ecosystems, several packaging producer agents want to buy recycled material from the waste treater, resulting in potential shortages and, consequently, lower recycled content in the packaging. The price of recycled material especially rises when some waste treater agents have a bargaining decision-style. However, problem-solving packaging producer agents continue to purchase recycled material despite higher prices, resulting in more expensive packaging. Conversely, the beverage producer agent goes for the lowest price, thus opting for packaging with less recycled content. Consequently, fluctuations in recycled content occur depending on the lowest price offered by the packaging producer agents. The top part of Fig. 7 shows that recycled content in a bargaining beverage producer's PET bottles fluctuates more frequently when the bargaining-part variable is 70 % or lower. In ecosystems with more bargaining agents, fluctuations are less common and may be caused by outliers.

Secondly, spikes are observed in the time series data of ecosystems comprising a problem-solving beverage producer agent and a large proportion of bargaining agents (bottom of Fig. 7). In these ecosystems, the beverage producer prefers packaging with high recycled content, while the ecosystem offers limited packaging options containing recycled material. When bargaining waste treater agents are present, the price of the recycled material increases as packaging producers buy it. Consequently, bargaining beverage producer agents may shift to cheaper virgin material instead of buying recycled material. Only a few problem-solving packaging producer agents offer recycled content, likely associated with higher prices for the beverage producer. The bottom of Fig. 7 also indicates that recycled content in a problem-solving beverage producer's PET bottles exhibits less fluctuation in ecosystems with lower values for the bargaining-parts variable.

A final explanation of the spikes in the time series is a shortage of recycled material, forcing packaging producer agents to supplement recycled material with virgin material. These shortages may occur when the maximum potential recycled content in packaging production exceeds the recycling rate of waste. This interpretation is supported by the limited occurrence of spikes in the drink carton and bag-in-box time series. These packaging types are made of material for which the available recycled material exceeds the amount useable as recycled content in new packaging.

Another noteworthy pattern emerges in the data for drink cartons. In ecosystems with a high value for the bargaining-part variable, the recycled content initially increases, followed by a drop. This phenomenon is most visible for the ecosystems with a high bargaining-part in Fig. 8. The sudden drop is explained by the fact that only one drink carton producer agent was modelled alongside multiple waste treater agents who recycle paper, aluminium, and plastic. Consequently, the drink carton producer agent can buy recycled material from bargaining waste treater agents at the initial price for multiple years, as the waste treaters only increase the price of the recycled material once they sell it to the packaging producer agent. This pattern is often observed in ecosystems with higher values for the bargaining-part variable, while it is less common in ecosystems with more problem-solving agents.

4.1.2. *Impact of decision-style composition on recycled content in beverage packaging*

The time series graphs elucidate the effect of the decision-style composition within the ecosystem. In general, ecosystems with a larger proportion of problem-solving agents tend to result in high recycled content in the beverage producer's packaging. A visual comparison of the average time series graphs suggests that the effect of the decision-style composition on the recycled content may also be affected by both the decision-style of the beverage producer and the decision-rule within the ecosystem. The statistical comparison of the scenarios gives insight into the consistency of these variations in the outcomes.

Fig. 9 shows the outcomes of the post hoc comparison of the scenarios through boxplots, illustrating the variance for each bargaining-part setting within each scenario. The letters above the boxplots indicate the significance group of each bargaining-part setting (p-value of 0.05). The boxplots show that each scenario has slightly different outcomes. In all scenarios, except scenario 3, the recycled content is significantly higher for an ecosystem with 90 % bargaining agents than an ecosystem with only bargaining agents. However, ecosystems with 80 % bargaining agents do not have significantly higher recycled content than ecosystems with 90 % bargaining agents. It is important to note that the variance of the outcomes is substantial, with most boxplots spanning from 0 to 1 or depicting outliers that may be more profound when the number of repetitions per scenario is larger.

Scenario 1 – Bargaining beverage producer and unanimity decision-rule: In scenario 1, ecosystems with 40 % bargaining agents or lower have a significantly higher recycled content than the 90 % bargaining ecosystems. The recycled content in ecosystems with a value for the bargaining-part variable between 90 % and 40 % does not differ significantly from the recycled content in ecosystems with 90 % bargaining agents nor from the recycled content in ecosystems with 40 % or less bargaining agents.

Scenario 2 – Problem-solving beverage producer and unanimity decision-rule: For scenario 2, a different outcome is shown. The

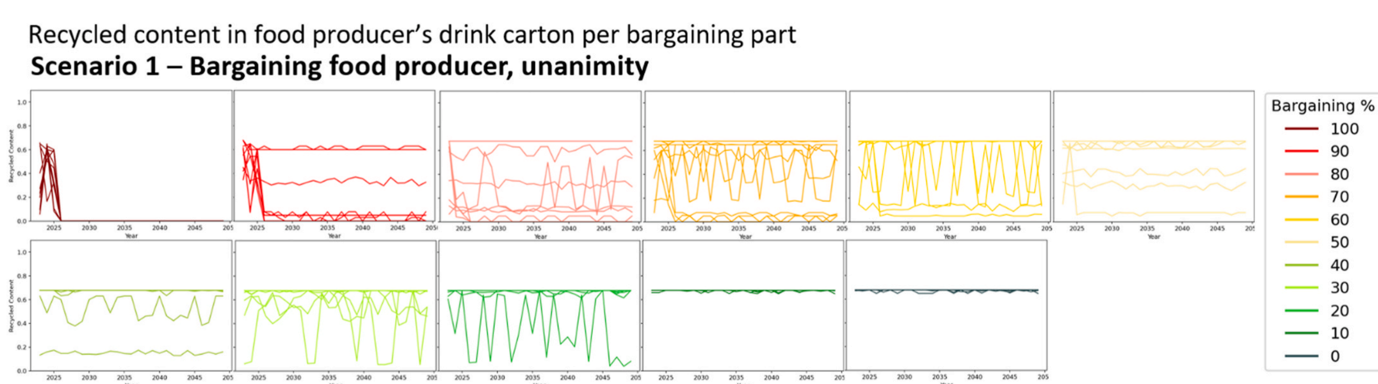

Fig. 8. Recycled content in drink carton for different bargaining percentages indicated by colour in separate graphs, showing an increase and drop of recycled content in ecosystems with mainly bargaining agents. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

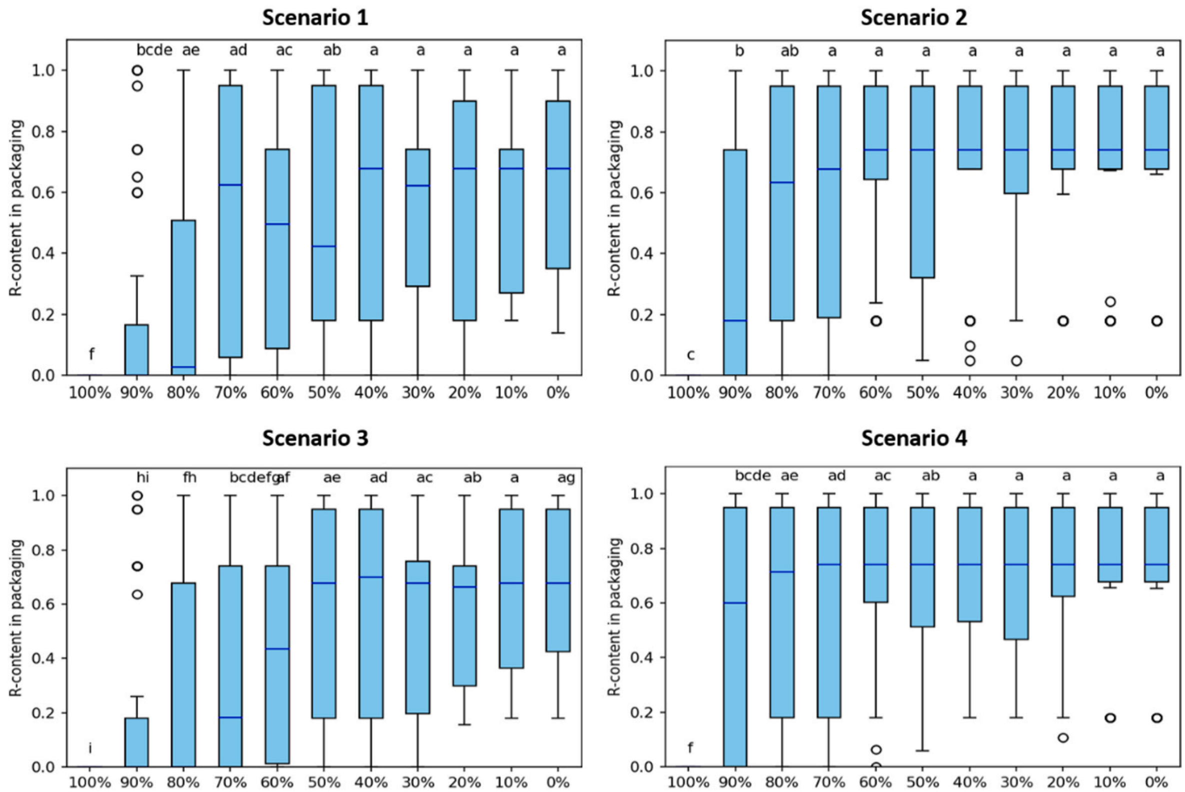

Fig. 9. Boxplot of recycled content in 2050 for each bargaining-part setting in the four scenarios. The letters above the boxplot indicate the significance scenario: boxplots with the same letter do not differ significantly. In all scenario's, the recycled content is significantly higher for ecosystems with 90 % bargaining agents than in ecosystems with 100 % bargaining agents.

ecosystems with 70 % or less bargaining agents have significantly higher recycled content than ecosystems with 90 % bargaining agents. Ecosystems with 80 % bargaining agents in this scenario do not significantly differ from either 90 % or 70 % or less bargaining agents.

Scenario 3 – Bargaining beverage producer and hierarchy decision-rule: Scenario 3 shows a more gradual increase in recycled content, like scenario 1. Unlike other scenarios, ecosystems with 90 % bargaining agents in scenario 3 do not result in significantly higher recycled content than ecosystems with only bargaining agents. Ecosystems with 80 % bargaining agents have a higher recycled content than the ecosystems with only bargaining agents but do not differ significantly from ecosystems with 90 % bargaining agents. The recycled content keeps gradually increasing with lower values for the bargaining-part variable, but no significant difference is identified between ecosystems with 60 % or fewer bargaining agents.

Scenario 4 – Problem-solving beverage producer and hierarchy decision-rule: Scenario 4 shows a similar pattern as scenario 1. Ecosystems with 40 % bargaining agents or lower have significantly higher recycled content than 90 % bargaining ecosystems. The ecosystems with a bargaining-part setting between 90 % and 40 % do not have significantly higher recycled content than ecosystems with 90 % bargaining agents or those with 40 % or fewer bargaining agents.

4.2. *Experimentation: Comparing centralized and decentralized waste management scenarios*

The results of the experiments indicate more stable supply of recycled material in a centralized waste management scenario compared to a decentralized scenario, where the ecosystem included multiple waste treaters with different decision-styles. Fig. 10 illustrates that the

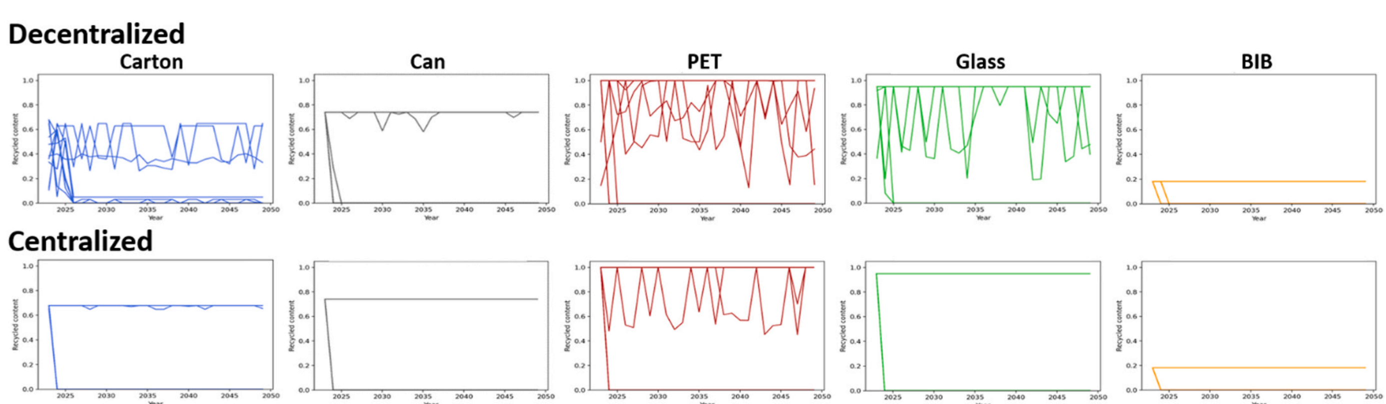

Fig. 10. Recycled content in the beverage producer's packaging in decentralized (top) and centralized (bottom) waste management scenarios, showing that central waste treatment can help overcome fluctuations in recycled content.

recycled content in the beverage producer agent's packaging is either zero or the maximum potential recycled content in the centralized waste management scenario, depending on the decision-style of the central waste organization. However, PET packaging's recycled content still fluctuates, most probably due to recycled material shortages. This pattern is also observed in drink cartons which contain PET. In some simulations, packaging producer agents capable of supplying large enough volumes to the beverage producer agent may have their turn later than smaller packaging producer agents who cannot meet the beverage producer agent's demand, resulting in limited recycled content in the packaging. Furthermore, the raw material demand did not differ between ecosystems with centralized or decentralized waste treatment.

These outcomes suggest that centralized waste treatment could lead to a more stable use of recycled material in packaging. However, the circular ecosystem's success in reducing packaging waste would depend entirely on the decision-style of the central waste treater.

Results from additional experimentation are provided in Appendix B, exploring the effects of reducing secondary material volume, increasing maximum potential recycled content and increasing recycling rates.

5. Discussion

This study sheds light on the dynamics of packaging waste in a circular food packaging ecosystem in the Netherlands. By using an ABM, the study shows how actor behaviour and decision-making can substantially affect the performance of circular ecosystems. Previous ABM studies in the circular economy and waste management domains mainly focused on consumer behaviour (e.g., Lieder et al., 2017; Meng et al., 2018; Koide et al., 2023) or on specific types of organizations, like producers (Albino et al., 2016; Fraccascia et al., 2017) or waste-treaters (Farahbakhsh et al., 2023). Unlike these studies, our approach explicitly incorporated multiple different organizational actors—beverage producers, packaging producers, and waste treaters—each with their own decision-style derived from Scharpf's (1988a) framework. This model allows us to analyse the effects of both different decision-rules (like unanimity vs. hierarchy) and decision-styles (such as bargaining vs. problem-solving).

Our focus on inter-organizational decision-making—and how it affects closed-loop material flows—provides a novel contribution. To highlight the differences between our model and previous ABM studies in this field, we summarise these distinctions in Appendix C. Our findings stress the importance of collaboration between actors in the food packaging ecosystem, enabling the use of recycled material, knowledge-sharing, and innovation.

5.1. *The impact of actor decision-making on ecosystem performance*

Experiments with the ABM reveal that the supply of recycled material in a circular food packaging ecosystem can fluctuate over time. These fluctuations lead to varying degrees of packaging waste reduction, and can be traced back to the decision-styles of ecosystem members and occasional shortages of recycled materials. The analysis shows that such fluctuations were more profound in ecosystems where there is an imbalance between bargaining and problem-solving actors. This imbalance can cause recycled content to vary greatly, due to price adjustments by waste treaters and the material selection processes of packaging producers. The literature supports these findings: uncertainty about costs can hold back the adoption of sustainable packaging (Afif et al., 2022) and material selection is a critical but complex step in moving towards a circular economy (Zhu et al., 2022).

Our results are consistent with Scharpf's (1988b) concept of the 'joint decision trap'. They demonstrate that ecosystems governed by unanimity decision-rules and dominated by profit-driven (bargaining) actors often become locked in suboptimal recycling outcomes. This happens because actors tend to delay or avoid circular initiatives that might undermine their own economic interests, resulting in coordination failures and stalled collective progress. These patterns provide clear empirical support for Scharpf's theoretical construct (1988a), where competing organizational objectives inhibit joint action in the absence of mechanisms to ensure mutual gain.

However, our model also shows that the presence of a key focal actor with a problem-solving decision-style, such as the beverage producer in our simulation, can help overcome the joint decision trap. When this central actor prioritises the collective goal of circularity over individual profit, the ecosystem can achieve significantly higher recycled content in packaging by 2050. This finding is consistent with previous insights on the impact of 'keystone actors' within business ecosystems (Iansiti and Levien, 2004; Yoon et al., 2022). A keystone actor can drive change by signalling long-term commitment, taking on initial risks, and encouraging other stakeholders to coordinate their efforts. Notably, this suggests that transformation towards circularity does not require all ecosystem actors to change simultaneously. Leadership from one or a few central actors can be sufficient to unlock collaborative strategies and reduce packaging waste. This insight points to an implication for policymakers: supporting early-stage collaborative initiatives in industry can be an effective lever to catalyse circularity, even if not all actors immediately adopt circular strategies.

Furthermore, our findings indicate that a hierarchy decision-rule, where certain actors hold greater decision-making power, could promote recycling in ecosystems with mostly bargaining actors, but further research is needed. Overall, these results empirically illustrate both the institutional barriers and the transformative potential described in Scharpf's framework, with particular emphasis on the critical role of focal actors in shaping coordination and circularity outcomes.

5.2. *Recycled material shortages*

The occurrence of recycled material shortages may limit achieving higher recycled content in the beverage producers' packaging. These shortages occur when the demand for recycled material is greater than the available supply, usually because recycling rates do not meet the technical potential for recycled content. In the model, packaging producers are assumed to request the maximum feasible recycled content, but in reality, this would require very high recycling rates to avoid material shortages. Shortages are observed for aluminium, PET, and glass.

Market studies are projecting similar potential shortages in recycled material in the Netherlands, specifically for plastic (Thoden van Velzen et al., 2019; KPMG, 2023). Recycled material shortages can be a challenge for circular ecosystems focusing on closed-loop recycling, as the material mass must be balanced but processes in the value chain are hardly 100 % efficient. The model does not account for material losses, but in practice, recycling rates must exceed the maximum recycled content to make up for these losses. This means that if the packaging is made of 100 % recycled material, there would need to be almost perfect recovery and minimal material degradation, or a reduction in overall packaging volumes.

Technological innovation could enhance closed-loop recycling to further reduce packaging waste. However, the success of these innovation depends on how actors in the ecosystem behave. Besides, circular ecosystems should not rely solely on end-of-the-pipe technologies and innovation. Instead, they should also consider strategies such as material reduction, packaging reuse or substituting material, for example, with bioplastics (Rosenboom et al., 2022; Markevičiūtė and Varžinskas, 2022). Ironically, these strategies may eventually decrease the volume of secondary materials available, but additional experimentation suggests that this does not directly affect the potential of the Dutch food packaging ecosystem to reduce waste (Appendix B1). Conversely, simply improving recycling rates and innovating to improve the maximum recycled content may not be sufficient to effectively reduce waste in the Dutch food packaging ecosystem (Appendix B2 and B3). Therefore, higher-level circular strategies are needed to overcome limitations related to material shortages. Ecosystem actors should be encouraged and supported in actively pursuing these strategies.

5.3. Centralized vs. decentralized waste management

Our findings indicate that centralized waste treatment could be useful to mitigate the fluctuations in recycled content and raw material demand. Centralization means that all recycled material in consolidated and managed by a single actor. This could lead to more stable supply at a consistent price. However, the success of this setup is dependent on the decision-style of the waste treater. Previous studies have emphasized the potential of a centralized waste management system as it helps with standardization, economies of scale and data collection (Esmaeilian et al., 2018; Massoud et al., 2019; Mohammadi et al., 2021). On the contrary, decentralized waste management has also been proposed as the more sustainable or cost-efficient waste management strategy in other research (Joshi et al., 2019; Kerdlap et al., 2020; Shanmugiah et al., 2024), but is more often suggested for organic waste management (Righi et al., 2013; Tian et al., 2021; De Souza and Drumond, 2022).

With upcoming regulatory changes, the central orchestration of waste treatment in the Netherlands holds the potential to facilitate circular ecosystems. The Dutch waste management structure could orchestrate this central waste treatment besides transparently monitoring packaging waste and recycling. A clear ecosystem architecture can facilitate these two roles. Centrally organizing waste treatment can stabilize the dynamics of packaging waste in the Netherlands and help overcome fluctuations in recycled content. Additionally, the waste management structure should promote closed-loop recycling and higher-level circular strategies, including packaging reduction and reuse, to further enhance circularity.

5.4. Limitations and future research

To improve the current model and ensure its applicability in the real world, it is important to address the study's limitations and identify areas for future research. One limitation of the model is its deterministic agent behaviour, where agents choose between cheaper or more circular packaging options. In reality, packaging decisions are influenced by various factors like occasion, marketing, and CO_2 footprint. A general limitation of ABM is that it often overlooks qualitative factors related to human behaviour, including emotions, complex psychological factors, and subjective choices, as these are difficult to incorporate into the model's rules (Palafox-Alcantar et al., 2020). Future research could benefit from incorporating more adaptive and negotiated behaviour among agents, for instance by allowing changes to decision-styles over time or including explicit bargaining and consensus-building processes. Such theoretical enhancements could deepen the understanding of how institutions and evolving inter-organizational relationships influence the dynamics in circular ecosystems.

The model's material selection process for packaging producers is overly simplistic, assuming they opt for the cheapest recycled material regardless of availability. In reality, producers will consider both material cost and volume availability and may consider other criteria like material quality and environmental performance (Mudgal et al., 2024). Additionally, agents in the model have limited adaptivity and their interactions are limited to observing information and making decisions, without direct collaboration. Adding traits like talkativeness, agreeableness and critical thinking (Bergner et al., 2016) could enhance the model's accuracy in reflecting real-world circular ecosystems. Furthermore, financial components are simplified in the model. Hypothetical prices were used for raw and recycled materials, which could be improved by incorporating actual price data to better represent the economic dynamics of the Dutch food packaging ecosystem.

The model focuses on a closed-loop recycling ecosystem, omitting other potential circular ecosystems such as packaging reuse or alternative materials. Glass bottle reuse is included in a simplified form but does not account for return logistics. A refined model could incorporate alternative circular strategies, such as packaging reuse or alternative materials, to explore their potential to reduce packaging waste. This may require additional agents, such as outlets and consumers.

Finally, the circular ecosystem relies on the availability of information regarding the materials used by actors, which presents a potential bottleneck. The model is built on the implicit assumption that data on recycled material volumes and recycled content is accessible, allowing actors connect. This type of data sharing would require a data-sharing infrastructure, which is currently not widespread. The Dutch waste management structure recently started monitoring waste volumes and recycling rates, providing limited circularity-related data (Interview with Waste Management). Additionally, packaging producers and beverage producers do not always indicate the recycled content in their packaging due to missing information (Interview with Packaging Developer). Research emphasizes that waste management can promote retaining material value through improved data sharing and cooperation between the actors in the ecosystem (Salmenperä et al., 2021). Digital technologies could facilitate safe and transparent data-sharing, connecting actors within the ecosystem to enable effective waste reduction (Rossi and Srai, 2024). These technologies could be supported by the Dutch waste management structure or an independent broker. Future research should further explore the implications of limited data and the role of digital platforms in circular ecosystems.

6. Conclusion

This study contributes to the research field of circular economy by advancing the understanding of how organizational decision-making behaviour influences the success of circular ecosystems in reducing waste. By employing an ABM, this research provides novel insights into the interplay between actor decision-styles, material flows, and ecosystem stability, demonstrating how individual and collective behaviour shape circularity outcomes. Specifically, it highlights the critical role of a focal actor, such as a beverage producer, in driving ecosystem-wide improvements in recycled content, even in ecosystems consisting mainly of actors prioritizing individual profit. This challenges the common assumption that an individual actor cannot drive a transition to circularity within an ecosystem due to the belief that other actors will not change their behaviour.

The study extends existing research on circular ecosystems by identifying potential implications related to organizations' decisions, such as recycled material shortages. Additionally, experimentation illustrates the potential benefits of centralized waste management in mitigating fluctuations in material availability. Although this research focuses on the Dutch context, the findings are transferable to countries or regions with similar policy environments, particularly those implementing centralized waste management systems, extended producer responsibility schemes, or deposit-return systems for packaging materials. Countries with regulatory frameworks that promote inter-organizational collaboration, transparent material flows, and data-sharing infrastructure are likely to benefit most from the insights presented here. Conversely, in countries with highly fragmented or informal waste management, additional adaptation may be required to account for regulatory and infrastructural differences. The conceptual and methodological approach, however, remains relevant for any context aiming to foster effective circular ecosystems through collaborative decision-making.

The practical insights gained from the ABM experimentation underscore its ability to support strategy development for circular ecosystems. Methodologically, it enhances the application of ABM in the circular economy domain by incorporating organizational decision-making dynamics, emphasizing the need for more nuanced behavioural representations of composite actors in circular economy modelling.

Finally, this research indicates the directions for future studies that integrate more realistic decision-making processes, collaborative strategies, and multi-dimensional sustainability assessments in circular ecosystems. This study underscores the importance of organizational decisions and collaboration in fostering effective circular ecosystems, providing valuable insights for researchers, industry stakeholders and policymakers aiming to accelerate circularity transitions.

CRediT authorship contribution statement

Annoek Reitsema: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Eric Onderdelinden:** Writing – review & editing, Writing – original draft, Validation, Investigation, Funding acquisition, Data curation, Conceptualization. **Gijsbert Korevaar:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Data curation, Conceptualization. **Amineh Ghorbani:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Annoek Reitsema reports financial support was provided by Deloitte. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendices.

Supplementary Information.

Appendix A. – Model parameters, sources and key assumptions

Table 1
Parameter setup and sources

Material	Part of modelling concept	Variable	Value	Unit	Source and comment
–	Beverage producer	Total product volume	1,000,000	Liter	Assumption
All	Beverage producer	Part of total weight	*confidential*	%	Product brand management of beverage company, values known by researcher
		Part of total product volume	*confidential*	%	Product brand management of beverage company, value known by researcher
Drinking carton	Beverage producer	Packaging volume	1	Liter	Website beverage company
		Packaging weight	0.032	kg	Website packaging producer
		Use times	1	#	Afvalfonds Verpakkingen, 2023
	Packaging producer	Number of producers	1	#	Interview with packaging developer of beverage company, one packaging producer has almost complete monopoly
		Required materials	paper; aluminium; plastic	list	Website packaging producer
		Material parts	69; 4; 2.7	list of %	Website packaging producer
		Maximum potential recycled content	87; 74; 18	list of %	Hanemaaijer et al., 2023; PRN, 2022; Afvalfonds Verpakkingen, 2023
	Waste treater	Number of treaters	3	#	Assumption based on interview with Dutch waste management structure
		Amount of waste	82,800,000	kg	Milieu Centraal, 2023
		Recycling rate total	31	%	Thoden van Velzen and Smeding, 2022
Aluminium can	Beverage producer	Packaging volume	0.25	Liter	Website beverage company
		Packaging weight	0.0091	kg	Weighting by researcher
		Use times	1	#	Afvalfonds Verpakkingen, 2023
	Packaging producer	Number of producers	5	#	Assumption
		Required materials	aluminium	list	Assuming that the weight of other materials in the packaging (e.g., coatings) is negligible
		Material parts	100	list of %	
		Maximum potential recycled content	74	list of %	Afvalfonds Verpakkingen, 2023, based on the closed-loop recycling rate prior to implementation of the Dutch deposit-return system on cans
	Waste treater	Number of treaters	3	#	Assumption based on interview with Dutch waste management structure
		Amount of waste	42,750,000	kg	Afvalfonds Verpakkingen, 2023
		Recycling rate total	74	%	Afvalfonds Verpakkingen, 2023
PET-bottle	Beverage producer	Packaging volume	0.3	Liter	Website beverage company
		Packaging weight	0.023	kg	Weighting by researcher
		Use times	1	#	Afvalfonds Verpakkingen, 2023
	Packaging producer	Number of producers	5	#	Assumption
		Required materials	PET	list	Assuming that the weight of other materials in the packaging (e.g., coatings) is negligible
		Material parts	100	list of %	
		Maximum potential recycled content	100	list of %	Interview with packaging developer of beverage company
	Waste treater	Number of treaters	3	#	Assumption based on interview with Dutch waste management structure
		Amount of waste	32,760,000	kg	Hanemaaijer et al., 2023; Afvalfonds Verpakkingen, 2023, 6 % of the total plastic waste in the Netherlands is PET and the rest is other plastic

(*continued on next page*)

Table 1 (*continued*)

Material	Part of modelling concept	Variable	Value	Unit	Source and comment
		Recycling rate total	48	%	Afvalfonds Verpakkingen, 2023
Refillable glass bottle	Beverage producer	Packaging volume	0.2	Liter	Website beverage company
		Packaging weight	0.155	kg	Weighting by researcher
		Use times	30	#	KIDV, 2022a
	Packaging producer	Number of producers	5	#	Assumption
		Required materials	glass	list	Assuming that the weight of other materials in the packaging (e.g., coatings) is negligible
		Material parts	100	list of %	
		Maximum potential recycled content	95	list of %	KIDV, 2022a
	Waste treater	Number of treaters	3	#	Assumption based on interview with Dutch waste management structure
		Amount of waste	256,000,000	kg	Afvalfonds Verpakkingen, 2023, 50 % of the total glass in the Netherlands is in the deposit-return system
		Recycling rate total	79	%	Afvalfonds Verpakkingen, 2023
Bag-in-Box	Beverage producer	Packaging volume	18	Liter	Website beverage company
		Packaging weight	0.073	kg	Website beverage company
		Use times	1	#	Afvalfonds Verpakkingen, 2023
	Packaging producer	Number of producers	5	#	Assumption
		Required materials	plastic	list	Assuming that the weight of other materials in the packaging (e.g., coatings) is negligible
		Material parts	100	list of %	
		Maximum potential recycled content	0.18	list of %	Hanemaaijer et al., 2023
	Waste treater	Number of treaters	3	#	Assumption based on interview with Dutch waste management structure
		Amount of waste	513,240,000	kg	Hanemaaijer et al., 2023; Afvalfonds Verpakkingen, 2023, 6 % of the total plastic waste in the Netherlands is PET and the rest is other plastic
		Recycling rate total	48	%	Afvalfonds Verpakkingen, 2023
Paper	Waste treater	Number of treaters	3	#	Assumption based on interview with Dutch waste management structure
		Amount of waste	139,000,000	kg	Holwerda et al., 2019; Afvalfonds Verpakkingen, 2023, 10 % of the total Dutch paper and cardboard waste is food packaging
		Recycling rate total	87	%	Afvalfonds Verpakkingen, 2023
All	Waste treater	Start-price	0.1	€	Variables that allow flexibility for future experimentation, now all set at the same value for all packaging types
		Increase in price if bargaining and selling	0.1	€	
		Decrease in price if problem-solving and not selling	0.1	€	
		Raw material price	0.1	€	

Table 2
Overview of modelling assumptions

Assumption	Description/Implication
Fixed decisions-styles	Each agent (beverage producer, packaging producer and waste treater) is assigned either a "bargaining" or "problem-solving" style from the start of a simulation, which does not change during the run.
Deterministic behaviour	Agents follow predefined decision rules (e.g., choosing cheapest material or highest recycled content), with no probabilistic or random variations in their choices.
No learning or adaptation	Agents do not update their decision-making approach based on past outcomes or new information; the strategies remain constant over time.
Limited actor types	The model only includes beverage producers, packaging producers, and waste treaters as active agents; other ecosystem actors (e.g., consumers, NGOs) are treated as part of the environment.
No capacity and compatibility constraints	All packaging producers can supply the packaging type that fits the current production line of the beverage producer, simplifying real-world constraints like production capacity limitations and technological compatibility.
Simplified economic variables	Material prices are set at the start and adjust by fixed increments if agents sold or did not sell in the previous year; no major external shocks or volatile market changes are included in the simulations.
Single-year contracting cycle	Beverage producers and packaging producers assess their partnerships annually, simplifying real-world long-term contract complexities.
Organization-wide decision-style	All beverage producer agents have the same decision style in the model because they are part of the same organization. The model does not consider differences in decision-styles across departments in the organization.
Annual material demand calculation	Each packaging producer agent annually calculates the demand for required materials, which could partially consist of recycled material.
Simplified market dynamics	All produced packaging and recycled material is sold, either to the beverage - or packaging producer or the environment. Market dynamics, including changes in demand, have not been considered in the model.

Appendix B – Additional experimentation and results

On top of the two scenarios presented in this study, three additional experiments where conducted using the ABM to explore potential waste management approaches. These scenarios consider waste management strategies or policies that result in secondary material volume reduction, maximum potential recycled content increase and recycling rate increase. In all scenarios, the behaviour variables are fixed to represent 90 % bargaining actors, a problem-solving beverage producer and a unanimity decision-rule. The other parameters are set in line with the parameters presented in Appendix A. The scenarios are compared to a baseline scenario, which has the same parameter setup but without any additional measures.

B1. Secondary material volume reduction

Experimental design

In this scenario, the waste volume and subsequent available secondary material are reduced annually across all material types. This could be the result of a reduction in waste, caused by waste management approaches that focus on reducing material use in packaging (e.g. circular design) or the promotion of reusable packaging through new legislation, such as the recent plastic packaging fee (RVO, 2025c).

The Dutch government is phasing out disposable plastics in foodservice (SUPD) and mandating reusable options in retail and hospitality (RVO, 2025c). Additionally, supermarkets are expanding **packaging-free aisles** and refill systems, further cutting packaging waste (Albert Heijn, 2022). The Dutch Institute for Sustainable Packaging (KIDV) promotes lightweighting and material efficiency in packaging design, supporting steady annual reductions (KIDV, 2020). In 2022, the amount of packaging waste saw a slight reduction compared to 2021 (Eurostat, 2024), which emphasizes the relevance of assessing the potential implications of this scenario. This scenario assumes a 1 % reduction of secondary material volumes. Consequently, the packaging volumes produced by the packaging producers also decrease by 1 % per year.

Results

The time series data for the recycled content in the beverage producer's packaging did not exhibit clear patterns that differ from the baseline scenario, where waste volume remained constant (Figure B1). Drink cartons showed an initial increase in recycled material content in most simulations, followed by a decline. Cans and BIB showed more fluctuations in recycled content than in the baseline scenario, while PET and glass bottles demonstrated fewer fluctuations in recycled content when the waste volume decreased. These observations suggest that the variations observed are probably caused by uncertainties within the model rather than by the waste reduction.

The time series data for raw material demand shows a decreasing trend, which aligns with the reduction in packaging or material volume resulting from the reduced waste volume. Overall, these results indicate that a decrease in the availability of secondary material in the Netherlands would not have a direct effect on the potential of the Dutch food packaging ecosystem to further reduce waste.

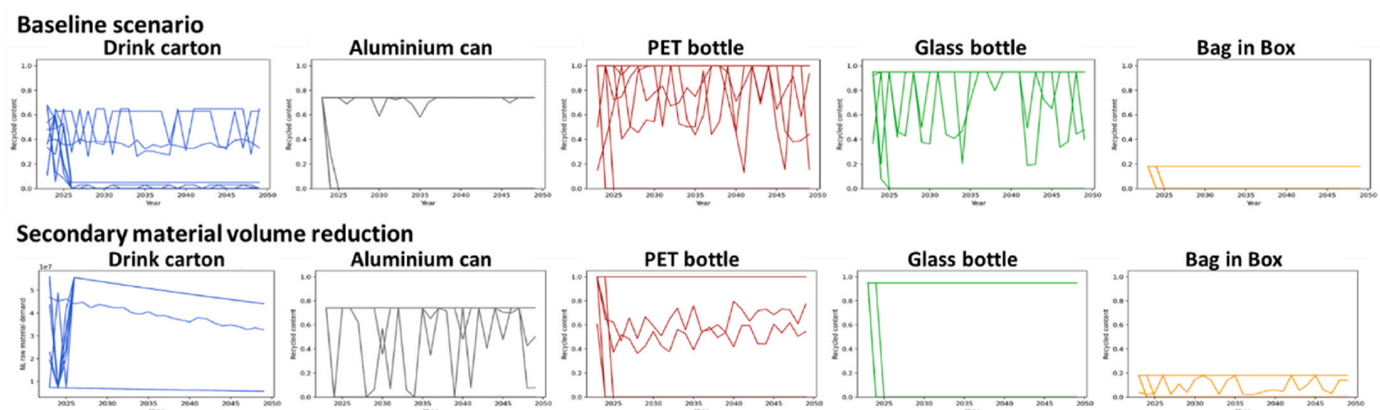

Fig. B1. Recycled content in the beverage producer's packaging in scenario where secondary material volumes reduces 1 % per year (lower graphs) compared to a baseline scenario (upper graphs), showing similar patterns suggesting variations in outcomes are probably caused by uncertainties within the model rather than by the material reduction.

B2. Maximum potential recycled content increase

Experimental design

This scenario concerns innovation related to the maximum potential recycled content in packaging. Various waste management approaches in the Netherlands could drive an annual increase in the maximum potential recycled content in packaging, including the extended producer responsibility (EPR) regulations, recycled content mandates, or innovation subsidies.

The EU Single-Use Plastics Directive (SUPD) and the Circular Economy Action Plan (CEAP) push for minimum recycled content in plastic bottles and packaging (European Commission, 2025a & 2025b). The Netherlands could implement stricter national targets to gradually increase the recycled content. Furthermore, producers pay fees based on the recyclability and recycled content of their packaging under the Dutch waste management structure (ILT, 2024). A policy adjusting these fees to favour higher recycled content could incentivize gradual increases. Finally, the Rijksdienst voor Ondernemend Nederland (RVO) provides subsidies for circular packaging innovations, such as the Circular Economy Incentive Scheme (DEI + Circular Economy) and the subsidy circular plastics NL (CPNL) (RVO, 2025a & 2025b). These incentives could support new technologies in plastic sorting, chemical recycling, or material blending, increasing the feasible recycled content over time.

Overall, a combination of stricter EPR schemes, recycled content regulations and financial incentives for innovation could potentially drive an annual increase in the maximum potential recycled content in packaging. In the scenario, this innovation is represented by a 1 % annual increase in maximum potential recycled content that can be used in new packaging.

Results

Experimentation shows that the recycled content in different packaging could increase over the years if innovation focused on improving the maximum potential recycled content. The experiment indicates that while PET packaging already has a maximum potential recycled content of 100 %, allowing no room for improvement, all other packaging types theoretically have the potential for higher recycled content. BIB packaging currently has a low maximum potential recycled content of 18 %, suggesting the most room for improvement. The time series data of the recycled content in the beverage producer's packaging illustrates increasing trends in multiple simulations of drink cartons, cans and BIB. In contrast, this trend is seen for glass in the initial years until the maximum potential recycled content of 100 % is reached. However, as depicted in graphs in Figure B2, the outcomes exhibit considerable variation. This variation suggests that while innovation to improve the maximum potential recycled content could facilitate higher recycled content in packaging, the actual success of circular ecosystems in increasing recycled content and reducing waste is influenced by other variables.

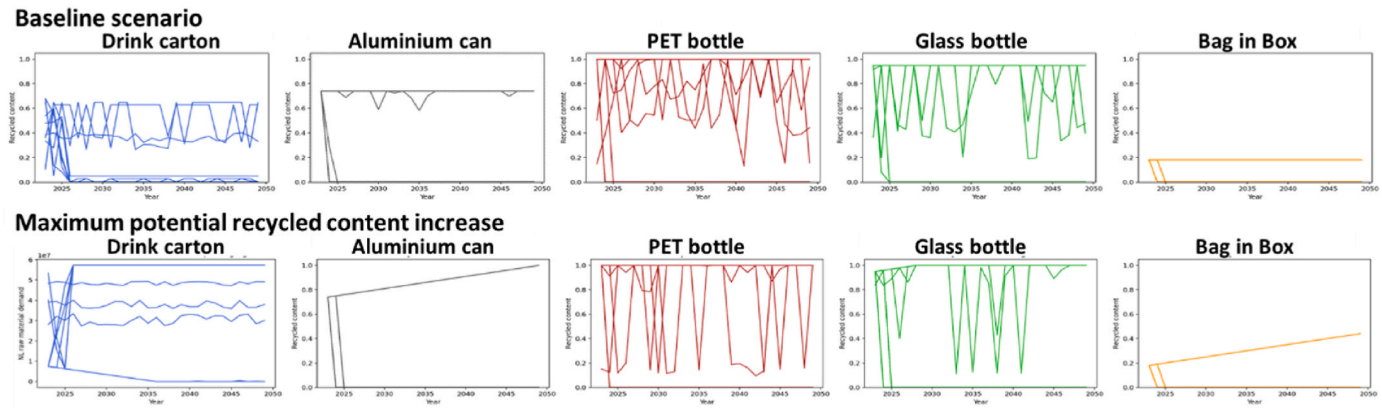

Fig. B2. Recycled content in the beverage producer's packaging in scenario where maximum potential recycled content increases with 1 % per year (lower graphs) compared to a baseline scenario (upper graphs), showing that recycled content in packaging may increase, although variation in the results is considerably.

B3. Recycling rate increase

Experimental design

This scenario considers an annual increase in the recycling rate of waste treaters. Could be driven by various waste management strategies or policies in the Netherlands, such as investments in recycling infrastructure and changes in consumer behaviour. The Dutch government has been enhancing recycling capabilities through investments in infrastructure in the past years (Van Eijk et al., 2022). Additionally, the Dutch government has developed the "Behavioural Strategy for Citizens and the Circular Economy" (Rijksoverheid, 2023). This strategy outlines approaches to encourage sustainable consumption patterns, such as promoting recycling. Educational campaigns and incentives are designed to make circular practices more accessible and appealing to the public.

Overall, this scenario analyses the implications of increased recycling rates, implementing a 1 % annual increase of the recycling rate of waste treaters for all materials.

Results

This scenario assessed the effect of recycling rate innovation within the Dutch food packaging ecosystem. While one might expect that such innovation could mitigate recycled material shortages, fluctuations were still observed in the time series data for the recycled content and raw material demand. These fluctuations can be attributed to the recycled material selection process of bargaining packaging producers, which prioritises the cheapest material over sufficient supply. Similar to the previous experiment, this scenario yielded a considerable variation in outcomes, as is depicted in the graphs in figure B3. This finding indicates that more than focusing solely on improving the recycling rate may be required to reduce waste in the Dutch food packaging ecosystem effectively.

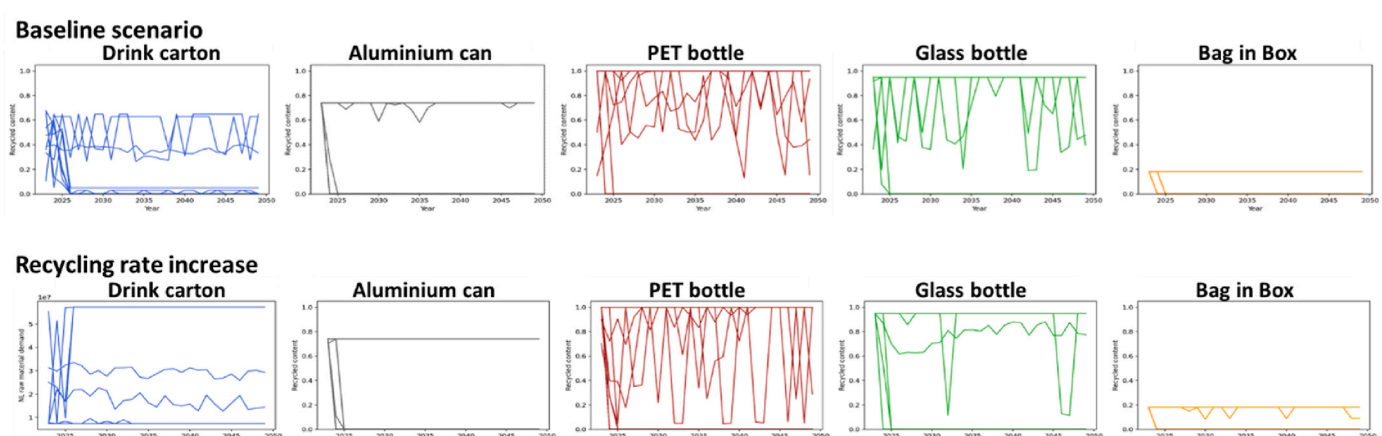

Fig. B3. Recycled content in the beverage producer's packaging in scenario where recycling rate increases with 1 % per year (lower graphs) compared to a baseline scenario (upper graphs), showing that fluctuations in recycled content are still evident, but results vary considerably.

Appendix C. – Differences between our ABM and previous research

To clarify the novelty and scope of our modelling approach, Table 3 summarises key differences between our study and several representative ABM applications in the circular economy and waste management domains.

Table 3
Comparison of related ABM studies in circular economy and waste management

Study	Modelled agents	Decision logic/behavioural rules	Strategic focus	Our study's distinction
Lieder et al. (2017)	Consumers	Socio-demographic factors, product utility functions, social network structures and inter-agent communication	Marketing and pricing strategies for circular business models	Multiple ABM studies focus on consumer behaviour, while our study models organizational decision-making dynamics and coordination.
Meng et al. (2018)	Households	Policy-driven recycling choices	Household recycling	
Koide et al. (2023)	Consumers	Bounded rationality	Product-level circular economy strategies	
Albino et al. (2016)	Industrial producers	Increasing performance without planning by central orchestrator	Contract negotiation, self-organization of symbiotic networks	Our model also includes waste treaters instead of solely industrial producers. Additionally, the actors in our model have explicit decision-styles, enabling analysis of behavioural diversity.
Fraccascia et al. (2017)	Industrial producers	Resource sharing to improve economic performance	Policies to support emergence of industrial symbiosis	
Ghali et al. (2017)	Industrial producers	Social structure, trust and knowledge diffusion	Impact of social factors on the emergence of industrial symbiosis	
Lange et al. (2021)	Industrial producers	Theory of planned behaviour	Robustness of industrial symbiosis networks	
Walzberg et al. (2020)	PV producers and recyclers	Theory of planned behaviour	Closed-loop recycling of PV modules	Focused on PV sector, while our study is on packaging. Also, our study integrates decision-styles and rules.
Farahbakhsh et al. (2023)	Waste treaters	Social pressure and techno-economic feasibility	Technology uptake in waste treatment	We simulate coordination and joint decision-traps among multiple agent types.
This study	Beverage producers, packaging producers, waste treaters	Decision-style (bargaining/problem-solving), decision-rules (unanimity/hierarchy)	Circular packaging ecosystem, joint decision trap	Integrates diverse agent types and explicit theoretical mapping (Scharpf) to ecosystem dynamics

Data availability

Data will be made available on request.

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