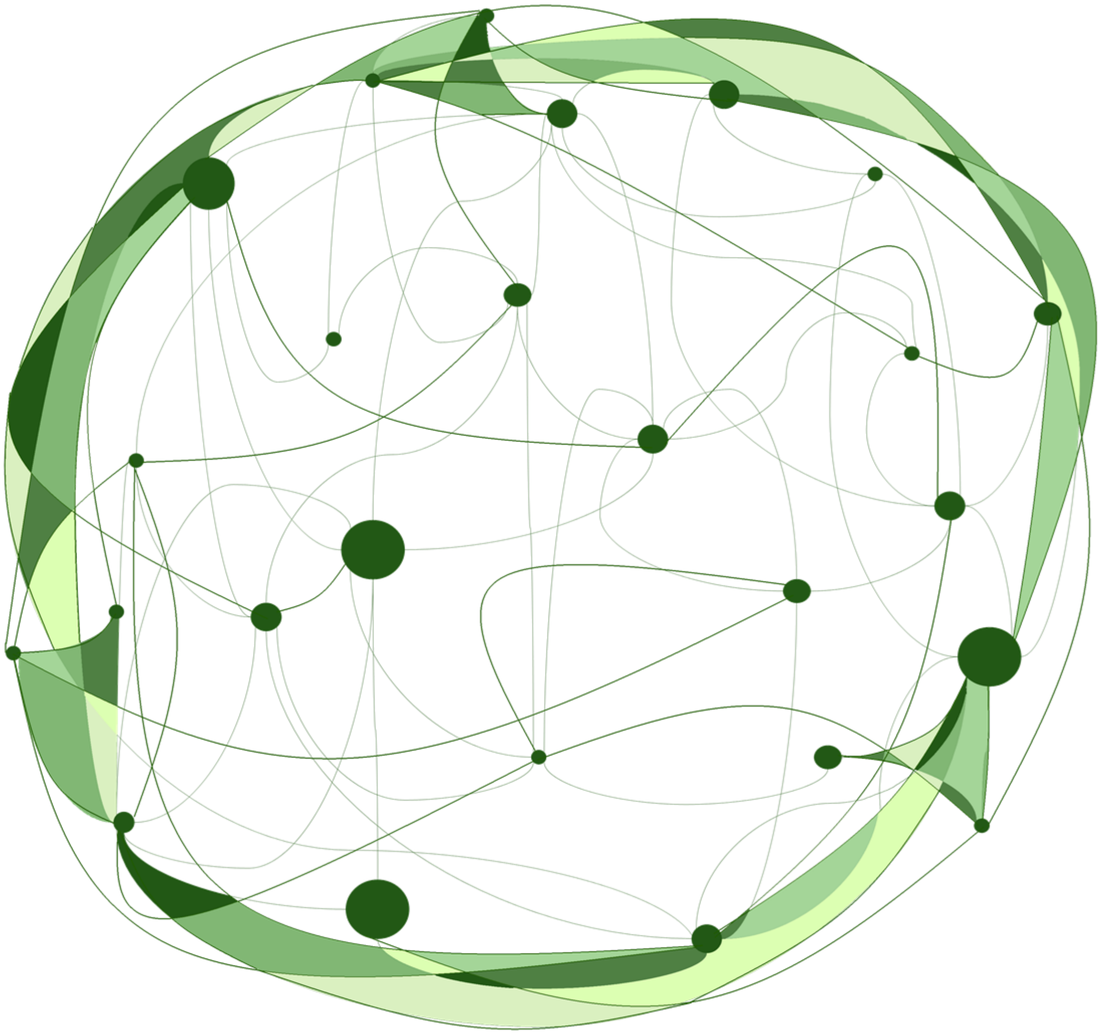
How to reduce packaging waste?

Agent-Based Modelling of a circular food packaging ecosystem in the Netherlands



By

Annoek Reitsema

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How to reduce packaging waste? Agent-Based Modelling of a circular food packaging ecosystem in the Netherlands

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by

Annoek Reitsema
Student number TU Delft 5130557 and Leiden University s1941259

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First supervisor:	Dr. ir. G. Korevaar	Engineering Systems and Services
Second supervisor:	Dr. A. Ghorbani	Multi-Actor Systems
Senior external supervisor:	Ir. E. Onderdelinden	Deloitte NL Technology Vision & Architecture
Junior external supervisor:	Ir. I. Miu	Deloitte NL Technology Vision & Architecture

Preface

"What you do makes a difference, and you have to decide what kind of difference you want to make."
— Jane Goodall

For millions and millions of years, natural ecosystems have been the ultimate teachers, revealing connections and dependencies among species, creating an interplay of life where flora, fauna, and other living organisms function in harmony. As humans, we, too, have crafted our own ecosystems, comprising individuals, organizations, technologies, and governing rules. However, unlike the well-balanced interplay in nature, our human-made ecosystems have often neglected the boundaries set by our planet, leading to disruptions in our environment. However, in the grand picture of the natural ecosystem, we humans and our artificial ecosystems are also connected to the rest of the natural environment and thus carry a responsibility to protect its balance.

Last year, during a hiking trail vacation in the Netherlands, the beauty of nature's collaboration amazed me as it always does. Yet, as many of you might have experienced during walks, my eyes were drawn to packaging waste scattered along the trail. This contrast between the natural ecosystem's harmony and the human-made ecosystem's disarray struck me, sparking my idea to explore the impact of packaging waste and its potential solutions.

During my research, I was excited to realize that even a few proactive actors can create significant change in our human-made ecosystems. As stated by Jane Goodall, every action we take matters and holds the potential to make a positive difference. Through this thesis, I hope to inspire industries and individuals alike to embrace circular ecosystems, contributing to a collective effort to reduce packaging waste.

I am very grateful for the support from various people during my thesis. First, I want to thank my supervisors from TU Delft, Gijsbert Korevaar and Amineh Ghorbani, for their guidance and feedback during my thesis. Your support has helped me to stay focused and critical, but most of all, enthusiastic about the research. Secondly, I want to thank my Deloitte supervisors, Eric Onderdelinden and Ioana Miu, for the valuable discussions and feedback, which have been of great support to scope, structure and improve the research. Furthermore, I want to thank the interviewees who took the time to provide me with helpful insights during this research. Additionally, special thanks to Deloitte for the opportunity to write my thesis in such an inspiring environment. Overall, I want to express my gratitude for having met so many inspiring people during the master's program, leading me to believe that we are on our way to a more sustainable future. Finally, I would like to thank the people closest to me, my family and friends, who have constantly supported me during my studies.

In the report that follows, I hope you can find both exciting new insights and inspiration to make a positive difference.

Annoek Reitsema

Executive summary

Reducing packaging waste requires organisations to look beyond their own products, services and business models and take an ecosystem approach. Organisations are actors who can collaborate with other actors to create a circular value proposition in circular ecosystems. Various circular ecosystems focus on reducing packaging waste; however, it is unknown how circular ecosystems alter material flows in the packaging system, especially considering the uncertainty of actor behaviour. This thesis aims to fill this research gap by studying the dynamics of packaging waste in a circular food packaging ecosystem in the Netherlands.

The research takes a complex adaptive socio-technical systems approach and combines a systematic literature review and a case study with interviews to develop an agent-based model (ABM). The literature review and case study were used to identify the social and technical components of the Dutch food packaging ecosystem, including the actors, their interactions and behaviour, as well as the different packaging materials and the processes related to their production, use, disposal, and waste treatment. A case study on a food producer was used to define the social and technical components more specifically. Additionally, the environment was described in which the Dutch food packaging ecosystem operates. The inventory of the social and technical components and the environment served as the basis for conceptualising the ABM.

The ABM includes three types of agents, representing the food producer, packaging producers and waste treaters. These agents can form circular ecosystems focused on closed-loop recycling. The ABM incorporates organisational decision-making theory to account for actor behaviour, considering two decision-styles and two decision-rules. The decision-styles can result in agents prioritising high recycled content (problem-solving) or low price (bargaining). The decision-rules can be unanimity, where all actors have equal chances, or hierarchy, where some actors hold an advantage. Besides these variables related to actor behaviour, the ABM also integrated variables related to Dutch waste, material prices, and innovation to improve closed-loop recycling.

The implemented ABM was used to explore the effect of the different variables on the dynamics of packaging waste in circular ecosystems. The results emphasised that not all ecosystem actors are required to establish circular ecosystems, and packaging waste could be reduced if a few actors in the food packaging ecosystem prioritise circularity over individual profit. However, the decision-style of the food producer does have a significant impact in ecosystems dominated by actors prioritising individual profit. If the food producer prioritises circularity, circular ecosystems can be established, starting with only a small part of the food packaging ecosystem. These small circular ecosystems can significantly reduce packaging waste. An important condition for circular ecosystems to emerge is the availability and sharing of information on recycled material volumes and recycled content in packaging within the food packaging ecosystem.

Furthermore, circular ecosystems might be limited by recycled material shortages, depending on the packaging type, which can cause fluctuating recycled content in packaging. A centrally orchestrated waste treatment could assure the stabilisation of the recycled material supply and, therefore, the recycled content in packaging. Technological innovation can increase the maximum potential recycled content in packaging and the recycling rate, but additional changes to actor behaviour or material price are needed to utilise this innovation. On top of that, other high-level circularity strategies should be employed to overcome limitations related to material shortage. Using recycled material could be incentivised through subsidies or taxes on raw materials. However, the effectiveness of such measures will depend on the decision-making of the packaging producers.

The discussion reflected on the results, the ABM and the overall research, indicating the limitations and implications and suggesting future research directions. Overall, further refinements can improve the ABM's accuracy and enhance its suitability for analysing potential circular ecosystems for waste reduction.

In conclusion, this research elucidates the dynamics of packaging waste in a circular food packaging ecosystem in the Netherlands, considering actor behaviour. The ABM provides an analytical tool for studying circular ecosystems that can be used to further investigate the potential of collaboration in circular ecosystems and analyse specific cases in the food packaging industry. By leveraging the ABM and emphasising the potential of actor collaboration, circular packaging ecosystems can facilitate a more sustainable food packaging industry.

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List of Abbreviations

ABM	Agent-based model
BIB	Bag in Box
CE	Circular Economy
EPR	Extended Producer Responsibility
EU	European Union
HDPE	High-density polyethene
IT	Information Technology
KIDV	Kennisinstituut Duurzaam Verpakken (Netherlands Institute for Sustainable Packaging)
KPI	Key Performance Indicator
Kton	Kiloton (1,000,000 kilogram)
LDPE	Low-density polyethene
NGO	Non-governmental organisation
PBL	Planbureau voor de Leefomgeving (Netherlands Environmental Assessment Agency)
PE	Polyethene
PET	Polyethene-terephthalate
PKO	Platform Ketenoptimalisatie (Platform Chain Optimisation)
PMD	Plastic, metal and drink cartons
PP	Polypropylene
SLR	Systematic literature review
StAV	Stichting Afvalfonds Verpakkingen (Packaging Waste Fund)
TV&A	Technology Vision & Architecture
UML	Unified Modelling Language
VNG	Vereniging van Nederlandse Gemeenten (Association of Dutch Municipalities)

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1 Introduction

Global economic growth has improved living conditions worldwide (Roser, 2020) but has also resulted in resource depletion and waste generation due to the linear nature of most economies (Kaza et al., 2018; OECD, 2019; Worldbank, 2022). In a linear economy, products are produced, used and disposed of (Ellen MacArthur Foundation, 2023). Due to the linearity of global economies, waste generation is expected to grow to 3.4 billion tonnes worldwide by 2050 (Kaza et al., 2018). A significant portion of this waste is packaging material used to contain and protect food, beverages, and other everyday consumer goods. In Europe, for example, packaging material makes up 36% of municipal solid waste (European Commission, 2022). Packaging is useful because it prevents products from damage and spoilage, which reduces wasting those products (Humbert et al., 2009; Molina-Besch et al., 2019; Silvenius et al., 2011). However, there are downsides to the use of packaging.

Packaging changes into packaging waste after its disposal, considering that waste is "any substance or object which the holder discards or intends or is required to discard" according to the Waste Framework Directive *(Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on Waste and Repealing Certain Directives, 2018).* Packaging waste has negative impacts on the environment. Incineration and landfilling of packaging material results in greenhouse gas emissions (CIEL et al., 2019), littering jeopardises marine and terrestrial life via suffocation and toxification (De Souza Machado et al., 2018; UNEP, 2021) and material fragmentation into micro-particles can affect species in numerous ways, including potential effects on human health (UNEP, 2021; Vethaak & Legler, 2021). It is essential to reduce packaging waste through more sustainable practices while preserving its beneficial properties to protect goods. A reduction of packaging waste is in line with sustainable development, which ensures that "the needs of the present generation are met without compromising the ability of future generations to meet their needs" (WCED, 1987).

1.1 Circular ecosystems to reduce packaging waste

The Circular Economy (CE) is considered a fundamental approach to overcoming the environmental problems related to waste (Ellen MacArthur Foundation, 2013). The CE is "a generative system in which resource input and waste, emission and energy leakage are minimised" (Geissdoerfer et al., 2017). The CE consists of four main strategies: narrow, slow, close, and regenerate material and energy flows. These strategies involve using less material and energy (*narrow*), prolonging product lifetimes (*slow*), reusing products and materials (*close*), using non-toxic materials and renewable energy, and regenerating natural ecosystems (*regenerate*) (Bocken et al., 2016; Geissdoerfer et al., 2017; Konietzko et al., 2020). The ultimate goal of the CE and its corresponding strategies is to decouple economic growth from environmental burden by reducing waste and increasing efficiency (Ghisellini et al., 2016).

The CE strategies can be translated into measures that minimise packaging waste while considering packaging's short life-cycle, the product it will contain and the required packaging properties (Meherishi et al., 2019; Rijksoverheid, 2021). In some cases, the packaging material may be reduced or even discarded entirely to *narrow* the loop (De Volkskrant, 2021; NOS, 2019). Other packaging materials can be recycled after their use to *close* the loop (Hopewell et al., 2009; Villanueva & Wenzel, 2007). Reuseable packaging is emerging as an effective way to *slow* and *close* the loop, for example, in the form of deposit-return systems on bottles or dispensers for refilling a reusable container (De Volkskrant, 2021; Ellen MacArthur Foundation, 2019). Alternatively, biobased or biodegradable materials can be used for single-use packaging as part of the *regenerate* strategy (Kale et al., 2007; Rydz et al., 2015). The suitability of CE approaches depends on the packaging requirements; therefore, various CE approaches are needed for a sustainable packaging system.

While individual organisations can make their products and practices more circular (Bocken et al., 2014; Pieroni et al., 2020), scholars emphasise the importance of inter-organisational collaboration to address sustainability challenges (Ghisellini et al., 2016; Hileman et al., 2020; Lozano, 2007). Organisations are actors who can form collaborative networks in which they exchange information and knowledge with each other (Graça & Camarinha-Matos, 2015). This network of interconnected actors was first described as a business ecosystem by Moore (1993, 1996). Collaboration in a business ecosystem provides useful resources, alliance partners and information about the market (Zahra & Nambisan, 2012). Because of this, an ecosystem can create competitive advantage (Dyer & Singh, 1998) and symbiosis, in which organisations strengthen each other by sharing benefits from cooperation (Yoon et al., 2022). On top of that, competitors can collaborate in ecosystems to spark innovation. Although paradoxical, competition in combination with cooperation (i.e. coopetition) can positively affect organisational performance (Riquelme-Medina et al., 2022). Overall, inter-organisational collaboration in ecosystems has great potential for addressing complex, multi-actor sustainability challenges like the CE transition (Kanda et al., 2021).

Building on the concept of business ecosystems, a 'circular ecosystem' is a network of interconnected and heterogeneous actors that transcends industrial boundaries and collectively pursuits a circular value proposition, creating potential economic and environmental sustainability (Trevisan et al., 2022). As Konietzko et al. (2020) argue, "circularity needs to be understood as a property of a system … rather than a property of an individual product or service". Organisations should thus look beyond their own products, services and business models (Konietzko et al., 2020). Additionally, the transformation from linear business models to a circular economy touches not only production and distribution but also consumption and waste treatment (Kirchherr et al., 2017). A balance of various actors, including organisations and consumers, should collaborate in a circular ecosystem to improve the circularity of a system (Tate et al., 2019).

Circular ecosystems can play a vital role in the reduction of packaging waste. There are various examples of circular ecosystems that aim to reduce packaging waste, for example, a glass recycling ecosystem (Hsieh et al., 2017), an ecosystem that produces ecological tiles from recycled cardboard packaging (Barquete et al., 2022) and deposit-return systems on bottles (Zhou et al., 2020). However, these circular ecosystems ask for changes in infrastructure and consumer behaviour (Natuur & Milieu, 2021). Additionally, circular ecosystems can be hurdled by poor alignment among actors (Barquete et al., 2022) and are affected by institutions such as ethical values and cultural familiarity (Asgari & Asgari, 2021). Furthermore, technological uncertainties and limitations and economic factors can hamper actors from adopting more circular practices (Farahbakhsh et al., 2023). As a result, the packaging industry clings to end-of-the-pipe solutions in mixed-stream recycling and is resistant to alternative systemic changes that are proven more effective, such as the PET deposit-return system (Hanemaaijer et al., 2023). Overall, the capacity of circular ecosystems to reduce packaging waste is recognised, but further studies are needed that explore the dynamics of packaging waste in circular ecosystems, considering the uncertainty of actor behaviour (Trevisan et al., 2022).

1.2 Problem formulation

Packaging changes into waste after its disposal, and this packaging waste forms a threat to the environment and potentially human health (UNEP, 2021; Vethaak & Legler, 2021). Therefore, packaging waste needs to be reduced. Organisations should look beyond their own products, services and business models and take an ecosystem approach to make their practices more circular (Konietzko et al., 2020). Organisations can join forces with a circular value proposition in circular ecosystems, and there are various examples of circular ecosystems focussing on reducing packaging waste (Barquete et al., 2022; Hsieh et al., 2017; Zhou et al., 2020). However, multiple variables affect the dynamics of packaging waste in circular ecosystems (Barquete et al., 2022; Liu et al., 2022). So far, literature has not addressed the dynamics of food packaging waste in circular ecosystems, especially considering the uncertainty of actor behaviour (Trevisan et al., 2022).

Recent literature on circular ecosystems emphasises the need for quantitative studies based on empirical data (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). To overcome this, cases of circular ecosystems can pose as examples for larger systemic changes (Ellen MacArthur Foundation, 2019; Natuur & Milieu, 2021) and can be used as the basis to develop an agent-based model (ABM). An ABM can simulate actor behaviour in different scenario's to explore and analyse potential outcomes ex-ante (Van Dam et al., 2013). However, to the best of the researcher's knowledge, no previous studies have modelled circular ecosystems in an ABM.

This study uses ABM to analyse the dynamics of packaging waste in circular food packaging ecosystems for a specific food producer in the Netherlands to examine the effectiveness of these circular ecosystems in reducing packaging waste. By simulating actor behaviour in a food packaging ecosystem under various conditions, the potential effects on packaging waste can be explored. The results can assist the industry and policymakers in making informed decisions on feasible circular ecosystems.

1.3 Research questions and objectives

In line with the research gap and problem statement, this study aims to answer the research question:

What are the dynamics of packaging waste in a circular food packaging ecosystem in the Netherlands, considering actor behaviour?

Four sub-questions are formulated to answer the main research question. The objectives of these sub-questions are explained, and the research method to answer the question is proposed.

1. What is a circular ecosystem and how can it be applied to the Dutch food packaging ecosystem?
    - *Objective:* Explanation of the circular ecosystem concept and its application to the Dutch food packaging ecosystem.
    - *Method:* Literature review
2. What does the current food packaging ecosystem in the Netherlands look like?
    - *Objective:* Identification of social and technical components of the food packaging ecosystem in the Netherlands.
    - *Method:* Literature review and case study
3. Can the dynamics of a food packaging ecosystem be conceptualised in an ABM and if so, how?
    - *Objective:* Conceptualisation and formalisation of an ABM based on theories, concepts and data from sub-question 1 and 2.
    - *Method:* Agent-based modelling and expert validation
4. Based on simulations, what is the potential of circular ecosystems to reduce packaging waste in the Dutch food packaging ecosystem?
    - *Objective:* Performing experiments with changing circular ecosystem variables in the ABM and analysing their effect on the packaging waste in the Dutch food packaging ecosystem.
    - *Method:* Agent-based modelling

1.4 Scope

Reducing packaging waste via circular ecosystems requires a combination of technologies and the involvement of stakeholders in and beyond the supply chain, including consumers (Niero et al., 2017). The emergence of circular packaging ecosystems can be hampered by costs (Hanemaaijer et al., 2023) and is influenced by contextual factors and legislation (Barquete et al., 2022). The packaging ecosystem is approached as a complex adaptive socio-technical system due to the diversity of actors, their behaviour, and their interactions, as well as the range of technological options and external factors (Section 2.2.3). However, Van Dam et al. (2013) argue that “everything influences everything”. In light of this complexity, it is important to define clear system boundaries to elucidate dependencies that are relevant for decision-making on circular ecosystems in the packaging system.

1.4.1 Research scope

This study is carried out as a thesis for the master’s programme Industrial Ecology. The time for the research is six months. The thesis is written with the support of the Technology Vision & Architecture (TV&A) department of Deloitte Netherlands. The department aims to bridge the gap between business strategy and technology by using IT architecture and operates in various sectors (Deloitte, 2023b). Experts within the department were consulted continuously to guide the research in the most socially relevant direction.

1.4.2 Actor identification

This research involves multiple actors related to the problem statement and research motivation. The food packaging ecosystem is the problem owner, including multiple actors such as supermarkets, retailers, waste managers and customers. The thesis has been carried out for a master at the TU Delft and Leiden University with the support of Deloitte. Deloitte’s TV&A department can advise the food packaging ecosystem on the potential of circular ecosystems to become more circular, and the thesis can function as a practical guide for this advice.

1.4.3 Geographical scope

This study focuses on the food packaging ecosystem in the Netherlands for multiple reasons. The country aims to be completely circular by 2050, which echoes in changing legislation and infrastructure (Rijksoverheid, 2016). This transition is extensively monitored by multiple organisations, which provides quantitative data for this study. Despite being a European leader in recycling packaging waste (Afvalfonds Verpakkingen, 2021), the Netherlands has limitedly implemented more efficient strategies like reusing and reducing (Hanemaaijer et al., 2023). Furthermore, the TV&A department operates predominantly in the Netherlands, and therefore, the available data and connections to the industry are most abundant for the Dutch packaging ecosystem. Considering this potential and the extensive reporting on the Dutch packaging system, this research focuses on the Netherlands. This scope relates to geographical demarcation and the considered institutions, including Dutch legislation and actor behaviour.

1.4.4 Sectorial scope

There are different approaches to scope research on the reduction of packaging waste. One option is to study the circularity of a certain material, such as plastic (Hahladakis & Iacovidou, 2018; Kerdlap et al., 2020) or paper (Villanueva & Wenzel, 2007). Another option is to examine a certain actor group and their behaviour, such as consumers (Meng et al., 2018) or the waste treatment industry (Farahbakhsh et al., 2023). This study uses an ecosystem approach that includes various packaging materials and actors. Therefore, it is preferred to focus on a specific sector instead of a specific material or actor group.

Multiple factors have contributed to the selection of the food sector as the subject of this study. Firstly, the industry uses diverse materials for packaging, each with different potential for circular strategies (Afvalfonds Verpakkingen, 2021). Secondly, packaging requirements are dependent not only on legislation regarding sustainability and circularity but also on regulations governing food quality and consumer health (RVO, 2021). Thirdly, the ecosystem involves numerous actors who could form a circular ecosystem, including consumers. Lastly, several examples of circular ecosystems exist in the Dutch food packaging ecosystem (e.g. Albert Heijn, 2022; Pieter Pot, 2023; Statiegeld Nederland, 2023). Therefore, this research focuses on the food packaging ecosystem in the Netherlands and, more specifically, on consumer food packaging. Logistic packaging such as pallets, crates, and wrappers are used in the supply chain and handled differently than the final consumer packaging. The scope of this research does not consider logistic packaging.

1.4.5 Temporal scope

Circular ecosystems can emerge quickly, but their evolution and diffusion into the larger system often require infrastructure changes and integration of systems, which can take years (Schelfaut, 2021). Legislation can support and accelerate the success of circular ecosystems, leading to faster system changes (Rijksoverheid, 2023b). As the Netherlands aims to be a CE by 2050, the temporal scope of this study is limited to 2050.

1.5 Relevance

1.5.1 Scientific relevance

Research on circular ecosystems has been emerging since 2016, and there is still a lot unknown about the structure, mechanisms and dynamics of such ecosystems (Trevisan et al., 2022). Previous research on ecosystems has used a complex adaptive system perspective and showed that collaboration in ecosystems helps to increase sustainable performance and sustainability-oriented innovation (Graça & Camarinha-Matos, 2021; Hileman et al., 2020; Van de Wetering et al., 2017). Similarly, a complex adaptive system perspective has been used to study the circularity of packaging and the effects of actor behaviour on the reduction of packaging waste (Farahbakhsh et al., 2023; Kerdlap et al., 2020; Meng et al., 2018). However, the effect of circular ecosystems on packaging waste dynamics has not yet been studied, considering the complexity of actor behaviour (Trevisan et al., 2022). Scharpf's (1988b) study showed that actors' individual decision-making behaviour affects the outcomes in joint decision-making, which is required in circular ecosystems. Individual decision-styles and decision-rules could lead to suboptimal outcomes, also known as the 'joint decision trap' (Scharpf, 1988b). This thesis uses the organisational decision-making theory by Scharpf (1988) for conceptualising actor behaviour in an ABM that can be used to assess the dynamics of packaging waste in a circular food packaging ecosystem. The outcomes of this study build on existing theory and contribute to scientific research in the field of circular ecosystems, sustainable food packaging systems and agent-based modelling.

1.5.2 Social relevance

Organisations should collaborate with others in the transition towards a CE to overcome the negative environmental impacts of packaging waste (Konietzko et al., 2020). To make effective decisions, organisations must understand how collaboration in a circular ecosystem can facilitate their circularity targets. This study builds on the organisational decision-making theory by Scharpf (1988b), which gives an institutional explanation for the paradox of the 'joint decision trap'. By basing an ABM on this social theory, the outcomes of this study can help actors in the food packaging ecosystem to understand the potential of circular ecosystems to reduce packaging waste and the effect of organisational decision-making behaviour on this potential. Additionally, the novel way of simulating circular ecosystems in an ABM can provide Deloitte's TV&A department with a tool to analyse the dynamics of packaging waste in circular ecosystems while considering organisational decision-making behaviour. This tool can support them in advising clients on how to improve circularity.

1.5.3 Relevance for Industrial Ecology

Industrial Ecology is a multi-disciplinary research field focussing on analysing complex systems and developing sustainable solutions to environmental problems (Kapur & Graedel, 2004). One of the key areas of focus within the field of Industrial Ecology is waste management and the circular economy (Ghisellini et al., 2016). Reducing waste in the food packaging ecosystem strongly depends on circular economy principles (Batista et al., 2019; Ellen MacArthur Foundation, 2013). However, the food packaging ecosystem involves a complex interplay of actors, technologies, and policies (Niero et al., 2017). Agent-based modelling is used in Industrial Ecology to analyse complex systems and identify factors influencing environmental outcomes. The method has previously been used to study various aspects of circularity in waste management (e.g. Ceschi et al., 2021; Farahbakhsh et al., 2023; Kerdlap et al., 2020). This thesis relates to the field of Industrial Ecology because it analyses the pressing sustainability issue of packaging waste with a complex adaptive socio-technical systems approach through agent-based modelling.

1.6 Outline

This thesis aims to address the dynamics of packaging waste in a circular food packaging ecosystem, considering actor behaviour. The packaging ecosystem is approached as a complex adaptive socio-technical system including different actors and technologies. The theoretical framework and methodology are described and motivated with a research flow diagram in Chapter 2. Chapter 3 presents a literature review to decompose the food packaging ecosystem in the Netherlands, complemented by a case study of a specific food packaging ecosystem in the Netherlands. The information in this chapter is used in Chapter 4 for the conceptualisation and implementation of the ABM. Chapter 5 explains the experiments that have been performed. In Chapter 6, the results are presented and analysed. The validity of the model, the study and the results are covered in Chapter 7, discussing the study's limitations and providing recommendations. Finally, the research is concluded and summarised in Chapter 8.

2 Research approach

Chapter 2 explains the research approach and methodology used in this thesis. Section 2.1 starts by outlining the theoretical framework used in this study. Next, the methodology is defined in Section 2.2, combining the theory of circular ecosystems and complex adaptive socio-technical systems. Finally, a flowchart of the overall research approach is shown in Section 2.3.

2.1 Theoretical framework

This study focuses on the reduction of packaging waste in the Dutch food packaging ecosystem, taking a complex adaptive socio-technical system approach. Before the formulation of the methodology, it is useful to identify what a circular food packaging ecosystem entails and why this system should be approached as a complex adaptive socio-technical system. This section provides the theoretical framework used in this study and answers sub-question 1:

What is a circular ecosystem and how can it be applied to the Dutch food packaging ecosystem?

The section starts with an explanation of the circular ecosystem concept in Section 2.1.1, followed by an identification of the concept's application to the Dutch food packaging ecosystem in Section 2.1.2. Finally, Section 2.1.3 motivates why the Dutch food packaging ecosystem should be approached as a complex adaptive socio-technical system.

2.1.1 Circular ecosystem concept

Collaboration among organisations is crucial in addressing sustainability challenges, and forming collaborative networks in a business ecosystem can create competitive advantage and symbiosis (Dyer & Singh, 1998; Yoon et al., 2022). Inter-organisational collaboration in ecosystems has great potential for addressing complex, multi-actor sustainability challenges like the circular economy transition (Ghisellini et al., 2016; Hileman et al., 2020; Lozano, 2007). Given that circularity is a system-level concept, it stands to reason that circular ecosystems are a more appropriate means of achieving circularity than focusing solely on circular products or services (Konietzko et al., 2020). This study uses the definition of the circular ecosystem concept by Trevisan et al. (2022):

"We define a circular ecosystem as: a system of interdependent and heterogeneous actors that go beyond industrial boundaries and direct the collective efforts towards a circular value proposition, providing opportunities for economic and environmental sustainability." – Trevisan et al. (2022)

2.1.2 Circular food packaging ecosystem

Circular ecosystems have been recognised as a promising approach to reducing packaging waste, as demonstrated by various examples such as glass recycling (Hsieh et al., 2017), recycled cardboard floor tiles (Barquete et al., 2022), and bottle reuse (Zhou et al., 2020). The transition from a linear to a circular packaging ecosystem involves the development and integration of the supply chain, including disposal and recovery, reverse logistics and circular waste treatment such as recycling or reuse (Meherishi et al., 2019). Within the Dutch food packaging ecosystem, different circularity strategies can be employed to form circular ecosystems that focus on the reduction of packaging waste. These strategies are also known as the R-ladder: Refuse and rethink (R1), Reduce (R2), Reuse (R3), Repair and Repurpose (R4), Recycle (R5) and Recover (R6). The circular value proposition of a circular packaging ecosystem can rely on any of those circularity strategies.

A first potential value proposition of a circular ecosystem could be the refilling of packaging by the producer, relating to strategy R3: Reuse. An example of this circular ecosystem is the Dutch deposit-return system handling refillable beer bottles. These glass bottles can be refilled up to 30 times before being recycled with residual glass (KIDV, 2022b). Technological innovation is expected to introduce other options for refillable packaging (Ellen MacArthur Foundation, 2019). This type of circular ecosystem requires a take-back scheme and return logistics, which rely on collaboration with outlets and consumers.

A second option would be the refilling of packaging by the consumer, relating to strategy R2: Reduce or R3: Reuse. Such a circular ecosystem might require an alternative way of selling a product, for example, in large dispensers (Albert Heijn, 2022). Again, such circular ecosystems require collaboration with outlets and consumers. Additionally, collaboration with innovative niche players can be useful for quicker awareness of technological innovation that could be adopted to reduce packaging material or facilitate the reuse of packaging.

Another possibility for the Dutch food packaging ecosystem is the recycling of materials to become a circular ecosystem, in line with strategy R5: Recycling. Preferably, the recycling of packaging would be closed-loop, using old packaging in the production of similar new packaging. A closed-loop circular ecosystem would require collaboration with waste treaters and packaging producers. Conversely, open-loop recycling could also be used to form circular ecosystems, using disposed packaging for the production of alternative products. This circular ecosystem would require collaboration with waste treaters and other producers that can recycle the packaging waste into high-quality recycled products.

Moreover, the Dutch food packaging ecosystem has various options for circular ecosystems, surpassing the possibilities explained in this section. Nevertheless, the suitability of various circular ecosystems depends on the packed product and its packaging requirements. A case study of a specific product is useful for a more concrete conceptualisation of the Dutch food packaging ecosystem and is incorporated into the methodology.

2.2.3 Complex adaptive socio-technical systems

The Dutch food packaging ecosystem should be approached as a complex adaptive socio-technical system because it involves not only technical components, such as materials and manufacturing processes (e.g. Chen et al., 2020; Di Foggia & Beccarello, 2022) but also social components, such as supply chain management and consumer behaviour (e.g. Batista et al., 2019; Carter & Rogers, 2008; Steenis et al., 2017). Reducing packaging waste requires consideration of available technologies and involved stakeholders in and beyond the value chain, including consumers (Niero et al., 2017). However, there is no single recipe for reducing packaging because the ecosystem changes and reorganises to adapt to its environment, making it a complex adaptive system (Holland, 1992).

2.2.3.1 Social components

The social components of a socio-technical system include actors with their objectives, interactions and behaviour (Van Dam et al., 2013). The actors and objectives in the Dutch food packaging ecosystem are diverse: some focus on product sales, others rely on packaging waste for their operations, and another group of actors is committed to protecting the environment. Additionally, the influence of these actors in the food packaging ecosystem varies. Some actors, known as keystone actors (Iansiti & Levien, 2004), greatly influence the system. However, organisations surrounding those keystone actors also play an essential part in sustainability transformations (Hileman et al., 2020). Nevertheless, given these actors' varying levels of influence, a hierarchical structure may exist within the Dutch food packaging ecosystem.

To reach their objectives, the actors within the food packaging ecosystem interact with each other various ways, for example, through material exchange and financial transfers (Kanda et al., 2021). The interactions transcend the boundaries of the value chain and involve actors within the total ecosystem.

Furthermore, actors exhibit certain behaviour that influences and is influenced by the actors' objectives and interactions. Organisations 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). Scharpf's decision-making framework for composite actors is used in this study to simplify the decision processes of organisations (Scharpf, 1988a). A recent study by Eslamizadeh et al. (2022) on industrial community energy systems showed the suitability of this framework for conceptualising organisational behaviour in an ABM. The decision-making framework is shown in Figure 1. The vertical axis presents three potential decision-styles (problem-solving, bargaining or confrontation), and the horizontal axis presents three potential decision-rules (unanimity, majority, or hierarchy). During the decomposition of the Dutch food packaging system, this framework is used to characterise the decision-making behaviour of the system's organisations.

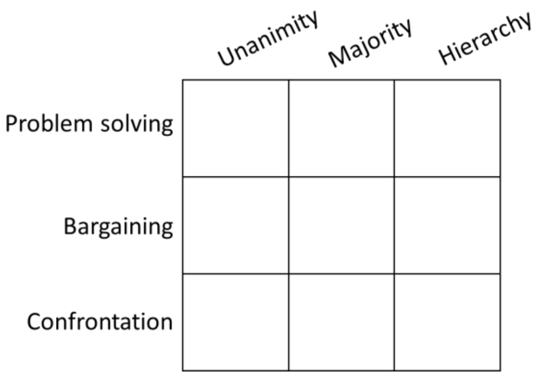

Figure 1. Decision-making framework (Scharpf, 1988a)

Overall, adopting more circular practices relies on the different actors, their behaviour and their interactions (Farahbakhsh et al., 2023; Meng et al., 2018). Therefore, it is crucial to carefully consider these social components when studying circularity in the Dutch packaging system.

2.2.3.2 Technical components

In a socio-technical system, the technical components comprise physical elements and technological artefacts (Van Dam et al., 2013). In the context of the packaging ecosystem, the technical components include operational processes and materials. More efficient operational practices can reduce the amount of energy and material required, thus enhancing the circularity of the ecosystem (Niero et al., 2017). The transition to a circular ecosystem requires changes in operational processes, with some processes being added, such as return-transport, and others becoming obsolete, such as using toxic chemicals (Guillard et al., 2018). Improving the circularity of materials is also a multifaceted issue, as some materials are more suitable for reuse or recycling, while others help regenerate natural ecosystems (Hahladakis & Iacovidou, 2018; Rydz et al., 2015). Improving the circularity of the packaging ecosystem requires the recognition of the strengths and limitations of different technical options.

It is important to note that this study uses NetLogo to implement the ABM. This software does not provide thorough insights into the model's material and energy balances. The model assumes infinite sources of raw materials and energy as well as infinite waste sinks, which is a conceptual choice that enables a more convenient implementation of the system. Although the model does not balance materials and energy by default, the balance was carefully monitored during implementation to prevent extreme imbalance.

2.2.3.3 Complex and adaptive behaviour

To study the social and technical components of the Dutch food packaging ecosystem, the ecosystem should be approached as a complex adaptive system constantly evolving and changing due to self-organisation, co-evolution, and emergent behaviour. Previous studies have shown the effectiveness of this approach in explaining the behaviour of business ecosystems in general (Peltoniemi & Vuori, 2008). The approach is deemed equally suitable to analyse the Dutch food packaging ecosystem for multiple reasons. First, the packaging ecosystem's actors can form a circular ecosystem through self-organisation: the participants are gathered without an external or internal lead (Barquete et al., 2022). Secondly, the interactions in a circular ecosystem result in emergent behaviour, consisting of unpredictable properties or patterns that arise in the system while not being present in one single actor (Konietzko et al., 2020). Thirdly, the relationships within a circular ecosystem can result in the actors' co-evolution, improving the actors' performance simultaneously and creating a shared competitive advantage (Trevisan et al., 2022). Self-organisation, co-evolution and emergent behaviour are all characteristics of complex adaptive systems (Holland, 1992; Holling, 2001; Levin et al., 2013; Stacey, 1995). Circular ecosystems in the packaging ecosystem should therefore be approached as complex adaptive socio-technical systems

2.2.4 Summary and remarks

Section 2.1 of this study establishes the theoretical framework to answer the first sub-question of this study:

What is a circular ecosystem and how can it be applied to the Dutch food packaging ecosystem?

This study uses the circular ecosystem definition by Trevisan et al. (2022), who described a circular ecosystem as "a system of interdependent and heterogeneous actors that go beyond industrial boundaries and direct the collective efforts towards a circular value proposition, providing opportunities for economic and environmental sustainability."

Circular ecosystems can apply to the Dutch food packaging ecosystem in various ways, as these ecosystems can employ different circular strategies to formulate a circular value proposition. For example, circular ecosystems can focus on reusable packaging or recycling materials. The suitability of different circular value propositions depends on the specific product and packaging requirements. To effectively study circular ecosystems in the Dutch food packaging ecosystem, the Dutch food packaging ecosystem should be approached as complex adaptive socio-technical systems. This approach is used because the Dutch food packaging ecosystem involves both social and technical components that form a complex adaptive system that constantly adapts and reorganises in response to changes in its environment.

Overall, Section 2.1 establishes the theoretical framework by defining a circular ecosystem, exploring its application to the Dutch food packaging ecosystem, and explaining why this ecosystem should be approached as a complex adaptive socio-technical system. This section sets the foundation for formulating the methodology and the research in subsequent sections.

2.2 Methodology

The complex adaptive socio-technical system approach has been used to formulate the methodology to study circular ecosystems. Three methods are combined to answer the research questions: agent-based modelling based on information from a systematic literature review and a case study. The study is substantiated and validated through expert discussion.

2.2.1 Agent-based modelling

Agent-based modelling is a powerful simulation technique that can be used to get a natural understanding of complex adaptive socio-technical systems (Den Hartigh et al., 2005; Senyo et al., 2019; Van Dam et al., 2013). It is therefore deemed a suitable research method to study circular ecosystems in the Dutch packaging system. ABM allows prior analysis of circular ecosystems and the potential effects of different ecosystem variables, which can gain insights into the possible outcomes and prevent ineffective changes. This study uses the methodology proposed by Van Dam et al. (2013), which includes ten steps:

Step 1: Problem formulation and actor identification
Step 2: System identification and decomposition
Step 3: Concept formalisation
Step 4: Model formalisation
Step 5: Software implementation
Step 6: Model verification
Step 7: Experimentation
Step 8: Data analysis
Step 9: Model validation
Step 10: Model use

2.2.1.1 Problem formulation and actor identification

This method's first step is to understand the problem under study and the actors involved (Van Dam et al., 2013). The focus on circularity and ecosystems was defined in collusion with Deloitte's TV&A experts because industries are exploring opportunities to become more circular and collaborate with others. A systematic literature review (SLR) was conducted to explore the current state of scientific research in the field of circularity and ecosystems, presented in Section 2.1. Through the review, the notion of 'circular ecosystems' was found as the overarching concept of circularity and business ecosystems. The most relevant and recent literature on circular ecosystems was used for the problem formulation, presented in Section 1.2. Actor identification is included in the scope description of the study in Section 1.4 and is elaborated on in Section 3.1.

2.2.1.2 System identification and decomposition

The second step identifies the system and its boundaries, as was done in Section 1.4, and decompose it into its components. The decomposition process includes an inventory phase, in which the systems' physical and social entities are distinguished, and a structuring phase, in which the actors and interactions are structured, and the environment is characterised (Van Dam et al., 2013). This study required the decomposition of the food packaging ecosystem in the Netherlands. For this decomposition, the SLR from Step 1 was extended with additional search terms, including scientific articles and grey literature, such as reports and government documents. The SLR is described in Section 2.2.2. Additionally, a case study was used to understand the actors and interactions in a food packaging system, explained in Section 2.2.3. The results of the decomposition of the Dutch food packaging ecosystem are presented in Chapter 3.

2.2.1.3 Concept and model formalisation, software implementation and model verification

In the third step, the list of concepts and entities from Step 2 was structured to conceptualise the ABM of the food packaging ecosystem. This inventory was translated into computer-understandable analogues, such as numbers, strings and booleans (Van Dam et al., 2013). The fourth step, involving the model formalisation, was used to understand the actor's behaviour and the order of the behaviour and interactions (Van Dam et al., 2013). For this purpose, a model narrative was created. Next, the ABM was implemented in NetLogo version 6.3.0 (Wilensky, 1999). Afterwards, Step 6 was executed, which concerned verification of whether the model was doing what it was supposed to do. This verification is done by performing various test runs and tracking agent behaviour. Steps 3 to 6 are presented in Chapter 4.

2.2.1.4 Experimentation

Relevant experiments were set up for Step 7 in discussion with experts based on the possibilities in the model and the most relevant insights. The experimentation starts with a sensitivity analysis of the variables related to decision-making behaviour of the actors. Next, eight additional experiments were performed to assess the affect of variables related to Dutch waste, price, and innovation. The experimental design and its validation are presented in Chapter 5.

2.2.1.5 Data analysis

The data from the experiments was analysed for Step 8 (Van Dam et al., 2013). The data analysis included data visualisation, pattern identification and interpretation as well as statistical data analysis. The data analysis of Step 8 presents the results that are described and discussed in Chapter 6.

2.2.1.6 Model validation and model use

The ABM and results were validated for Step 9 through discussions with ecosystem and ABM experts. Next, Step 10 was used to critically assess the results and consider the limitations of the model. The results of Steps 9 and 10 are presented in the form of a discussion in Chapter 7, together with suggestions for potential future research. Finally, conclusions are drawn from the results in Chapter 8.

2.2.2 Systematic literature review

A systematic literature review (SLR) was conducted to complete Steps 1 and 2 of the agent-based modelling. The first objective was to explore the current state of scientific research in the field of circularity and business ecosystems. The second objective was to decompose the food packaging system in the Netherlands and the potential circular ecosystems in that system. Web of Science and Google Scholar were used during this review.

For the first objective, search terms related to ecosystems, circularity and complex systems were used, which resulted in a vast number of articles. The most relevant articles were identified and scanned to get a general understanding of the field. Next, the most relevant terms were combined into new search terms and "circular ecosystem" was identified as an additional term in the field. The search resulted in a list of 155 articles. The exact search terms and number of articles per search term are shown in Appendix A. The titles of the articles were scanned, and 30 articles were removed from the list due to unrelated topics. The abstracts of the remaining articles were read to determine their relevance, which resulted in the additional removal of 30 articles. The 95 remaining articles have been categorised by their content into six categories: background, social components, technical components, complex adaptive systems, circular ecosystems and ABM. An explanation of the category, the number of articles and the use of the articles are shown in Table 1.

For the second objective, the literature review was substantiated with additional concrete search terms and grey literature, such as reports, government documents and organisational websites. The search terms were directed to understanding the Dutch food packaging system (Chapter 3). Snowballing was used on relevant literature and websites to get a more thorough understanding of the system. Literature on circular ecosystems was used to identify potential circular ecosystems for the Dutch food packaging system (Section 2.1.1). Snowballing was used on the most relevant articles about circular ecosystems to find specific information.

Table 1. Categorisation of articles from SLR and their application.

Category	Content	Articles	Used for
Background	Information on CE in general, policies related to CE and business ecosystems in relation to CE	16	Chapter 1 and 2
Complex adaptive systems	Information on complex adaptive system dynamics and CAS methodology	7	Chapter 1 and 2
Social components	Information on social elements of CE transition in complex systems, such as actor roles and behaviour	11	Section 3.1
Technical components	Information on technical elements of the CE transition in complex systems, such as use of digital technologies	6	Section 3.2
Circular ecosystems	Information on circular ecosystems, their drivers, barriers and dynamics.	33	Chapter 2 and 3
ABM	Information on agent-based modelling of complex adaptive systems and agent-behaviour in relation to CE strategies	22	Chapter 4

2.2.3 Case study

After the decomposition of the Dutch food packaging system, the case of a specific product was used as the basis for the ABM. Case studies are useful for getting a realistic understanding of ecosystems and their dynamics (Barquete et al., 2022; Hsieh et al., 2017; Niero et al., 2017) and have been demonstrated as a good foundation for ABMs of collaborative systems (Lange et al., 2021; Ma et al., 2021; Værbak et al., 2021). The choice for a specific product gives a concrete ecosystem to base the ABM on. For confidentiality, this report addresses the producer of the case study's product as Food and Beverage Company X.

2.2.3.1 Food and Beverage Company X

The selected case study was Food and Beverage Company X, which is a Dutch multinational cooperative that produces a popular beverage. The case was selected for several reasons. First, beverages inherently require packaging to be contained between production and consumption, unlike some other food products. Secondly, the selected beverage is sold in various packaging formats, which makes it less reliant on a specific packaging type. This versatility of packaging options poses multiple opportunities to set up circular ecosystems. Furthermore, Food and Beverage Company X makes efforts to improve the sustainability of their packaging.

Food and Beverage Company X posed the case to base the ecosystem in the ABM on. The ABM of Food and Beverage Company X's ecosystem could then be used to explore the implementation of circular ecosystem practices in the Dutch food packaging system.

2.2.3.2 Data collection

The data for the case study was collected in several ways. First, qualitative input data was retrieved from an interview with the Packaging Developer of Food and Beverage Company X. The interviewee has worked at Food and Beverage Company X as a Packaging Developer for six years and currently holds the position of team lead for a Packaging Development team. This interview gave insight into the packaging design and selection process of Food and Beverage Company X. The interview resulted in multiple factors influencing the decision for a certain packaging combined with their level of importance. The notes from the interview are shown in Appendix B.1.

Next, some qualitative data was confirmed by Food and Beverage Company X's Brand Management of the studied product and a Logistics Account Manager of Food and Beverage Company X. Additionally, quantitative data was assembled by the Brand Management and Logistics Account Manager comprising percentages of the total packaging weight for the different packaging types. The use of this quantitative data improved the accuracy of the ABM results. The digital notes on this qualitative and quantitative data are presented in Appendix B.2

Last, the results from the Dutch food packaging ecosystem analysis in Chapter 3 were validated by a second interview with a Business Analyst from the Dutch waste management structure. The interviewee has more than ten years of experience with the packaging waste file in the Netherlands. His work mainly concerns the monitoring of packaging recycling. This interview focussed on the waste management processes and collaboration within the waste management structure. Additionally, the interview was used to verify the system diagrams of the Dutch food packaging system. Additional information from the interview was used to assess the ABM's validity in representing the Dutch food packaging system. The notes from the interview are shown in Appendix B.3.

2.3 Research flowchart

The flowchart in Figure 2 shows the research approach of the thesis. It includes the main methods and processes and relates them to the research questions and the ten steps of the ABM methodology by Van Dam et al. (2013).

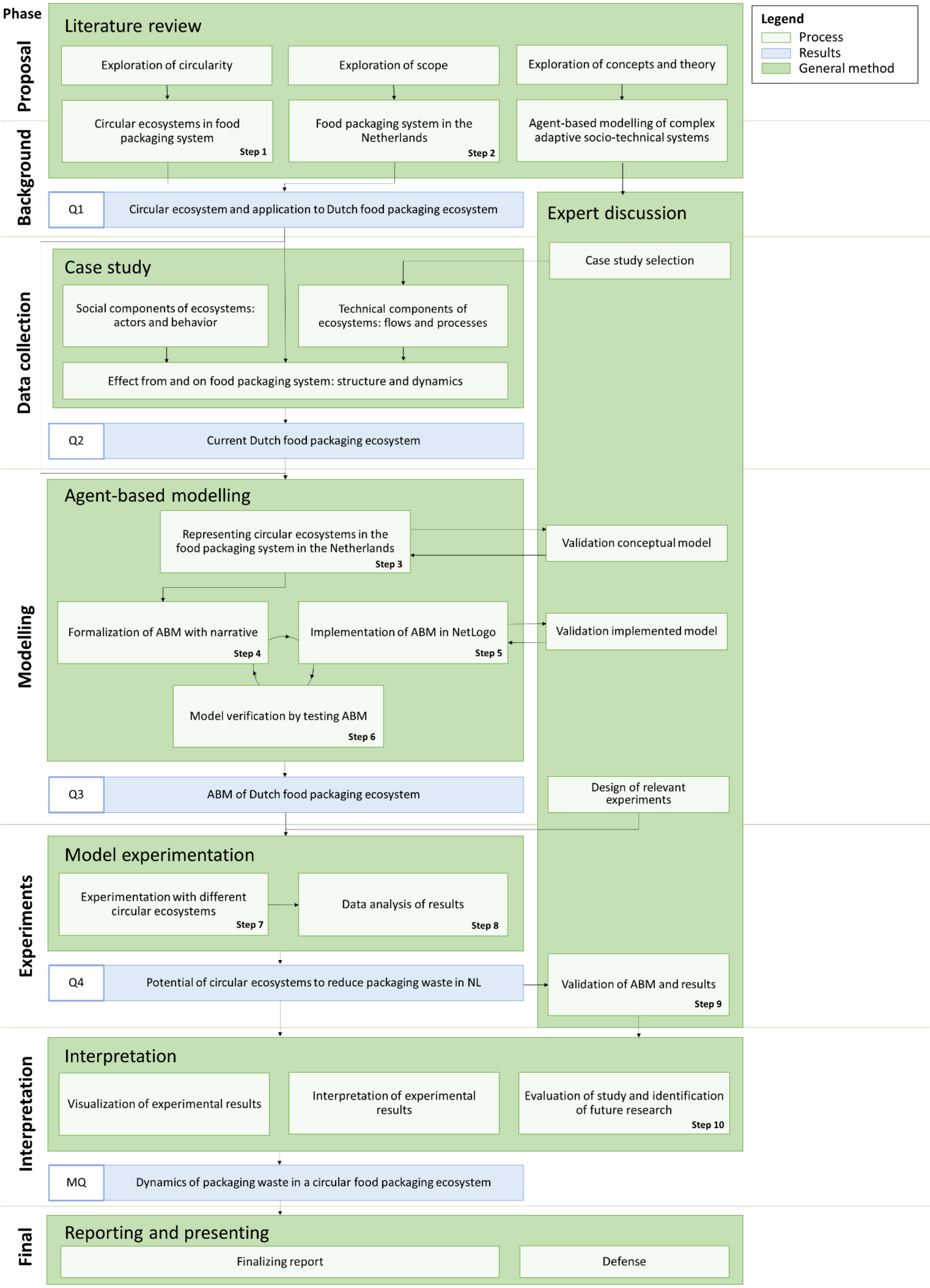

Figure 2. Research flowchart, main methodologies, and link with the ten steps of ABM by Van Dam et al. (2013).

3 Food packaging ecosystem in the Netherlands

This chapter entails the system identification and decomposition for Step 2 of agent-based modelling by Van Dam et al. (2013). This inventory of the system aims to answer the second sub-question:

What does the current food packaging ecosystem in the Netherlands look like?

The Dutch food packaging system is approached as a complex adaptive socio-technical system. The social components include actors, interactions and behaviour, while the technical components include materials and operational processes. Furthermore, the Dutch food packaging system is part of an environment that includes Dutch legislation and institutions. Lastly, specific information from a case study has been used to better understand the components affecting a Dutch food packaging ecosystem. Section 3.1 identifies the social components, Section 3.2 concerns the technical components, Section 3.3 explains the environment of the Dutch food packaging system, and Section 3.4 discusses the case study of Food and Beverage Company X. The chapter ends with a summary and remarks on the findings.

3.1 Social components

This section first describes the various actors within the Dutch food packaging system and subsequently identifies the dependencies between the different actors. The section is based on information from the SLR and the interviews with the Packaging Developer of Food and Beverage Company X and the Business Analyst from the Dutch waste management structure (notes in Appendix B.1 and B.3, respectively).

3.1.1 Actors

The Dutch packaging system involves various actors with different functions, roles, and objectives. The actors identified from the literature review include producers and importers, outlets, consumers, municipalities, waste treaters and the waste management structure. The interview with the Packaging Producer from Food and Beverage Company X also provided three extra actors: machine producers, non-governmental organisations, and universities.

3.1.1.1 Producers and importers

The producers and importers include the <u>material producers</u>, the <u>packaging producers</u> that manufacture packaging from virgin or recycled materials and the <u>food producers</u> that pack their products in packaging. In some cases, food producers design and develop their packaging and ask packaging producers to manufacture their packaging design. In other cases, food producers buy pre-made packaging for their products. After the packing process, products are transported to distribution centres and wholesalers that further distribute the products to stores, restaurants and other outlets. The packaging producers and food producers that pack their products must adhere to the extended producer responsibility (EPR) effective in the Netherlands (Section 3.3.3.1). In the Netherlands, this EPR is collectively executed by a waste management structure (Section 3.1.1.6). In total, about 2400-2500 companies market more than 50,000 kilogram of packaging material. These companies are legally obliged to pay a fee for the packaging they sell or use. The money raised is used to cover the costs of waste collection, sorting and recycling.

This study uses a specific food and beverage producer as a case study for the conceptualisation of the ABM. Section 3.4 presents more detailed information on the producer, its product, its processes and its supply chain.

3.1.1.2 Outlets

The outlets sell the packed products to the consumers. Outlets include supermarkets, stores, restaurants, and sports canteens, amongst others. The outlets decide which products they sell and in which packaging format, although the choice depends on the outlet’s consumers. The selection of a specific packaging solution depends on the occasion in which the product will be consumed. Different packaging requirements are needed for different occasions, such as consuming a product at home, in a restaurant, or on the go. Larger packaging is typically preferred for home consumption and therefore sold in supermarkets, while packaging is unnecessary in a restaurant setting, and on-the-go packaging should be easily disposable or closable.

Some outlets have an additional role in the packaging system. Many supermarkets offer collection points for the deposit-return system. The set-up of a collection point is mandatory for supermarkets larger than 200 square meters and staffed gas stations (Statiegeld Nederland, 2023). Other outlets, such as restaurants, collect and return used packaging as well. In that case, the product is consumed at the outlet, and the packaging is left at the location.

3.1.1.3 Consumers

The food packaging system is heavily influenced by consumers. The consumer buys the packed product, uses the product, and disposes of the packaging. The consumer's demand for a certain product and its packaging affects the design, selection and production of packaging materials (KIDV, 2022c). The disposal or return of packaging by consumers also has important implications for the circularity of the packaging system. The purchase and disposal phases are largely affected by consumer behaviour, which results in complex and adaptive behaviour within the Dutch food packaging ecosystem. Consumer behaviour depends on factors such as the consumer's motivation, opportunity and ability (Ölander & Thøgersen, 1995). Section 3.1.3.2 further depicts consumer behaviour.

3.1.1.4 Municipality

The municipalities collect consumer waste and bring it to sorting facilities contracted by Stichting Afvalfonds Verpakkingen (StAV). This organisation is described in Section 3.1.1.6. The Netherlands has 342 municipalities as of January 2023 (Rijksoverheid, 2023a). Most municipalities in the Netherlands are collectively represented by the association called Vereniging van Nederlandse Gemeenten (VNG). VNG and StAV together form Platform Ketenoptimalisatie (PKO) that monitors and evaluates the arrangements in the Ketenovereenkomst. The Ketenovereenkomst is an agreement between VNG and StAV and includes two models that municipalities can use for waste collection and recycling of plastic, metal and drink cartons (PMD).

The municipalities can either use a source-separation model, in which consumers separate PMD from other waste, or a post-collection separation model, in which the waste is separated by a dedicated facility (VNG & StAV, 2020). In the first model, the municipality is responsible for the quality of the PMD, while in the second model, the quality is secured by a contracted facility. Nedvang b.v. (Section 3.1.1.6) advises municipalities on optimising waste collection, separation, and quality assurance. Municipalities must work with waste treaters acknowledged by Nedvang b.v to be eligible for compensation.

3.1.1.5 Waste treaters

Waste treaters receive the packaging waste from the municipalities and take care of the sorting, separation, recycling, and other waste treatment. Some waste treaters take care of one material; others treat multiple or all sorts of material (Nedvang b.v., 2023). Part of the waste is recycled in the Dutch packaging system (closed-loop recycling), another part is recycled outside of the Dutch packaging system (open-loop recycling), and the last part is incinerated and enters the atmosphere in the form of emissions.

Based on the interview with the Dutch waste management, three types of waste treaters can be distinguished: waste sorters, recyclers, and waste incineration facilities. In the Netherlands, only a handful of sorters sell sorted and separated recycled material to recyclers. The waste sorting capacity is a bottleneck in the Dutch packaging system, so part of the Dutch waste is sorted abroad. Next, the recyclers further process the recycled material and use it to make products. The currently non-recycled waste is transported to waste incineration facilities. In the Netherlands, the waste incineration facilities are often owned by local authorities. In some cases, they are part of a heat network, making local authorities dependent on the heat produced in these plants. Because of this dependency, waste might be imported when the Dutch waste supply is insufficient to produce enough heat for the heat network to function (Interview with Business Analyst from Dutch waste management structure).

3.1.1.6 Waste management structure

In the Netherlands, the EPR is executed by a waste management structure comprising five non-profit organisations. The producers of packaging and packed goods pay a waste management fee per kilogram of packaging placed on the market to finance this waste management structure.

<u>Stichting Afvalfonds Verpakkingen</u> (StAV) receives the waste management fee from businesses to collectively execute the legal responsibility of the EPR. This fee is used to arrange and pay for the collection and recycling

activities by the municipalities, waste sorters and recyclers and fund the other organisations within the waste management structure. Municipalities and sorters receive compensation for the collected and sorted waste and must provide information to StAV. Additionally, the StAV reports on the annual packaging brought to the market and corresponding recycling rates (Afvalfonds Verpakkingen, 2023b).

Nedvang b.v registers data on the collection and recycling of all packaging waste in the Netherlands, which are provided to StAV to use for the annual monitoring report. This data is also used to advise StAV on the compensations for municipalities and waste treaters. Until recently, the recycling rates were based on the amount of recycled material from waste sorters. However, the new measuring point is the amount of material recycled by recyclers because some recycled material might still be lost during further sorting or cleaning. Since the new measuring point is located after the recyclers, they must also report information to Nedvang. In turn, Nedvang supports municipalities and waste treaters in improving their performance (Nedvang, 2023).

Kennisinstituut Duurzaam Verpakken (KIDV) assists and informs companies on improving the recyclability and sustainability of packaging. The KIDV provides information, tools, and training based on scientific and practical knowledge (KIDV, 2023).

Statiegeld Nederland is the executing organisation of the deposit-return system in the Netherlands. The organisation coordinates the deposit and return logistics, including the handling fees for return points (Statiegeld Nederland, 2023).

NederlandSchoon focuses on preventing and tackling litter by using various instruments. These instruments include campaigns targeted at consumers and advice for producers. The overall goal of NederlandSchoon is to induce behavioural changes that reduce littering (NederlandSchoon, 2023).

3.1.1.7 Machine producers

Food producers own production lines of machines used for packaging their products. These machines require a significant investment of 10-20 million euros and typically have a lifespan of 10 to 20 years. New machines are mainly purchased when the current ones need replacement or when markets change, resulting in different packaging requirements. The machines are nearly always designed for a certain packaging type, and the packaging must meet the dimensions and characteristics that can be used in those machines. The machine producer can customise the machines according to the specific requirements and preferences of the food producers. In some cases, the machine producer additionally supplies the required packaging, in which case the food producer buys a product-service system rather than only a production line.

3.1.1.8 Non-governmental organisations (NGOs)

Non-governmental organisations (NGOs) play an important role in the packaging ecosystem. They can exert pressure on different actors to improve the sustainability of packaging. For example, an NGO can affect a food producer’s reputation through certain actions or advertisements, which might change the demand for a certain product.

3.1.1.9 Universities

Actors within the packaging ecosystem can benefit from collaboration with universities, who carry out research, provide knowledge and help innovate to improve the circularity of packaging.

3.1.2 Dependencies

The interactions between actors within the Dutch food packaging system are based on different dependencies, as the actors depend on each other in multiple ways. The three dependencies distinguished in the Dutch food packaging system are material, financial and information dependencies. It is important to note that the physical and information dependencies also relate to the technical components: the former represents material flows, and the latter often relies on information technology. However, this study regards these flows as interactions between actors, which are considered social components when following Van Dam et al.'s interpretation of components in socio-technical systems (2013). This intertwinement already shows the sometimes ambiguous division between social and technical components.

3.1.2.1 Material dependencies

Material dependencies are the flows of material from one actor to another. These dependencies naturally include the supply chain, in which the packaging is produced, used and sold, after which the product is consumed and the packaging is disposed of. Municipalities collect the packaging waste and transport the waste to the waste treaters. The material is then either recycled into new packaging, recycled into another product, or incinerated and emitted into the atmosphere. There are additional material dependencies, such as the litter from the consumer to the environment and litter from the consumer to NederlandSchoon. Furthermore, there are material dependencies related to the deposit-return system: packaging is returned to the outlet by the consumer and the outlet returns the packaging to the recycler, either via the food producer or directly to the recycler (Statiegeld Nederland, 2023). Lastly, there is a material dependency between machine producers and food producers, as they supply the machines for the production lines of the food producers. The material dependencies are shown in Figure 3.

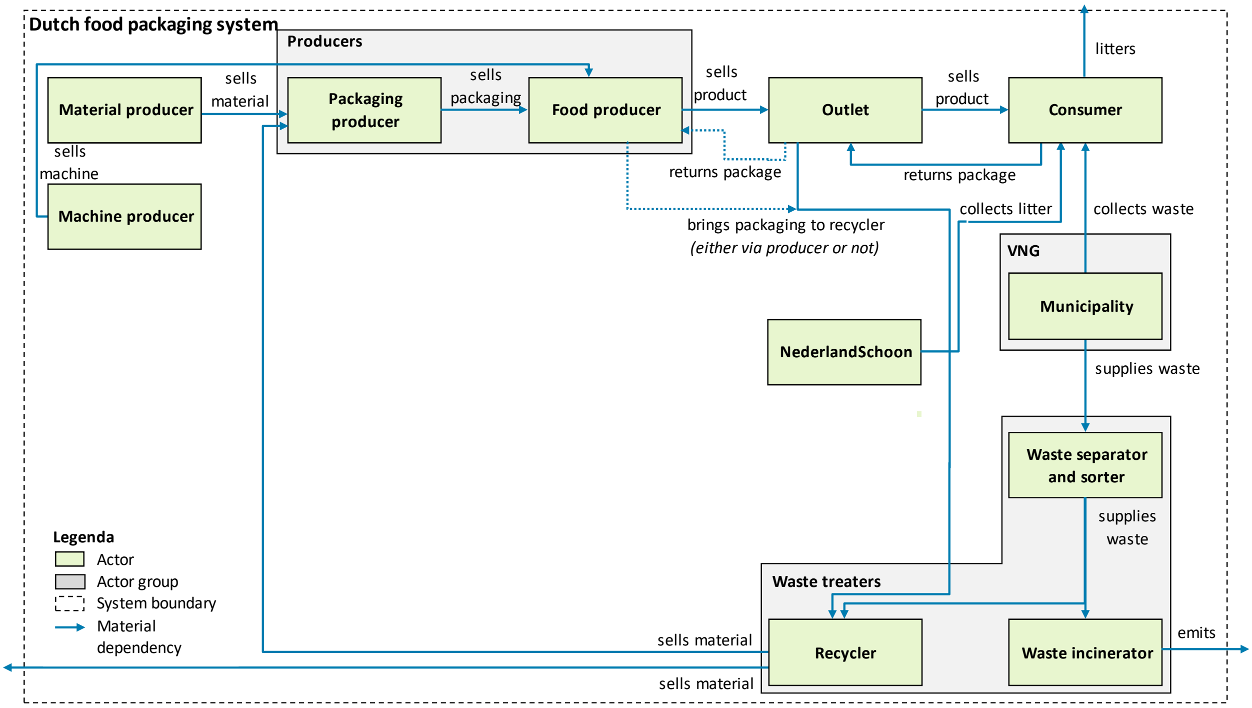

Figure 3. Material dependencies in the Dutch food packaging ecosystem.

3.1.2.2 Financial dependencies

Financial dependencies include the payments to buy products, the payment of taxes and fees, funding and subsidising and the refund of deposits. The financial dependencies in the supply chain naturally have opposite directions from the material dependencies. Additionally, some packaging is part of the deposit-return system, for which consumers pay a fee that is refunded when the packaging is returned to a collection point.

In the current linear economy, the packaging's value is lost after consumption, and the material is seen as waste that must be treated. Because of this, municipalities and waste treaters are paid by the Dutch waste management structure to handle the waste. As discussed in the previous section, waste treatment is paid via the extended producer responsibility (EPR). Additionally, the Dutch consumers pay a waste collection tax to their municipality (Ministry of the Interior and Kingdom Relations, 2021). Furthermore, recyclers can sell recycled material and products to packaging producers or other producers. The financial dependencies in the Dutch food packaging system are shown in Figure 4.

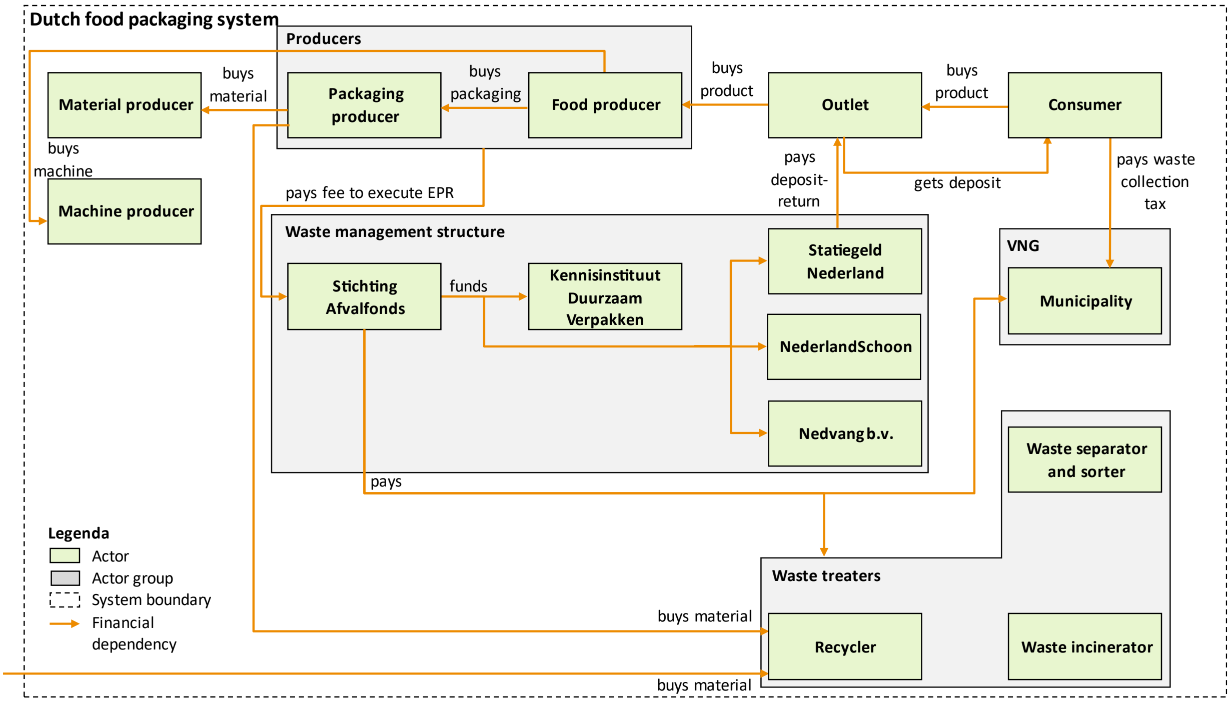

Figure 4. Financial dependencies in the Dutch food packaging ecosystem.

3.1.2.3 Information dependencies

Information dependencies include relations based on various forms of data. This data can be advice, activating information, protocols, legislation, control data or election results. Participation in a platform is also regarded as a form of information dependency. In the context of the Dutch food packaging system, the waste management structure plays a vital role in collecting and sharing information. The waste management structure sets protocols municipalities and waste treaters must follow to collect data on waste volumes.

Consequently, municipalities and waste treaters must report the volumes of waste and recycled material to the waste management structure to receive compensation. This data is reported to the government to monitor the progress towards the Dutch recycling targets. Furthermore, the waste management structure has an informing role by guiding the improvement of circularity to producers, consumers, and municipalities.

The Dutch food packaging system is influenced by three external actors who are not directly part of the system but have information dependencies with the system. These actors consist of local, national and European governments, NGOs and universities. The local and national government, elected by the Dutch population (consumers), establishes legislation that aligns with European regulations. The legislation provides a framework in which the Dutch food packaging system operates. Moreover, the government sets recycling targets, which are monitored through the Dutch waste management structure. Secondly, universities conduct research that can steer the Dutch food packaging system towards more sustainable practices. They contribute to innovation, such as developing new technologies to increase recycling rates or maximum potential recycled content in packaging. Finally, NGOs can exert power over the packaging system, as they can influence various actors through campaigns, petitions, or other instruments.

The information dependencies in the Dutch food packaging system are shown in Figure 5.

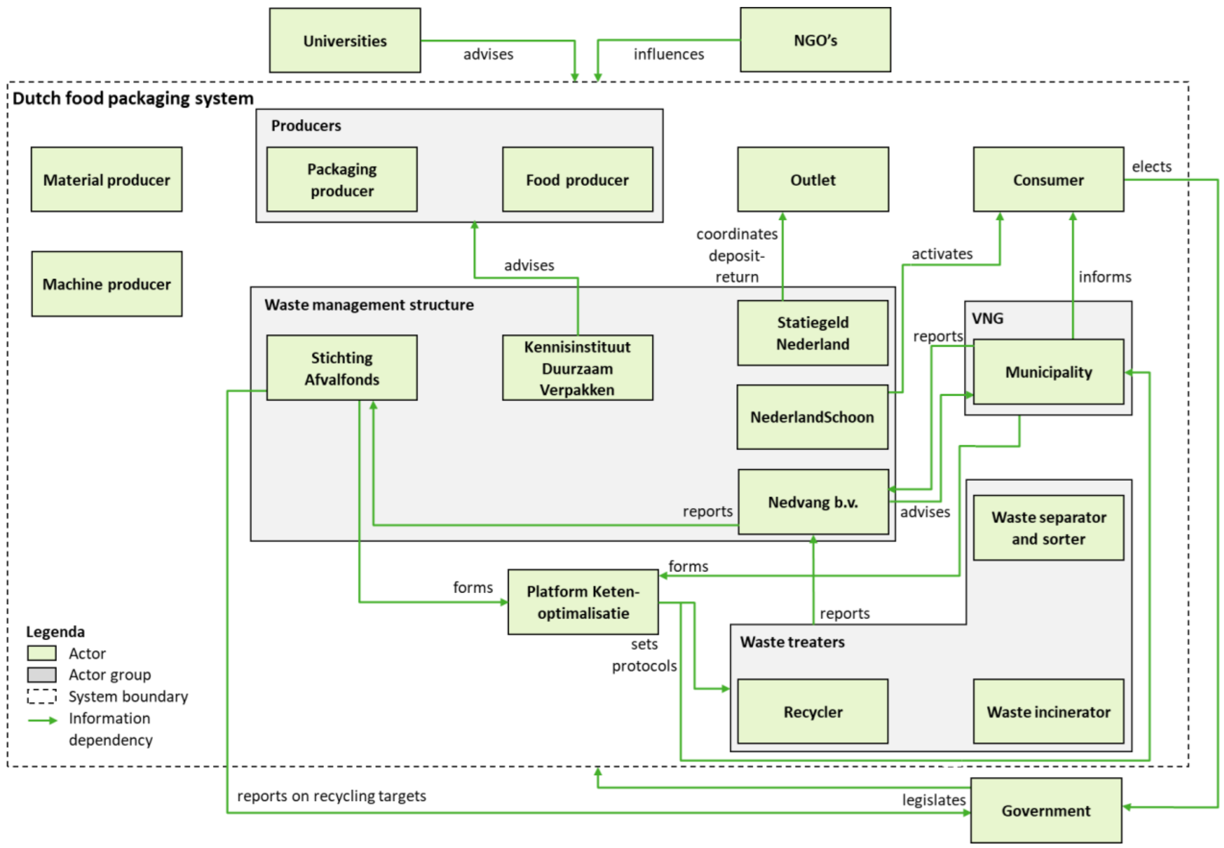

Figure 5. Information dependencies in the Dutch food packaging ecosystem.

All dependencies in the Dutch food packaging system have been accumulated in Figure 6.

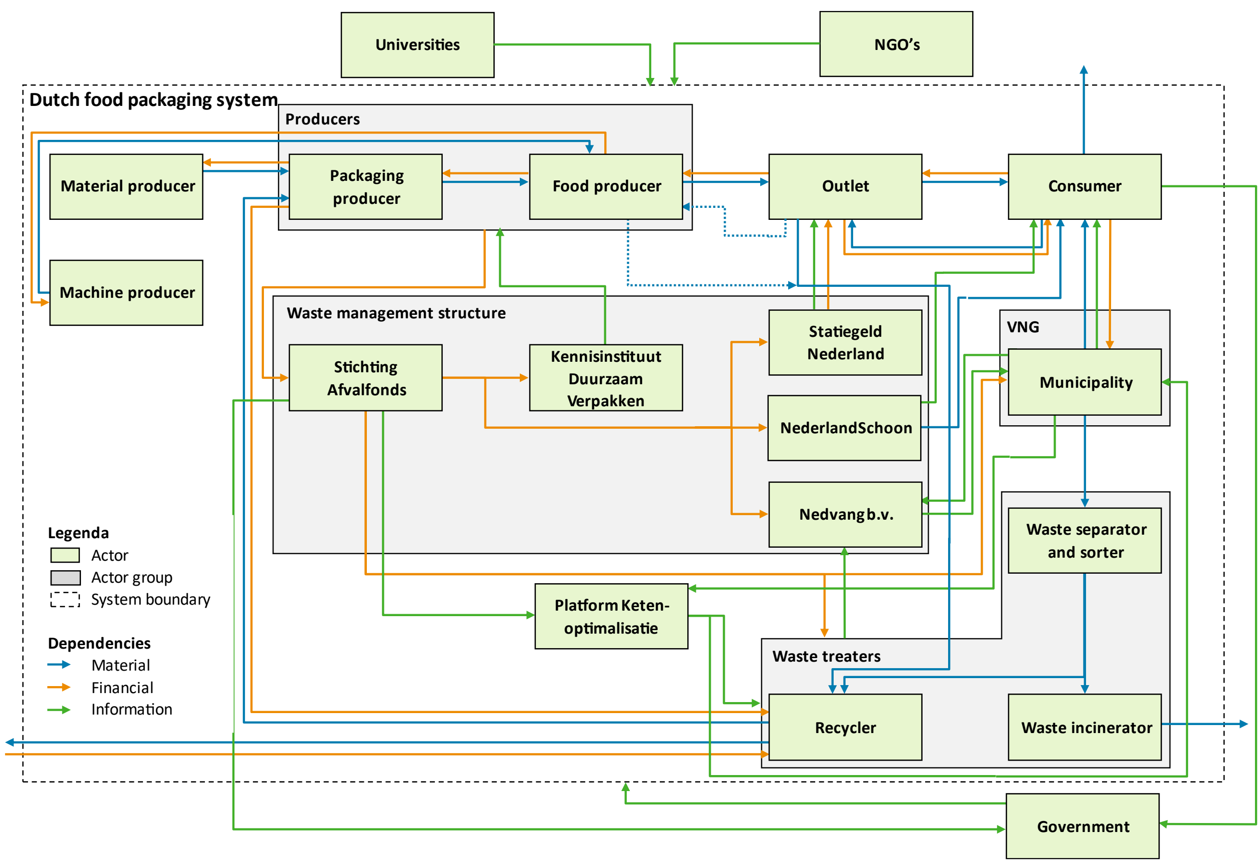

Figure 6. Material, financial and information dependencies in the Dutch food packaging ecosystem.

3.1.3 Behaviour

Part of the complexity and adaptivity of the Dutch food packaging ecosystem is caused by the uncertainty of actor behaviour within the ecosystem. This last part of Section 3.1 discusses the behaviour of actors in the Dutch food packaging ecosystem. Within this system, actor behaviour can be divided into two main categories: consumer behaviour and organisation behaviour.

3.1.3.1 Consumer behaviour

Consumers are individual actors making multiple decisions that affect the waste streams within the Dutch food packaging system. Notably, they decide whether they buy a certain product, where they buy it and how they dispose of the packaging. Consumer behaviour can be understood using the motivation-ability-opportunity model by Ölander & Thøgersen (1995). According to this model, the consumers' behaviour depends on their motivation, which are their intentions affected by their beliefs, attitude, and social norms. However, consumer behaviour is not only dependent on motivation but also on the consumers' ability and opportunity. The former concerns the consumer's skills and knowledge, and the latter concerns external factors such as the context (Ölander & Thøgersen, 1995).

In the food packaging system, the consumers' motivation, ability, and opportunity to make certain choices are influenced by a plethora of factors. For example, a recent study showed that Dutch consumers' intention to purchase recycled plastic products depends on anticipated conscience, value for money and perceived functionality and is negatively affected by contamination risks (Magnier et al., 2019). Other researchers showed that social norms and perceived behavioural control greatly affect post-consumer recycling behaviour (Tong et al., 2018). Additionally, the consumers' ability to make more sustainable decisions depends on the provision of information, for example, on the packaging material and the correct way to dispose of it, but also on the consumers' skills and feelings of self-efficacy (KIDV, 2022). Lastly, the opportunity for sustainable consumer behaviour is affected by available infrastructure and packaging options during purchase and disposal (KIDV, 2022c; Tong et al., 2018).

Overall, consumer behaviour in the Dutch food packaging system is extremely versatile and dependent on many factors. As this study aims to analyse circular ecosystems, the conceptualisation focuses on organisational behaviour. In line with this scope, consumer behaviour is simplified in the ABM in this study.

3.1.3.2 Organisation behaviour

The main focus of this study is on the second category of actors in the Dutch food packaging ecosystem, which concerns organisations. As explained in the methodology, the organisational decision-making framework by Scharpf (1988a) is used to characterise organisational behaviour in the Dutch food packaging ecosystem.

When considering decision-styles, problem-solving and bargaining are the most probable styles for decision-making in a collaboration context. The problem-solving decision-style focuses on cooperation and pursuing common goals as a group. In contrast, the bargaining decision-style is fuelled by self-interest while being unconcerned about the outcome for others. The confrontational decision-style refers to the interactions in which winning is the main driver of decision-making, and collective gain is interpreted as no gain (Scharpf, 1988a). The realisation of a circular ecosystem requires collaboration; therefore, the confrontation decision-style is assumed unsuitable in a collaborative ecosystem.

With regards to decision-rules, the potential decision-rules are unanimity and hierarchy. The Dutch food packaging ecosystem comprises private and public sector organisations that can collaborate. Unanimity is the most common style *between* private sector organisations, and hierarchy is the common style *within* private organisations and *between* public and private sector organisations. The majority decision-rule is less relevant in this study, as the decision-rule is mainly used *within* the public sector, for example, in elections or voting on bills (Scharpf, 1988a). The unanimity rule could be considered the most likely decision-rule within an ecosystem, as decisions are made *between* private sector organisations. However, when the ecosystem is perceived as an organisation of multiple organisations, the hierarchy decision-rule may come into play. This would imply that certain organisations hold more power in decision-making than others. Overall, both unanimity and hierarchy could be the decision-rule in the packaging ecosystem.

In summary, four relevant combinations of decision-rules and styles can be used to characterise the decision-making process of actors in the Dutch food packaging ecosystem. These combinations are shown in Figure 7.

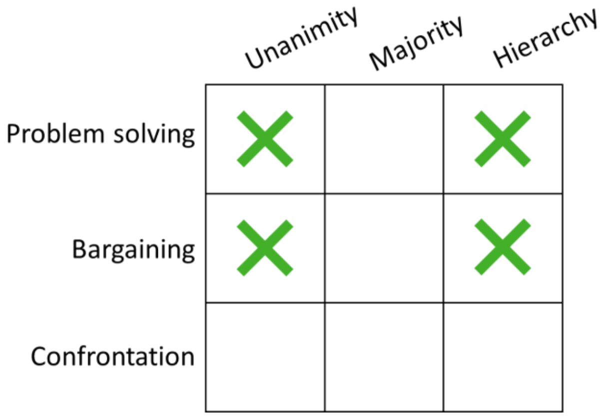

Figure 7. Combinations of decision-rules and styles used to characterise organisations in the Dutch food packaging system (based on decision-making framework by Scharpf, 1988)

3.2 Technical components

The technical components of the Dutch food packaging ecosystem concern the materials and processes within the system. This section distinguishes six packaging types: glass, paper and cardboard, drink cartons, plastic, aluminium, and steel. The production and recycling processes are described for these materials. Additionally, digital technologies are important in realising a circular packaging ecosystem. A detailed description of the digital technologies used in the food packaging system falls outside the scope of this study. However, Section 3.2.7 will shortly discuss the role of digital technologies in the transition to a circular food packaging ecosystem. The section ends with an overview of the technical components.

3.2.1 Glass

In 2021, the Dutch market saw the introduction of 512 kton of glass packaging material (Afvalfonds Verpakkingen, 2021). Glass is a popular material for producing bottles and jars intended for food items with a long shelf life (KIDV, 2022b). Its production requires sand, limestone, sodium carbonate and temperatures around 1500 °C (Afvalfonds Verpakkingen, 2021). After production, the glass is moulded in the desired packaging shape (KIDV, 2022b).

In the Netherlands, glass should be disposed of in designated glass bins that may have separate compartments for different colours of glass (Afvalfonds Verpakkingen, 2021). After collection, the glass is sorted and separated from other materials via multiple processes that include the use of magnets, sieves, cyclones, lasers and cameras (Afvalfonds Verpakkingen, 2021). Subsequently, the glass is stored for a few weeks or shortly heated to remove excess food or liquids. Afterwards, the shards can be melted and recycled into new packaging or other products (KIDV, 2022b).

The Netherlands recycled 79% of the disposed glass in 2021 into new glass packaging or other glass products (Afvalfonds Verpakkingen, 2021). The amount of recycled glass that can be included in new packaging depends on the colour of the glass: transparent glass can contain between 25 and 60% recycled glass, green glass can contain between 85 and 95% recycled glass, and brown glass can contain between 70 and 85% recycled glass (KIDV, 2022b). Additionally, the Netherlands employs a deposit-return system for beer bottles, which can be refilled approximately 30 times before being recycled (KIDV, 2022b). As these bottles make up approximately half of the Dutch glass packaging, the total circularity percentage of glass packaging in the Netherlands was 89% in 2021 (Afvalfonds Verpakkingen, 2021)

3.2.2 Paper and cardboard

Afvalfonds Verpakkingen reported that 1.390 kton of paper and cardboard was used as packaging material in 2021, of which 90% was recycled after disposal (Afvalfonds Verpakkingen, 2021). However, it is important to note that paper and cardboard packaging includes all cardboard boxes used for transport and non-food products. In fact, the amount of food packaging accounts for less than 10% of the total paper and cardboard packaging (Holwerda et al., 2019). Additionally, the recycling rate of paper and cardboard food packaging is anticipated to fall below the general recycling rate because paper or cardboard food packaging is often bleached, coloured, laminated or coated, complicating its recycling (Holwerda et al., 2019).

The process of production and recycling paper and cardboard packaging is similar, with new paper and cardboard products containing 87% recycled paper material in the Netherlands (PRN, 2022). To produce new food packaging, recycled paper fibres are combined with new cellulose fibres. The resultant mixture is then formed and pressed into sheets of paper and cardboard, which are subsequently dried and refined into the desired packaging form (Holwerda et al., 2019).

Paper and cardboard packaging should be disposed of in dedicated paper bins (Afvalfonds Verpakkingen, 2021). After waste collection, waste paper companies sort, clean and compress paper waste into bales, which are sold to paper and cardboard producers (PRN, 2022). At the paper producer, the paper is dissolved in water to produce pulp and to separate the paper fibres from contaminants such as tape and staples. Further processing is necessary for bleached and printed paper and cardboard food packaging in the form of deinking and bleaching. Eventually, the paper pulp is prepared for recycling into new paper products (Holwerda et al., 2019).

3.2.3 Drink cartons

Drink cartons require special attention. The volume of drink carton waste was 4.6 kilogram per person in 2019 (Milieu Centraal, 2023), totalling approximately 83 kton. Although the packaging is made of at least 70% carton, it is not recycled with paper and cardboard because it contains plastic and aluminium (Afvalfonds Verpakkingen, 2021). Instead, it should be disposed of with plastic and metal (PMD) or residual waste, after which it is sorted, separated, and recycled. The current recycling rate of drink cartons is low because recycling is hindered by hard-to-remove product residuals in the packaging and the challenging recycling process of the plastic and aluminium layers (KIDV, 2022a). Because of this, the recycling rate of drink cartons was only 31% in the Netherlands in 2020 (Thoden van Velzen & Smeding, 2022).

The production and recycling of drink cartons differ from general paper and cardboard processes. In addition to cardboard material, drink cartons may contain layers of aluminium foil and multiple films made of low-density polyethene (LDPE), as well as a cap made of high-density polyethene (HDPE) or polypropylene (PP) (KIDV, 2022a). This composition of different materials complicates the recycling process. While paper fibres can be recycled into pulp, recycling the by-product called PolyAl poses challenges (Thoden van Velzen & Smeding, 2022). Furthermore, paper fibres from the recycling of drink cartons are not used in the production of new drink cartons, which limits the application to open-loop recycling (KIDV, 2022a).

3.2.4 Plastic

In 2021, 546 kton plastic packaging material was introduced to the Dutch market in 2021 (Afvalfonds Verpakkingen, 2021). Plastic, a group of materials made of artificial polymer chains, is commonly used in food packaging due to its low weight, durability, strength, water resistance, and cost-effectiveness in manufacturing (Kirwan et al., 2011). The most common types of plastic food packaging include polyethene-terephthalate (PET), polyethene (PE) and polypropylene (PP) (Plastics Europe, 2022). Most plastics are derived from monomers like ethylene and propylene, which are of fossil origin (Geyer et al., 2017). The polymers are produced by stringing together these monomers and are often in the form of a powder or granules (KIVO, 2023). While a detailed description of the production processes of the various types of plastics and packaging types falls outside the scope of this study, in general, polymers can be used for laminating and coating, film and sheet production, as well as for creating entire packaging through thermoforming or injection moulding techniques (Riley, 2012).

Dutch plastic packaging waste is recycled through three main systems: separate collection from households (PMD), mechanical recovery from mixed municipal residual waste, and a deposit-return system on small and large PET bottles (Brouwer et al., 2018; Statiegeld Nederland, 2023). The former two recycling systems rely on waste stream sorting and often result in molecular pollution and contamination. As a result, the recycled granulate derived from these processes is typically used in low-level recycling of non-food packaging and non-packaging applications (Brouwer et al., 2018). In contrast, the deposit-return system on PET bottles results in closed-loop recycling of relatively large volumes of PET into new packaging because of the high polymeric purity and low levels of molecular contamination (Brouwer et al., 2018).

In the Netherlands, the current recycling rate for plastic packaging is 49%, with the residual plastic packaging being incinerated (Afvalfonds Verpakkingen, 2021). However, it is important to note that this recycling rate includes closed-loop recycling of only 18% of plastic packaging material, with the remaining being recycled into lower-grade materials such as garden furniture and marker posts (Hanemaaijer et al., 2023). Moreover, only 35% of the packaging is suitable for high-level recycling, whereas 52% of the plastic packaging is usable for low-level recycling, and 13% is not recyclable at all (Brouwer et al., 2021; Natuur & Milieu, 2021). The success of the deposit-return system is evidenced by the fact that 20 to 25% of closed-loop recycled polymers are PET, even though only 6% of all plastic packaging is PET (Hanemaaijer et al., 2023). This translates to 60 to 75% closed-loop recycling of PET.

3.2.5 Aluminium

In 2021, the monitoring of metal packaging waste was divided into two categories, namely aluminium and ferrometals (steel). According to Afvalfonds Verpakkingen (2021), the total amount of aluminium packaging on the Dutch market was 45 kton in the same year. To produce aluminium, bauxite is mined and processed into alumina, which is converted into aluminium through electrolytic reduction (Visual Capitalist, 2022). The material is then rolled into sheets, which can be used to produce food packaging (RAVN, 2023). The vast majority of aluminium packaging is beverage cans, accounting for 21% of Dutch metal waste in 2016 (Roos Lindgreen & Bergsma, 2017), translating to approximately 95% of the total Dutch aluminium waste.

In the Dutch food packaging ecosystem, aluminium waste is collected through PMD and municipal residual waste. After incineration, aluminium is extracted from the bottom ash via an Eddy current separator. This process involves creating loops of electric current that make the aluminium magnetic, followed by the ejection and collection of the material (Afvalfonds Verpakkingen, 2021). The aluminium is sold to recyclers within and outside the EU and is recycled into new packaging or other products, such as bicycles and engines (RAVN, 2023). As of April 2023, aluminium cans are included in the Dutch deposit-return system, along with PET bottles, to reduce littering and improve the circularity of the system up to 100% (Nijenhuis, 2022; Statiegeld Nederland, 2023). Currently, 74% of aluminium waste is recycled (Afvalfonds Verpakkingen, 2021).

3.2.6 Steel

Ferrometals, or steel, are the second type of metal used in food packaging. In 2021, the total volume of steel in the Dutch market amounted to 157 kton (Afvalfonds Verpakkingen, 2021). Steel is a good material for food cans due to its preservation properties, enabling food to remain fresh for prolonged periods (Kadoya, 2012). Steel food cans account for 71% of the metal food packaging used in the Netherlands (Roos Lindgreen & Bergsma, 2017), translating to 91% of the total steel packaging. The production process for steel cans involves using tinplate or chromium/chromium oxide-coated steel obtained from iron ore (Koelsch Sand & Patel, 2020). Similar to aluminium packaging, the metal is rolled into sheets which are used to produce the desired packaging. Afterwards, the cans are typically coated with an interior lining, for example, PET, to prevent steel corrosion and maintain food quality (Koelsch Sand & Patel, 2020).

In the Netherlands, steel food packaging is collected through PMD or municipal residual waste and separated from the bottom ashes post-incineration, similar to aluminium packaging (Afvalfonds Verpakkingen, 2021). These ferrometals are collected with magnets and can be melted for reuse in new metal products. The efficient recovery process of steel results in the current recycling rate of 95% (Afvalfonds Verpakkingen, 2021).

3.2.7 Digital technology

On top of the physical technologies and artefacts, digital technologies also play a role in the Dutch food packaging system. Digital technologies can enable the transition to a circular packaging system, for example, by tracking and tracing reusable packaging (Ellsworth-Krebs et al., 2022), facilitating data sharing on used materials (Kofos et al., 2022) and informing consumers on waste disposal (Sadeghi et al., 2022). A recent study showed that a solid digital infrastructure could improve sustainability performance, even without strong cultural factors promoting collaboration (Zoppelletto & Bullini Orlandi, 2022).

On the other hand, the digital infrastructure of ecosystems becomes more complex with more components and interactions, which imposes several risks (Caporuscio et al., 2021). In addition, the environmental sustainability of digital technologies can be questionable due to their energy consumption and the critical materials used to produce them (Ipsen et al., 2019). Overuse of such technologies can contradict the principles of a circular economy. While digital technologies can support CE strategies and enhance communication and collaboration in the ecosystem (Liu et al., 2022), the ultimate goal of reducing packaging waste must not be forgotten.

This research considers information as a social component within the Dutch food packaging system. Information can be shared between actors in the Dutch food packaging system and can be used to report, monitor, analyse and innovate to reduce packaging waste. However, this study does not include software and hardware behind the collection, storing, sharing and use of this information as technological components of the Dutch food packaging system.

3.2.8 Overview

The variety of materials and processes in the Dutch food packaging system are portrayed in the technology diagram in Figure 8. The arrows in the diagram do not represent proportions of waste, closed-loop and open-loop recycling. The data on volumes, recycling rate and system has been accumulated in Table 2.

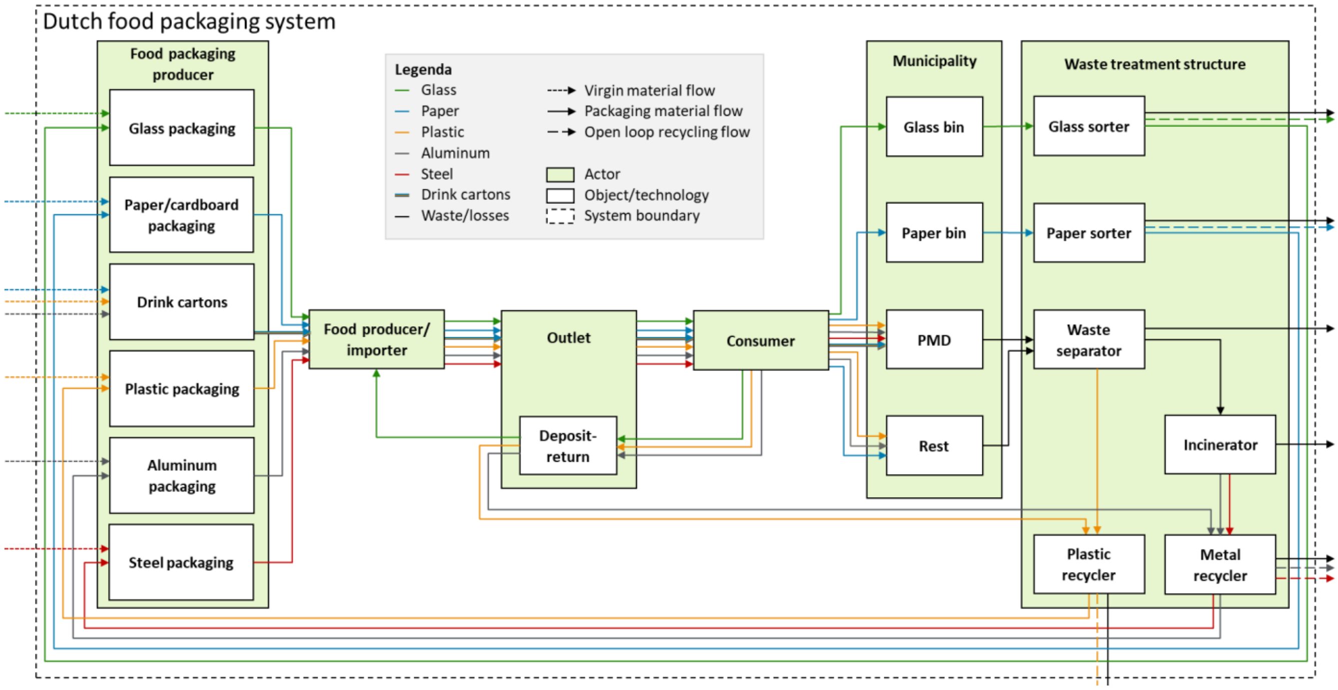

Figure 8. Technology diagram of material streams and processes in the Dutch food packaging system.

Table 2. Data on volumes and recycling of food packaging materials in Dutch food packaging system, including the different recycling systems and closed-loop recycling.

Material	kton on market (2021)	Total recycling	Recycling system	What	Closed-loop
Glass	512	79%	Deposit-return	Beer bottles *(~ 50 % of total glass)*	30 x refill
			Dedicated glass recycling	All other glass	25 - 95%
Paper/cardboard	139	90%	Dedicated paper recycling	Paper and cardboard food packaging *(~10% of all paper/carboard packaging)*	87%
Drink cartons	83	31%	PMD/rest	Drink cartons	0%
Plastic	546	48%	Deposit-return	PET *(6% of total plastic)*	60 - 75%
			PMD/rest	All other plastic	18%
Aluminium	45	74%	Deposit-return	Beverage cans *(~ 95% of total aluminium)*	Up to 100%
			PMD/rest	All other aluminium packaging	74%
Steel	157	95%	PMD/rest	All steel packaging	95%

3.3 Environment

The Dutch food packaging ecosystem is influenced by its environment, which includes geographic, political, and temporal factors, as well as Dutch and European legislation.

3.3.1 Geographic, political, and temporal context

The Netherlands is a small country located on the northwestern coast of Europe, bordered by Germany, Belgium, and the North Sea. The country has a parliamentary democracy and holds elections for the parliament and prime minister every four years. Since 2010, the liberal, right-wing VVD has been the largest party leading the Cabinet, with coalitions including Christian-democratic, social-democratic, social-liberal, and Christian-social parties (Ministry of the Interior and Kingdom Relations, 2022). This study considers the current zeitgeist of 2023 as the temporal context.

3.3.2 Dutch Circular Economy program

In 2016, The Dutch government launched a nationwide program with the goal of being a CE by 2050 (Rijksoverheid, 2016). To support this goal, the Dutch environmental assessment agency PBL conducts research on the impact of various policies and monitors the progress of the transition (PBL, 2020). Both PBL and other Dutch organisations, such as Afvalfonds Verpakkingen (2021) and Natuur & Milieu (2021), extensively analyse the material streams and circular strategies related to packaging. This program monitors the transition, forms a vision for the Dutch economy and provides direction and support for industries (Rijksoverheid, 2016, 2021).

3.3.3 Legislation

The Dutch food packaging ecosystem is subject to various European and Dutch legislation. European legislation forms the basis for setting out Dutch legislation.

3.3.3.1 European Packaging and Packaging Waste Directive (94/62/EC)

In 1994, the European Packaging and Packaging Waste Directive (94/62/EC) was established to regulate packaging waste in the European Union *(European Parliament and Council Directive 94/62/EC of 20 December 1994 on Packaging and Packaging Waste, 1994)*. The directive aims to prevent and reduce the impact of packaging waste on the environment. To achieve this, the directive provides minimum requirements for the design and production of packaging, and for the collection, recycling, and disposal of packaging waste. Additionally, the directive sets targets for the recovery and recycling of packaging waste and requires member states to implement EPR schemes (Section 3.3.3.3).

More recently, the EU implemented a directive that aims to reduce the environmental impact of single-use plastics by limiting their use and encouraging organisations to explore more sustainable alternatives *(Directive (EU) 2019/904 of the European Parliament and of the Council of 5 June 2019 on the Reduction of the Impact of Certain Plastic Products on the Environment, 2019)*. In the Netherlands, a surcharge of € 2.30 must be paid for every 1,000 pieces of single-use plastics on top of the EPR (Afvalfonds Verpakkingen, 2023a).

3.3.3.2 Dutch waste management plan

In 2014, the first version of the Dutch packaging decree was set up, which includes the essential requirements for packaging *(Besluit beheer verpakkingen, 2014).* This decree was revised in 2021 in line with the changes in European legislation. The revised decree entails recycling and reuse targets, methods for monitoring recycling and an extension of the EPR (Section 3.3.3.3). A framework agreement for packaging has been set out by the national government, the packaging industry and the municipalities to implement the decree *(Landelijk afvalbeheerplan 2017-2029 (LAP3), 2021).* Additionally, the directive for separate collection of household waste regulates municipal waste collection *(Besluit gescheiden inzameling huishoudelijke afvalstoffen, 2020),* in line with the Dutch environmental management plan *(Wet milieubeheer, 1993)*.

3.3.3.3 Dutch extended producer responsibility

Dutch packaging producers and food producers that pack their products must adhere to the extended producer responsibility (EPR) effective in the Netherlands. The EPR obliges producers and importers of packaging and packed goods to organise the collection and recycling of the packaging material (Rijkswaterstaat, 2023). The EPR is collectively executed by a waste management structure, including Afvalfonds Verpakkingen, Nedvang, KIDV, Statiegeld Nederlands and NederlandSchoon. These actors have been described in Section 3.1.1.6. The price of the EPR differs per material, depending on the costs of collection, sorting and recycling (Afvalfonds Verpakkingen, 2023a).

An effective way to improve the recyclability of plastic packaging is to use a single type of plastic per packaging. This strategy has been encouraged in the Netherlands by the introduction of rate differentiation in 2019, whereby the EPR fee is lower for easily sortable and recyclable plastics with a positive market value than for packaging that is more difficult to recycle (Afvalfonds Verpakkingen, 2021). The prices per food packaging material are shown in Table 3.

Table 3. EPR tariffs per packaging material in €/kilogram, excluding value added tax (Source: Afvalfonds Verpakkingen, 2023).

Material	**Tariff in €/kg (excl. VAT)**
Glass	€ 0.060
Paper and cardboard	€ 0.012
Plastics *(regular)*	€ 1.050
Plastics *(low)*	€ 0.790
Drink cartons	€ 0.700
Aluminium	€ 0.160
Steel	€ 0.250

3.3.3.4 Deposit-return regulations

The deposit-return system is mandated via the Dutch packaging decree *(Besluit beheer verpakkingen, 2014).* The system was initially limited to beer bottles and large PET bottles; however, it has expanded to include small PET bottles as of July 2021 and aluminium cans as of April 2023 (Statiegeld Nederland, 2023). Currently, activists plead to expand the deposit-return system to include all types of beverage packaging (Schram, 2022). The prices of the deposits are presented in Table 4.

Table 4. Deposits per packaging type in the Dutch deposit-return system (Source: Statiegeld Nederland, 2023)

Packaging	**Deposit in € per piece**
Glass beer bottles	€ 0.10
Plastic beer crates	€ 1.50
PET bottles *(large)*	€ 0.25
PET bottles *(small)*	€ 0.15
Aluminium cans	€ 0.15

3.3.3.5 Other legislation

There are several other regulations related to food packaging in addition to the legislation described in the sections above. The EU General Food law concerns food safety and quality, which also relates to packaging requirements *(Regulation (EC) No 178/2002 of the European Parliament and of the Council of 28 January 2002 Laying down the General Principles and Requirements of Food Law, Establishing the European Food Safety Authority and Laying down Procedures in Matters of Food Safety, 2002).* In the Netherlands, these regulations are included in the Dutch Commodities Act, which states the rules on hygienic preparation, packaging and labelling of foods *(Warenwet, 1935)*. Food safety and quality are important aspects of food packaging and can, therefore, limit the application of recycled material into new food packaging (Geueke et al., 2018). Although relevant, this research does not include a detailed assessment of the effect of recycled materials on food quality.

3.4 Case study

This section zooms in on the case study of Food and Beverage Company X and its packaging ecosystem, considering the social, technical, and contextual components of the Dutch food packaging system identified in the previous sections. The case study serves as a tangible inventory providing a practical foundation for the conceptualisation of the ABM in Chapter 4. By basing the ABM on a case study, the model has a more realistic foundation instead of relying solely on theoretical and hypothetical constructs. The content of this section is based on multiple sources, including online information about the case study product, insights obtained from the Interview with the Packaging Developer of Food and Beverage Company X and confirmation from the Brand Management team responsible for the product.

3.4.1 Packaging types

Food and Beverage Company X has a diverse packaging portfolio to penetrate various markets. Each packaging type is sold through different outlets and is part of a certain recycling system. The product is available in nine different packaging formats, each with varying product volumes, materials, and weights. The materials used in the packaging are consistent with those outlined in Section 3.2, except for the plastic bottle. The plastic bottle is made of 100% recycled PET (excluding the sleeve and cap) and is not subject to the deposit-return system that applies to other PET bottles. The packaging types and their characteristics are presented in Table 5.

Table 5. Nine packaging formats for the product of Food and Beverage Company X and their characteristics.

Packaging type	Volume (L)	Material	Weight packaging (kg)	Outlet	Recycling system
Small carton	0.2	Drink carton	0.008	Stores	PMD/rest
Medium carton	0.5	Drink carton	0.023	Stores	PMD/rest
Large carton	1	Drink carton	0.032	Stores	PMD/rest
XL carton	1.5	Drink carton	0.044	Stores	PMD/rest
Aluminium can	0.25	Aluminium	0.0091	Stores, Restaurants, Other	Deposit-return
Plastic bottle	0.3	PET	0.023	Stores, Restaurants, Other	PMD/rest
Plastic cup	0.23	Plastic and aluminium	-	Stores	PMD/rest
Glass bottle	0.2	Glass	0.155	Restaurants	Deposit-return
Pouch in box (4x)	3	Plastic	0.073	Restaurants	PMD/rest and paper

3.4.2 Packaging volumes

On top of general information on the various packaging types, data has been collected on the sales volumes of the product per packaging type. The product's Brand Manager at Food and Beverage Company X provided information on the proportions of different packaging formats in relation to the total packaging weight. Five packaging formats comprise 1% or more of the total packaging weight sold annually: the one-litre drink carton, the aluminium can, the recycled PET bottles, the glass bottles, and the Bag in Box (BIB). Therefore, these five packaging types are used in the conceptualisation. Due to confidentiality, the proportion data is not shared in this report. However, the data is used as input for the ABM.

3.4.3 Packaging selection process

Packaging selection is an important process when moving from a linear to a circular packaging ecosystem. The interview with the Packaging Developer of Food and Beverage Company X gave insight into the packaging selection process and the different components affecting this process.

First of all, the design flexibility of packaging depends on the type of packaging. PET bottles, for example, offer many possibilities in terms of shape and material. However, beverage cartons are mainly from Tetra Pak, which supplies both the production line and the packaging material. Although it is possible to choose a different packaging supplier, the packaging must meet the dimensions and characteristics suitable for Tetra Pak's production line. In the case of most other packaging, such as aluminium cans and glass bottles, the machine manufacturer and the packaging supplier are not the same actor.

Projects like the introduction of recycled PET bottle (rPET) start by identifying market trends. Previously, plastic bottles were made of HDPE, and these production lines needed replacement. Importantly, new packaging must meet the requirements to ensure the quality and shelf life of the product. The selection of a new packaging type occurs at a strategic level, taking into consideration costs (total cost of ownership), usage (different occasions) and sustainability (CO2 footprint and circularity). Subsequently, a business case is developed for the new packaging format. During the design and selection process, Food and Beverage Company X looks beyond the Dutch borders, as their products are sold worldwide, and the investment in a production line involves planning for the next 20 years.

3.4.3.1 Costs

The main investments of Food and Beverage Company X are the production lines. The company owns various production lines of machines used for packaging their products. These machines require a significant investment of 10 to 20 million euros and typically have a lifespan of 10 to 20 years. New machines are mainly purchased when the current ones need replacement or with changes in the market. The manufacturers of the filling machines customise the machines according to the specific requirements and preferences of Food and Beverage Company X.

The packaging material, including the EPR, is only a small portion of the overall costs. In the Netherlands, certain additional costs are less important than in other countries. For example, the drink cartons in the Netherlands are equipped with caps to prolong the product's shelf life. In countries where these small cost additions are a bigger concern, omitting the cap is considered a good option.

3.4.3.2 Usage

The occasion in which the product is consumed affects the desired design of the product. Different occasions necessitate different packaging requirements. For instance, larger packaging is preferred for home consumption, packaging is not required in a restaurant setting and packaging for on-the-go scenarios should be easily disposable or closable. Therefore, not all packaging is sold at all different outlets.

3.4.3.3 Sustainability

As sustainability is part of Food and Beverage Company X's strategy, the CO_2 footprint and circularity of the packaging are considered during the design and selection process. For example, the new rPET bottles are made from 100% recycled PET. The use of rPET often requires newer machines due to the variation in PET quality and the increased likelihood of contamination and colour discrepancies associated with higher rPET content. Although the rPET bottles are made of recycled PET, they are not recycled into new rPET bottles in the Netherlands because they are not part of the deposit-return system. Currently, PET is the only common type of plastic used for recycling in food packaging. In the future, recycled PE and PP can offer more options, but the current availability of these materials is limited according to the Packaging Developer of Food and Beverage Company X.

Regarding other types of packaging, the opportunities for circularity vary. For instance, glass bottles for restaurant use are refilled, and single-use glass bottles are no longer employed. Next, the powdered form of the product is sold in pouches in carton boxes, but this is limited to B2B (business-to-business) transactions. Although there have been attempts to sell the powdered product directly to consumers (B2C), some issues and a decline in quality have led to a preference for the liquid variant of the product. Lastly, tapping the product from a larger packaging is technically possible. However, once the packaging is opened, the product is no longer sterile, which can pose hygiene concerns.

3.4.4 Supply chain and logistics

As the Food and Beverage Company X is a cooperative, it operates in the interests of its members and relies on the supply volumes of its members. The company has factories in the Netherlands and abroad, including factories in Belgium and Germany. In these factories, the product is processed and packed. As mentioned in the previous section, the company is involved in the packaging design and -selection process but does not produce the packaging itself. Food and Beverage Company X prepares, fills, and seals the packaging. In the case of the glass bottles, the packaging is cleaned and refilled by Food and Beverage Company X. Afterwards, the product is sold to stores or wholesalers who resell to the catering industry and other sales locations, such as sports canteens and on-the-go outlets.

3.5 Summary and remarks

The analysis in Sections 3.1, 3.2 and 3.3 has dissected the social and technical components of the Dutch food packaging ecosystem, and its environment. In addition, Section 3.4 focused specifically on the case study concerning Food and Beverage Company X and its packaging ecosystem. This chapter aimed to answer the second sub-question:

What does the current food packaging ecosystem in the Netherlands look like?

The system analysis shows that the current food packaging ecosystem in the Netherlands consists of both social and technical components. The system includes a variety of actors, such as food producers, packaging producers and waste treaters. These actors fulfil different functions within the Dutch food packaging ecosystem. Additionally, the actors interact with each other. These interactions can relate to material, financial or information dependencies. Furthermore, the Dutch food packaging ecosystem relies on both consumer behaviour and organisational decision-making behaviour, characterised by different decision-styles and -rules. With regard to the technical components, the Dutch food packaging ecosystem comprises six main packaging materials that are produced, used, collected, and treated in different ways. Besides the processes and technologies related to these materials, improving circularity in the Dutch food packaging ecosystem may also rely on digital technologies. Finally, the Dutch food packaging ecosystem is part of a larger environment, which sets the context and legislation in which the system operates.

Chapter 3 has effectively dissected the current Dutch food packaging ecosystem. The resulting inventory of identified components is used in Chapter 4 to conceptualise an ABM for Food and Beverage Company X's packaging ecosystem. However, some critical remarks should be addressed before starting the model conceptualisation.

The current food packaging ecosystem in the Netherlands consists of multiple interconnected layers, including the actors' behaviour, the different dependencies between actors, a variety of materials and the environment layer setting the rules governing the ecosystem. The integration of these layers alone can give rise to complex adaptive behaviour, even without considering the uncertainty of actor behaviour. The complexity of the Dutch food packaging ecosystem is thus not only attributed to the uncertainty of actor behaviour.

While the Dutch context has been useful for an in-depth analysis of the packaging system, it is important to recognise that the Dutch food packaging ecosystem is part of broader European and global food packaging ecosystems. The Packaging Producer of Food and Beverage Company X emphasised that a broader European or global perspective is preferred over a Dutch perspective during decision-making within the company. Moreover, various components of the Dutch food packaging ecosystem are closely intertwined with those of other countries. The Business Analyst of the Dutch waste management structure stressed that packaging may be produced outside the Netherlands and imported, while waste may be exported and recycled abroad. Hence, the geographic scope of this study may be limited. Nevertheless, this specific scope is useful for a more tangible conceptualisation of the ABM.

Finally, it should be acknowledged that the analysis of the Dutch food packaging ecosystem is not exhaustive. Financial and economic components, for example, have yet to be extensively explored, aside from the financial dependencies and the Dutch packaging tariffs discussed in Sections 3.1.2 and 3.3.3, respectively. Similarly, the analysis does not include a detailed explanation of the different environmental impacts associated with different materials, despite their potential influence on material selection. These components might influence waste reduction in the Dutch food packaging system but fall outside the scope of this study.

In summary, Chapter 3 has analysed the Dutch food packaging ecosystem, resulting in an inventory of components used for the subsequent model conceptualisation. While the limitations of the analysis should be considered, the complex adaptive socio-technical system approach offers a comprehensive overview of the Dutch food packaging ecosystem.

4 Model conceptualisation and implementation

This chapter selects and structures the relevant actors, attributes, interactions, and environment for the ABM of Food and Beverage Company X's ecosystem, using concepts, theory, and data from Chapter 3 as the inventory. The chapter discusses the concept formalisation (Step 3), model formalisation (Step 4), model implementation (Step 5) and model verification (Step 6) of ABM (Van Dam et al., 2013). These steps help to answer sub-question 3:

Can the dynamics of a food packaging ecosystem be conceptualised in an ABM and if so, how?

The conceptualisation has been substantiated through expert discussions. Experts from Deloitte's TV&A department were consulted to verify modelling choices and assumptions related to the representation of the ecosystem in the model. Additionally, academic ABM experts supported the conceptualisation of organisational behaviour in the model and the introduction of nondeterministic components. In Section 4.1, the agents are described and structured by narrowing down the relevant actors and connecting them to the relevant attributes. Next, the environment and its attributes are structured and described in Section 4.2 and the interactions between the actors and the environment in the food packaging ecosystem are structured in Section 4.3. The assumptions related to the conceptualisation are explained in each section. The structured model concept is subsequently used to formulate the system's narrative in Section 4.4. Finally, Sections 4.5 and 4.6 discuss the model implementation and verification.

4.1 Structuring of agents

Within the ecosystem of Food and Beverage Company X, three main actors play a pivotal role in improving circularity: the food producer itself (Food and Beverage Company X), packaging producers and waste treaters. These three actors can collectively form the smallest potential circular ecosystem and make decisions that impact the success of the circular ecosystem. Figure 9 shows this smallest circular ecosystem and the physical and financial dependencies between the actors. The figure does not represent information flows because the model assumes complete information. Complete information means that all actors can access each other's information and can use it to make their decisions. The assumption of complete information is often made in ABMs (e.g. Gan & Cheng, 2015; Liang et al., 2020). However, information could, in reality, be missing or inaccessible to certain actors. This limitation of the model is discussed in Section 7.2.2.

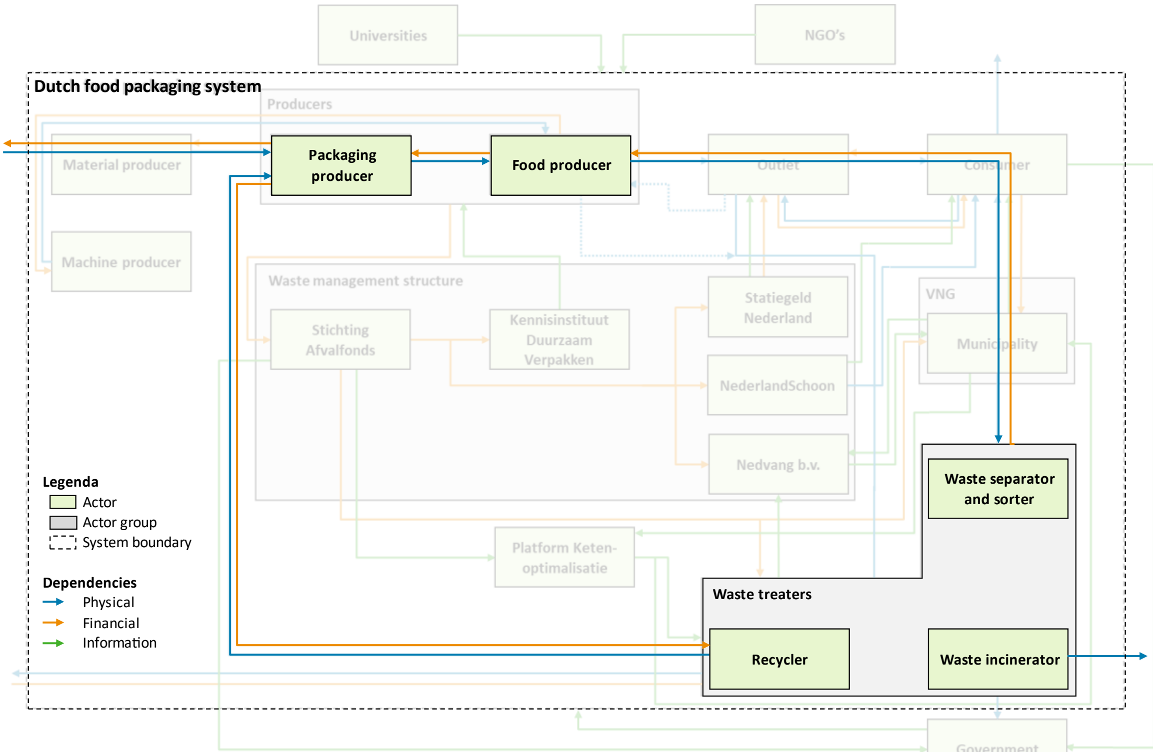

Figure 9. Selection of smallest potential circular ecosystem from actor inventory.

While other actors such as outlets, municipalities and consumers influence the decisions made by these three actors, their influences can also be represented as variables in the environment. Therefore, the ABM only represents packaging producers, food producers and waste treaters as agents. The processes of these agents are described in the following sections. The other actors are represented in the environment variables, explained in Section 4.2.

4.1.1 Food producers

The first agent in the ABM is the food producer, which is Food and Beverage Company X. The food producer's packaging selection process is based on an interpretation of the interview with the Packaging Developer of Food and Beverage Company X.

Although Food and Beverage Company X represents a single food producer, the company sells its product in various packaging types. Five of these packaging types are sold in large quantities, each accounting for more than 1% of the total packaging weight sold according to the product's Brand Manager of Food and Beverage Company X. Although the total sold packaging weight is unknown, the product volume in each packaging is known, enabling a calculation of the proportions of the packaging types in relation to a total product volume. By doing this, an input variable for total product volume can be used in the model for further calculations.

The food producer is divided into five parts, each representing one packaging type, to start setting up an ecosystem in the ABM. All five parts are referred to as food producers. Each food producer packs a certain product volume, constituting a portion of the total product volume. Consequently, the food producer has a packaging demand based on the product volume, volume per packaging, weight per packaging and use times per packaging.

Every food producer requires a packaging supplier with a sufficient amount of the correct packaging type. Each year, the food producers can seek a new packaging producer. The choice for a packaging producer depends on the decision-style of the food producer. If the food producer has a bargaining decision-style, he looks for a packaging producer with the best price. On the other hand, if the food producer has a problem-solving decision-style, he looks for a packaging producer with the highest overall recycled content.

The flowchart of the food producer's packaging selection process is presented in Figure 10.

<u>Assumptions</u>

- To overcome the unknown total product volume produced by Food and Beverage Company X, a hypothetical yearly product volume of 1,000,000 litres is used. An input variable is created to allow the use of actual product volume data.
- While the contract length with the packaging supplier may vary, a regular contract of one year is assumed.
- The choice for a packaging producer depends on the food producer's production line, which is purchased every 10 to 20 years. The model assumes that all packaging producers can supply the packaging type that fits the current production line.
- The decision-style is deterministic, meaning that a bargaining food producer always opts for the lowest-priced packaging, and a problem-solving food producer always opts for packaging with the highest recycled content. Two probability sliders (p-bargaining-true and p-problem-solving-true) are created to enable the introduction of uncertainty in the actors' behaviour. These sliders would allow, for example, a bargaining food producer occasionally to choose packaging with high recycled content and a problem-solving food producer to choose for the lowest price.

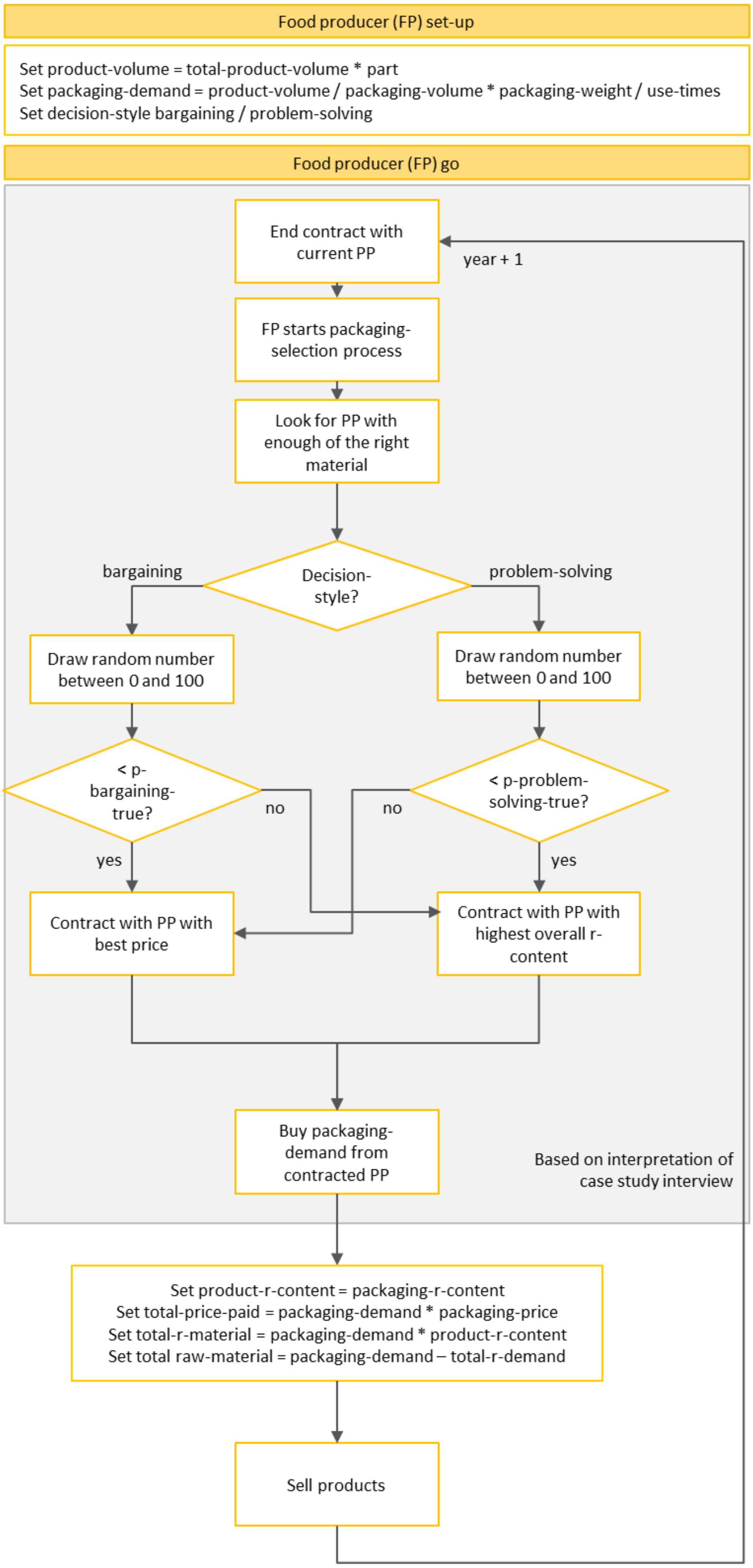

Figure 10. Flowchart of the model concept of the food producers' packaging selection process.

4.1.2 Packaging producers

Food and Beverage Company X’s ecosystem includes multiple packaging producers. The packaging producers’ material selection process is based on literature and the interviews with the Dutch waste management structure and the Packaging Developer of Food and Beverage Company X.

In line with the research scope, only Dutch producers are considered. The exact number of packaging producers per packaging type is unknown, except for one packaging producer with an almost complete monopoly on drink cartons. For the other packaging types, information is available on the amount of waste per packaging type in the Netherlands. Therefore, the model creates hypothetical packaging producers for each of the remaining packaging types, each producing a random portion of the total waste for that packaging type.

In the ABM, packaging producers produce a randomly assigned packaging volume that varies per setup but remains constant throughout the simulation. Each packaging producer has a designated list of required materials corresponding to their specific packaging type. Additionally, the packaging producer has a list indicating the proportions of different materials used in the packaging and a list specifying the maximum potential recycled content for each material.

Every year, the packaging producer calculates the material demand for each required material. This material demand is split into a recycled material demand and a rest material demand. In the case of a recycled material demand, the packaging producer looks for a waste treater that can supply the correct material. Packaging producers with a bargaining decision-style compare the lowest-priced recycled material with the virgin material price, purchasing the most affordable option, whether that is recycled or virgin material. Conversely, a problem-solving packaging producer looks for the waste treater offering the most recycled material and buys it, regardless of the price. If the recycled-material supply falls short of the packaging producer’s demand, the packaging producer recalculates the rest material demand and buys the material from the environment. Subsequently, each packaging producer calculates the overall recycled content of the packaging based on the recycled content of each material. Finally, the packaging producer determines the packaging price using the prices of recycled and virgin material before selling the packaging to either Food and Beverage Company X or another food producer in the environment.

Figure 11 presents the flowchart outlining the packaging producers' material selection process.

<u>Assumptions</u>

- The model assumes the presence of five packaging producers per packaging type, except for the drink carton producer, of which there is only one.
- In each setup, hypothetical random packaging volumes are assigned to the packaging producers. However, these volumes remain constant throughout the simulation, assuming a stable packaging production throughout the years.
- Proportions of different required materials are specified for drink cartons. For the other packaging types, only one material is stated as the required material. This simplification disregards additional materials used in other packaging types, such as plastic coatings in aluminium cans, various layers of different plastics in BIB packaging, paper labels on glass bottles and the non-PET cap and sleeve on PET bottles. Although these materials constitute a small part of the total packaging, they could be incorporated into the model.
- The maximum potential recycled content of the material is constant over the years, assuming no innovation that improves the potential to use recycled material in new packaging. However, a slider is included in the model to set a yearly innovation rate, allowing for improvements to the potential recycled content that can be used in new packaging.
- Similar to the food producers, the decision-making behaviour of packaging producers is deterministic in this model. The probability sliders can be used to introduce variation in the decision-making behaviour.

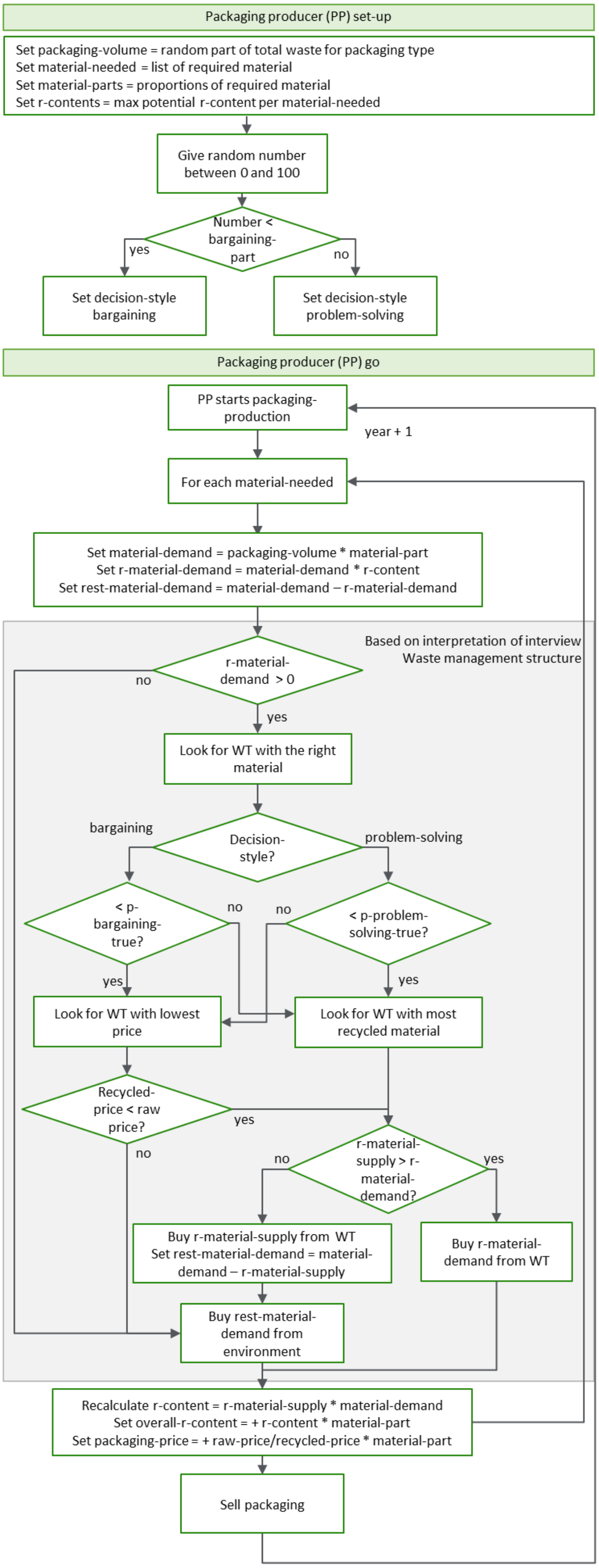

Figure 11.Flowchart of the model concept of the packaging producers' material selection process.

4.1.3 Waste treaters

The final actor group within Food and Beverage Company X's ecosystem consists of waste treaters. The waste treaters' selling process is based on literature and the interviews with the Dutch waste management structure and the Packaging Developer of Food and Beverage Company X.

The Dutch food packaging ecosystem includes waste sorters, incinerators, and recyclers, which are collectively represented as waste treater agents. Although specific numbers regarding the number of waste treaters are missing and inadequate for representing the composite 'waste treater' agents, data on waste volumes per material type are available and serve as the basis for modelling the waste treaters. Similar to the packaging producers, the model generates hypothetical waste treaters for each material, each responsible for handling a randomly assigned portion of the total Dutch waste volume for that material.

In the ABM, the hypothetical waste treaters are created for each material who collect and treat a randomly assigned waste volume that varies in each setup but stays constant during the simulation. Additionally, each waste treater is assigned a predefined starting price for the recycled material, which they use as the initial selling price.

At the beginning of each year, the waste treater recycles a part of the collected waste, determined by the current recycling rate of that specific material in the Netherlands. The recycling rate of the waste treater can fluctuate up to 10% higher and lower than the average recycling rate, varying annually. If the waste treater supplied to one of the packaging producers in the previous year and has a bargaining decision-style, they increase the price of the recycled material, aiming to maximise their profit. On the other hand, if the waste treater did not supply to any packaging producer in the previous year and has a problem-solving decision-style, they reduce the price of the recycled material, preferring closed-loop recycling as the 'greater good'. For this adjusted price, the waste treater sells its recycled material to the packaging producers or the environment.

Figure 12 shows the flowchart of the waste treaters' process.

<u>Assumptions</u>

- The ABM creates three waste treaters for each material. This number is based on the fact that there is a limited number of sorters and recyclers in the Netherlands, which was mentioned in the interview with the waste management structure. Input variables in the ABM have been created to allow flexibility in the number of waste treaters in the model.
- The model assumes that each waste treater sorts and recycles one material. In reality, waste treaters may handle multiple materials within a single facility (e.g., collective sorting of PMD by a single sorter).
- The recycling rate is expected to differ slightly for the different waste treaters, and the Dutch recycling rate is therefore used as an average. The actual recycling is determined by the recycling rate plus or minus 10%, changing annually.
- This concept assumed a constant average recycling rate for all recyclers throughout the years, aligned with the current Dutch recycling rate. However, a slider is included in the model to set a yearly innovation rate, allowing for improvements to recycling technologies that increase the recycling rate of the waste treaters.
- Similar to the other agent, the decision-making behaviour of waste treaters is deterministic in this model. Probability sliders are created to enable the implementation of variation in the decision-making behaviour.
- It is assumed that bargaining waste treaters selling to the environment and problem-solving waste treaters selling to packaging producers do not alter the recycled price.

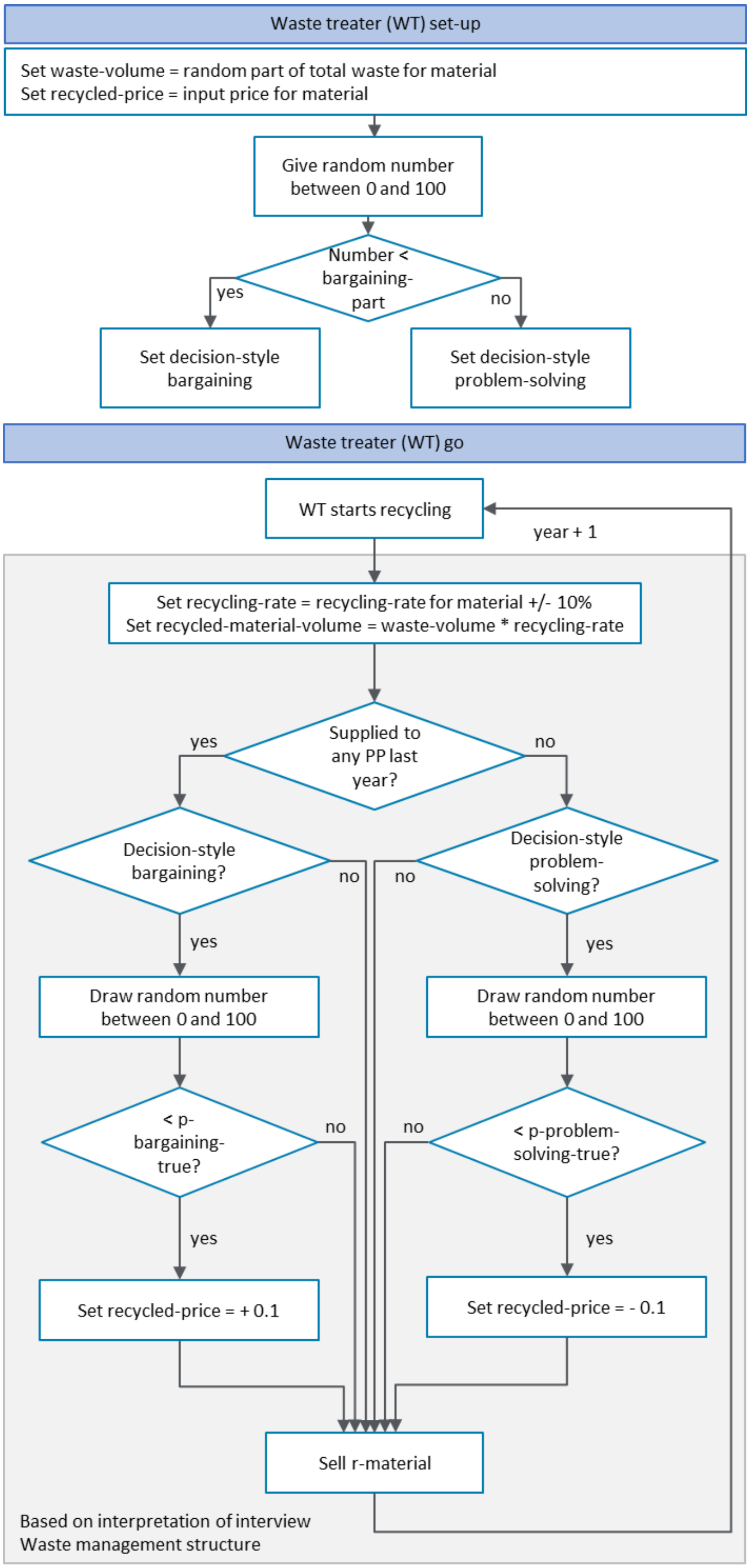

Figure 12.Flowchart of the model concept of the waste treaters' waste selling process.

4.2 Structuring of environment

In the ABM, the environment encompasses the variables representing the ecosystem's context. The Food and Beverage Company X's ecosystem is located in the Netherlands. Therefore, the environmental context described in Section 3.3 can be adopted. Additionally, the model's environment can represent the influence of other actors in the Dutch food packaging ecosystem who are not modelled as agents. This enables the conceptualisation of a more comprehensive representation of the Dutch food packaging ecosystem without modelling all actors as agents. Multiple input variables, sliders, and switches are incorporated into the ABM to receive data representative of the Netherlands. This section explains these environmental variables.

4.2.1 Behaviour variables

Organisational decision-making behaviour in the ABM is categorised into four categories. The food producers can adopt a bargaining or problem-solving decision-style, determined by a switch. The ratio of bargaining and problem-solving decision-styles in the other organisations is determined with a slider, allowing the ecosystem to comprise a range of 0 to 100 % bargaining actors, with the remaining percentage representing problem-solving actors. The decision-style of actors is assigned during the setup phase and remains the same throughout the simulation.

As explained in Section 4.1, the decision-style is deterministic, meaning that a bargaining agent always acts like a bargaining agent, and a problem-solving agent always acts like a problem-solving agent. Two probability sliders (p-bargaining-true and p-problem-solving-true) are incorporated in the ABM to introduce uncertainty in actor behaviour.

The decision-rule in the ecosystem can be unanimity or hierarchy, which applies to all actors. In the unanimity setting, all packaging producers have equal chances of being the first to purchase recycled material. Conversely, in the hierarchy setting, packaging producers are ordered based on packaging volume, and priority is given from largest to smallest for purchasing recycled material.

4.2.2 Dutch waste variables

Next, the physical flows in the Dutch food packaging ecosystem should be integrated into the model. Different variables are used to enter quantitative data on Dutch food packaging waste. An input variable is employed to represent the total waste per material, reflecting the current waste volume in the Netherlands. Additionally, recycling rates per material can be inputted to represent the current rates in the Netherlands. Waste treaters use these variables to calculate their waste and recycled material volumes. Furthermore, input variables are needed for the maximum potential recycled content in new packaging. This information enables packaging producers to calculate the maximum potential recycled content in their packaging.

The variables related to Dutch waste indirectly represent some other actors in the food packaging ecosystem. The recycling rate not only relies on the efficiencies of the waste treaters but is also affected by the losses in the outlets, at the consumer and during the waste collection by the municipalities. Furthermore, the data on waste volumes is reported to Nedvang b.v., who in turn reports it to StAV.

4.2.3 Price variables

Price variables have to be integrated into the model to enable agents to choose based on the recycled content and the price of different packaging materials. Adjustable sliders are implemented to determine the price for each raw material, ranging from 0 to 1. Similarly, a slider is available for setting the starting price of recycled material, which is used by the waste treaters, also ranging from 0 to 1. These prices represent hypothetical values per kilogram and can be used for various experimental setups. The sliders allow testing scenarios such as identical initial prices, slightly or significantly lower or higher raw material prices, or progressively increasing raw material prices.

The price variables represent the influence of other actors in the Dutch food packaging ecosystem, notably the material producers and the government, which could introduce subsidies or taxes on materials or processes.

4.2.4 Innovation variables

The model includes two sliders to control innovation rates. The first slider can be used to adjust the innovation rate for the maximum potential recycled content usable in new packaging. Additionally, the second slider can be used to adjust the innovation rate for improving the recycling rate of different materials. Additionally, a switch is available to change the waste stream of PET in the circular ecosystem. In the current Dutch system, PET bottles from Food and Beverage Company X are not included in the deposit-return system. Using this switch makes it possible to explore the implications of integrating PET bottles into the Dutch deposit-return system.

Innovation within the Dutch food packaging ecosystem could come from various actors, such as universities, NGOs or new food producers and packaging producers who found innovative ways to improve the circularity of food packaging. Additionally, the inclusion of PET bottles in the Dutch deposit-return system depends on outlets, consumers and Statiegeld Nederland. Overall, the innovation variables incorporate the potential influence of multiple ecosystem actors in the environment.

4.2.5 Time

The ABM's timeframe spans from 2023 to 2050, aligning with the temporal scope of this research.

4.2.6 Performance metrics

In order to conduct meaningful experiments and address sub-question 4 of this research, several key performance indicators (KPIs) are used. These KPIs are formulated with the primary modelling question, i.e. sub-question 4, in mind:

Based on simulations, what is the potential of circular ecosystems to reduce packaging waste in the Dutch food packaging ecosystem?

The modelling question requires the integration of two aspects in the performance metrics. First, the model should give insight into the effect of circular ecosystems on packaging waste generated by a food and beverage company (Food and Beverage Company X in this case study). However, the company's actual packaging waste is dependent on the materials in the packaging. Therefore, KPIs are used that address the types of materials used by the company, including raw material, open-loop recycled material, and closed-loop recycled material.

Primarily, the company's waste reduction efforts should aim to maximise the use of closed-loop recycled material. Closed-loop recycling would reduce packaging waste generation, as material is recycled into new packaging. The second option involves using open-loop recycled material, which reduces waste generated by other companies but does not directly impact the company's waste. The last option is using raw material, which results in new waste that could potentially be open-loop recycled into other packaging or products, depending on the broader ecosystem. However, in that case, the food and beverage company cannot recycle or reuse the material itself. The recycled content of each packaging type is measured each year and functions as the KPI to measure the waste reduction potential. Additionally, the model incorporates a KPI to measure the effect of the dynamics in the circular food packaging ecosystem on the price paid by the food producers.

The second aspect that should be incorporated in the performance metrics concerns the potential of circular ecosystems to reduce packaging waste in the Dutch food packaging ecosystem as a whole. The ABM does not cover the entire Dutch food packaging system, which includes other food and beverage companies, as it specifically models the ecosystem of a particular food and beverage company. Nevertheless, the model can provide insights into the raw material demand of packaging producers in the Netherlands in different circular ecosystems. One KPI to measure this effect is the raw material demand of packaging producers for each material. Additionally, the fate of Dutch waste can be assessed by measuring the volumes of incinerated waste, as well as closed-loop and open-loop recycled material. Furthermore, the average recycled material price for the different materials is monitored to see the price changes.

An overview of the global variables is presented in Figure 13.

Environment setup

Behaviour
bargaining-part = between 0 and 100%
p-bargaining-true = between 0 and 100%
p-problem-solving-true = between 0 and 100%
unanimity? = true / false

Dutch waste
For each material
  waste-volume = Dutch volume
  recycling-rate = Dutch recycling rate
  r-content = Dutch maximum closed-loop recycling of material

Price
For each material
  raw-material-price = between 0 and 1
  start-r-material-price = between 0 and 1

Innovation
content-innovation-rate = between 0 and 0.1
recycling-innovation-rate = between 0 and 0.1
deposit-return-PET? = true/false

Time
year = 2023

Environment output

Food producer KPIs
For each packaging type
  product-r-content
  price-paid-per-kg
  price-paid-total
kg-raw-material-FP
kg-open-loop-FP
kg-closed-loop-FP

Dutch packaging ecosystem KPIs
For each material
  raw-material-demand-NL
  average-r-material-price
kg-incinerated-NL
kg-open-loop-NL
kg-closed-loop-NL

Figure 13. Overview of input variables and KPIs used to set up the environment of the model.

4.3 Structuring of interactions

The last step of the model conceptualisation concerns structuring the interactions between the agents and the environment. To represent the interactions, a flowchart has been created that shows all agents' processes and decisions as well as their relation to the environmental output (Figure 14). A large version of the flowchart is attached in Appendix C. The rectangles represent the processes in the model, the diamonds represent a decision, and the trapezes represent the start and end of a run. Regular arrows represent the flow of the simulation, and dashed arrows show the interactions between the different agents.

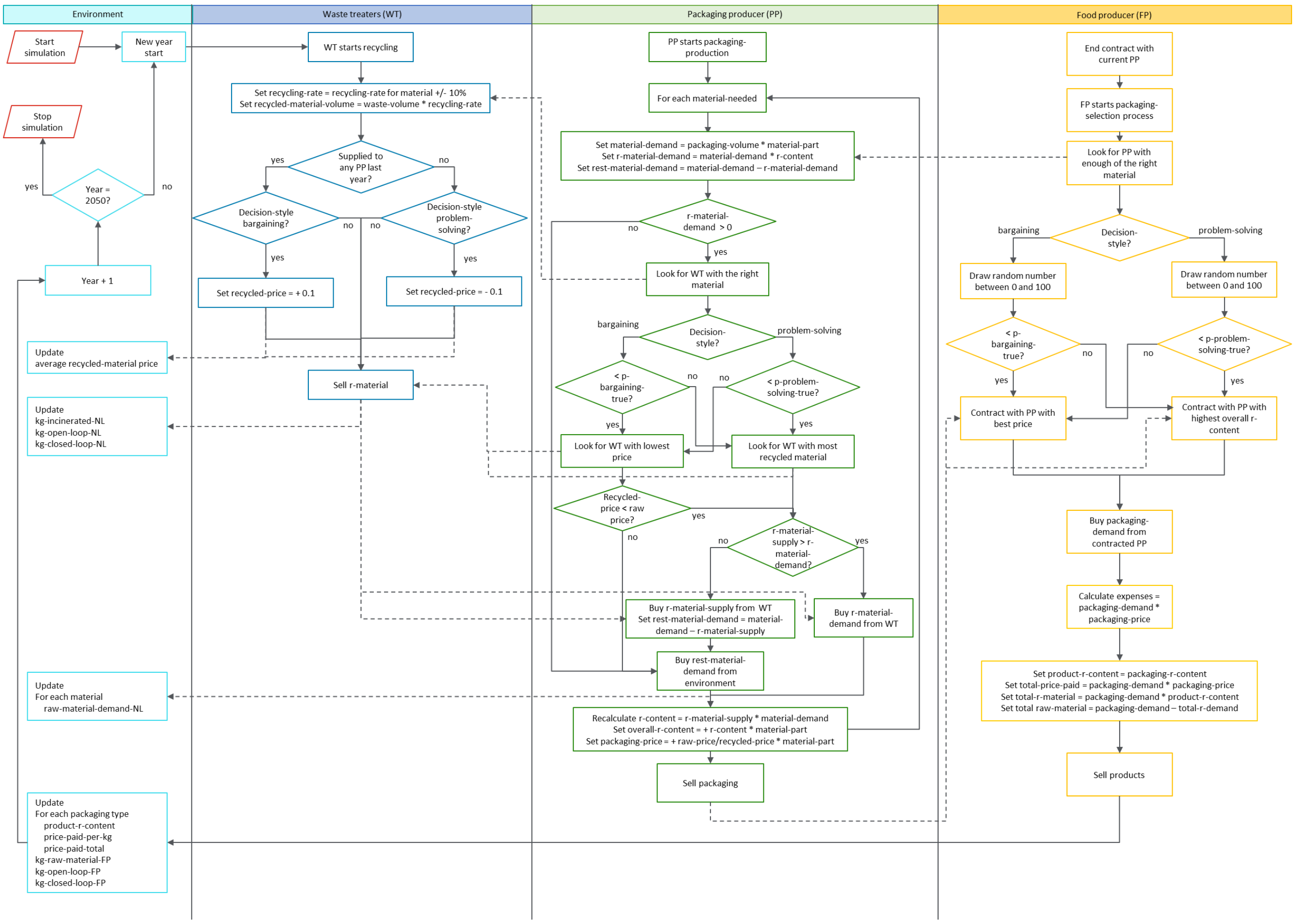

Figure 14. Flowchart of interactions between the actors and their processes in the model.

4.4 Model narrative

Next, the model concept has to be described in computer-understandable language to enable implementation in NetLogo. This model formalisation uses a narrative that explains the order of processes and interactions between the agents. This section explains the setup and the go procedures within the model.

4.4.1 Setup

The model starts with a setup. In this setup, the food producers, packaging producers and waste treaters are created and given a specific location in the model's interface. Each agent is assigned a decision-style and the required variables, which receive input from the modeller via the NetLogo interface. The agent turns orange if it has a bargaining decision-style and green if it has a problem-solving decision-style. The size of the waste treaters and packaging producers is relative to their waste- and packaging volume, respectively. After the setup, the model can start running with time steps of one year.

4.4.2 Go – waste treaters go

Every year starts with the waste treaters receiving a waste volume, which they handle and recycle with the recycling rate for that type of waste. Depending on their decision-style and whether they sold recycled material within the ecosystem in the previous year, they can adjust the price of the recycled material. If the waste treater had a contract with one or more packaging producers last year, this contract ends at the beginning of the new year. The sum of the total waste volume of all waste treaters minus the total volume of recycled material of all waste treaters is used as the Dutch incinerated waste KPI.

4.4.3 Go – packaging producers go

Next, the packaging producers calculate their material demand per material type used in their packaging. The recycled material demand is then calculated depending on the maximum potential recycled content for that packaging. The rest material demand is the material demand minus the recycled material demand. If the recycled material demand exceeds 0, the packaging producers can consider buying from a waste treater. In that case, they look up the recycled material volume of the waste treaters and see the price of that material. If the decision-rule is unanimity, the packaging producers start the material purchase process in a random order. In contrast, if the decision-rule is hierarchy, they purchase in order of largest to smallest packaging producer.

If the packaging producer has a bargaining decision-style, it compares the price of the cheapest recycled material with the price of virgin material and chooses the most affordable option. When the raw material is cheaper, the recycled material demand is changed into rest material demand. If the packaging producer has a problem-solving decision-style, he buys recycled material from the waste treater with the highest recycled material volume. If the material is bought from the waste treater, the recycled material demand is subtracted from the waste volume of the waste treater, and a link is created from the waste treater to the packaging producer. The link is grey if the material supply was the same as the demand and red if the material supply was lower than the demand. If the recycled material supply was lower than the demand, the rest material demand is adjusted. The rest material demand is then bought from the environment, updating the raw material demand variable.

The packaging producer then produces the packaging and calculates the overall recycled content and the total price of the packaging. The sum of the recycled material volume used by all packaging producers is used as the Dutch closed-loop recycling KPI.

4.4.4 Go – food producers go

Subsequently, the food producers have a packaging demand, depending on the product volume of their packaging type. Each year, the contract with the packaging producer of last year is ended, removing the link from the packaging producer to the food producer. The food producers start looking for packaging producers that sell the right packaging type and a packaging volume higher or the same as the food producer's packaging demand. Depending on their decision-style, they either buy the packaging from the packaging producer with the lowest price or the packaging producer with the highest overall recycled content in the packaging. A link is created from the packaging producer to the food producer.

The food producer uses the overall recycled content and packaging price of the supplying packaging producer as its product's recycled content and the price paid per kilogram. The latter is used to calculate the total price paid.

4.4.5 Go – show ecosystem

At the end of the year, the circular ecosystems are shown. A circular ecosystem is present if a waste treater supplies material to the packaging producer, who supplies packaging to the food producer, who supplies waste to that same waste treater. In this case, the links that create the circular ecosystem turn green.

4.4.6 Go – calculate remaining KPIs

Finally, the KPIs are calculated. The closed-loop recycled material is calculated by summing the total recycled material of food producers in a circular ecosystem. Open-loop recycled material is calculated by summing the total recycled material of all food producers and subtracting the closed-loop recycled material. The raw material of the food producers is calculated by summing the total rest material demand of the food producers. The Dutch open-loop recycled material is calculated by summing the total recycled material of all waste treaters and subtracting the Dutch closed-loop recycled waste.

4.5 Model implementation

After the model conceptualisation and formalisation, the model is implemented in the model environment NetLogo version 6.3.0 (Wilensky, 1999). This software enables the implementation of ABMs and uses a relatively simple syntax. Due to its simplicity, implementing more complex models is more challenging and therefore requires many assumptions, which have been emphasised in Section 4.2.

The interface of the ABM is presented in Figure 15. The left part of the model shows the input variables for the food producer, the packaging producers, and the waste treaters. The food producer's variables include the part of the total product volume and total packaging weight, the packaging volume, packaging weight and use times per packaging for all five packaging types. The packaging producer's parameters allow the input for the number of producers per packaging type and the maximum potential recycled content per material in the different packaging types and include a monitor of the total number of packaging producers. The lower left corner includes the waste treatment parameters: the number of treaters, the total waste, the recycling rate and the starting price of the recycled material per material type. The environment variables are presented as switches and sliders next to the food and packaging producer input variables. The middle square represents a potential visual output of a model run. At the bottom and right of this display, the output variables used as KPIs are presented in graphs. A larger version of Figure 15 is presented in Appendix H.

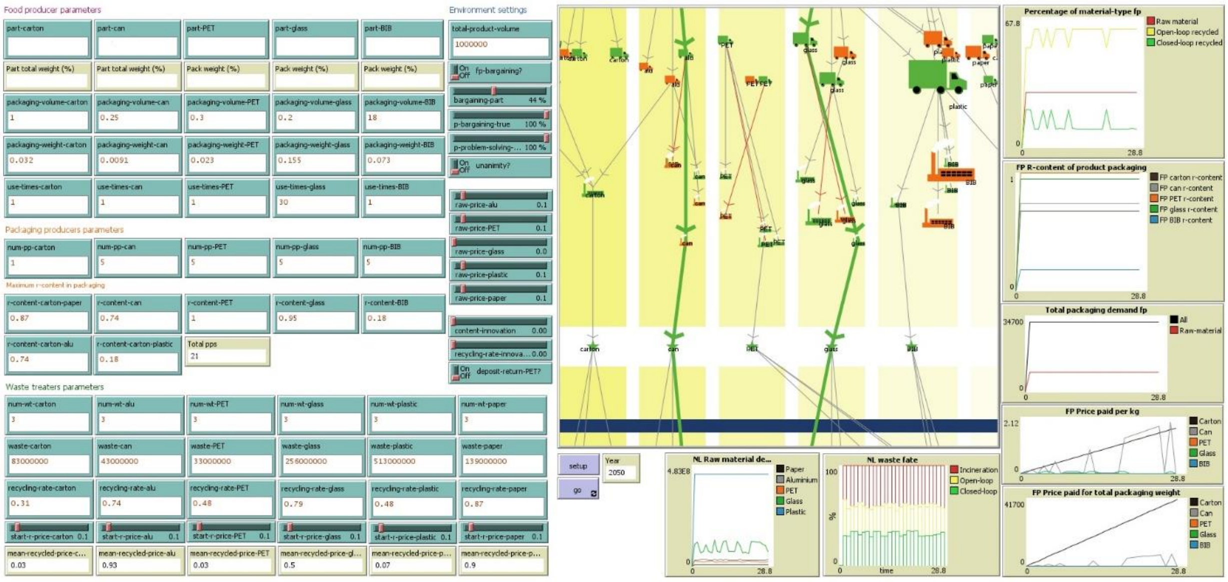

Figure 15. Visualisation of the interface of the implemented ABM in NetLogo.

After the implementation, the model parametrisation has been carried out to define parameters for the variables in the model. The parameters were based on the data collected during the SLR and interviews with the Packaging Developer of Food and Beverage Company X and the Business Analyst of the Dutch waste management structure. An overview of the parameters is shown in Appendix D.

The final version of the NetLogo model can be found in Appendix G.

4.6 Model verification

Following the software implementation, model verification was conducted to ensure the correct implementation of the model in NetLogo. Throughout the model implementation process, verification procedures were consistently carried out for each procedure addition or modification, assessing whether the model produced the expected outcomes. Once the model was finalised, a structured verification was executed, following methods by Van Dam et al. (2013). This process included a code walk-through, thorough recording and tracking of agent behaviour, and extreme-value testing.

To ensure the reproducibility of results, random elements were eliminated by fixed parametrisation of random variables and a fixed random seed. The code walk-through identified procedures that required small adjustments and helped to clean up the code. Subsequently, recording and tracking agent behaviour resulted in the detection of some inaccurate or missing agent behaviour, requiring some modifications to the order of commands within the procedures. Lastly, the outcomes of the extreme-value testing aligned closely with the expected results, confirming the accurate implementation of the model. Appendix E provides a more comprehensive description of the model verification process. Based on the findings from the verification process, it can be concluded that the model has been implemented correctly, achieving the intended functionality.

4.7 Summary and remarks

Chapter 4 focused on developing the ABM to simulate the dynamics of a Dutch food packaging ecosystem centred around Food and Beverage Company X. Following Steps 3 to 6 of the ABM methodology by Van Dam et al. (2013), the chapter aimed to answer sub-question 3:

Can the dynamics of a food packaging ecosystem be conceptualised in an ABM and if so, how?

The dynamics of a food packaging ecosystem can be conceptualised in an ABM, evident from the successfully implemented model in NetLogo. The conceptualisation began with identifying three key agents: the food 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. The processes of these agents were formulated based on information from literature, interviews with the Packaging Developer of Food and Beverage Company X and the Business Analysts of the Dutch waste management structure, and quantitative data from the Brand manager of the product from Food and Beverage Company X. The other actors in the Dutch food packaging ecosystem have been represented in the model via the environment variables. The environment was structured by defining various variables related to agent behaviour, Dutch waste, pricing, and innovation, along with performance metrics that can be used to analyse the potential of circular ecosystems to reduce packaging waste.

Next, a model narrative was formulated by describing the processes of the agents in chronological order and connecting them to each other and the environmental variables. This narrative was used for the implementation in NetLogo. Finally, the model was verified with a code walk-through, recording and tracking of agent behaviour, and extreme-value testing. The conceptualisation and implementation have resulted in a running model that can be used to analyse the potential of circular ecosystems to reduce packaging waste.

While the final ABM captures various dynamics of a food packaging ecosystem, it covers only a part of all dynamics in the Dutch food packaging ecosystem. The dynamics primarily relate to the behaviour of organisations in the ecosystem and specific changes to variables in the ecosystem, representing different scenarios. However, the model does not account for dynamics such as consumer behaviour and preferences, interactions of the food packaging ecosystem with other ecosystems or economic fluctuations over time.

Additionally, the model assumes static decision-making behaviour of actors. However, decision-making behaviour may evolve over time in response to public awareness and changing social attitudes. Changes in actor behaviour might come with some delay that could, for example, be related to the time needed to change the organisation's strategy or install new production lines.

Furthermore, the model treats the food packaging ecosystem as a single entity, disregarding spatial and geographic variations. In reality, the dynamics in circular ecosystems may depend on spatial proximity, and waste treatment can differ across regions. Although spatial and geographic components can affect the dynamics in the food packaging ecosystem, these components have not been integrated into the model.

Moreover, adaptivity is not fully integrated into the ABM. While the model captures decision-making behaviour, it does not account for feedback loops and adaptive behaviour among the actors. In reality, actors may learn from past experiences and adapt their behaviour accordingly. However, the dynamics related to such adaptive behaviour of agents are limited in the model.

Finally, NetLogo syntax facilitates easy implementation of an ABM but has limitations when modelling more complex system dynamics. The software also lacks reliable insights into material and energy balances, which can pose implications related to the assumption of infinite raw materials, energy sources, and waste sinks. Although this limitation has been considered during the implementation of the ABM, it should be acknowledged that NetLogo is unsuitable for reliable input-output analysis of materials and energy.

In conclusion, the successful development of the ABM shows that the dynamics of the food packaging ecosystem can be effectively conceptualised in an ABM by using Steps 3 to 6 of the ABM methodology by Van Dam et al. (2013). The ABM can be used for experimentation with multiple ecosystem variables. However, the model's limitations should be recognised and considered during the model experimentation. The following chapters discuss the experimental design and findings from the experiments.

5 Model experimentation

This chapter provides an overview of the experimental setup used in this study, in line with Step 7 of ABM by Van Dam et al. (2013). The experimentation concerns an exploration of ecosystem variables to identify the effects of changes in these variables on the dynamics of packaging waste in a circular food packaging ecosystem. The experiments were designed to systematically investigate the effect of different variables on the model outcomes. The experimental design is explained in more detail in Section 5.1. Subsequently, Section 5.2 is used to discuss the validity of the experiments.

5.1 Experimental design

The experimental design consists of a sensitivity analysis of the agent's decision-making behaviour and a data analysis of other circular ecosystem variables related to Dutch waste, price, and innovation.

Due to multiple sources of uncertainty, the model produces variable results. NetLogo randomises the sequence in which agents perform their procedures, thereby preventing potential first-mover advantage (Van Dam et al., 2013). Additionally, the model's variability is caused by model variables that are random by design. Random variables in this study's ABM include the waste volume of waste treaters and the packaging volume of packaging producers, which are random portions of the total Dutch waste for specific packaging types in 2021. Furthermore, the recycling rate is randomised using the current Dutch rate plus or minus 10%.

Considering the uncertainty these random variables introduce, the results of a single simulation should not be considered definitive. Multiple repetitions are required to enable the analysis of the variability and identify patterns in the outcomes (Van Dam et al., 2013). Therefore, multiple simulations were conducted using the same values, generating a range of results for both the sensitivity analysis and the variables experimentation.

5.1.1 Sensitivity analysis

The sensitivity analysis aims to analyse the model's sensitivity to changes in decision-making behaviour variables in a structured way. The sensitivity analysis concerns a one-factor-at-a-time (OFAT) analysis, in which one variable is changed while keeping the others fixed. OFAT is a suitable sensitivity analysis to gain insight into dynamics and patterns produced by the ABM (Ten Broeke et al., 2016). In this sensitivity analysis, the focus is on investigating the effect of decision-making behaviour in circular ecosystems on the dynamics of food packaging waste, specifically considering three behaviour variables:

- Composition of decision-styles within the ecosystem
- Decision-style of the food producer
- Decision-rule employed within the ecosystem

Specific parameters are modified to examine these variables: "*bargaining-part*", *"fp-bargaining?"* and *"unanimity?".* The first variable explores the composition of decision-styles in the ecosystem. The experiments begin with an ecosystem of 100% bargaining actors, followed by step-by-step decreases of 10% in each experiment until the final ecosystem of 0% bargaining actors is reached. This step-by-step experimentation for the ecosystem composition is conducted four times to enable experimentation with the second and third behaviour variables.

The second variable examines the decision-style of the food producer, which can be either bargaining or problem-solving. By changing this variable, the effect of the food producer's decision-style on the circular ecosystem's outcomes can be assessed.

For the third variable, the decision-rule is considered, which can be either 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, allowing for an analysis of the effect of the decision-rule in the circular ecosystem.

The experimental setup is summarised in Table 6. The first column shows the setting for the *"bargaining-part"* variable, and the top row shows the settings for the variables *"fp-bargaining?"* and "*unanimity?*". The other input variables are set following the parameters described in Appendix C, ensuring consistency across all runs. Every setting is used for ten simulations, amounting to 440 experiments in total.

For the four experiment groups, time series data is collected on the recycled content in the food producer's products and the price paid per kilogram by the food producer. Within these 440 experiments, five packaging types are used, each with specific parameters for recycled content and the price paid per kilogram. This results in a comprehensive data frame of 2,200 rows containing the time series data. Furthermore, data is gathered on the raw, open-loop, and closed-loop recycled material used by the food producer in 2050, combining all packaging types.

Table 6. Overview of the variable settings during the sensitivity analysis and the number of repetitions per experiment.

Bargaining-part (%)	**Group 1** fp-bargaining? = TRUE unanimity? = TRUE	**Group 2** fp-bargaining? = FALSE unanimity? = TRUE	**Group 3** fp-bargaining? = TRUE unanimity? = FALSE	**Group 4** fp-bargaining? = FALSE unanimity? = FALSE	Total
100	n = 10	n = 10	n = 10	n = 10	*n = 40*
90	n = 10	n = 10	n = 10	n = 10	*n = 40*
80	n = 10	n = 10	n = 10	n = 10	*n = 40*
70	n = 10	n = 10	n = 10	n = 10	*n = 40*
60	n = 10	n = 10	n = 10	n = 10	*n = 40*
50	n = 10	n = 10	n = 10	n = 10	*n = 40*
40	n = 10	n = 10	n = 10	n = 10	*n = 40*
30	n = 10	n = 10	n = 10	n = 10	*n = 40*
20	n = 10	n = 10	n = 10	n = 10	*n = 40*
10	n = 10	n = 10	n = 10	n = 10	*n = 40*
0	n = 10	n = 10	n = 10	n = 10	*n = 40*
Total	*n = 110*	*n = 110*	*n = 110*	*n = 110*	*n = 440*

By systematically exploring different values for the behaviour variables and conducting numerous simulations, the sensitivity analysis provides insights into the role of decision-making behaviour in circular ecosystems for reducing packaging waste. After the sensitivity analysis, a set of favourable behaviour parameters is used for the subsequent experimentation with other ecosystem variables.

5.1.2 Variable experimentation

Following the sensitivity analysis of actor behaviour, the next experimentation phase aims to investigate the effect of other variables on circular ecosystems' effectiveness in reducing packaging waste. This round of experimentation explores factors beyond actor behaviour while using a fixed set of favourable actor behaviour settings identified in the previous analysis. Experimentation with these variables can give a deeper understanding of their influence on the outcomes of circular ecosystems. The variables include factors related to Dutch waste, prices, and innovation, aligning with the four variable types in Section 4.2. While the behavioural variables are thoroughly tested during the sensitivity analysis, the other variables are examined with specific experiments, representing different interventions for the Dutch food packaging ecosystem. The data analysis aimed to answer the following seven questions:

1. What happens if the secondary material volume in the Netherlands reduces over the years?
2. What happens if waste treatment is centrally organised?
3. What happens if the raw material price increases over the years?
4. What happens if the price of raw material is much higher than that of recycled material?
5. What happens if the maximum potential recycled content in packaging increases over the years?
6. What happens if the recycling rate of waste increases over the years?
7. What happens if both maximum potential recycled content and recycling rate increase over the years?
8. What happens if PET becomes part of the deposit-return system?

During these experiments, the behaviour variables are fixed to represent 90% bargaining actors, a problem-solving food producer and a unanimity decision-rule. The other parameters are set in line with the parameters presented in Appendix C.

First, the settings are used to run ten simulations representing experimental group 0. This experimental group has not undergone any change in variables yet. Subsequently, the eight experiments are carried out. Similarly, each experimental setup is used for ten simulations to enable the identification of patterns. These experiments lead to a total of 80 simulations.

For the first experiment, the waste volume decreases by 1% annually and subsequently, the available secondary material as well. A 1% reduction of waste each year could, for example, be caused by reduced material use in packaging or the promotion of reusable packaging through new legislation, such as the recent plastic packaging fee (Rijksoverheid, 2023c). Consequently, the packaging volumes produced by the packaging producers also decrease by 1% per year.

The second experiment considers centrally organised waste treatment, meaning that the total waste volume is managed by one organisation. This is, for example, the case in Belgium (Fost Plus, 2023). This experiment is carried out by setting the number of waste treaters at one for each packaging material and giving all waste treaters the same decision-style.

In the third experiment, the raw material has an annual hypothetical price increase of 0.1, similar to the recycled material price adjustment by waste treaters. Such a price increase can be imposed by contextual factors such as legislation, material shortages or increasing energy prices (NOS, 2022).

The fourth experiment explores a scenario the cost of raw material exceeds that of recycled material. In this experiment, the price of raw materials is set at 3, which surpasses the maximum price increase by waste treaters in 27 years, while the start price for recycled material remains at 0.1. This hypothetical scenario could arise if the Dutch government incentivises using recycled material through subsidies or if environmental or social costs are incorporated into the price of raw materials. Currently, such costs are not accounted for in raw material prices, despite estimations that the environmental costs of global raw material mining range from € 0.4 and € 5 trillion annually (Arendt et al., 2022).

The fifth experiment concerns innovation related to the maximum potential recycled content in packaging. This innovation is represented by a 1% annual increase in maximum potential recycled content that can be used in new packaging. This innovation can be introduced with the content-innovation variable.

Similar to the fifth experiment, the sixth experiment considers an annual 1% increase in the recycling rate of waste treaters. The experiment can be performed by using the recycling-rate-innovation variable.

The seventh experiment both has a 1% annual increase in the maximum potential recycled content and a 1% annual increase in the recycling rate of waste treaters. The abovementioned innovation can, for example, be fuelled by collaboration with universities, research institutes or start-ups (Interview Packaging Developer).

Finally, the eighth experiment considers the integration of recycled PET bottles in the Dutch deposit-return system. The model has integrated a switch that moves the PET waste from general plastic waste to the PET waste treaters instead. Integrating recycled PET bottles in the deposit-return system can enable closed-loop recycling of PET and increase the material's lifespan. In Belgium, PET bottles are already part of the PET system (Interview Packaging Developer).

An overview of the changing variables per experiment is presented in Table 7. Similar to the sensitivity analysis, time series data was collected on the recycled content in the food producer's products and the price paid per kilogram by the food producer. Additionally, the time series data for the Dutch raw material demand has been collected per material type. As there are five packaging types, the 90 experiments generate 450 time series for the recycled content, the price paid per kilogram and the Dutch raw material demand.

Table 7. Overview of the variable settings during the variable experimentation.

Experiment ID	Question	Variable type	Changing variable
1	Secondary material volume reduction	Dutch waste	waste-volume – waste-volume * 0.01 each year and packaging-volume – packaging-volume * 0.01 each year
2	Central waste treatment	Dutch waste	num-waste-treaters = 1 for each material and 1 decision-style for all waste-treaters
3	Raw material price increase	Price	raw-price + 0.1 each year
4	High raw material price	Price	raw-price = 3
5	Maximum potential recycled content increase	Innovation	content-innovation = 0.01
6	Recycling rate increase	Innovation	recycling-rate-innovation = 0.01
7	Maximum potential recycled content and recycling rate increase	Innovation	content-innovation = 0.01 and recycling-rate-innovation = 0.01
8	PET in deposit-return	Innovation	deposit-return-PET = TRUE

5.2 Experiment validation

The experimental design for this study was developed through discussions and consultations with experts from Deloitte’s TV&A department and academic experts in the field of ABM. These discussions were valuable for crafting a relevant and effective experimental design that aligns with the research objectives.

At the start of the expert discussions, the implemented model in NetLogo was presented, showcasing its functionality and the integrated variables. The broad array of variables poses various possibilities for potential experiments to explore the reduction of packaging waste in a food packaging ecosystem. During the discussions, a range of potential experiments was considered, discussing the potential outcomes and their value in understanding the dynamics of circular ecosystems. Through these discussions, it was determined that the experiments should first focus on the decision-styles of organisations and the decision-rule in the ecosystem with a sensitivity analysis and build on that with additional experiments with other variables.

Experts from Deloitte’s TV&A departments emphasised the relevance of experiments that elucidate the required actor behaviour to establish effective circular ecosystems. Relevant insights could relate to the decision-style composition in the ecosystem, the decision-style of food producers or other clients interested in ecosystems, and the decision-rule governing the ecosystem. Given these experts’ experience in advising clients on ecosystem opportunities, the outcomes of these experiments have the potential to provide valuable insights into the requirements for establishing circular ecosystems.

The experimental design was refined in discussion with academic experts in the field of ABM. Considering the time constraints of a master thesis, careful deliberations were made regarding the choice of ecosystem variables to focus on. The discussions resulted in an experimental design that starts with a sensitivity analysis of the behaviour variables and subsequently explores other circular ecosystem variables in the data analysis.

Furthermore, the discussions with the academic experts helped to ensure that a sufficient number of experiments would be conducted to yield valuable results and enable statistical analysis in the sensitivity analysis. Each experimental setup was repeated ten times to generate sufficiently sized experimental groups.

In conclusion, the contributions of the expert discussions with both Deloitte's TV&A department and academic ABM experts have enhanced the design of the experiments. These discussions validated that the experimental design effectively addresses the research objectives, explores relevant ecosystem variables, and generates valuable insights into the potential of circular ecosystems in reducing packaging waste.

6 Results

This chapter discusses the results of the model experimentation, following Step 8 of ABM by Van Dam et al. (2013). The results aim to answer sub-question 4:

Based on simulations, what is the potential of circular ecosystems to reduce packaging waste in the Dutch food packaging ecosystem?

The section starts with the sensitivity analysis of the actor behaviour (Section 6.1), followed by the analysis of the additional experiments on variables related to Dutch waste, price, and innovation (Section 6.2).

6.1 Sensitivity analysis

The data from the 440 simulations was collected and processed in Python 3.10. In order to visualise the data and identify patterns, graphs were created for the time series data of the recycled content and the price paid per kilogram for each material. Figure 16 illustrates two of these graphs, where the x-axis represents the time series and the y-axis represents the recycled content. The colour of the lines corresponds with the percentage of the ecosystem with a bargaining decision-style. The left graph presents all individual time series of the recycled content in aluminium can packaging in experiment Group 1 (with a bargaining food producer and a unanimity decision-rule), highlighting the variation between different runs. On the right, the time series are combined into a group average for the bargaining parts to improve visual clarity. The complete sets of visualisations for all experiments is shown in Appendix F.1, F.2 and F.3.

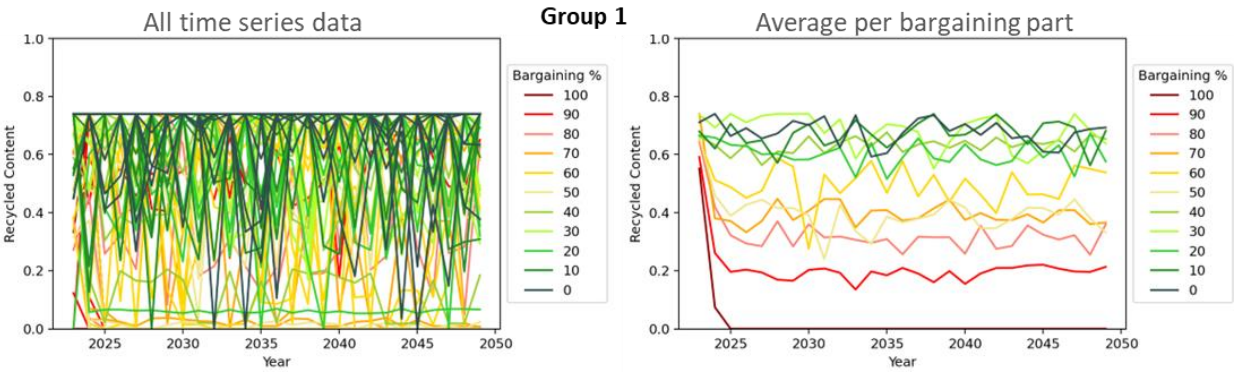

Figure 16. Example of data visualisation of the recycled content time series for aluminium cans in experiment Group 1. On the left all time series data, on the right the average of the time series per bargaining part.

6.1.1 Pattern identification and interpretation

This section analyses and discusses the patterns identified in the sensitivity analysis. First, the recycled content time series are interpreted in Section 6.1.1.1, and afterwards, the price paid time series are examined in Section 6.1.1.2.

6.1.1.1 Recycled content time series

Several observations stand out when looking at the figures of the time series data for recycled content per packaging. The first noteworthy observation is the presence of spikes in the time series, which arise from the food producer's annual decision for a packaging producer and the packaging producer's annual decision for raw or recycled material. The spikes are especially prevalent in ecosystems where the food producer has a different decision-style than most of its ecosystem. There could be multiple explanations for the presence of these spikes.

First of all, the spikey time series data are present in ecosystems with a bargaining food producer and a lower bargaining-part, indicating a larger proportion of problem-solving actors in the ecosystem. In such ecosystems, several packaging producers 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 increases when some waste treaters have a bargaining decision-style. However, problem-solving packaging producers still purchase recycled material despite the higher price, resulting in more expensive packaging.

Conversely, the food producer goes for the lowest price, thus opting for packaging with less recycled content. As a result, fluctuations in recycled content occur depending on the lowest price that can be offered by the packaging producers. The top part of Figure 17 demonstrates that the recycled content in a bargaining food producer’s PET bottles fluctuates more frequently when the bargaining part of the ecosystem is 70% or lower. In ecosystems with more bargaining actors, fluctuations are less common and could be caused by outliers.

Secondly, the spikes are observed in the time series data of ecosystems comprising a problem-solving food producer and a large proportion of bargaining actors. In these ecosystems, the food producer prefers packaging with high recycled content, while the ecosystem offers limited packaging options containing recycled material. Particularly with bargaining waste treaters in the ecosystem, the price of the recycled material increases when packaging producers buy it. Bargaining food producers may then shift to cheaper virgin material instead of buying recycled material. Only the few problem-solving packaging producers offer recycled content in packaging, most likely associated with higher prices for the food producer. The bottom of Figure 17 shows that the recycled content in a problem-solving food producer’s PET bottles exhibits reduced fluctuation with lower bargaining parts.

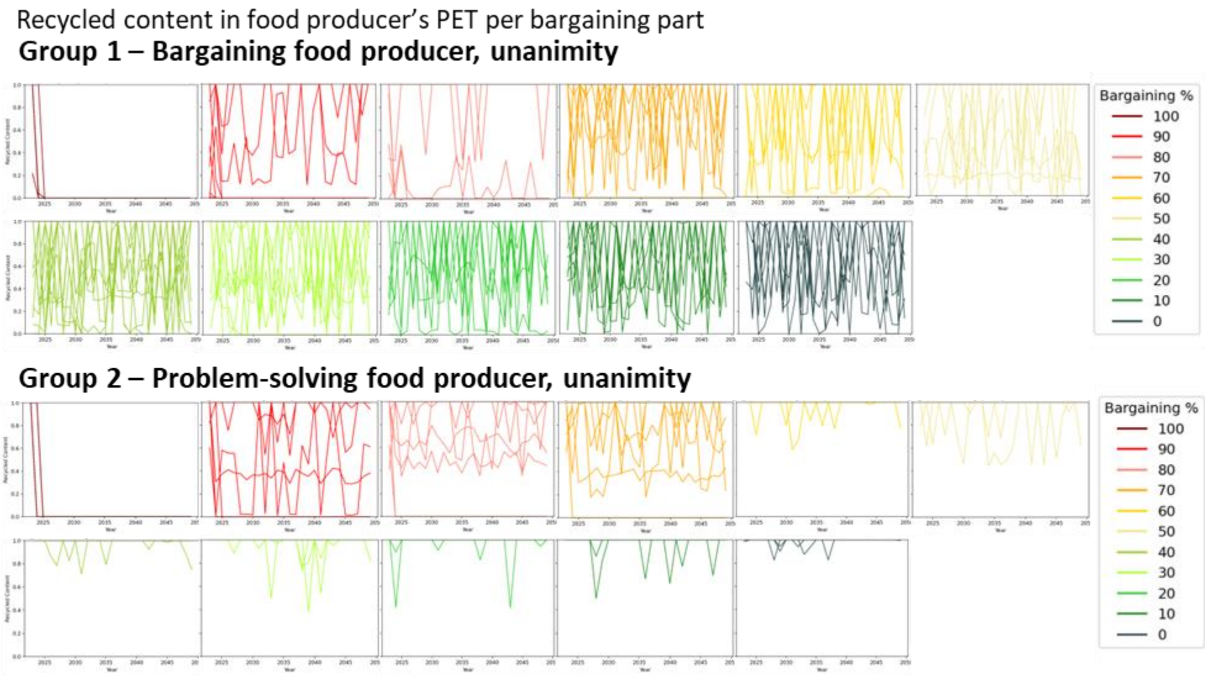

Figure 17. Recycled content in PET bottles for each bargaining percentage indicated by colour in separate graphs. The top shows the recycled content time series in Group 1, the bottom shows the recycled content time series in Group 2.

A final explanation of the spikes in the time series is a shortage of recycled material, requiring packaging producers to supplement recycled material with virgin material. These shortages in recycled material could result from the maximum potential recycled content in packaging production surpassing the recycling rate of waste. This interpretation is supported by the limited appearance 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 that can be used as recycled content in new packaging.

Another interesting pattern emerges in the experiments for drink cartons. In experiments with high bargaining parts, it is observed that the recycled content initially increases, followed by a drop (Figure 18). This phenomenon is explained by the fact that only one drink carton producer has been modelled alongside multiple waste treaters who recycle paper, aluminium, and plastic. Consequently, the drink carton producer can buy recycled material from bargaining waste treaters at the initial price for multiple years, as the waste treaters only raise the price of the recycled material once they sell it to the packaging producer. This pattern is often observed in ecosystems with high bargaining parts, while it is less common in ecosystems with more bargaining actors.

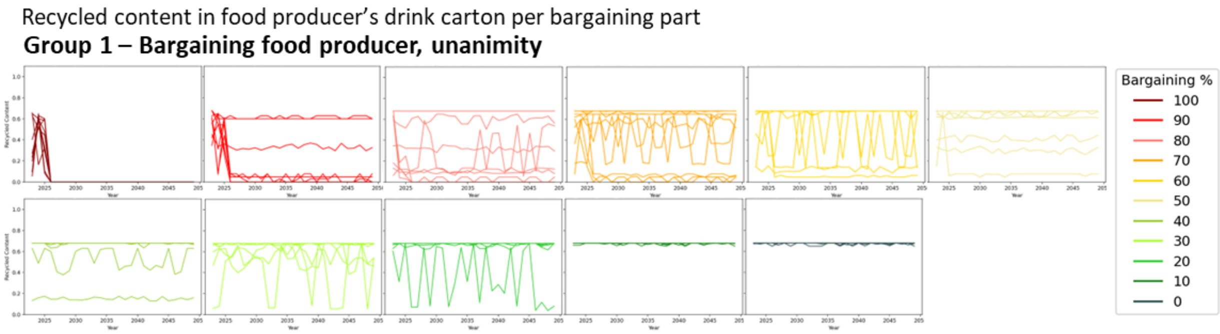

Figure 18. Recycled content in drink carton for different bargaining percentages indicated by colour in separate graphs, showing an increase and drop in ecosystems with mainly bargaining actors.

Furthermore, the average time series graphs elucidate the effect of the decision-style composition within the ecosystem. In general, ecosystems with a larger proportion of problem-solving actors tend to result in high recycled content in the food 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 food producer and the decision-rule within the ecosystem. A more comprehensive analysis is conducted in Section 6.3 to examine these variations in outcomes.

6.1.1.2 Price paid time series

Similar to the recycled content time series, graphs were generated to illustrate the time series data on the price paid by the food producer for different packaging types. Again, each experiment group was visualised in two graphs: one graph including all individual time series and one graph presenting the average per bargaining part. Visual interpretation of these graphs led to additional insights.

First, the time series data shows an upper limit that increases annually, resulting in a straight upwards slope in the figures (e.g. Figure 19). Considering the settings in the model, it is important to note that the price of recycled material can increase without limitations, potentially reaching a maximum of 2.8 per kilogram in 2050 if the packaging is entirely made of recycled material. This value is derived from the starting price of 0.1, with a maximum annual increase of 0.1 for 27 years. Indeed, the figures demonstrate that the price often increases over time.

The price paid per kilogram can demonstrate fluctuations in ecosystems that comprise a combination of bargaining and problem-solving actors. The top graphs in Figure 19 show that the price paid by a bargaining food producer mostly remains below or around 0.1 per kilogram in a unanimity setting. However, for almost all bargaining-part settings in Group 1, some outliers are observed where the paid price increases far beyond 0.1. The figures suggest that prices rise more frequently in ecosystems with a small proportion of bargaining actors. This pattern may be caused by scenarios where some waste treaters have a bargaining decision-style, while most packaging producers adopt a problem-solving style. In such cases, bargaining waste treaters can continuously increase their price without losing packaging producers as their customers, which leaves the food producer no choice but to purchase expensive packaging.

An increase in paid price is not observed in ecosystems comprising solely bargaining or problem-solving actors. In an ecosystem with exclusively bargaining actors, the price remains constant at the raw material price of 0.1, as all actors prefer the lowest price and bargaining waste treaters do not reduce their price if they have no sales in the ecosystem. Conversely, in ecosystems containing only problem-solving actors, the price drops to 0, as all waste treaters reduce their prices by 0.1 if they have no sales in the first year.

The bottom graphs in Figure 19 shows a different phenomenon. In the experiment group of a problem-solving food producer in a unanimity setting, the price paid per kilogram frequently exceeds the 0.1 threshold in ecosystems with both bargaining and problem-solving actors. Because of this, a clear slope is observed in all graphs with an upper limit that increases throughout the years. The price increase appears to occur more frequently in ecosystems with relatively balanced proportions of bargaining and problem-solving actors. The price paid in ecosystems with 60% bargaining actors exceeded 0.1 in 40 out of 50 time series. Similarly, for ecosystems with 70% and 50% bargaining actors, this occurred in 34 and 33 out of 50 time series, respectively.

The frequency of occurrences decreases as the proportion of bargaining and problem-solving actors becomes increasingly imbalanced. This pattern may be explained by the power of bargaining waste treaters in such ecosystems, as they can drive up the price of recycled material while packaging and food producers pay the price regardless. In ecosystems with a relatively smaller number of problem-solving actors, bargaining waste treaters are less likely to find customers in the ecosystem willing to pay high prices. On the other hand, in ecosystems with relatively few bargaining actors, problem-solving actors have a lower likelihood of being compelled to buy from an expensive bargaining waste treater.

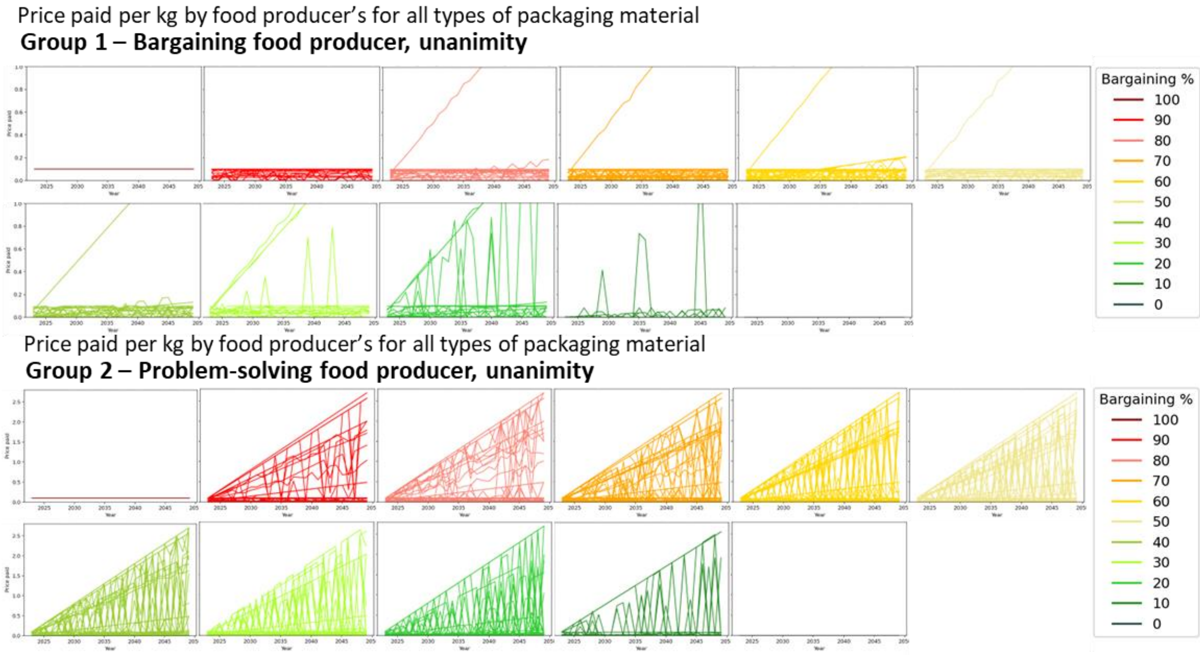

Figure 19. Price paid by food producer for all products, with each bargaining percentage indicated by colour in separate graphs. The top shows the price paid time series for Group 1, the bottom shows the price paid time series for Group 2.

The graphs clearly show frequent fluctuations in the paid price, with the upper limit increasing over the years. The observed spikes in the price paid per kilogram might again be explained by material shortages resulting in the inevitable use of 'cheap' raw material. However, the graphs for drink cartons and Bag in Box also show spikes in these time series. Another explanation could be that the ecosystem consists of a combination of bargaining and problem-solving waste treaters. With this context, it would be a case of random luck who is the first packaging producer who finds the waste treater with a problem-solving style and thus a low recycled material price. However, the food producer is dependent on the packaging producers with a large enough packaging volume, thus relying on the packaging producers' luck to find a problem-solving waste treater.

Most importantly, the graphs for the price paid per kilogram must be interpreted carefully and conservatively. Outliers are prominent and have a substantial effect on the average price. Furthermore, the time series data illustrated in the graphs heavily relies on modelling choices and assumptions. Therefore, no extensive analysis comparing different groups is conducted to avoid potentially misleading conclusions.

6.1.2 Data analysis

After visually interpreting the time series data, an additional analysis is conducted to examine the effect of the different ecosystem variables on the recycled content in the food producer's packaging. First, the recycled content in 2050 is compared for the different bargaining parts to determine what compositions lead increased recycled content. Afterwards, the four experimental groups are compared to examine the effect of the food producer's decision-style and the ecosystem's decision-rule on the recycled content.

For the first analysis, the different bargaining parts are compared in each experimental group, while for the second analysis, the experimental groups are compared in each bargaining part. For these two analyses, data for all packaging types, bargaining parts and experiment groups were combined into one large data frame.

First, the residuals were calculated, which represent the difference between the recycled content of the experiment and the mean of all experiments in that group (either the bargaining part or the experiment group). These residuals were tested for normality by analysing the skewness and kurtosis, with skewness measuring the symmetry or asymmetry of the distribution and kurtosis indicating the heaviness of the tails relative to a normal distribution. If both skewness and kurtosis of the residuals are between -2 and 2, the residuals are considered to follow a normal distribution (Cain et al., 2017).

Next, the homogeneity of variances across different groups was tested. Levene's test for homoscedasticity was used for the groups with normally distributed residuals, while the more robust Brown-Forsythe test was used for groups with residuals that do not follow a normal distribution. If the p-value of these tests is below 0.05, the assumption of homoscedastic data distribution is rejected, meaning that the variances within the different bargaining parts or experiment groups are unequal (Garson, 2012).

Once the assumptions were tested, the appropriate statistical test was performed to test the null hypothesis that there is no difference in recycled content between different bargaining parts (first analysis) and experiment groups (second analysis). If the p-value of the test was below 0.05, the null hypothesis was rejected, and the alternative hypothesis was accepted, stating that there is a significant difference in recycled content between the groups. Subsequently, a post hoc analysis was conducted to identify the specific groups that significantly differ.

6.1.2.1 Comparison between bargaining parts

Table 8 provides an overview of the first analysis, including the performed tests of each experiment group and the corresponding results.

Table 8. Statistical tests used in the comparison of the different bargaining parts within the experiment groups and their outcomes.

Statistical tests	**Group 1**	**Group 2**	**Group 3**	**Group 4**
Skewness of residuals	0.41	-0.14	0.41	-0.16
Kurtosis of residual	-0.88	-1.16	-0.97	-1.24
Assumption of normality	TRUE	TRUE	TRUE	TRUE
Homoscedasticity test	Levene's	Levene's	Levene's	Levene's
Homoscedasticity p-value	0.0	0.0	0.0	0.0
Assumption of equal variance	FALSE	FALSE	FALSE	FALSE
Performed test	Welch's ANOVA	Welch's ANOVA	Welch's ANOVA	Welch's ANOVA
P-value	2.97e-76	2.82e-97	3.36E-78	1.29e-97
Significant difference	TRUE	TRUE	TRUE	TRUE
Performed post-hoc	Games-Howell	Games-Howell	Games-Howell	Games-Howell

Figure 20 presents the outcomes of the post hoc comparison through boxplots, illustrating the variance for each bargaining part within each experiment group. The letters above the boxplots indicate the significance groups to which each bargaining part belongs. Bargaining parts with the same letters do not significantly differ, while those without the same letter have a significant difference in the recycled content of the food producer's product.

The boxplots show that each experiment group has slightly different outcomes. In all groups, except group 3, the recycled content is significantly higher for an ecosystem with 90% bargaining actors than an ecosystem with only bargaining actors. However, ecosystems with 80% bargaining actors do not have a significantly higher recycled content than ecosystems with 90% bargaining actors. 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 experimental groups would be larger.

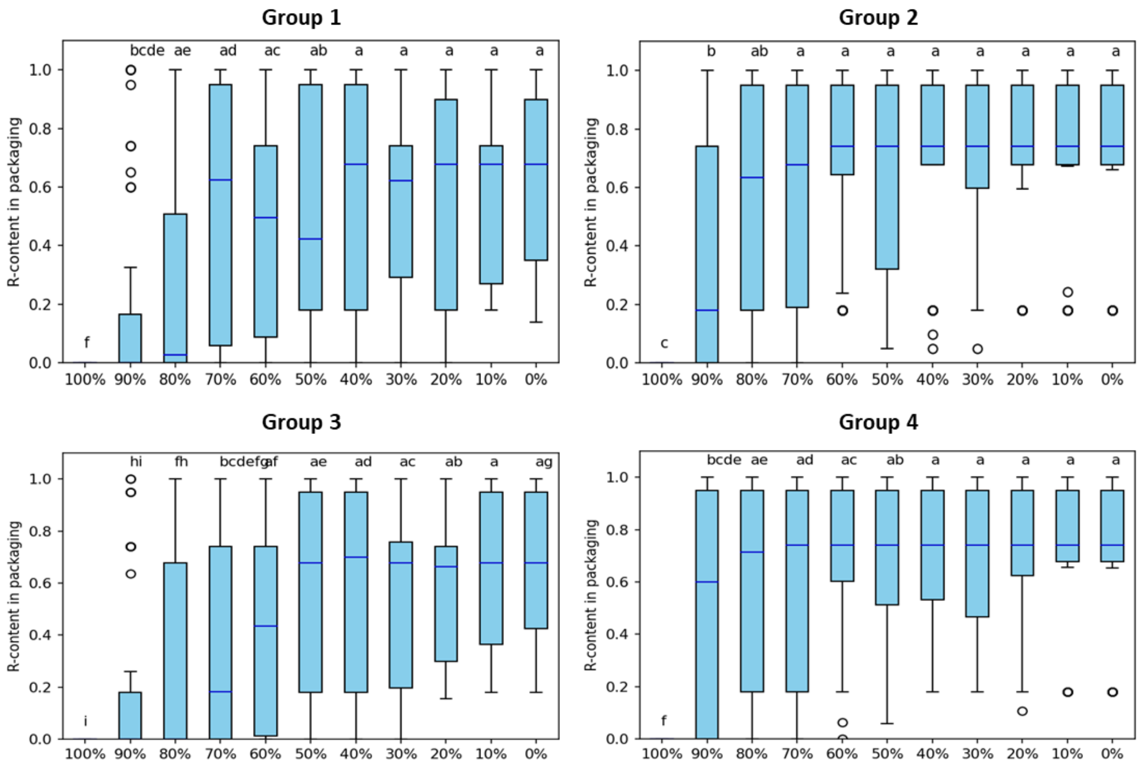

Figure 20. Boxplot of recycled content in 2050 for each bargaining part in the four experiment groups. The letters above the boxplot indicate the significance group: boxplots with the same letter do not differ significantly.

In Group 1, which has a bargaining food producer and a unanimity decision-rule, ecosystems with 40% bargaining actors or lower have a significantly higher recycled content than the 90% bargaining ecosystems. The recycled content in ecosystems with a bargaining part between 90% and 40% does not differ significantly from the recycled content in ecosystems with 90% bargaining actors nor from the recycled content in ecosystems with 40% or less bargaining actors.

A different outcome shows for Group 2, where the food producer has a problem-solving decision-style, and the decision-rule is unanimity. For this experiment group, the ecosystems with 70% or less bargaining actors have significantly higher recycled content than ecosystems with 90% bargaining actors. Ecosystems with 80% bargaining actors in this experiment group do not significantly differ from either 90% or 70% or less bargaining actors.

Group 3 shows a more gradual increase in recycled content, similar to group 1. This experiment group consists of experiments in which the food producer has a bargaining decision-style, and the decision-rule is hierarchy. Unlike other groups, ecosystems with 90% bargaining actors in Group 3 do not result in significantly higher recycled content than ecosystems with only bargaining actors. Ecosystems with 80% bargaining actors have a higher recycled content than the ecosystems with only bargaining actors but do not differ significantly from ecosystems with 90% bargaining actors. The recycled content keeps gradually increasing with lower bargaining parts, but no significant difference is identified between ecosystems with 60% or fewer bargaining actors.

Finally, Group 4, entailing experiments with a problem-solving food producer in a hierarchy ecosystem, shows the same pattern as group 1. Ecosystems with 40% bargaining actors or lower have significantly higher recycled content than 90% bargaining ecosystems. The ecosystems with a bargaining part between 90% and 40% do not have significantly higher recycled content than ecosystems with 90% bargaining actors or those with 40% or fewer bargaining actors.

6.1.2.2 Comparison between experimental groups

For the second analysis, the recycled content in the different experimental groups was compared for each bargaining part. Table 9 provides an overview of the performed experiments in this comparison and the corresponding outcomes.

Table 9. Statistical tests used in the comparison of the different experimental groups and their outcomes.

Statistical tests	**90%**	**80%**	**70%**	**60%**	**50%**	**40%**	**30%**	**20%**	**10%**	**0%**
Skewness of residuals	0.05	-0.28	-0.45	-0.79	-0.72	-0.72	-0.70	-0.78	-0.91	-0.91
Kurtosis of residual	-1.72	-1.65	-1.40	-0.79	-0.87	-0.96	-1.02	-0.79	-0.46	-0.46
Assumption of normality	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE
Homoscedasticity test	L	L	L	L	L	L	L	L	L	L
Homoscedasticity p-value	0.0	0.18	0.07	0.0	0.01	0.55	0.94	0.62	0.97	0.97
Assumption of equal variance	FALSE	TRUE	TRUE	FALSE	FALSE	TRUE	TRUE	TRUE	TRUE	TRUE
Performed test	WA	OA	OA	WA	WA	OA	OA	OA	OA	OA
P-value	0.2e-3	0.6e-2	0.4	0.2e-3	0.02	0.3	0.1	0.2	0.1	0.3
Significant difference	TRUE	TRUE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	FALSE	FALSE
Performed post-hoc	G-H	T	-	G-H	G-H	-	-	-	-	-

These analyses elucidate that the food producer's decision-style and the ecosystem's decision-rule can significantly affect the recycled content, but only in some ecosystem compositions. The post hoc analysis of the four bargaining parts showed a significant difference between the experiment groups. The boxplots of the post hoc analysis are presented in Figure 21.

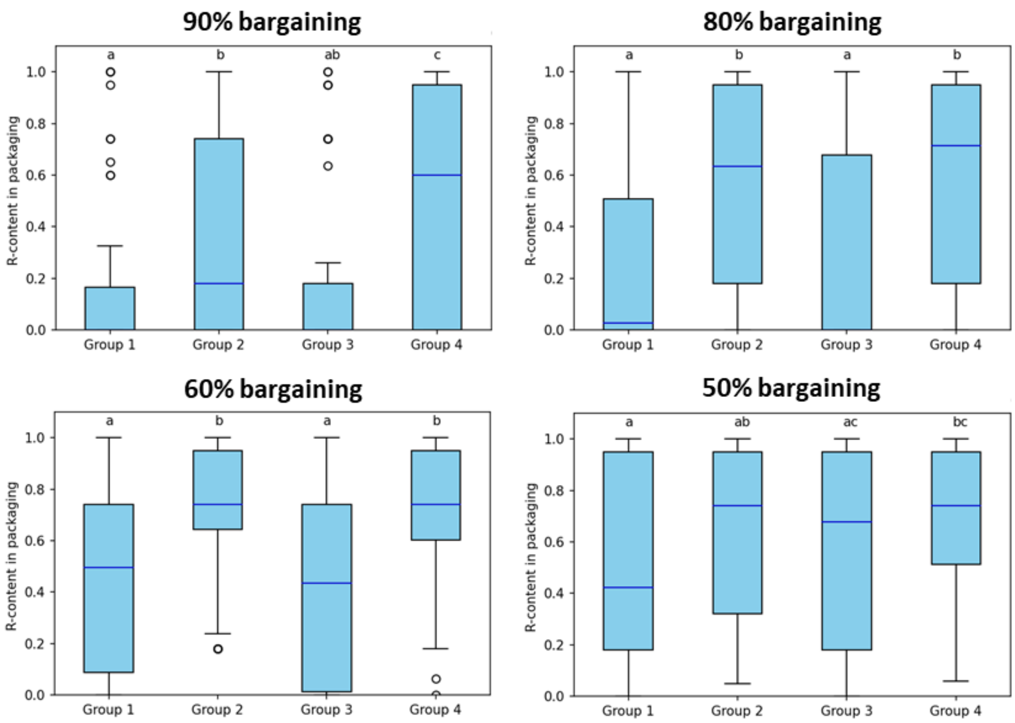

Figure 21. Recycled content in 2050 per experiment group for the bargaining parts with significant difference between groups. The letters indicate the significance group: boxplots with the same letter do not differ significantly.

The figures demonstrate that the food producer's decision-style significantly affects the recycled content in the final product. However, this effect is only prevalent in ecosystems with high proportions of bargaining actors. In such ecosystems, problem-solving food producers achieve significantly higher recycled content in their products than bargaining food producers. In a 90% bargaining ecosystem, this phenomenon is enhanced by a hierarchy decision-rule, resulting in even higher recycled content than the ecosystems with a unanimity decision-rule. However, this effect of a hierarchy decision-rule was not observed in ecosystems with other decision-style compositions.

6.2 Variable experimentation

After conducting the sensitivity analysis on the behaviour variables, eight additional experiments were conducted to explore the effect of other variables on the potential of circular ecosystems to reduce packaging waste. In these experiments, the behaviour variables were kept constant with 90% bargaining actors, a problem-solving food producer and a unanimity decision-rule. The analysis outcomes of the experiments were compared to Experiment 0, which served as the baseline with no changes in variables. For the analysis, time series data of the recycled content in the food producer's packaging was visualised and interpreted (Appendix F.4). Additionally, boxplots were generated to examine the recycled content of different packaging types in 2050 (Appendix F.5). Finally, time series graphs were created to investigate the raw material demand in the Netherlands and assess potential effects in the Dutch food packaging ecosystem that may not be evident from the food producer's recycled content data (Appendix F.6). The following sections present and interpret the findings of the experiments.

6.2.1 Dutch waste variables

The first two experiments introduced changes to the Dutch waste variables, exploring the effect of a reduction in secondary material volume in the Netherlands over the years (Experiment 1) and centralised waste treatment (Experiment 2).

6.2.1.1 Secondary material reduction

In this first experiment, the waste volume and subsequent available secondary material were reduced by 1% annually across all material types. The time series data for the recycled content in the food producer's packaging did not exhibit clear patterns that differed from Experiment 0, where waste volume remained constant. Again, 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 Experiment 0, while PET and glass bottles demonstrated fewer fluctuations in recycled content when the waste volume decreased. Similarly, the boxplots of recycled content in 2050 did not show a notable difference in variance between Experiment 0 and 1. 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.

6.2.1.2 Central waste treatment

Experiment 2 explored the scenario of centrally organising waste treatment. The results indicated a more stable supply of recycled material compared to Experiment 0, where the ecosystem included multiple waste treaters with different decision-styles. Figure 22 illustrates that the recycled content in the food producer's packaging is either zero or the maximum potential recycled content, depending on the decision-style of the central waste organisation. 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 as well. In some simulations, it could be the case that packaging producers capable of supplying the food producer with large enough volumes may have their turn later than smaller packaging producers who cannot meet the food producer's demand, resulting in limited recycled content in the packaging. The boxplot displayed a similar variation in outcomes as seen in Experiment 0, probably influenced by the decision-style of the waste treaters. Furthermore, the raw material demand did not differ from ecosystems without centralised waste treatment.

These outcomes suggest that centralising 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.

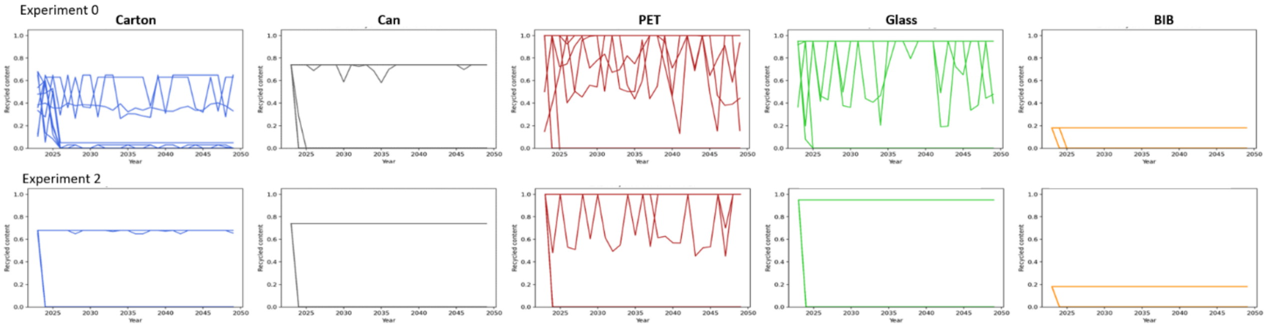

Figure 22. Recycled content in the food producer's packaging in Experiment 0 (top) and Experiment 2 (bottom), showing that central waste treatment can help overcome fluctuations in recycled content.

6.2.2 Price variables

The third and fourth experiments focused on changes in the price variables. The experiments in the sensitivity analysis considered the same starting price for raw and recycled material, while the waste treaters could adjust the latter over the years. Experiment 3 was carried out to understand what would happen if the raw material price increased over the years, and Experiment 4 assessed a scenario where the raw material price would exceed the recycled material price from the start.

6.2.2.1 Raw material price increase

The simulations for Experiment 3 revealed that an annual increase in material price could lead to greater fluctuations in the recycled content of the food producer's packaging. The graphs of Experiment 3 displayed more spikes compared to those of Experiment 0 (Figure 23). One possible explanation for this observation is that as recycled material becomes cheaper than raw material over the years, bargaining packaging producers start buying recycled material instead of raw material. However, if they buy recycled material from a bargaining waste treater, the treater increases the price of recycled material, thereby potentially causing raw material to become cheaper than recycled material again. This dynamic could lead to unstable recycled content in the packaging.

Another explanation for the spikey fluctuations in recycled content could be related to recycled material shortages, exacerbated by the food producer's reliance on packaging producers with a sufficient packaging volume. As the packaging producers buy from waste treaters in a random order each year, there may be years where they are the first to buy recycled material, while only a portion of their recycled material demand may be available in other years. However, this explanation is partially invalidated when examining the raw material demand across the entire ecosystem. Figure 23 shows that the raw material demand in the ecosystems also exhibits extreme fluctuations. Recycled material shortages would not be expected to fluctuate to this extent, as the recycling rate only varies within a range of 10% higher and lower than the Dutch recycling rate. Therefore, it is unlikely that these variations alone account for the observed fluctuations in raw material demand, such as the wide range between 80 million and almost 600 million kg in the simulations for drink cartons.

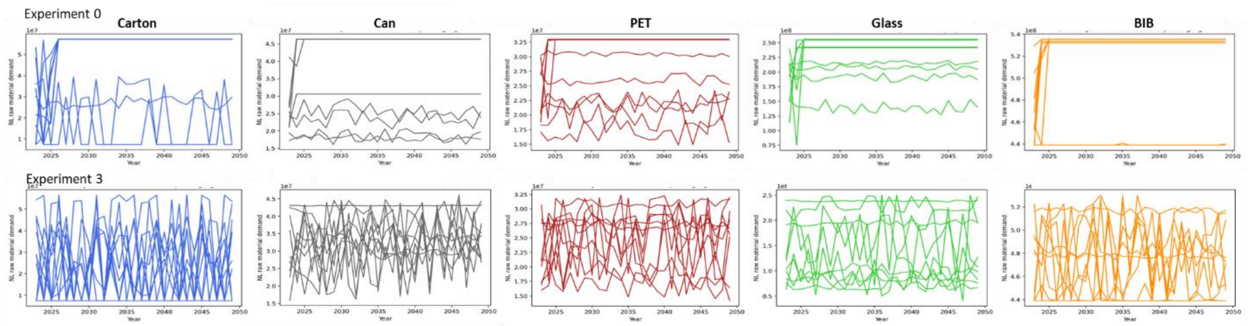

Figure 23. Raw material demand of the food packaging ecosystem in Experiment 0 (top) and Experiment 3 (bottom), showing that an increasing raw material price results in fluctuating raw material demand in the model.

A thorough analysis of the model and simulations reveals that the fluctuations are probably caused by a modelling assumption for bargaining packaging food producers. In the model, these producers seek the waste treater offering the cheapest recycled material without considering the volume of recycled material available at the treater. Consequently, the packaging producer ends up with the cheapest recycled material, but if the volume is insufficient, they substitute it with more expensive raw material instead of seeking additional recycled material from other waste treaters. This modelling assumption could explain the unrealistic pattern observed in this experiment, where bargaining packaging producers continue to purchase expensive raw materials despite the availability of cheaper recycled material at other waste treaters. This limitation is further discussed in Section 7.2.5.

Overall, an increase in raw material price leads to higher recycled content in the packaging as long as the raw material remains more expensive than recycled material. This is evident from the fact that the recycled content never becomes zero in any of the simulations in Experiment 3, while this does happen in all other experiments (except for Experiment 4). The boxplots of Experiment 3 in Figure 24 shows that there is almost no variation in outcomes for recycled content in 2050 when the material price increases with 0.1 annually, except for drink cartons which consist of multiple materials.

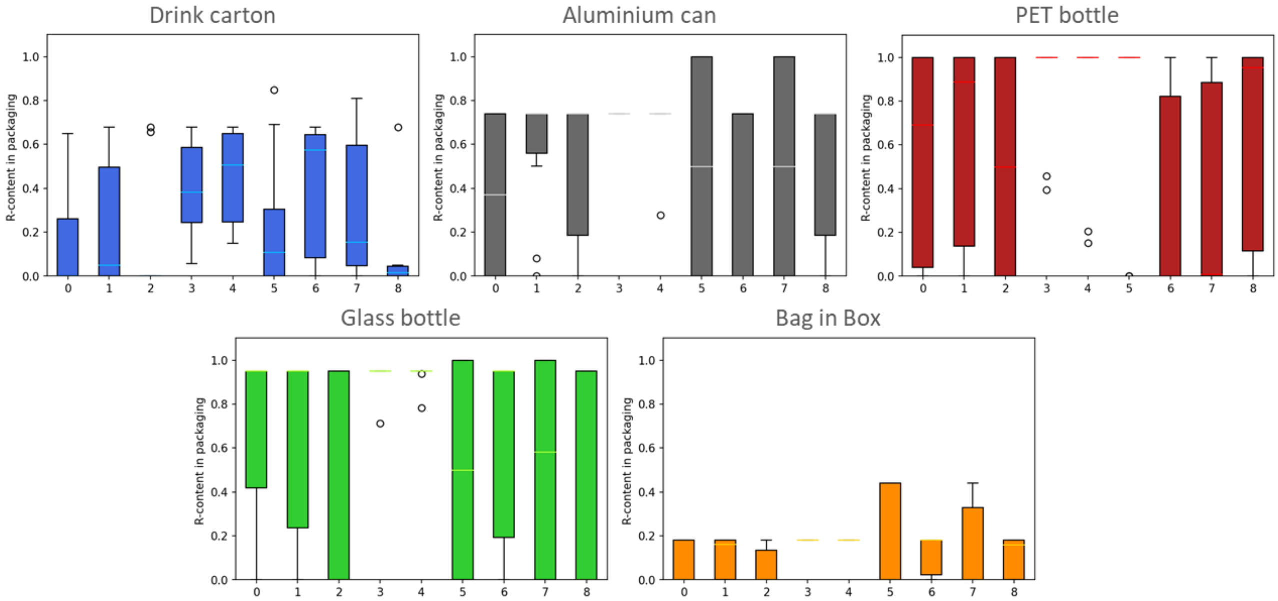

Figure 24. Recycled content in 2050 in different packaging types for the eight experiments.

6.2.2.2 High raw material price

Experiment 4 aimed to assess the effect of a high raw material price on the outcomes of the circular ecosystems. The experiment yielded results similar to those of Experiment 3. Again, the time series data for both the recycled content and the raw material demand in the Dutch ecosystem exhibited large fluctuations over the years. These fluctuations were unexpected, as it would be reasonable to assume that bargaining actors would prefer cheaper recycled material over more expensive raw material. As elaborated in Section 6.2.2.1, these fluctuations likely stem from the modelling choice that bargaining packaging producers look for the cheapest recycled material without considering the available volume and substitute it with raw material instead of seeking additional recycled material from other waste treaters. The implications of this modelling choice are discussed in Section 7.2.5. Similar to Experiment 3, a high raw material price resulted in higher recycled content in a 90% bargaining ecosystem compared to most other experiments, as the lower price incentivised the bargaining actors to opt for recycled material instead of raw material.

6.2.3 Innovation variables

The final four experiments relate to potential innovation in the Dutch food packaging ecosystem. Experiment 5 considers innovation that increases the maximum potential recycled content that can be used in the production of new packaging. Next, Experiment 6 assesses the effect of innovation that improves the recycling rate. Experiment 7 concerns a combination of innovation regarding the maximum potential recycled content and the recycling rate. Lastly, experiment 8 examines the effect of including PET in the Dutch deposit-return system.

6.2.3.1 Maximum potential recycled content increase

The fifth experiment 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 one, 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 0.18, suggesting the most room for improvement. The time series data of the recycled content in the food 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 one is reached.

Conversely, the time series data of the raw material demand demonstrate a contrasting trend, with a decline in raw material demand over the years in various simulations. However, as depicted in the boxplots of Experiment 5 in Figure 24, 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.

6.2.3.2 Recycling rate increase

Experiment 6 aimed to assess the effect of recycling rate innovation within the Dutch food packaging ecosystem. While the expectation was that such innovation could mitigate recycled material shortages, fluctuations were still observed in the time series data for both the recycled content and raw material demand. Again, 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, Experiment 6 yielded a considerable variation in outcomes, as is depicted in the boxplots for Experiment 6 in Figure 24. 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.

6.2.3.3 Maximum potential recycled content and recycling rate increase

Experiment 7 examined the combined effect of innovation related to the maximum potential recycled content and the recycling rate. The results mirrored the pattern observed in Experiment 5, with increasing trends in the recycled content and declining trends in raw material demand shown in multiple simulations for all packaging types except PET. However, fluctuations over time and variations in outcomes are also prevalent in the data of Experiment 7. These findings underscore the influence of other components on the outcomes of innovation-related interventions within the Dutch food packaging ecosystem.

6.2.3.4 PET in deposit-return

The final experiment explored the effect of including PET bottles in the Dutch deposit-return system, which would redirect the waste stream from BIB waste treaters to the PET waste treaters. The time series data indicated that this change in the ecosystem would not reduce the fluctuations in the recycled content in PET, despite the increased availability of recyclable material. The red boxplot for Experiment 8 in Figure 24 illustrates that although the median outcome of the simulations of Experiment 8 is relatively high, the recycled content in PET by 2050 varies considerably. Therefore, additional measures are likely required to address the recycled material shortages that limit the effectiveness of the circular ecosystem in reducing packaging waste.

6.3 Summary and remarks

The experimentation and results in Chapter 6 can be used to answer sub-question 4:

Based on simulations, what is the potential of circular ecosystems to reduce packaging waste in the Dutch food packaging ecosystem?

The findings in this chapter demonstrate that circular ecosystems hold the potential to effectively reduce packaging waste in the Dutch food packaging ecosystem by using recycled material in the production of new packaging. The reduction potential of these recycling circular ecosystems relies on multiple factors explored in a thorough sensitivity analysis and additional variable experimentation.

The sensitivity analysis elucidated that the recycled content could fluctuate in a circular food packaging ecosystem, resulting in subsequent variations in packaging waste reduction. The fluctuations may result from recycled material shortages and the decision-styles of the ecosystem actors. In ecosystems with imbalanced proportions of bargaining and problem-solving actors, fluctuations in recycled content were more profound. In these imbalanced ecosystems, the fluctuations could be attributed to the price adjustments by waste treaters and the material selection processes of packaging producers.

Moreover, ecosystems with a higher proportion of problem-solving actors were associated with significantly higher recycled content in packaging by 2050, mainly when the food producer also adopted a problem-solving decision-style. This finding shows that the ecosystem does not require all actors to have a problem-solving style for circular ecosystems to thrive. Starting with only a few problem-solving actors could significantly increase the recycled content in the food producer's packaging and thus reduce packaging waste.

Notably, the decision-style of the food producer significantly influenced the recycled content in ecosystems with predominantly bargaining actors, indicating the critical role of the food producer's behaviour in shaping circular ecosystem outcomes. The food producer, or another focal actor, can significantly reduce waste if they adopt a problem-solving style, meaning they choose circularity over individual profit.

Furthermore, a hierarchy decision-rule could enhance the recycled content in ecosystems with a high proportion of bargaining actors, but further research is needed. Overall, the sensitivity analysis results indicate the potential of circular ecosystems in reducing packaging waste and underscore the importance of decision-making behaviour in establishing successful ecosystems.

Eight additional experiments were conducted, building upon the sensitivity analysis of behaviour variables. These experiments were used to explore the dynamics within the Dutch food packaging ecosystem and the potential effect of variables related to Dutch waste, pricing and innovation on circular ecosystems' ability to reduce packaging waste.

The findings of these experiments indicate that a reduction in available secondary material does not directly affect the success of circular ecosystems. Furthermore, centralised waste treatment can contribute to a more stable supply of recycled material, resulting in fewer fluctuations in both recycled content within the packaging and raw material demand within the ecosystem. Price interventions to incentivise recycled material can yield higher recycled content and lower raw material demand in predominantly bargaining ecosystems but may also introduce increased fluctuations. However, these fluctuations are attributed to the packaging producer's material selection process in which seek the cheapest recycled material rather than sufficient recycled material volumes. Finally, innovation in the Dutch food packaging ecosystem has the potential to facilitate circular ecosystems. However, the wide range of outcomes emphasises the importance of considering other variables to ensure the effectiveness of such innovation in waste reduction.

Overall, the simulations of the various experiments showed the potential of circular ecosystems under various conditions to reduce packaging waste in the Dutch food packaging ecosystem. The results will be further discussed in the next chapter.

7 Discussion

Organisations are exploring their possibilities to improve the circularity of their practices and the opportunities to collaborate in ecosystems. However, the actual effect of circular ecosystems on waste streams has remained largely unknown, particularly considering the uncertainty of actor behaviour (Trevisan et al., 2022). Previous studies showed that individual decision-making behaviour of organisations could result in suboptimal outcomes in joint decision-making processes (Domenech & Bahn-Walkowiak, 2019; Scharpf, 1988a). Therefore, the success of circular ecosystems may depend on the behaviour of individual organisations within those ecosystems. Additionally, various other variables and dynamics can affect the success of circular ecosystems (Barquete et al., 2022; Gomes et al., 2023). This study aimed to shed light on the dynamics within the Dutch food packaging ecosystem and their effect on the potential of circular ecosystems to reduce packaging waste while considering actor behaviour. The main research question addressed in this study is:

What are the dynamics of packaging waste in a circular food packaging ecosystem in the Netherlands, considering actor behaviour?

An ABM was conceptualised and developed to answer this question based on an extensive literature review of the Dutch food packaging ecosystem and a case study of a specific food and beverage company. Subsequently, various experiments were conducted using the model, examining actor decision-making behaviour and eight potential interventions related to other variables in the ecosystem. The outcomes of these experiments were analysed to gain insights into the potential of circular ecosystems to reduce packaging waste under various conditions.

This chapter presents the reflections on the study, starting with a summary of the results in Section 7.1. The interpretation and discussion of these results are then provided in Section 7.2. Subsequently, Section 7.3 reflects on the research process and its limitations, including a discussion of the model's validity and utilisation for Steps 9 and 10 of the ABM methodology proposed by Van Dam et al. (2013). Finally, the chapter concludes with the practical implications of the findings and recommendations for future research in Section 7.4.

7.1 Summary of results

The results of this study involve several elements, all addressing specific sub-questions and steps related to the main research question. Initially, a comprehensive system analysis of the Dutch food packaging system was conducted, resulting in an extensive inventory of social and technical components, as well as contextual factors associated with the reduction of packaging waste. This inventory served as the foundation for conceptualising and implementing an ABM of a Dutch food packaging ecosystem. Subsequently, the model was used to conduct experiments to analyse the effect of actors' decision-making behaviour on the effectiveness of circular ecosystems in reducing packaging waste. Afterwards, eight additional experiments were conducted to assess the effect of variables related to Dutch waste, price and innovation on the dynamics of packaging waste under specific actor behaviour. The analysis of the experiment data revealed multiple patterns.

First, frequent spikes were observed in the time series for the recycled content in the food producers' packaging, which can be explained by shortages of recycled material. Additionally, the spikes are influenced by the decision-styles of the ecosystem actors. In ecosystems with a bargaining food producer and predominantly problem-solving actors, the recycled content tended to show more frequent fluctuations, as the food producer always preferred low-price packaging when offered, regardless of its potential lower recycled content. Conversely, problem-solving food producers exhibited more variability in recycled content in ecosystems dominated by bargaining actors. This variation can be explained by the price drive-up by bargaining waste treaters and the preference of bargaining packaging producers to use the cheapest material.

However, an interesting observation was made in the experiments with higher raw material prices than recycled material prices. In these experiments, the recycled content and the raw material demand exhibited increased fluctuations. These increased fluctuations are likely caused by the material selection process of packaging producers, who prioritised the cheapest recycled material over sufficient supply but are able to buy from only one waste treater. This process results in unnecessary substitution with expensive raw material rather than looking for additional recycled material.

Secondly, the price paid time series in the sensitivity analysis showed an increase over the years, primarily caused by potential price increases by bargaining waste treaters. The price rise was most profound in ecosystems with a problem-solving food producer, as they preferred recycled content over price considerations. Spikes were also observed in the time series data of the price paid per kilogram by the food producer, particularly in ecosystems comprising a combination of bargaining and problem-solving actors. In such ecosystems, it is a matter of luck who is the first packaging producer to find a waste treater with a problem-solving style and thus a low recycled material price.

Furthermore, the data analysis indicated that ecosystems with a small proportion of problem-solving actors (10%) will have significantly higher recycled content in packaging by 2050 compared to ecosystems with only bargaining actors. However, when the food producer has a bargaining decision-style, the next significant increase in recycled content only occurs when more than half of the actors in the ecosystem have a problem-solving decision-style. Conversely, when the food producer has a problem-solving decision-style, an ecosystem with only 30% problem-solving actors would yield significantly higher recycled content in the packaging than ecosystems with only 10% problem-solving actors.

The decision-style of the food producer affects the recycled content most in ecosystems with a high proportion of bargaining actors. In ecosystems where more than 50% of the actors have a bargaining decision-style, problem-solving food producers yield significantly higher recycled content in their packaging than bargaining food producers. However, differences ceased to appear in ecosystems with mainly problem-solving actors. Additionally, implementing a hierarchy decision-rule might facilitate an increase in the recycled content of problem-solving food producers. However, this accelerating phenomenon was observed only in ecosystems with 90% bargaining actors. Further experimentation is needed to better understand the role of the decision-rule on the dynamics of packaging waste in a circular food packaging ecosystem.

Finally, the additional experiments elucidated the dynamics of packaging waste caused by variables related to Dutch waste, prices, and innovation while considering specific actor behaviour settings.

The findings show that the success of circular ecosystems in reducing packaging waste would not be directly affected by a reduction in available secondary material. Additionally, centralised waste management can ensure a more consistent supply of recycled material, resulting in reduced fluctuations in recycled content and raw material demand.

Furthermore, the recycled content in packaging can increase in predominantly bargaining ecosystems through higher prices on raw materials relative to recycled materials. However, increasing raw material prices can result in more fluctuations in recycled content when bargaining packaging producers select material only by looking for cheapest price without considering whether the material volume is sufficient.

Finally, packaging waste reduction could be facilitated by innovation related to improving the recycling rate and maximum potential recycled content. However, the variety in outcomes of the innovation experiments indicates that more than innovation alone might be required to guarantee the success of circular ecosystems in reducing packaging waste.

7.2 Interpretation of results

The findings of this study provide valuable insights into the dynamics affecting waste reduction in circular ecosystems. This section aims to interpret the results and highlight their implications while acknowledging potential caveats.

7.2.1 Material shortages

The occurrence of recycled material shortages may limit achieving higher recycled content in the food producers' packaging. These shortages stem from a higher demand for recycled material than the available supply, caused by a lower recycling rate than the maximum potential recycled content. In the model, shortages are observed for aluminium, PET and glass. While aluminium is required in cans and drink cartons, only aluminium cans are currently recycled in the Netherlands. Food and Beverage Company X uses PET bottles made of 100% recycled material. However, these bottles are currently not recycled into new PET bottles in the Netherlands. Glass bottles contain up to 95% recycled content, while the current recycling rates are at 79%. The model assumes that all packaging producers can demand the maximum potential recycled content in their packaging, requiring recycling rates that meet or exceed the maximum potential recycled content.

Recycled material shortages can be a challenge for circular ecosystems focussing on closed-loop recycling because the material mass has to be balanced while material processing in the value chain is hardly 100% efficient. The model does not account for material losses throughout the value chain, but in reality, the recycling rate should be higher than the maximum potential recycled content to compensate for these losses. This means that if the packaging is made of 100% recycled material, either all material would have to be recycled with a recycling rate of 100% without any losses and degradation of materials, or the packaging should be made of less and less material. Therefore, it is important that circular ecosystems not only focus on closed-loop recycling but also adopt other circularity strategies such as material reduction, packaging reuse substituting material, for example, with bioplastics (Rosenboom et al., 2022).

7.2.2 Required actor behaviour

The sensitivity analysis results provide a better understanding of the required actor behaviour to enable successful circular ecosystems. In bargaining ecosystems, the recycled content in packaging is highly dependent on the decision-style of the food producer. If the food producer prioritises circularity over the lowest price, only a few other actors should have a problem-solving decision-style to increase the recycled content in packaging. According to one of Deloitte's experts, the current Dutch food packaging ecosystem primarily consists of bargaining actors focused on individual profit. The findings in this study underscore that the ecosystem does not require all actors to prioritise circularity over individual profit for circular ecosystems to reduce packaging waste effectively. Starting a circular ecosystem with only a few problem-solving actors could significantly reduce packaging waste in the Dutch food packaging system.

7.2.3 Availability of information

However, the success of circular ecosystems relies on two additional conditions that enable the effective execution of decision-making behaviour. First, the food producer must actively seek packaging producers using recycled material. This condition may be realistic considering food producers search for a packaging supplier (Interview Packaging Developer). The second condition requires the availability of complete information on the materials used by the actors in the ecosystem. This condition has been an implicit assumption in the ABM, as mentioned in Section 4.1. In an ecosystem with complete information, all agents can see and use each other's information. The need of complete information presents a potential bottleneck. In reality, the Dutch waste management structure only recently started monitoring waste volumes and recycling rates, providing limited circularity-related data (Interview Waste management). Additionally, packaging producers and food producers do not always indicate the recycled content in their packaging simply because the information is missing (Interview Packaging Developer). The availability of information is thus more limited than the model assumes.

The current ecosystem lacks a platform connecting the ecosystem actors and enabling them to share data on recycled material volumes and recycled content. A recent study emphasises the role of waste management in promoting the retention of material value during recycling, which can be supported by improved sharing of waste-related data and enabling cooperation between the actors in the ecosystem (Salmenperä et al., 2021). The Dutch waste management structure could play an important role in enabling data sharing in the Dutch food packaging ecosystem. Although Afvalfonds Verpakkingen monitors the waste volumes and recycling rates, there are currently no insights into how recycled packaging material is used (Interview Waste management). Until now, the orchestration of the chain by Afvalfonds Verpakkingen ended at the sorters, but in the coming years, their role in recycling will become increasingly important. This extended role could enhance more transparent data sharing within the Dutch food packaging ecosystem.

7.2.4 Effect of decision-rule

Furthermore, the decision-rule governing the ecosystem was analysed with the experiments. Although the unanimity decision-rule is most common between private-sector organisations (Scharpf, 1988a), the hierarchy rule might apply if the ecosystem would be governed as one single organisation comprising smaller entities. This scenario could arise if the Dutch waste management structure or another focal organisation actively orchestrates recycling. The model implemented hierarchy by giving larger packaging producers a first-mover advantage. Interestingly, this resulted in higher recycled content in the food producers' packaging within a 90% bargaining ecosystem, but no such effect was observed in other decision-style compositions. It should be noted that the current hierarchy rule in the model only influences the order of the packaging producer's decision, whereas, in reality, it would also affect other food producers who are not included in the ABM. Consequently, the decision-rule may have a more profound effect on the recycled outcome if the scope of the ABM were expanded to include a broader range of actors. The decision-rule has to be further assessed for more thorough insights into its effect on the dynamics of packaging waste in a circular food packaging ecosystem.

7.2.5 Fluctuations in outcomes

Fluctuations were observed in all data regarding recycled content in packaging, price paid and raw material demand. These fluctuations can be partly attributed to material shortages in the Dutch food packaging ecosystem. However, another potential cause for the fluctuations emerged through additional variable experimentation: bargaining packaging producers look for the cheapest recycled material, and if the supply fails to meet their material demand, they substitute it with raw material. This modelling choice resulted in unexpected fluctuations in the outcomes. Notably, in experiments where raw material was more expensive than recycled material, the bargaining packaging producers still opted for raw material because the model did not allow them to seek an alternative waste treater as additional supplier. This modelling choice can be questioned, as the packaging producer may prefer to buy more recycled material instead of raw material if the former is still cheaper. The model can be improved by enabling the packaging producer to re-evaluate the prices of recycled and raw materials if their material demand has not been met with their previous purchase. Nevertheless, this finding emphasises the importance of considering the quantities of available recycled material to increase packaging's recycled content instead of solely looking for the cheapest recycled material.

Conversely, centralised waste treatment could be a feasible intervention to mitigate the fluctuations in recycled content and raw material demand. In this setting, all recycled material would be consolidated and made available through a single actor, ensuring a more stable supply at a consistent price. It is important to note that the success of this setup is dependent on the decision-style of the waste treater. Considering the current Dutch waste management and the upcoming regulatory changes, the central orchestration of waste treatment in the Netherlands holds the potential to facilitate circular ecosystems. This centralised approach will be effective if the waste management promotes closed-loop recycling and higher-level circular strategies, including packaging reduction and reuse.

7.2.6 Potential of innovation for closed-loop recycling

Finally, the experimentation related to innovation demonstrated that relying solely on innovation for closed-loop recycling may not yield immediate and effective waste reduction outcomes in the Dutch food packaging ecosystem. The observed variations in outcomes suggest that other variables play important roles in shaping the performance of circular ecosystems, including actor behaviour and the price dynamics of raw and recycled materials. This finding is particularly interesting as it challenges the prevailing reliance on end-of-the-pipe recycling technologies and innovation within a part of the packaging industry, despite the limited efficiency of current technologies, especially for plastic recycling (Hanemaaijer et al., 2023). The findings emphasise the importance of complementing innovative technologies with ongoing efforts to change actor behaviour and incentivise the use of recycled material in packaging production. These multi-faceted approaches will be needed for the substantial reduction of packaging waste.

7.3 Reflection and limitations

Some caveats regarding the results have already been recognised in Section 7.2. In addition, this section reflects on the research, scrutinising the methodology and the validation and utilisation of the ABM.

7.3.1 Reflection on method

The methodology used in this study followed the ten steps of ABM proposed by Van Dam et al. (2013). The motivation to use this methodology was presented in Chapter 2, with three main reasons validating the use of an ABM to answer the research question. First, an ABM can be used to study complex adaptive systems, and the Dutch food packaging system is considered a complex adaptive system, which was supported by the system analysis in Chapter 3. Secondly, ABM is a suitable method to analyse the outcomes of potential circular ecosystems ex-ante, which could provide a response to the recent call in literature for quantitative studies based on empirical data (Trevisan et al., 2022), without the need to perform extensive in-situ experiments. Finally, ABM is a method that simulates actor behaviour, which is deemed an essential factor in the success of circular ecosystems (Barquete et al., 2022).

The ABMs inventory was created by combining an SLR and a case study. Relevant components were identified in academic and grey literature, which were then described and combined into system diagrams and data tables, as presented in Chapter 3. Furthermore, the results were refined and verified through interviews with the Packaging Producer of the Food and Beverage Company X and the Business Analyst from the Dutch waste management structure. The combination of literature and interviews resulted in a comprehensive understanding of the Dutch food packaging system. The critical remarks related to these results have been described in Section 3.5 and were considered during the conceptualisation of the model. Moreover, the conceptualisation and implementation steps resulted in a working ABM that includes multiple variables that can be used for experimentation. The successful model implementation confirms that the dynamics of a circular food packaging ecosystem can be conceptualised in an ABM.

7.3.2 Model validation

Multiple measures were taken throughout the research to ensure the model's validity. The case study of Food and Beverage Company X served as the foundation of the ABM, enabling the development of a more realistic model rather than a purely theoretical one. The interview with the Packaging Producer and the input from the Brand Manager provided insight into the packaging selection process of the food producer, including a wide variety of factors influencing the decision-making. Additionally, the inventory of components in the Dutch food packaging system was verified with the Business Analyst of the Dutch waste structure, resulting in nuances to the system analysis and additional information on the waste treaters' and packaging producers' processes.

The comprehensive overview of the ecosystem had to be narrowed down to be able to draw meaningful conclusions from experiments in the ABM. Inevitably, decisions had to be made on which components to include in the model conceptualisation without oversimplifying the system. The decisions on simplifications in the model were made and verified in discussion with experienced ABM experts and Deloitte's ecosystem experts. The assumptions and simplifications used in the model have been expressed in Section 4.1. Nevertheless, the simplifications within the model result in a limited representation of reality. The limitations should be considered when using the model for further experimentation and indicate areas of improvement within the model.

7.3.3 Considerations for model use

One limitation of the model is the deterministic behaviour of agents, who are depicted as choosing either the cheaper or more circular packaging option. In reality, the packaging selection process is influenced various other factors, such as the occasion, marketing, and CO_2 footprint, making the process more nuanced (Interview Packaging Developer). The ABM does allow for more nuanced actor behaviour by using a probability variable that indicates the probability of an actor behaving true to its decision-style. This variable has not been used in this study's experiments but could be used to analyse the effect of variable actor behaviour.

A second limitation is the simplification of financial components. The model uses hypothetical values for raw material and recycled material prices and assumes a hypothetic adjustment of prices by the waste treaters. The model could be improved by using actual price data and further developing the economic dynamics within the

Dutch food packaging ecosystems. These refinements would contribute to a more realistic representation of the dynamics within circular ecosystems.

Additionally, it is important to consider the limited representation of the material selection process employed by the packaging producer, which can lead to unexpected behaviour. If the packaging producer has a bargaining decision-style in the current model, he seeks the waste treater offering the cheapest recycled material, regardless of the available volume. Consequently, if the recycled material is cheaper but insufficient to meet the total material demand, the packaging producer opts for substitution with raw material. However, the packaging producer may have a more refined approach in reality. For example, they might only seek the cheapest recycled material at waste treaters that provide the necessary volumes. Alternatively, they might consider a second waste treater and compare their recycled material price to the raw material. Overall, the material selection process can be further refined to improve the model's accuracy.

Furthermore, the model focuses on three types of ecosystem actors capable of forming a closed-loop recycling circular ecosystem. However, this represents only one of the various circular ecosystems that could be applied to the food packaging ecosystem. Other types of circular ecosystems include reusing packaging or using alternative materials. The reuse of glass bottles by the food producer has been integrated into the model in a very simplified fashion, which divides the required packaging by the use times of the packaging but disregards additional material flows related to return logistics. The addition of 'outlet' agents could be used to refine the model and integrate the possible effects of reuse circular ecosystems.

A final limitation is the limited adaptivity of the agents in the current ABM. While the agents adapt to the parameters and variables of the model, their mutual interactions are limited to observing each other's information and making decisions. The model has not fully integrated the influence agents can have on each other's decisions, raising questions about the actual implementation of collaboration within the circular ecosystem. Incorporating a more collaborative decision-making process would be a valuable addition to the ABM, enabling a more thorough analysis of decision-making in circular ecosystems.

While the ABM has limitations in its current form, the model includes several variables that can be used for additional experimentation and further refinement of the model. The model poses a foundation for agent-based modelling of circular ecosystems, presenting a novel way of analysing actor behaviour and its effect on the potential of circular ecosystems to reduce packaging waste.

7.4 Recommendations

As the final part of the discussion, this section reflects on the social and scientific relevance of this study's findings by considering the practical implications of the results and suggesting future research.

7.4.1 Practical implications

Collaboration among organisations is required in the transition towards a CE to overcome the negative environmental impacts of packaging waste (Konietzko et al., 2020). Participation in circular ecosystems poses a strategy for organisations to become more circular by taking a systemic approach (Trevisan et al., 2022). However, the value and functioning of circular ecosystems should be clear for organisations to make effective decisions and be aware of potential drawbacks. The findings of this study can be translated into practical implications that can help organisations understand the potential of circular ecosystems.

The study resulted in the development of an ABM using organisational decision-making theory by Scharpf (1988a), which provides an explanation of how individual decisions can yield suboptimal outcomes in joint decision-making. The ABM is based on a case study from the Dutch food packaging ecosystem, which strengthens the study's practical representativity and relevance.

The findings of this study can serve as initial guidelines for the required behaviour of an organisation and its ecosystem to enable the establishment of circular ecosystems. The sensitivity analysis results show that choosing circularity over packaging costs can result in fruitful circular ecosystems. However, the price of recycled material might drive up if the waste treaters aim to maximize their profit while raw material prices remain constant. If the food producer, or another focal actor, adopts a problem-solving decision-style, only a small part of its ecosystem has to adopt a similar 'circularity decision-style' for circular ecosystems to work. An important requirement for this is transparent data-sharing between organisations, preferably via a shared platform, to enhance the easiness of finding suitable ecosystem partners.

Literature has pointed to waste managers as the orchestrators of such a platform (Salmenperä et al., 2021), which makes sense considering they currently form the central collection point for waste-related data. Additionally, the experiment with centralised waste treatment emphasises that central orchestration can stabilise the recycled material supply and resolve fluctuating recycled content in packaging. Central waste treatment in the Netherlands has the potential to support circular ecosystems, especially considering the anticipated regulatory changes. The central waste management should encourage closed-loop recycling and the adoption of higher-level circular strategies, including packaging reduction and reuse.

However, as emphasised by the Business Analyst of the Dutch waste management structure, the orchestration of the food packaging ecosystem requires mutual trust, resources, and regulation to enable execution. Moreover, the Dutch waste management structure must continue to monitor transparently in addition to the role of chain orchestrator. Deloitte's TV&A team could potentially help develop an ecosystem architecture that can facilitate these roles.

Additionally, Deloitte could help orchestrate circular ecosystems as an independent broker, connecting the right innovators, accelerators, and keystone actors within the ecosystem. Currently, a possibly relevant platform is set up by Deloitte to connect different actors in food technology, of which innovative packaging is an element (Deloitte, 2023a). Such a digital platform can help connect focal actors to organisations with similar decision-making behaviour, enabling the establishment or expansion of circular ecosystems.

Furthermore, innovation to improve closed-loop recycling can only facilitate packaging waste reduction through circular ecosystems alongside problem-solving actor behaviour. Collaboration with researchers or niche players can accelerate innovation to improve the recycling rate or the use of recycled material. However, innovation only results in successful circular ecosystems if actors actively aim to improve their circularity. Besides, the sector should not solely rely on end-of-the-pipe technologies and innovation but also consider other circularity strategies like packaging reduction or reuse.

Overall, the ABM provides Deloitte's TV&A department with a tool to analyse circular ecosystems under various conditions while considering organisational decision-making behaviour. The current model could be used for further experimentation, as explained in Section 7.3.3, to get additional insights. Especially with further refinement, this tool can support the TV&A department in advising clients on improving their circularity via ecosystems.

7.4.2 Future research

Research on circular ecosystems has been emerging since 2016, but no studies had focussed on the effect of circular ecosystems on packaging waste flows considering the complexity of actor behaviour (Trevisan et al., 2022). A complex adaptive systems approach was used in this study to develop an ABM of a Dutch food packaging ecosystem based on an extensive literature review and case study integrated with the decision-making behaviour theory by Scharpf (1988a). Combining methodologies gives the study scientific bearing while preserving its social relevance. Additionally, the study opens new doors for future research.

One opportunity for future research would be expanding the model to include a more comprehensive representation of actor behaviour and decision-making processes within circular ecosystems. As highlighted in Section 7.3.3, the current model assumes deterministic behaviour and does not fully capture the collaborative decision-making among ecosystem actors. By integrating a more realistic and collaborative decision-making process, future studies can delve deeper into the dynamics of circular ecosystems and assess the effect of different decision-making mechanisms on waste reduction outcomes.

Additionally, the model could be refined by incorporating alternative types of circular ecosystems beyond closed-loop recycling. Exploring and integrating circular strategies such as packaging reuse, alternative materials, and other innovative ecosystems would contribute to a broader understanding of potential solutions for reducing packaging waste. This expansion might require the addition of agents, such as outlets and consumers.

Furthermore, future studies could improve the model's representativity and validity by obtaining additional and more accurate data. This data includes actual pricing data for raw materials and recycled materials and additional empirical data on the behaviour and preferences of other ecosystem actors. This data could be retrieved from interviews with waste treaters and packaging developers or other ecosystem actors if they were to be added. Additionally, spatial and geographical information could be integrated into the model, as well as data on the connection of the Dutch food packaging ecosystem with other ecosystems. By incorporating more realistic data, the model can better simulate the processes within circular ecosystems, leading to more reliable results.

Future research could additionally analyse the potential of circular ecosystems beyond waste reduction and include other sustainability dimensions to provide a comprehensive understanding of circular ecosystems' impact. Additional metrics could be included, such as energy consumption, greenhouse gas emissions, and resource efficiency. A study by Lan and Yao integrated life-cycle assessment and techno-economic analysis into an ABM to study the environmental impacts of large-scale agricultural systems while considering actor behaviour (Lan & Yao, 2019). Similarly, future studies could integrate different methodologies in the ABM, allowing for a multi-dimensional analysis of circular ecosystems' overall sustainability and environmental impact.

Overall, further empirical validation and case studies are necessary to confirm the findings and insights gained from the model. Additional real-world observations within different contexts and geographic regions would enhance the validity of the model's results. Such case studies can also provide valuable insights into the practical implementation of circular ecosystems and identify potential challenges and barriers to their adoption, similar to the recent study by Barquete et al. (2022).

8 Conclusion

While organisations explore the opportunities to improve their circularity and collaborate in circular ecosystems, the dynamics of packaging waste in these ecosystems, especially considering actor behaviour, remained largely unstudied in previous literature. This thesis combined an extensive system analysis of the Dutch food packaging ecosystem, including a case study, with the organisational decision-making theory by Scharpf (1988) to conceptualise the circular ecosystems' dynamics of packaging waste in an ABM. This model was used to examine different variables affecting the Dutch food packaging ecosystem and explore the potential of circular ecosystems to reduce packaging waste. The findings and insights from each chapter contributed to a deeper understanding of the dynamics of packaging waste in the Dutch food packaging ecosystem. Four sub-questions were used to answer the main research question. By addressing these sub-questions in each chapter, this study shed light on various aspects of circular ecosystems and their potential implications for more sustainable packaging practices. This chapter answers the sub-questions in Section 8.1 and the main research question in Section 8.2.

8.1 Answering the sub-questions

What is a circular ecosystem and how can it be applied to the Dutch food packaging ecosystem?

Chapter 2 delved into the concept of a circular ecosystem and examined how it can be applied to the Dutch food packaging ecosystem. Through a thorough literature review, the fundamental principles of circularity were explored, defining the concept of circular ecosystems and their application to the Dutch food packaging ecosystem.

This study used the definition of circular ecosystems by Trevisan et al. (2022), describing it as "a system of interdependent and heterogeneous actors that go beyond industrial boundaries and direct the collective efforts towards a circular value proposition, providing opportunities for economic and environmental sustainability." The Dutch food packaging ecosystem can establish circular ecosystems in numerous ways using different circular strategies for formulating a circular value proposition. The suitability of a circular value proposition depends on the product and packaging requirements. A complex adaptive socio-technical system approach was used to study circular ecosystems in the Dutch food packaging ecosystem. This approach is included the analysis of social and technical components that form a system that constantly adapts and reorganises in response to changes in its environment.

Overall, this sub-question was used to describe the theoretical framework that was used for formulating the methodology and directing the research.

What does the current food packaging ecosystem in the Netherlands look like?

Next, Chapter 3 presented a comprehensive overview of the current Dutch food packaging ecosystem. This system analysis was based on academic and grey literature and further refined and verified through interviews with actors from the Dutch food packaging ecosystem. Additionally, data was collected on existing packaging materials, recycling rates and waste management practices.

The system analysis shows that the current food packaging ecosystem in the Netherlands comprises social and technical components. The system includes various actors, such as food producers, packaging producers and waste treaters, who have different functions within the Dutch food packaging ecosystem. The actors have interactions with each other related to material, financial or information dependencies. Furthermore, the Dutch food packaging ecosystem relies on organisational decision-making behaviour, characterised by different decision-styles and -rules, as well as consumer behaviour. The technical components in the Dutch food packaging ecosystem comprise six main packaging materials that are produced, used, collected, and treated in different processes. Additionally, improving circularity in the Dutch food packaging ecosystem involves using digital technologies. Moreover, the Dutch food packaging ecosystem is part of a larger environment, setting the context and legislation.

The findings related to this sub-question were described and visualised in multiple system diagrams to provide insights into the social and technical components of the Dutch food packaging ecosystem and its environment. Overall, this sub-question resulted in an inventory used for the subsequent conceptualisation and implementation of the ABM.

Can the dynamics of a food packaging ecosystem be conceptualised in an ABM and if so, how?

Chapter 4 focussed on conceptualising and implementing an ABM of the case study's food packaging ecosystem, answering the third sub-question. This chapter used Steps 3 to 6 of the ABM methodology described by Van Dam et al. (2013) and the information from the system analysis in Chapter 3.

The dynamics of a food packaging ecosystem can be conceptualised in an ABM, evident from the successfully implemented model in NetLogo. The conceptualisation included three agents who make decisions that affect the circularity of the food packaging ecosystem and can collectively form closed-loop recycling circular ecosystems. The processes of these agents were formulated, and the environment was structured, representing other actors in the Dutch food packaging ecosystem. Subsequently, the model narrative described the order of the processes, connecting them to each other and the environmental variables. This narrative was used for the implementation in NetLogo. Next, the model was verified with a code walk-through, recording and tracking of agent behaviour, and extreme-value testing. The conceptualisation and implementation resulted in a running model that could be used for experimentation.

The ABM captured various dynamics of a food packaging ecosystem. However, it covers only a part of all dynamics in the Dutch food packaging ecosystem. Nevertheless, the model's assumptions, modelling choices and limitations have been documented as transparently as possible to enable further refinement of the model. Overall, this sub-question resulted in a working ABM that was used for simulating circular ecosystems under various conditions.

Based on simulations, what is the potential of circular ecosystems to reduce packaging waste in the Dutch food packaging ecosystem?

Chapter 6 presented the results of simulations conducted to evaluate the potential of circular ecosystems to reduce packaging waste, considering multiple variables that might affect the ecosystems' dynamics. As explained in Chapter 5, multiple experiments were defined to assess these dynamics. First, the sensitivity analysis focussed on the effect of different behaviour variables within the ecosystem, considering the decision-styles of the food producer and the other actors in the ecosystem, as well as the decision-rule governing the ecosystem. Subsequently, a specific setup of behaviour variables was used to formulate additional experiments that assessed the effects of other variables related to Dutch waste, price and innovation.

The results showed that circular ecosystems hold the potential to significantly reduce packaging waste in the Dutch food packaging ecosystem. The findings elucidated that not all actors in the ecosystem have to prioritise circularity over profit for circular ecosystems to thrive. Starting with only a few actors could already significantly reduce packaging waste in the Dutch food packaging ecosystem. Additionally, the decision-style of the food producer is crucial in ecosystems dominated by actors that go for individual profit. If the food producer, or another focal actor, prioritises circularity over profit, establishing an effective circular ecosystem only requires a small number of actors who aim for improved circularity.

An important condition for successful circular ecosystems is the transparent sharing of recycling-related data, such as the recycled material volumes by waste treaters and the recycled content in packaging by the packaging producers. This data-sharing could be enabled by the Dutch waste management structure or by Deloitte as an independent broker. By providing an ecosystem platform for transparent and secure data sharing, compatible organisations could be connected and form a circular ecosystem through a collective circular value proposition.

Furthermore, circular ecosystems might be limited by recycled material shortages, depending on the packaging type, which can cause fluctuating recycled content in packaging. A centrally orchestrated waste treatment could assure the stabilisation of the recycled material supply and, therefore, the recycled content in packaging.

The use of recycled material could be incentivised through subsidies or taxes on raw material. However, the effectiveness of such measures will depend on the material selection process of the packaging producers.

Finally, technological innovation can facilitate the increase of the maximum potential recycled content in packaging and the recycling rate, but additional changes to actor behaviour or material price are needed to utilise this innovation. However, other high-level circularity strategies should also be employed to overcome limitations related to material shortage.

Overall, the answer to this sub-question elucidated the potential of circular ecosystems to reduce packaging waste in the Dutch food packaging ecosystem.

8.2 Answering the main question

What are the dynamics of packaging waste in a circular food packaging ecosystem in the Netherlands, considering actor behaviour?

The research conducted in this study sheds light on the dynamics of packaging waste in a circular food packaging ecosystem in the Netherlands. A comprehensive analysis was conducted by taking a complex adaptive systems approach and using an ABM to simulate the dynamics in a circular food packaging ecosystem while accounting for the uncertainties of actor behaviour.

The system analysis of the Dutch food packaging ecosystem reveals that circular ecosystems hold the potential to effectively reduce packaging waste in multiple ways. This potential of circular ecosystems in the Dutch food packaging ecosystem is exemplified by the case study showcasing a food and beverage company's successful participation in a circular ecosystem for their 100% recycled PET bottles. The interviews conducted for the case study emphasise the importance of collaboration among actors within the food packaging ecosystem, enabling the use of recycled material, knowledge-sharing and innovation. Based on the information from the system analysis, an ABM was conceptualised and implemented for a Dutch food packaging ecosystem that could form closed-loop recycling circular ecosystems. The model includes variables related to actor behaviour, Dutch waste, material prices and potential innovation in the ecosystem.

The simulations conducted in this study demonstrate that these different variables affect the dynamics of packaging waste. The experiments demonstrate that the success of circular ecosystems in reducing packaging waste depends on the actor's decision-making behaviour and that variables related to Dutch waste, price and innovation could also affect the outcomes.

The experiments with behaviour variables show that different combinations of decision-styles and -rules yield varying levels of recycled content in packaging and, subsequently, various levels of waste reduction. Overall, circular ecosystems can be established when actors prioritise circularity over waste while making decisions. Notably, not all actors in the ecosystem have to prioritise circularity for circular ecosystems to thrive. Starting with only a few actors in the ecosystem could significantly reduce packaging waste.

However, enabling circular ecosystems would require establishing a data-sharing infrastructure, which is currently not widespread. The model is built on the implicit assumption of available data on recycled material volumes and recycled content, facilitating actors to find other each other. A safe and transparent data-sharing platform should be facilitated, for example, by the Dutch waste management structure or an independent broker. Such a platform can connect the right innovators, accelerators, and keystone actors within the ecosystem to enable effective waste reduction through circular ecosystems.

Further packaging waste reduction could be facilitated by technological innovation to improve closed-loop recycling. However, successfully utilising innovative technologies will depend on the actors' behaviour in the food packaging ecosystem. Besides, actors should not solely rely on end-of-the-pipe technologies and innovation. Other, higher-level circular strategies should also be employed to overcome limitations related to material shortages. The actors in the ecosystem should be encouraged and supported to actively pursue these circular strategies.

Furthermore, centrally organised waste treatment can stabilise the dynamics of packaging waste in the Netherlands and help overcome fluctuations in recycled content. The Dutch waste management structure can orchestrate this central waste treatment besides transparently monitoring packaging waste and recycling. A clear ecosystem architecture can facilitate these two roles, which can be developed with the help of an independent third party.

Changes to the material prices could result in increased use of recycled material in predominantly bargaining food packaging ecosystems. However, the influence of price on the dynamics of packaging waste is reliant on the material selection process of the packaging producer. This finding emphasises that the Dutch government can incentivise using recycled material but that successful implementation of such incentives will still rely on the actors' decisions. It is thus important to involve and support these actors to ensure effective interventions.

Overall, the ABM provides an analytical tool that can be used by organisations to explore the potential of circular ecosystems and consultants that advise their clients on improving circularity via ecosystems. The current ABM has limitations, such as the deterministic behaviour of actors and simplified financial components, necessitating the development of more sophisticated and realistic representations of the Dutch food packaging system. Refinements in the ABM can enhance its suitability as a tool for analysing individual food packaging ecosystems and exploring potential circular ecosystems for waste reduction. Additionally, the ABM could integrate circular ecosystems based on other circular strategies, such as reusing packaging or using alternative materials. This integration will enable additional exploration of circular ecosystems and provide a more comprehensive understanding of their potential for waste reduction.

In conclusion, this research underlines the dynamics of packaging waste in a circular Dutch food packaging ecosystem and emphasises the importance of considering actor behaviour when analysing the potential to reduce packaging waste. By leveraging agent-based modelling and emphasising collaboration among actors, circular packaging ecosystems can be promoted, leading to a more sustainable food packaging industry.

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Appendix A – Systematic Literature Review

The search terms of the systematic literature review are presented in Table A.1. The left column contains the search round and the topic of the search, the middle column presents the search terms used for that topic and the right column indicates the results of that round. For round 1, these results include the most relevant terms found in the search and for round 2, the results present the number of articles found with the search terms.

Table A.1. Overview of round, search terms and results of the SLR

Topic	**Search terms**	
Round 1		*Most relevant terms*
Ecosystems	“business ecosystem*”, “technology ecosystem*”, “digital ecosystem*”, “digital business ecosystem*”, “platform ecosystem*”, “data ecosystem*”, “IT ecosystem*”, “information ecosystem*”, “ecosystem* perspective”	“business ecosystem*” and “ecosystem* perspective”
Circularity	“circularity”, “circular economy”, “CE”, “circular strategies”, “CE strategies”, “circular business”, “circular business model*”, “circular supply chain”	“circular economy” and “circular business model*”
Complex systems	“complex system*”, “complex adaptive system*”, “CAS”, “socio-technical system*”, “complexity”, “adaptivity”, “emergence”, “complex adaptive system* modeling”, “agent-based model*”, “agent-based modelling”, “ABM”	“complex adaptive system*”, “socio-technical system” and “agent-based model”
Round 2		*Articles*
Ecosystems and circularity	(“business ecosystem*” AND “circular economy”) OR (“ecosystem* perspective” AND “circular economy”) OR (“business ecosystem*” AND “circular business model*”) OR (“ecosystem* perspective” AND “circular business model*”) OR “circular ecosystem*”	69
Ecosystems and complex systems	(“business ecosystem*” AND (“complex adaptive system*” OR “socio-technical system*”)) OR (“ecosystem* perspective” AND (“complex adaptive system*” OR “socio-technical system*”)) OR (“business ecosystem*” AND “agent-based”) OR (“ecosystem* perspective” AND “agent-based”)	+ 22
Circularity and complex systems	(“circular economy” AND (“complex adaptive system*” OR “socio-technical system*”)) OR (“circular business model*”AND (“complex adaptive system*” OR “socio-technical system*”)) OR (“circular economy” AND “agent-based”) OR (“circular business model*” AND “agent-based”)	+ 64
	Total	**155**
	Removing of irrelevant articles by title	- 30
	Removing of irrelevant articles by abstract	- 30
	Final total	**95**

Appendix B – Interview notes

The interview notes in this Appendix have been confirmed by the interviewees and have been improved with their feedback.

B.1 Interview Packaging Developer Food and Beverage Company X

May 10, 2023

The interviewee has worked at Food and Beverage Company X as a Packaging Developer for six years and currently holds the position of team lead for a Packaging Development team. Food and Beverage Company X is a multinational cooperative. As the company is a cooperative, it operates in the interests of its members and relies on the supply volumes of its members. The company has factories in the Netherlands and abroad, including factories in Belgium and Germany. In these factories, the product is processed and packed. Food and Beverage Company X fills packaging but does not produce these packaging itself.

What does the packaging design and/or selection process look like? Which factors are considered during the design and/or selection process and how important are these factors?

The design flexibility of packaging depends on the type of packaging. PET bottles, for example, offer many possibilities in terms of shape and material. However, beverage cartons are mainly from Tetra Pak, which supplies both the production line and the packaging material. Although it is possible to choose a different packaging supplier, the packaging must meet the dimensions and characteristics suitable for Tetra Pak's production line. In the case of most other packaging, such as aluminium cans and glass bottles, the machine manufacturer and the packaging supplier are separated.

Projects such as those of the recycled PET bottles (rPET) start by identifying **market trends.** Previously, plastic bottles were made of HDPE and these production lines needed to be replaced. Importantly, new packaging must meet the requirements to ensure the **quality and shelf life of the product**. The selection of a new packaging type occurs at a strategic level, taking into consideration sustainability (**CO_2 footprint** and **circularity**), costs (**total cost of ownership**) and usage (for different **occasions**). The packaging material itself, including the EPR, is only a small portion of the overall costs. Subsequently, a business case is developed for the new packaging format. During the design and selection process, Food and Beverage Company X looks beyond the Dutch borders, as their products are sold worldwide and the investment in a production line involves planning for the next 20 years.

Food and Beverage Company X has a diverse packaging portfolio, as to penetrated various markets. This is in line with the OBPPC model (occasion, brand, package, price, and channel). The selection of a specific packaging solution depends on the occasion in which the product will be consumed. Different occasions, such as consuming a product at home, in a restaurant, or on the go, necessitate different packaging requirements. For instance, larger packaging is typically preferred for home consumption, while packaging is not required in a restaurant setting. On the other hand, packaging for on-the-go scenarios should be easily disposable or closable.

Consequently, it is impractical to adopt a single type of packaging for the entire product range. A uniform packaging approach, such as bags, might be theoretically possible, but packaging primarily serves **marketing purposes** and is tailored to meet **consumer preferences**. However, it is worth noting that there is a gradual shift occurring in de market with regards to the consumer's demand.

Circularity of packaging

Recently, new rPET bottles were implemented as packaging for the product, which are made from 100% recycled PET. PET is the only type of plastic currently approved for recycling in food packaging. The use of rPET often requires newer machines due to the variation in PET quality and the increased likelihood of contamination and colour discrepancies associated with higher rPET content. In the future, recycled PE and PP can potentially offer more options, but the current availability of these materials is limited.

In the Netherlands, the rPET bottles are not recycled into new rPET bottles, because they are not part of the deposit system. The deposit-return system does not apply to juice and dairy bottles. The exact reasons for this are not entirely clear, but retailers potentially affected this decision, as they are responsible for establishing return-stations while they receive limited compensation for them. In Belgium, on the other hand, the bottles are recycled into new bottles via a national PMD system organised by Fost Plus, similar to Afvalfonds Verpakkingen in the Netherlands.

Regarding other types of packaging, the opportunities for circularity vary. For instance, glass bottles are refilled for restaurant use, while single-use glass bottles are no longer employed. The powdered form of the product is sold in pouches in carton boxen, but this is limited to B2B (business-to-business) transactions. Although there have been attempts to sell the powdered product directly to consumers (B2C), some issues and a decline in quality have led to a preference for the liquid variant of the product. While tapping the product from a larger packaging is technically possible, once the packaging is opened, the product is no longer sterile, which can pose hygiene concerns.

In the Netherlands, certain additional costs are less important than in other countries. To prolong the product's shelf life, the drink cartons in the Netherlands are equipped with caps. In countries where these small costs additions are more of a concern, omitting the cap is considered a good option.

Which actors are involved in the design and/or selection process and the packaging itself? Are actors missing in this list:

- Material producer
- Packaging producer
- Food and Beverage Company X
- Outlets (including supermarkets, restaurants and on the go)
- Consumer
- Municipality
- Waste processors
- Waste management structure (including StAV, Nedvang, KIDV, Statiegeld Nederland and NederlandSchoon)
- Dutch Government

First, the machine producers are missing in this list. Food and Beverage Company X owns production lines of machines that are used for packaging their products. These machines require a significant investment of 10-20 million euros and typically have a lifespan of 10 to 20 years. New machines are mainly purchased when the current ones need replacement. The manufacturers of the filling machines customise the machines according to the specific requirements and preferences of Food and Beverage Company X.

In addition, non-governmental organisations (NGOs) play an important role in the packaging ecosystem. They can exert pressure on producers to improve the sustainability of packaging, as they can affect the company's reputation through certain actions or advertisement.

Moreover, it is important to consider the broader international perspective. Food and Beverage Company X produces and sells products in various countries, each with its own unique systems and regulations distinct from those in the Netherlands. As a result, Food and Beverage Company X adheres to European directives related to packaging rather than national directives such as those issued by the KIDV. To keep up with the rapidly changing legislation, it would be useful to make machines modular. This allows for components to be added, adjusted and removed from the production lines without having to purchase entirely new ones. Food and Beverage Company X is collaborating with universities to innovate within the production lines.

Lastly, it is worth noting that within Food and Beverage Company X, there are multiple stakeholders with diverse interests and perspectives.

B.2 Verification by Brand Management Product and Logistics Account Manager of Food and Beverage Company X

May 22, 2023

To verify information from the literature review, the Brand Management of the studied product was contacted with some additional questions. The same questions were sent to a Logistics Account Manager of Food and Beverage Company X. The Brand Management and Logistics Account Manager collectively answered the questions via e-mail.

Who produces the packaging?
We produce the packaging ourselves.

(NOTE: This is contradictory to the interview with the packaging developer. Although the labels and exterior of the packaging are designed by Food and Beverage Company X, the material and packaging itself is not produced by Food and Beverage Company X. The company is involved in the design of some packaging (such as the rPET bottle) but furthermore only prepares, fills and seals the packaging.)

Who packs the product?
Food and Beverage Company X packs the products.

Are the glass bottles refilled and if so, by who?
We clean and refill the glass bottles of the product.

How are the clients categorised? I have now distinguished between stores, catering industry (restaurants, hotels etc.) and on the go. And is it correct that the latter to buy the product via wholesales?
Indeed, the clients that purchase this product can be categorised as stores, catering industry and others (sports canteens/on the go). The latter indeed buy the product via wholesales.

Is there global data available on the sales for these different categories?
This data is confidential and can't be shared.

Is there general data available on sales volumes or ratios?
Can you provide more information on what kind of data you would need?

In the model, I make calculations on recycled and recyclable packaging material by using the amount of packaging material and recycling percentages of waste treaters in the Netherlands. I can calculate this with different types of data, e.g., product volume (without packaging material) and proportions of different packaging (e.g. about 40% in drink cartons, 10% PET bottles) or sales volumes per packaging type per month/year. The data does not necessarily have to be recent but would help me make a more accurate calculation, reducing the model's reliance on assumptions. Moreover, the company, product, numbers and all information referring to the company and product are anonymised in the report (which is only published in TU Delft's database).

Received information on the percentages of the packaging formats.

B.3 Interview Dutch Waste Management Structure

May 25, 2023

The interviewee has more than 10 years of experience with the packaging waste file in the Netherlands. His work mainly concerns the monitoring of packaging recycling. Organisation X is responsible for the execution of the Extended Producer Responsibility (EPR) in the Netherlands. The EPR applies to packaging producers and importers and packaging producers and importers (PIs). In total, there are about 2400-2500 companies that market more than 50,000 kg of packaging material. These companies are legally obliged to pay a fee for the packaging they sell or use. The money raised is used to cover the costs of waste collection, sorting and recycling. Organisation X reports information on these processes to the Dutch government. In addition, the organisation plays a supporting role for companies in preparing for and adapting to changing legislation. The legislation regarding packaging material has been expanding and changing rapidly over the past three years, both at European level and in the Netherlands.

<u>In the system diagram, the different actors and relationships within the Dutch waste system are visualised. Are there no actors or relationships missing?</u>

The government consists of the national government and local governments. Several waste incineration plants are owned by local authorities and in some cases, they are part of a heat network, making local authorities dependent on the heat produced in these plants. This direct connection between the government and the waste incineration plants is not clearly shown in the system diagram.

In addition, it should be emphasised that the government plays an important role, by imposing legislation and targets that the packaging system must meet. However, the Dutch packaging system currently outperforms the recycling targets. The general binding declaration (AVV), which is imposed by the government, ensures that companies are obliged to comply with the EPR and thus pay the rates for the packaging material they place on the market.

<u>Are there insights into the amount of open-loop and closed-loop recycling of packaging? And if so, how is closed-loop recycling measured?</u>

There are two different recycling targets in the Netherlands: the recycling targets and the circularity targets. As regards recycling targets, the amount of recycled material from waste sorters was used as the previous measuring point. However, the new measuring point is the actual amount of material recycled by recyclers, as part of the recycled material can still be lost during further sorting or cleaning.

As for the circularity objectives, these focus on the reuse of packaging, also known as product recycling, in contrast to material recycling. This mainly applies to B2B packaging, such as crates and pallets, which are reused in a pool system for about 25 years. After this period, the material of this packaging can be recycled into new B2B packaging. The only example of B2C reuse are the glass deposit beer bottles that are refilled in the Netherlands.

Currently, there are no insights into how the recycled packaging material is used (open-loop or closed-loop recycling). PET is returned to the PIs, which makes recycling more transparent. This will also be the case for aluminium cans. In the case of glass and paper, the new packaging already consists of a certain part of recycled material. However, in the case of mixed plastics, recycling is often to lower quality product and the recycled material is not used to produce new packaging.

The upcoming Packaging and Packaging Waste Regulation (PPWR) will further regulate recycling and the use of recycled material. For example, it will set requirements for the recycled content that packaging must contain. However, food contact requirements and potential new problems will have to be taken into account, such as sales of recycled material which is actually virgin material. For some materials, the price of recycled material is higher than that of virgin material, which can lead to this kind of trading. It may therefore be necessary to check whether the recycled content in a package is actually recycled content.

<u>How is information exchanged in the system?</u>

PIs are required by law to share information about their packaging. The tariffs and tariff differentiation can encourage PIs to opt for packaging that is easier to recycle. The tariff differentiation will be further expanded to also promote the use of recycled materials in new packaging. In this respect, other European member states can serve as an example for the Netherlands.

Municipalities and sorters receive compensation for the collected and sorted waste and must also provide information to Organisation X. Since the new measuring point is located after the recyclers, they will also have to report information to Organisation X. Finally, there are the waste incineration plants, which receive a small fee, but this is only a fraction of the total fees.

It is especially difficult to arrange enough sorting capacity, which is why part of the Dutch waste is sorted abroad. PMD, for example, is sorted in Germany. The location of recycling can also differ, in which a distinction is made between recycling within the Netherlands, within the EU or outside the EU.

<u>How does a waste process get recognised by the Dutch waste management?</u>

There are different types of waste processors. Firstly, there is the collector and in the case of B2C packaging waste, this is the municipality. In addition, there are sorters, of which there is only a hand full in the Netherlands. Finally, there are recyclers, and they often fall under trade associations that could also grant recognition. In general, companies want to be recognised by Organisation Y (part of Organisation X). In order to obtain recognition, various organisational aspects are assessed, such as reliability and transparency.

<u>Do recyclers sell the recycled material themselves?</u>

The chain looks like this: the municipality collects the packaging waste and then brings it to contracted sorters via Organisation Y. The sorters then sell the sorted material to recyclers. Until now, the orchestration of the chain by Organisation X ended at the sorters, but this has recently changed. In the coming years, Organisation X will play an important role in steering recycling. However, this poses major challenges, as the Dutch packaging system concerns a complex multi-stakeholder system. Orchestration requires mutual trust, resources, and regulation to enable execution. Moreover, certain decisions might turn out not to be the best ones. That is why it is important that Organisation X continues to monitor transparently in addition to the role of chain orchestrator. Organisation X is currently considering how these two roles can be fulfilled side by side.

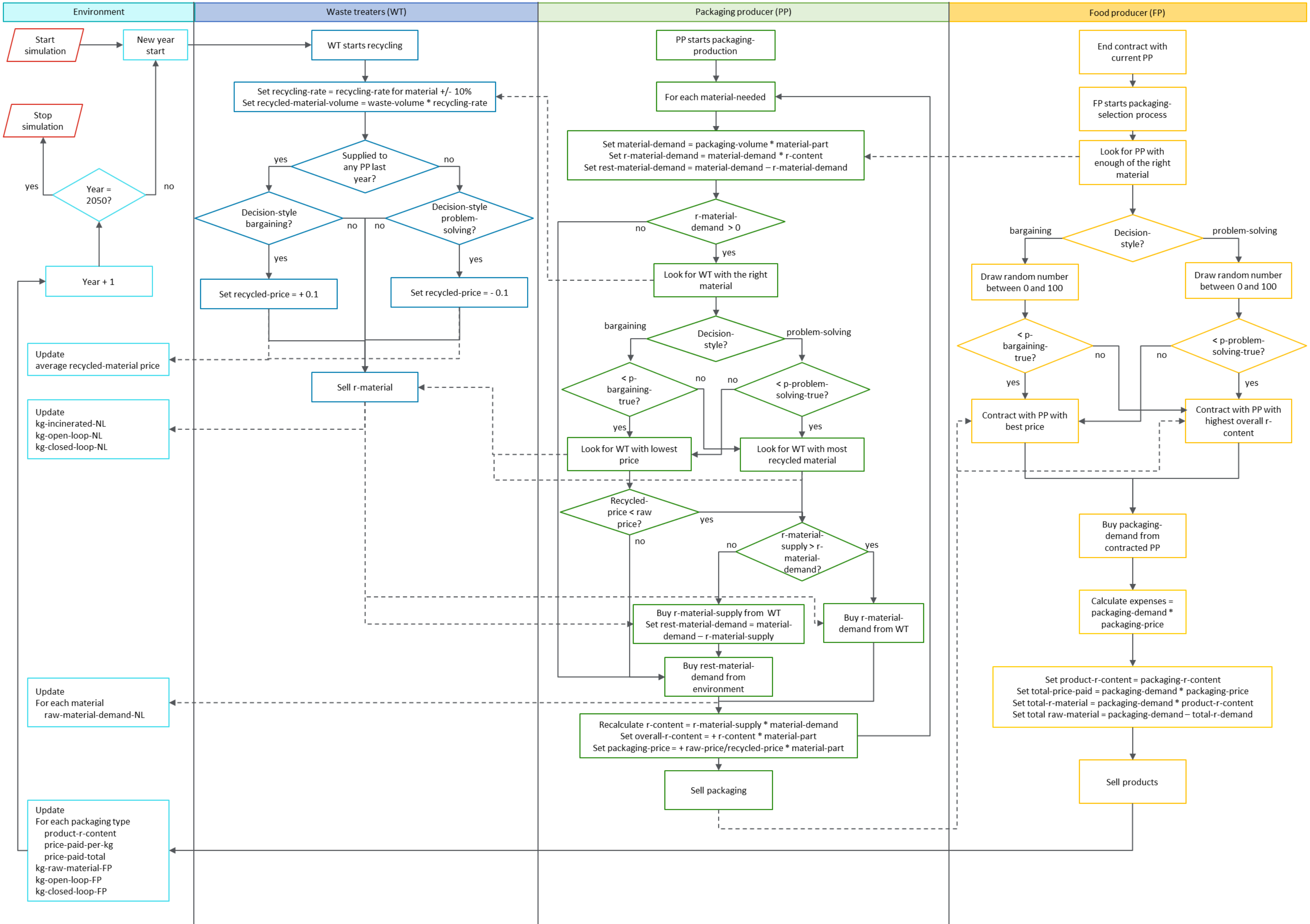
<u>Useful tips</u>

The Plastic Wijzer of Organisation X is a useful tool which describes the vision of Organisation X for the coming years. Furthermore, there are several interviews on the website of Organisation X and there is a magazine in which there is even more information.

Recyclass is a European party that has been working on the improvement of plastic recycling for years.

The PPWR, as mentioned above, concerns the upcoming European legislation on packaging and packaging waste.

Appendix C – Flowchart of interactions in the model concept



Appendix D – Parametrisation

The parameters used in the setup of the model are presented in Table D.1.

Sources

The food producer parameters are based on public information, the interview with the Packaging Developer of Food and Beverage Company X and data provided by the product's Brand Manager of Food and Beverage Company X. The part of the total weight and part of total product volume are known by the researcher but are not shared due to confidentiality reasons.

The packaging producer parameters are based on online data provided by packaging producers.

The waste treater parameters are based on public data on the Dutch waste volumes and recycling rates provided by Afvalfonds Verpakkingen (Afvalfonds Verpakkingen, 2021). The start price of recycled material and price adjustments have been simplified and are assumed to all be 0.1.

Finally, the number of packaging producers and waste treaters are hypothetical, as explained in Section 5.1.

Table D.1. Overview of parameters used in the model.

Food producer		**total-product-volume**				**1000000**	
Product	Part of total weight	Part of total product volume	Packaging volume	Packaging weight	Unit price	Price for litre	Use times
Carton			1	0.032	2.15	2.15	1
Can			0.25	0.0091	0.96	3.84	1
PET			0.3	0.023	1.33	4.43	1
Glass			0.2	0.155	0.72	3.60	30
BIB			18	0.073	38.75	2.15	1

Packaging producers				
Product	Number of	Required material	Material-parts	Max possible r-content
Carton	1	Paper; alu; plastic	0.69; 0.04; 0.027	0.87; 0.74; 0.18
Can	5	Alu	1	0.74
PET	5	PET	1	1
Glass	5	Glass	1	0.95
BIB	5	Plastic	1	0.18

Waste treaters							
Material	Number of	Total waste (total production)	Recycling-rate (+/- 10%)	Start-price	Increase in price if bargaining and selling	Decrease in price if problem-solving and not-selling	Raw price
Carton	3	82,800,000	0.31	0.1	0.1	0.1	-
Aluminium	3	42,750,000	0.74	0.1	0.1	0.1	0.1
PET	3	32,760,000	0.48	0.1	0.1	0.1	0.1
Glass	3	256,000,000	0.79	0.1	0.1	0.1	0.1
Plastic	3	513,240,000	0.48	0.1	0.1	0.1	0.1
Paper	3	139,000,000	0.87	0.1	0.1	0.1	0.1

Appendix E – Verification

E.1 Code walk-through

The implementation of the code was done in an iterative way, assuring that each addition or modification of a procedure resulted in the expected change in the model. After the implementation of all procedures, an extensive code walk-through was executed, in which the procedures were checked in consecutive order by comparing the outcomes of the procedures with expected outcomes. This is done by using the *show* function in the NetLogo command centre. An example of this walk through is shown in Figure E.1. In this example, first the total weight of raw material used by the food producer was checked as well as the part of the total (expected to be 100%). In the third command, the waste treaters are asked to show their recycling rate, which are in line with the expected rates.

Figure E.1. Example of command centre during the code walk-through.

Overall, the code walk-through resulted in some small adjustments to the code and some rewriting to clean up the code.

E.2 Recording and tracking of agent behaviour

During the implementation, the individual agents and their attributes were analysed many times. With every addition or adjustment of the code, agent behaviour was tracked by using the *inspect* function in NetLogo. The inputs, states and outputs of individual agents were recorded to assess if the agent's behaviour is as expected. As the agents are relatively simple, the 'outside' analysis is sufficient to test the accuracy of the behaviour (Van Dam et al., 2013). The recording and tracking of agent behaviour resulted in various changes to the procedures to improve the code.

One example of an error resolved during this step of the verification, was a change in the code of the waste treater. During the inspection, the paper waste treaters did not seem to increase the price of the recycled material, even though their decision-style was bargaining, and they did sell the material to a packaging producer in the previous year. The error was due to the fact that the *links* of the paper waste treaters to the packaging producers were removed before the waste treaters checked the links to make price adjustments. For the other waste treaters, this error did not show as they have *in-links* from the food producers. To resolve this error, the procedure was adjusted to make the waste treaters check their *out-links* instead of all *links* and only let the out-links die after the price adjustment instead of before.

E.3 Extreme-value testing

As a last step of verification, the behaviour of multiple agents was analysed under extreme values. By using extreme values, easy prediction of outcomes is possible which can be compared to actual outcomes. For example, if all actors in the ecosystem have a bargaining decision-style that is true a 100% of the time and the raw material price is lower than the recycled material price, it is expected that no recycled material will be used by the packaging producers and the recycled content is 0 in all food producer's products. Figure E.2 shows that indeed, these settings result in the expected outcomes.

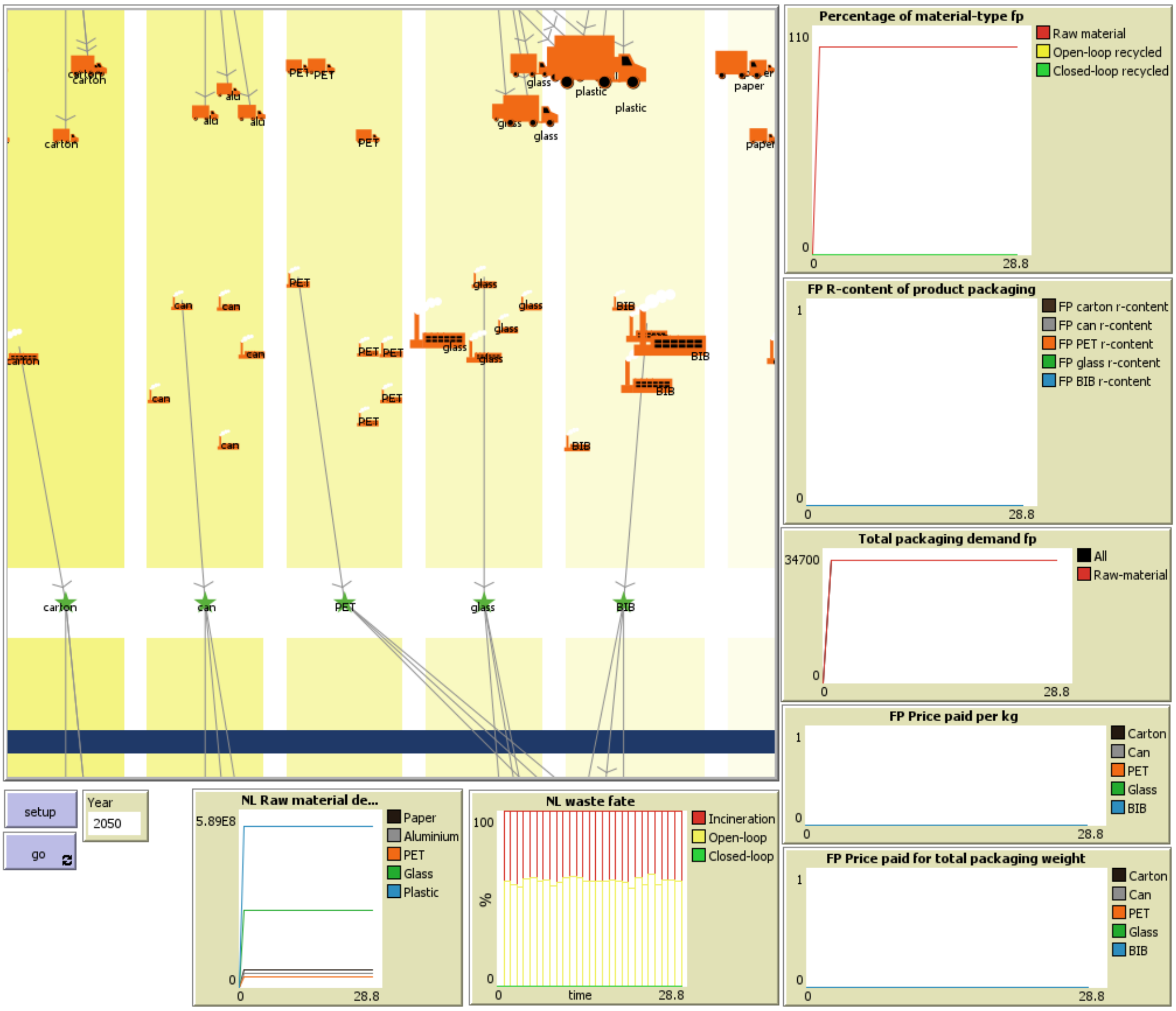


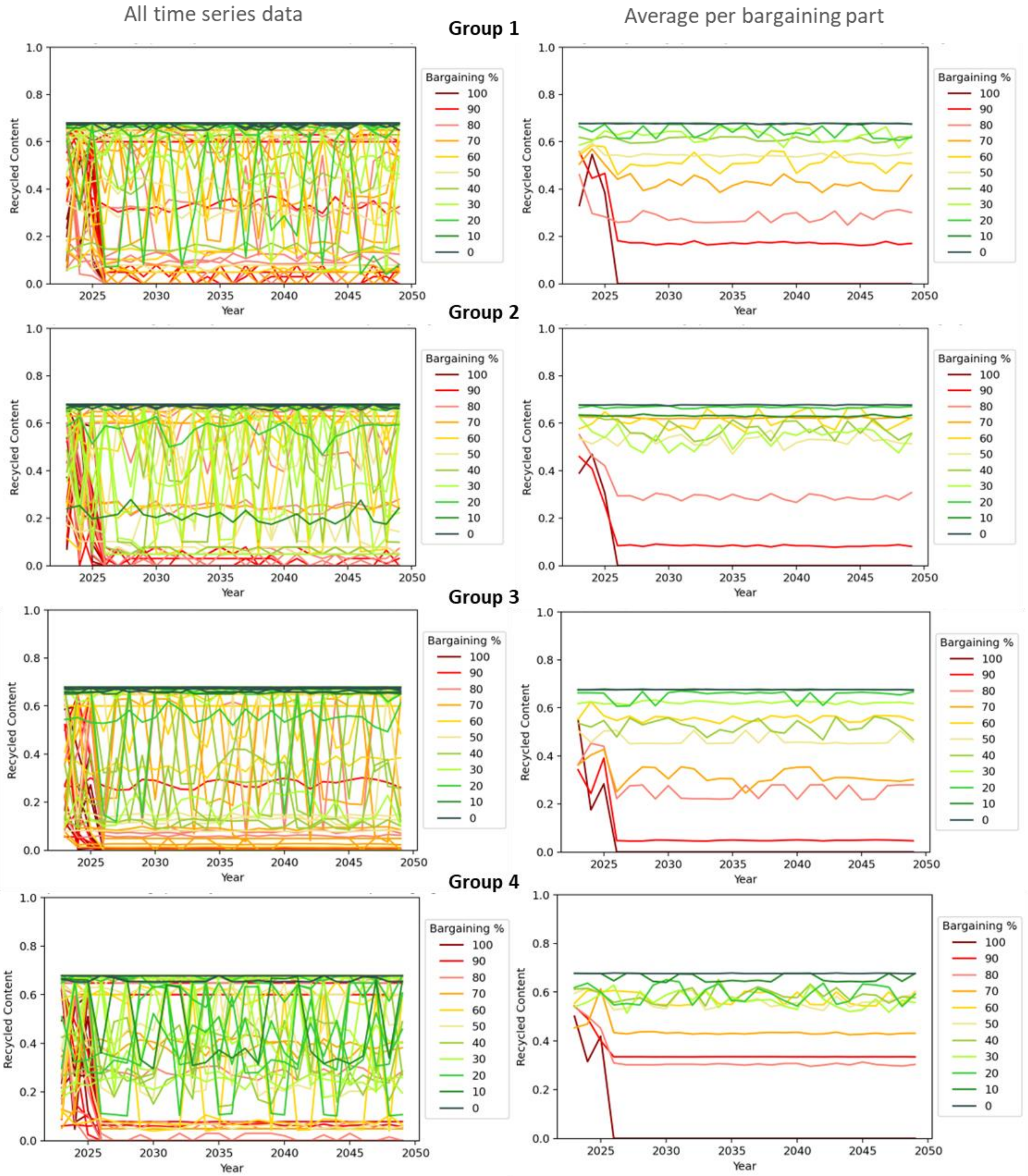
Figure E.2. Interface during verification in extreme value testing, showing that 100% bargaining actors in the ecosystem and raw material being cheaper than recycled material, no recycled material is used in the packaging.

Appendix F – Figures results

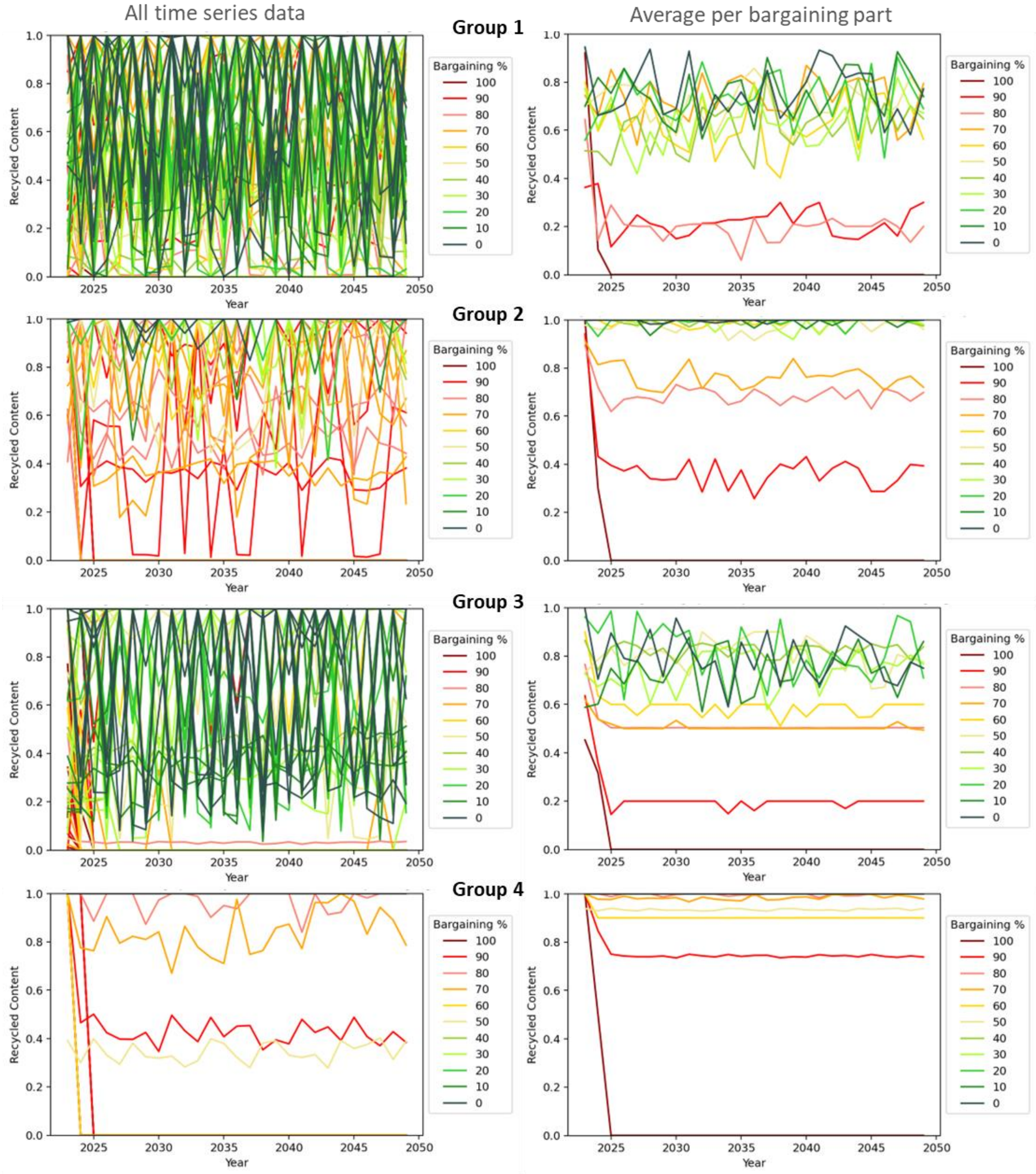
F.1 Sensitivity analysis – Recycled content time series

The collections of graphs below present the time series data of recycled content of the different packaging types for the four experiment groups. The graphs on the left contain all individual time series and the graphs on the right show the averages of the time series per bargaining part.

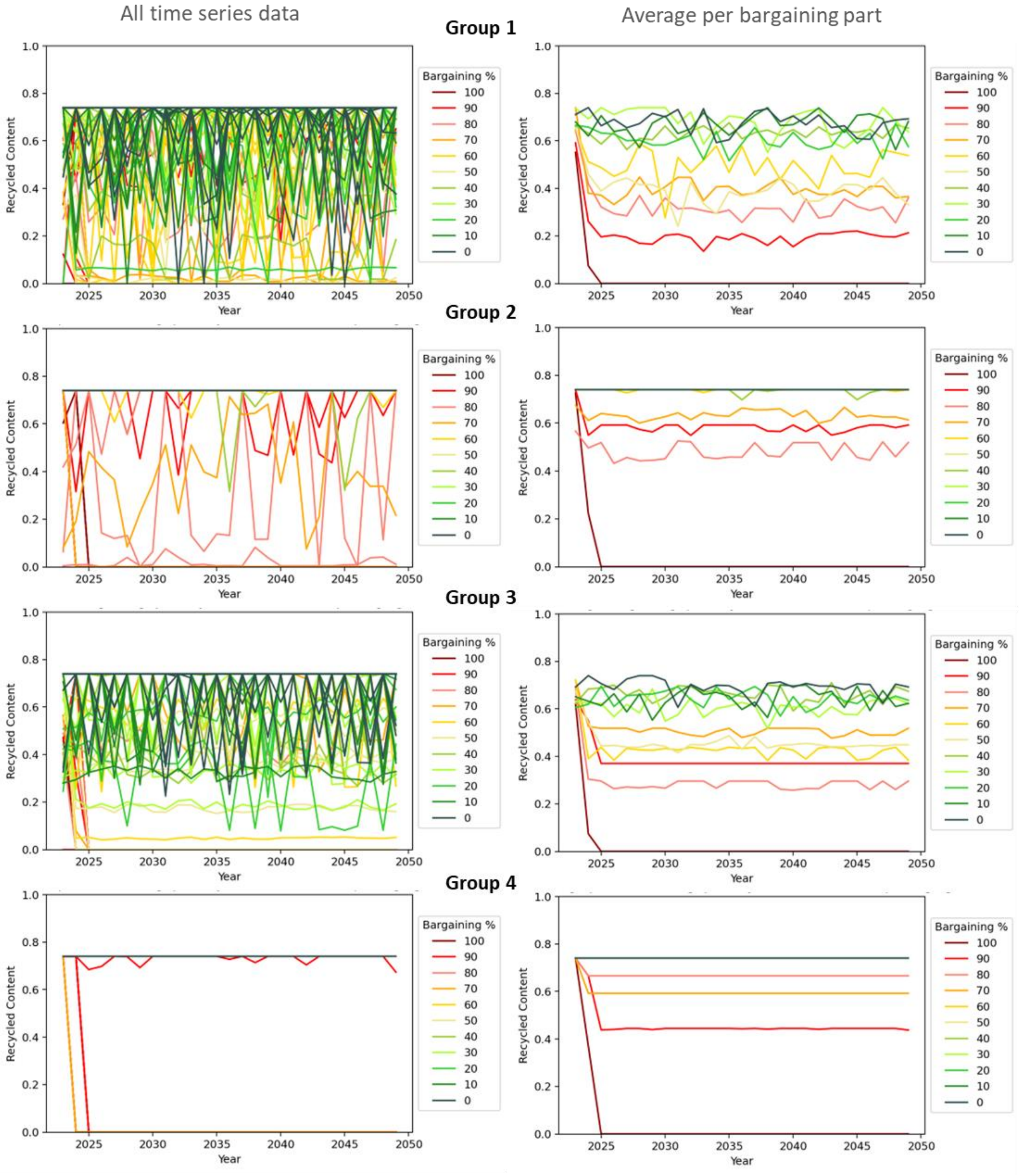
Recycled content in food producer’s drinking carton



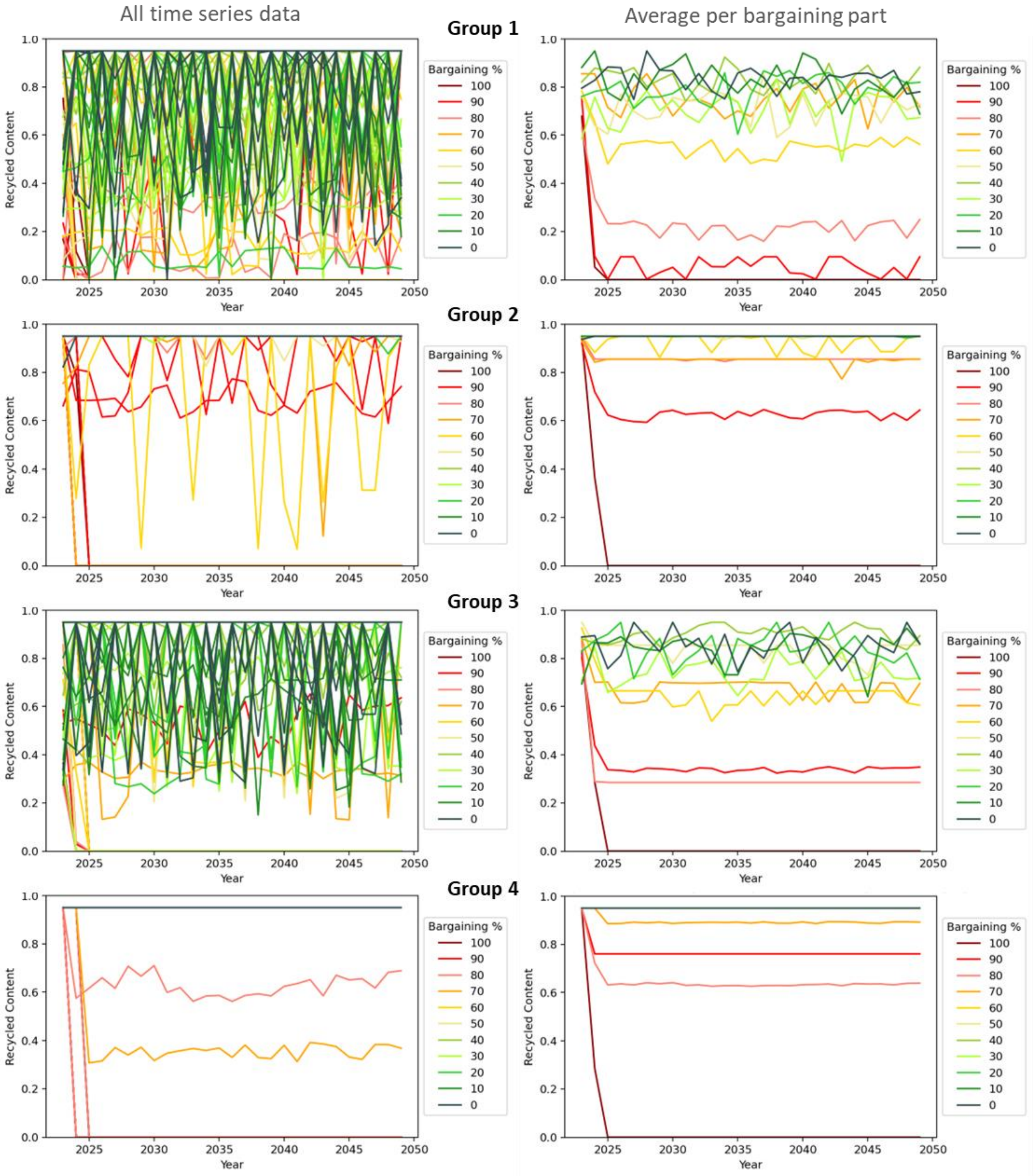
Recycled content in food producer's PET bottle



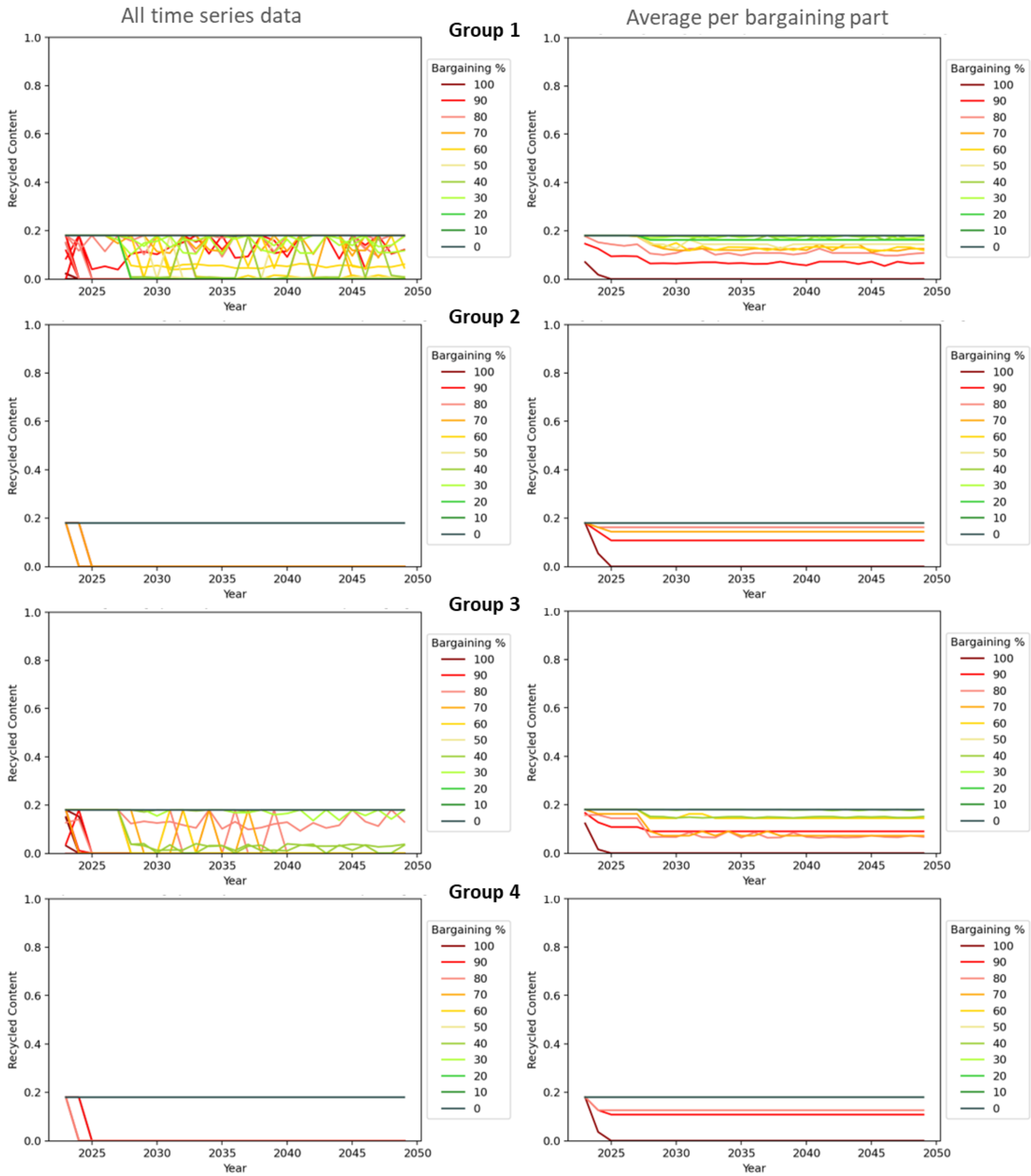
Recycled content in food producer’s aluminium can



Recycled content in food producer's glass bottle



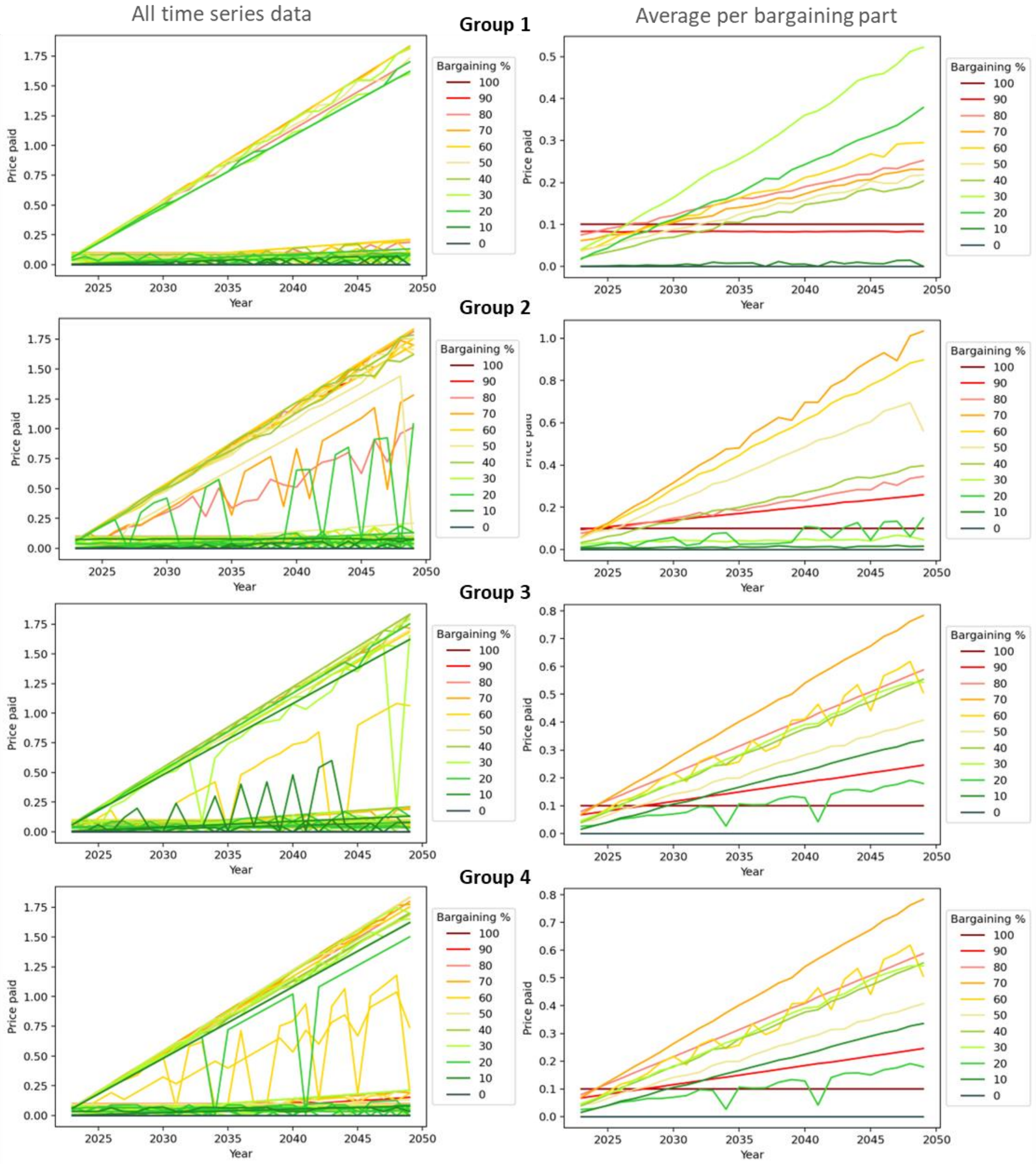
Recycled content in food producer's Bag in Box



F.2 Sensitivity analysis – Price paid time series

The collections of graphs below present the time series data of price paid per kilogram by the food producer of the different packaging types for the four experiment groups. The graphs on the left contain all individual time series and the graphs on the right show the averages of the time series per bargaining part.

Price paid per kg by food producer for drinking carton

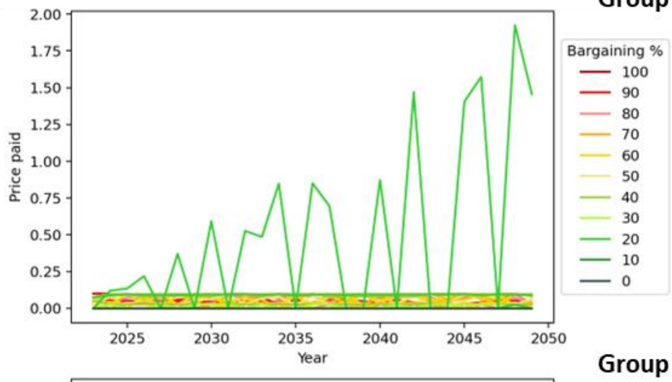


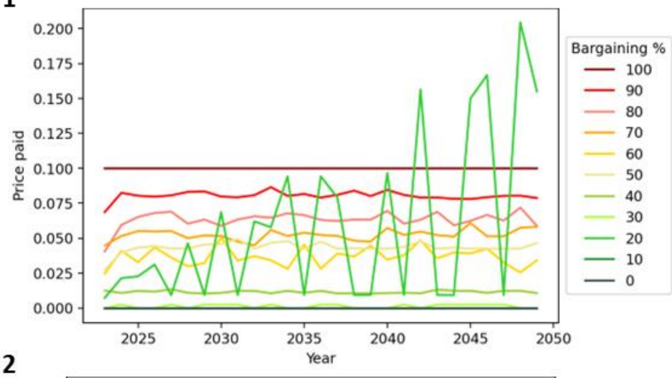
Price paid per kg by food producer for aluminium can

All time series data

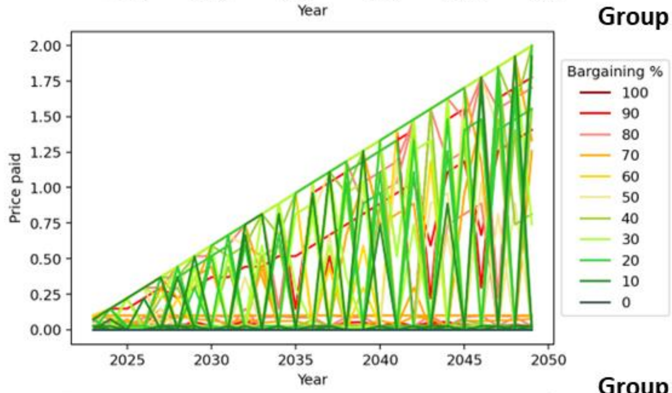
Average per bargaining part

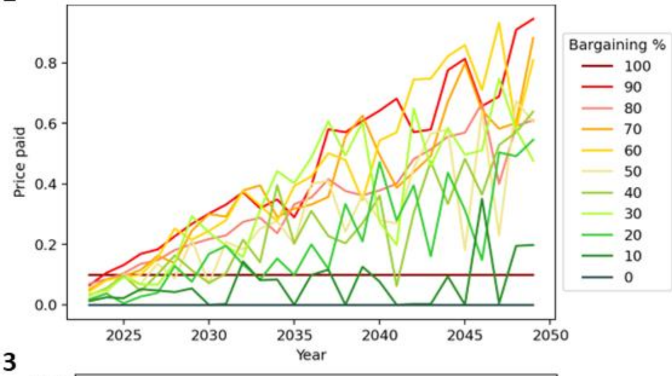
Group 1



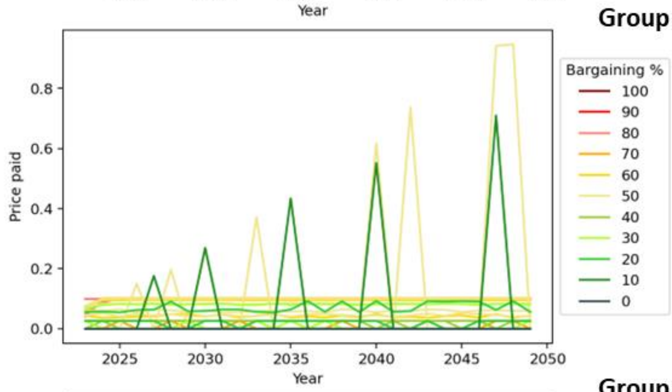


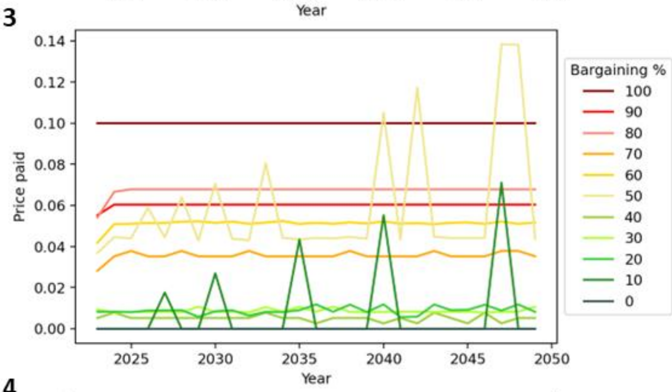
Group 2



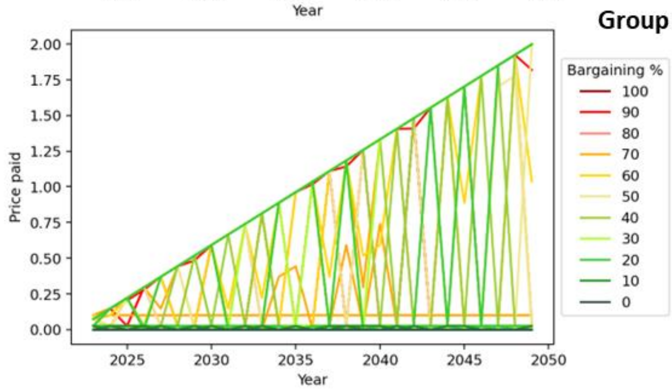


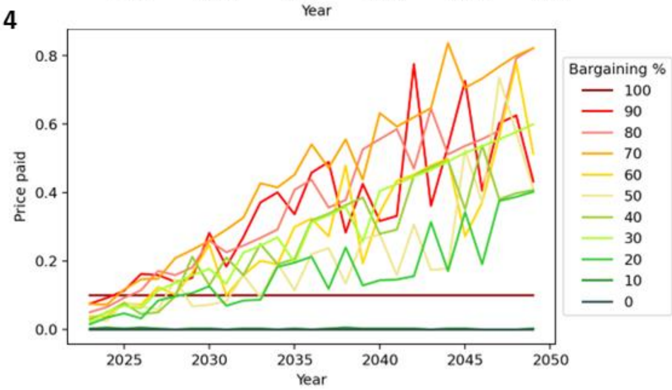
Group 3



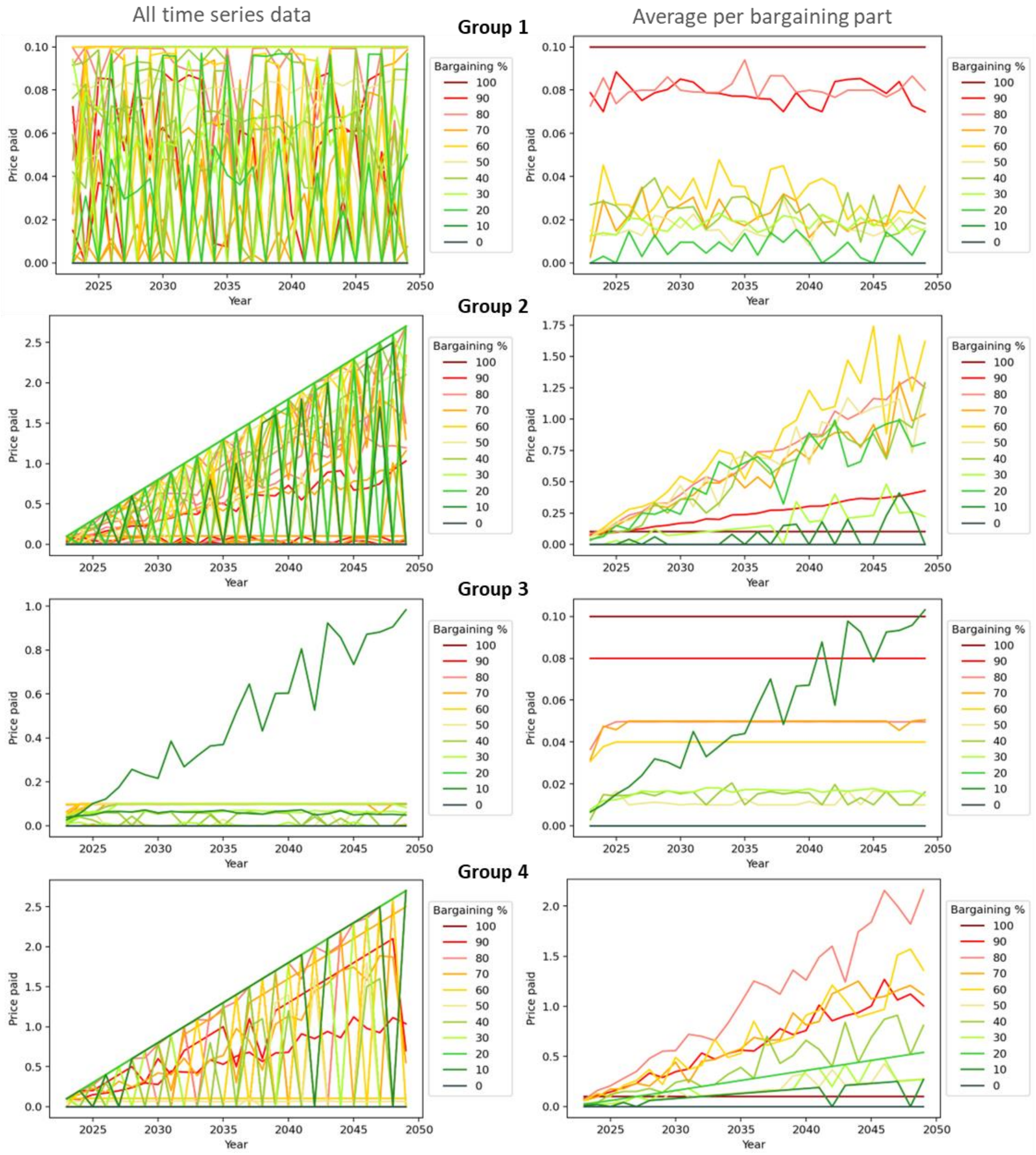


Group 4

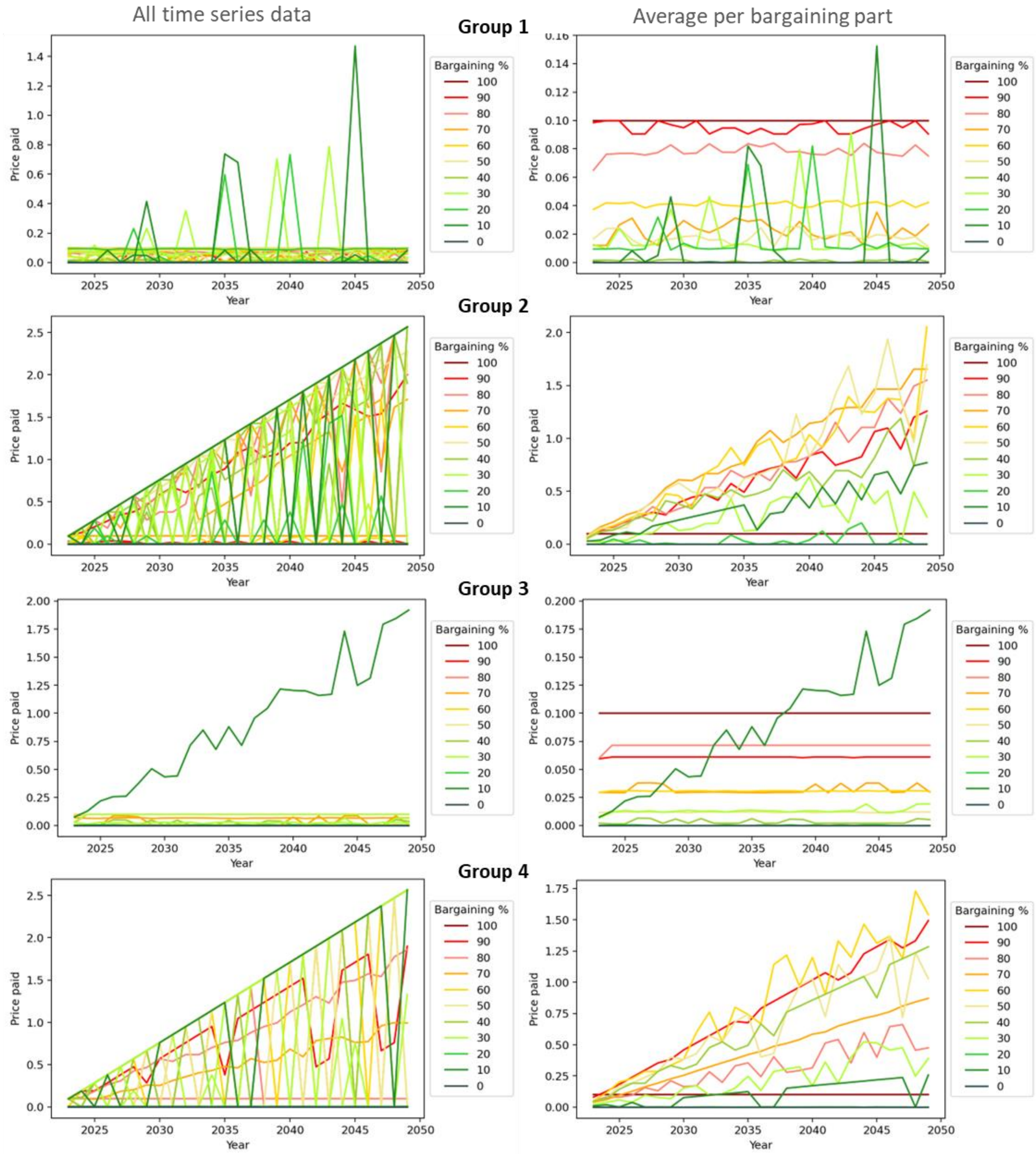




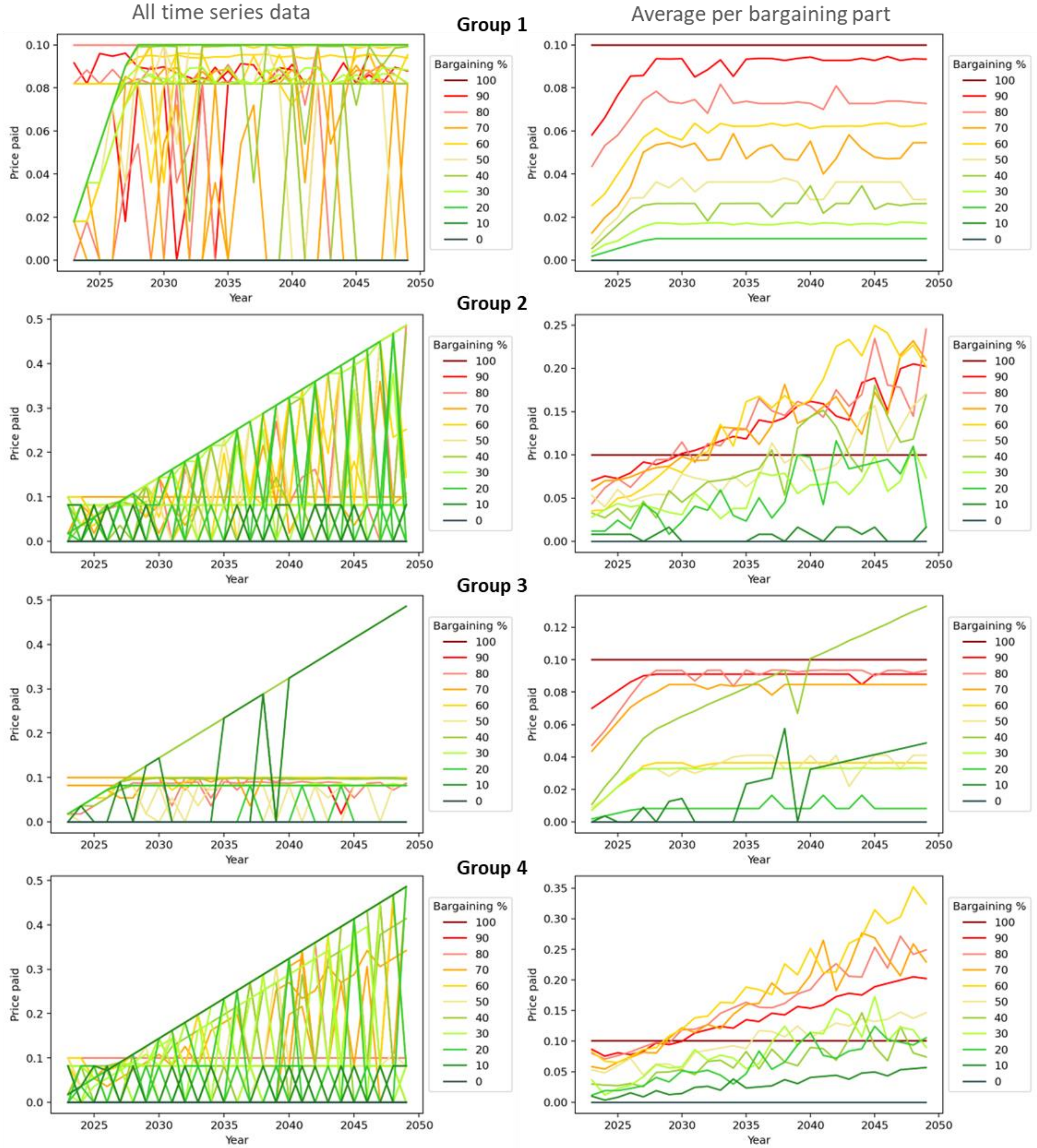
Price paid per kg by food producer for PET bottle



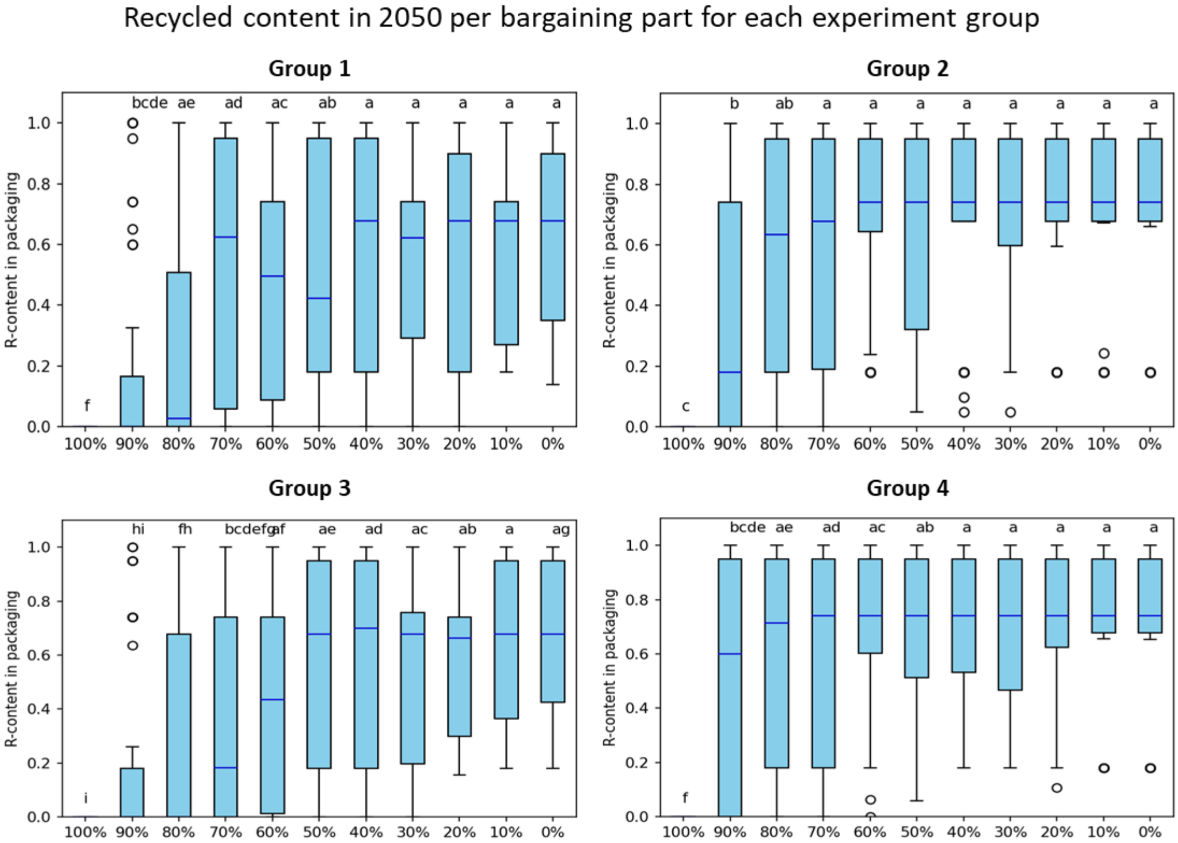
Price paid per kg by food producer for glass bottle



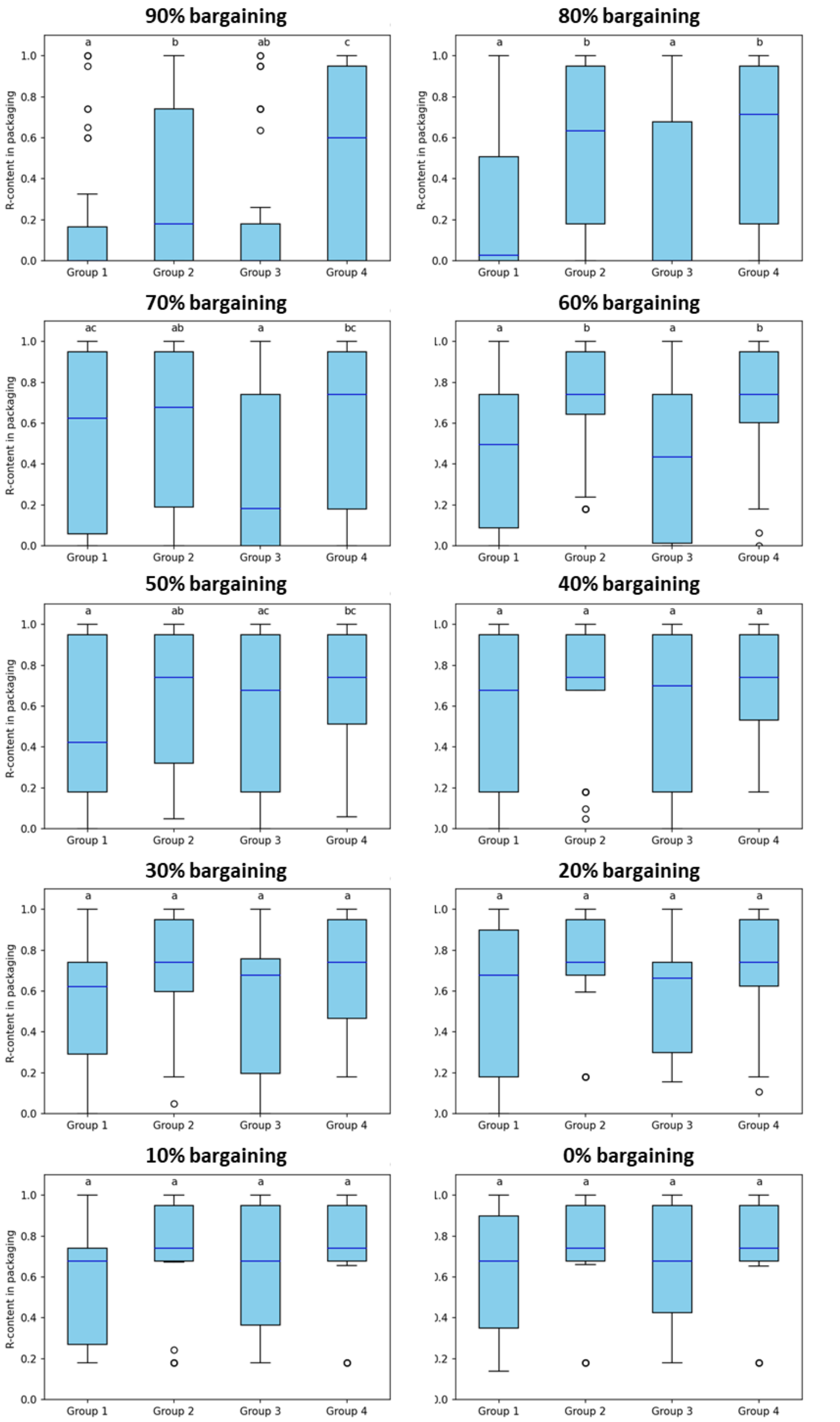
Price paid per kg by food producer for Bag in Box



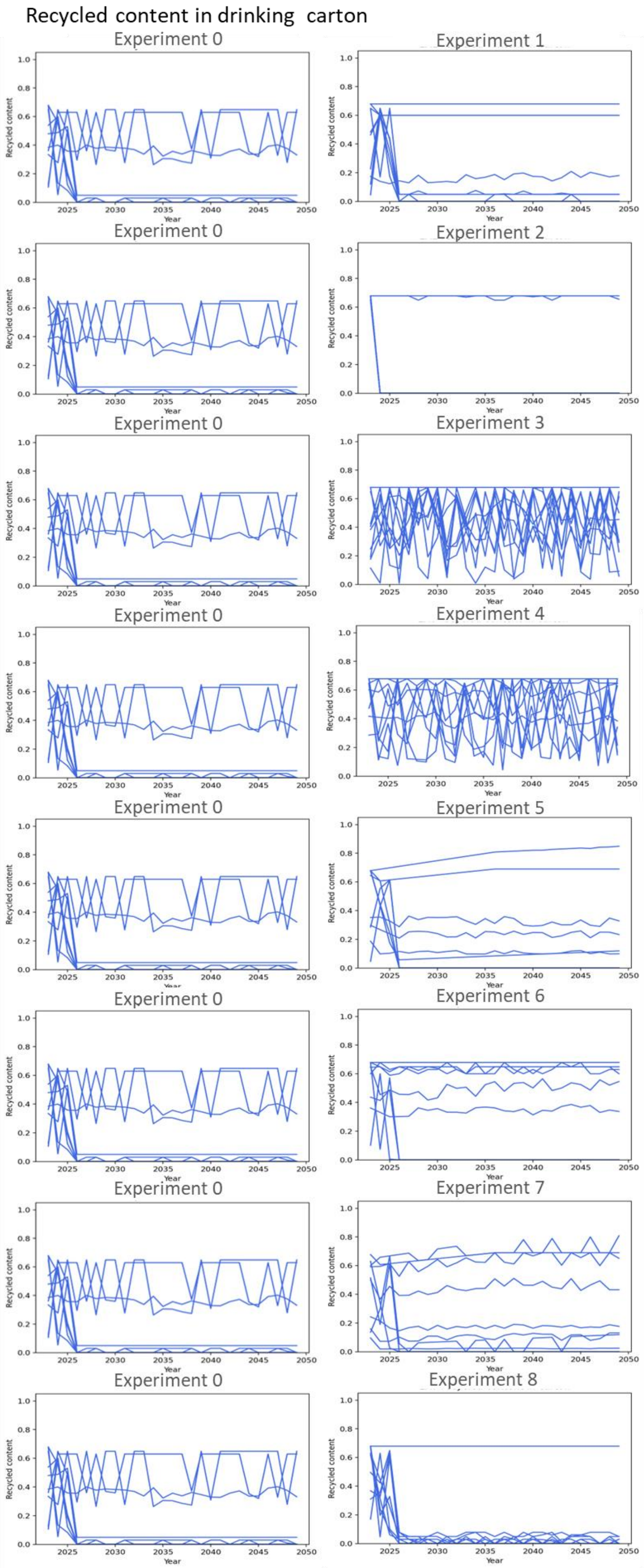
F.3 Sensitivity analysis – Data analysis boxplots



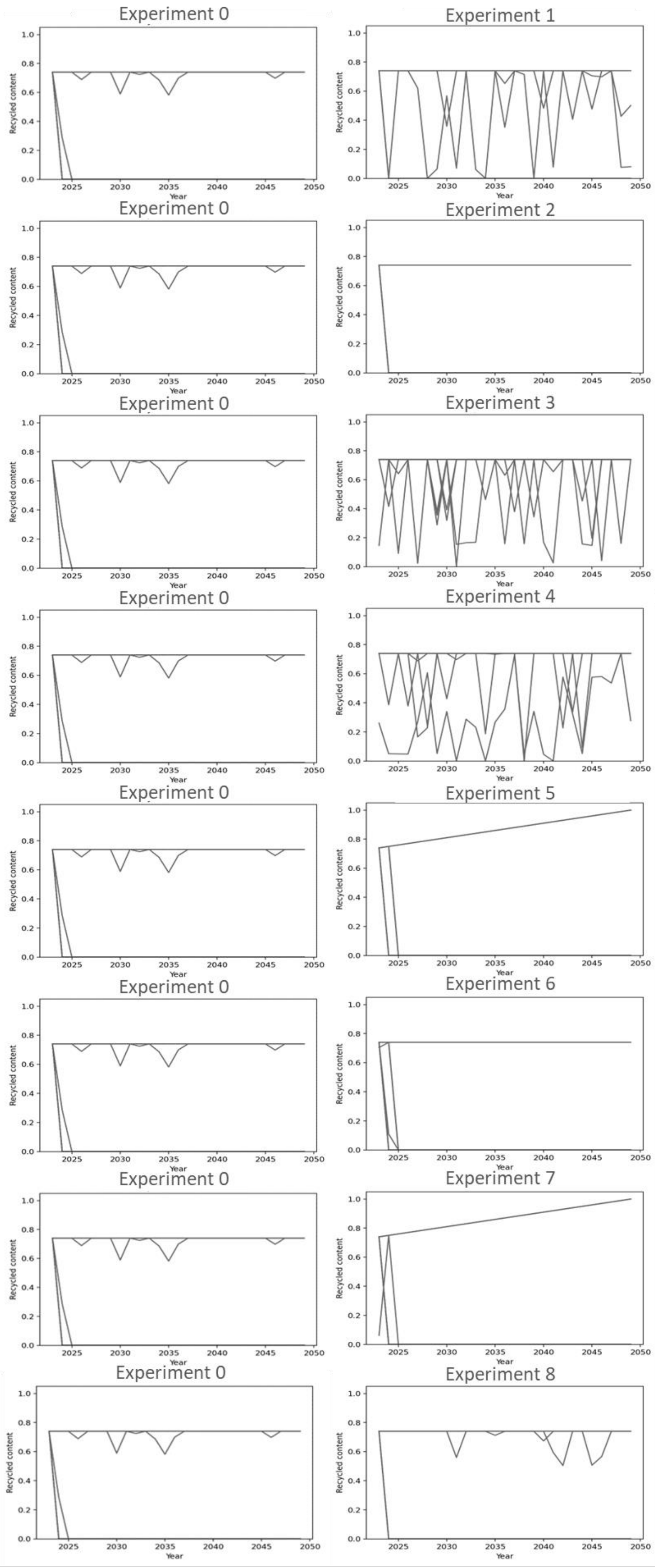
Recycled content in 2050 per experiment group for each bargaining part



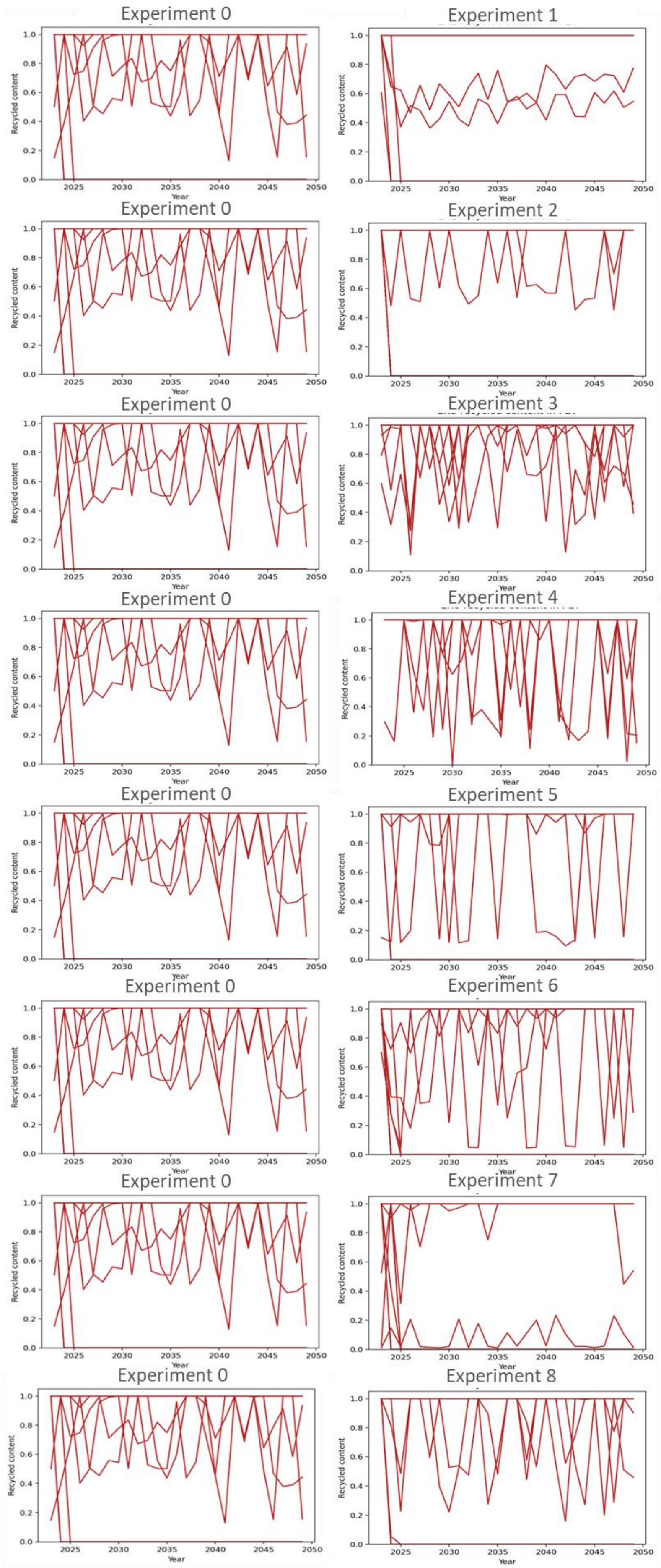
F.4 Variable experimentation – Recycled content time series



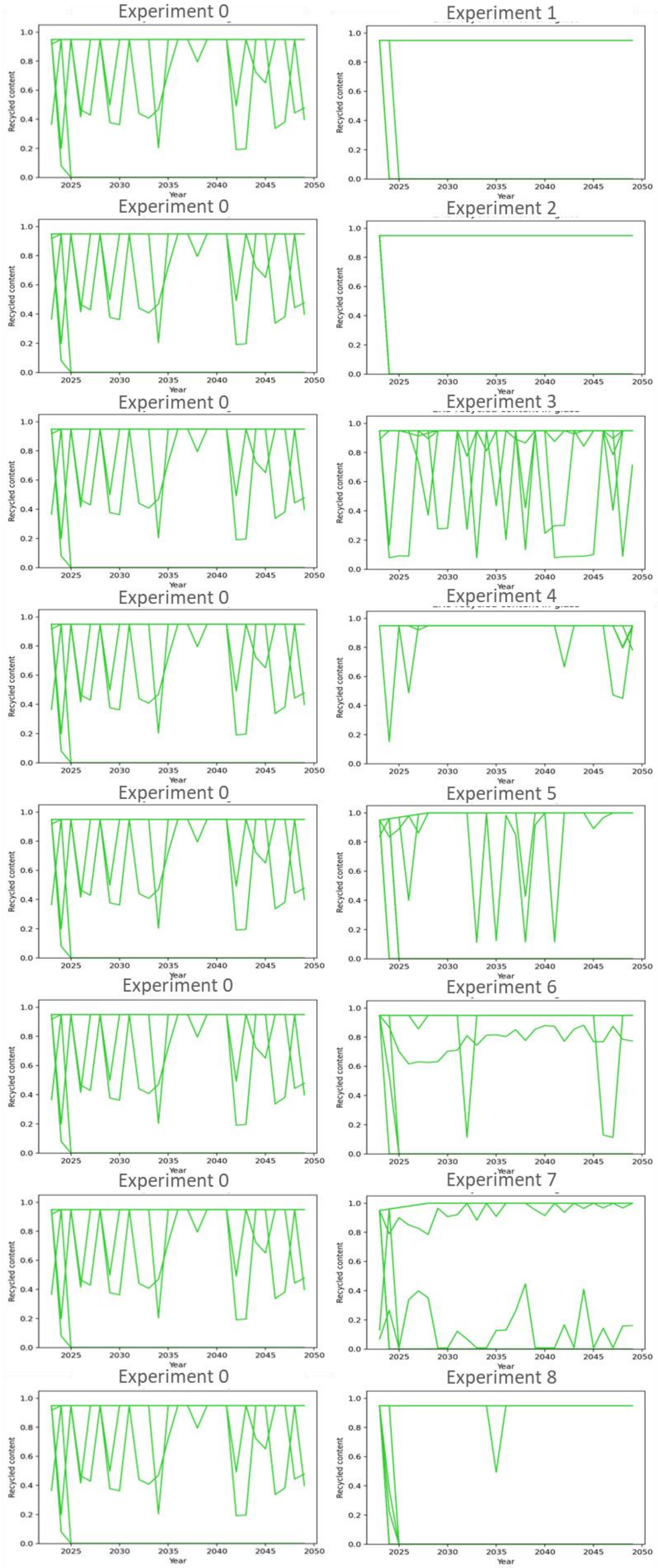
Recycled content in aluminium can

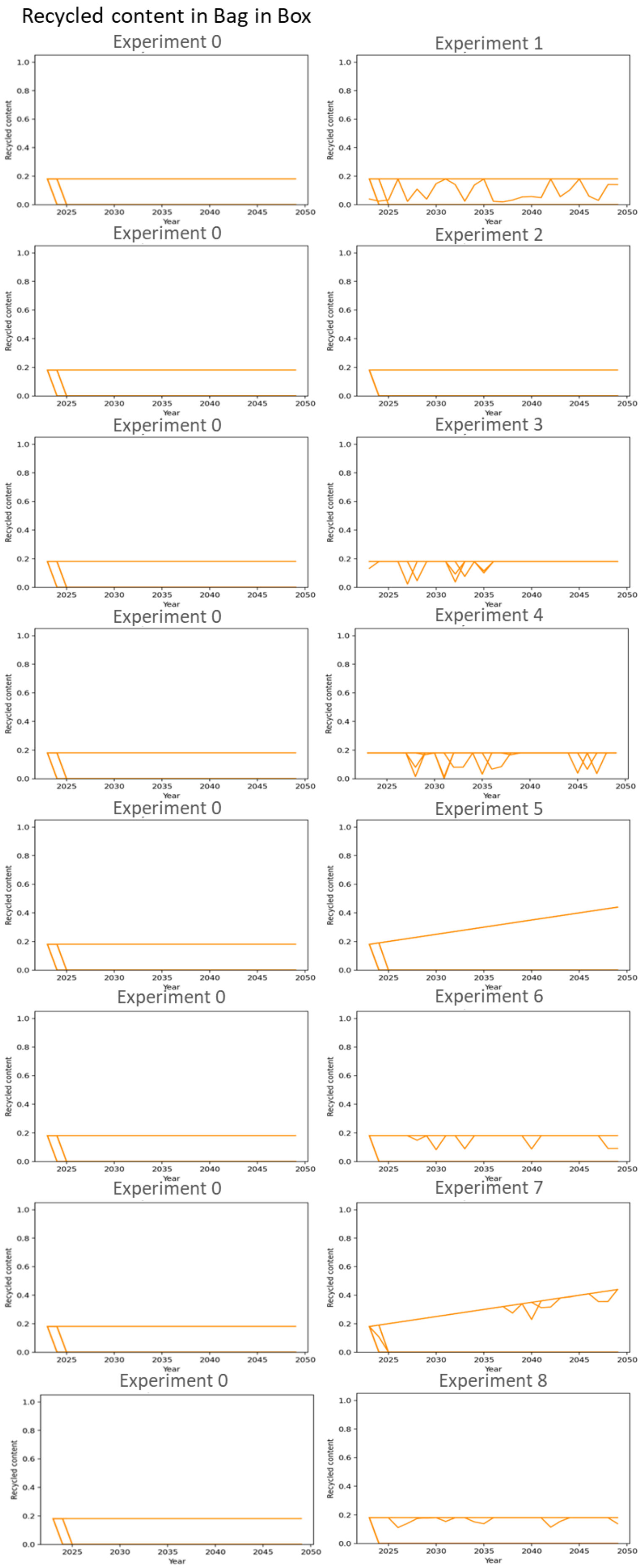


Recycled content in PET bottle



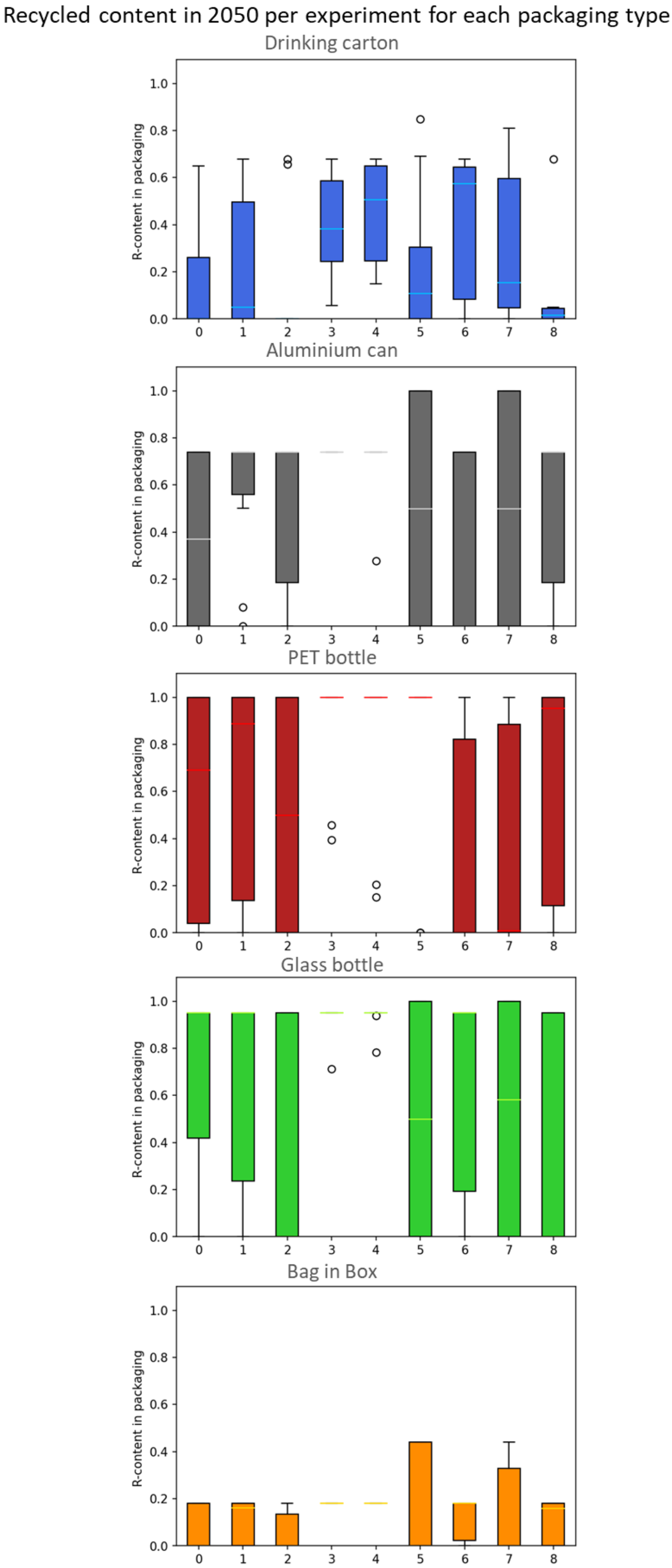
Recycled content in glass bottle



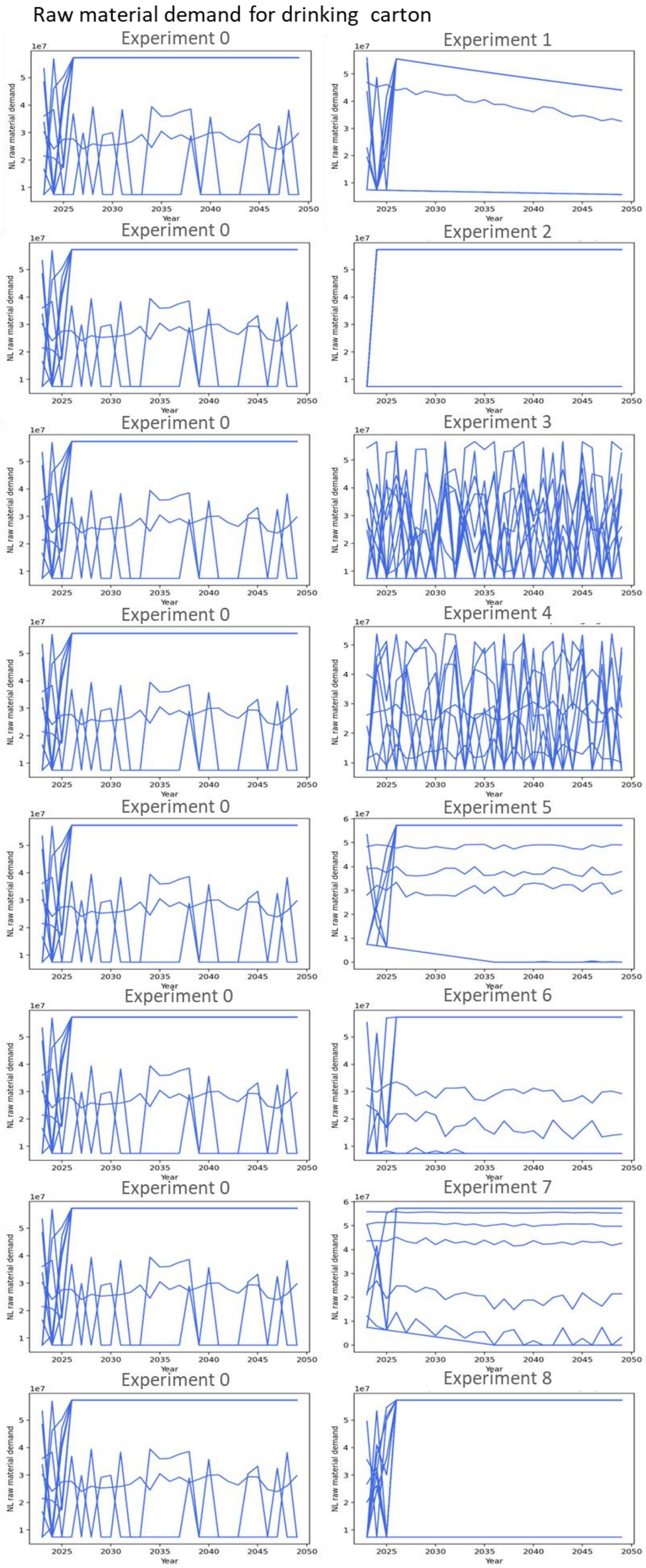


Recycled content in Bag in Box
Experiment 0
Experiment 1
Experiment 0
Experiment 2
Experiment 0
Experiment 3
Experiment 0
Experiment 4
Experiment 0
Experiment 5
Experiment 0
Experiment 6
Experiment 0
Experiment 7
Experiment 0
Experiment 8
Recycled content
Year

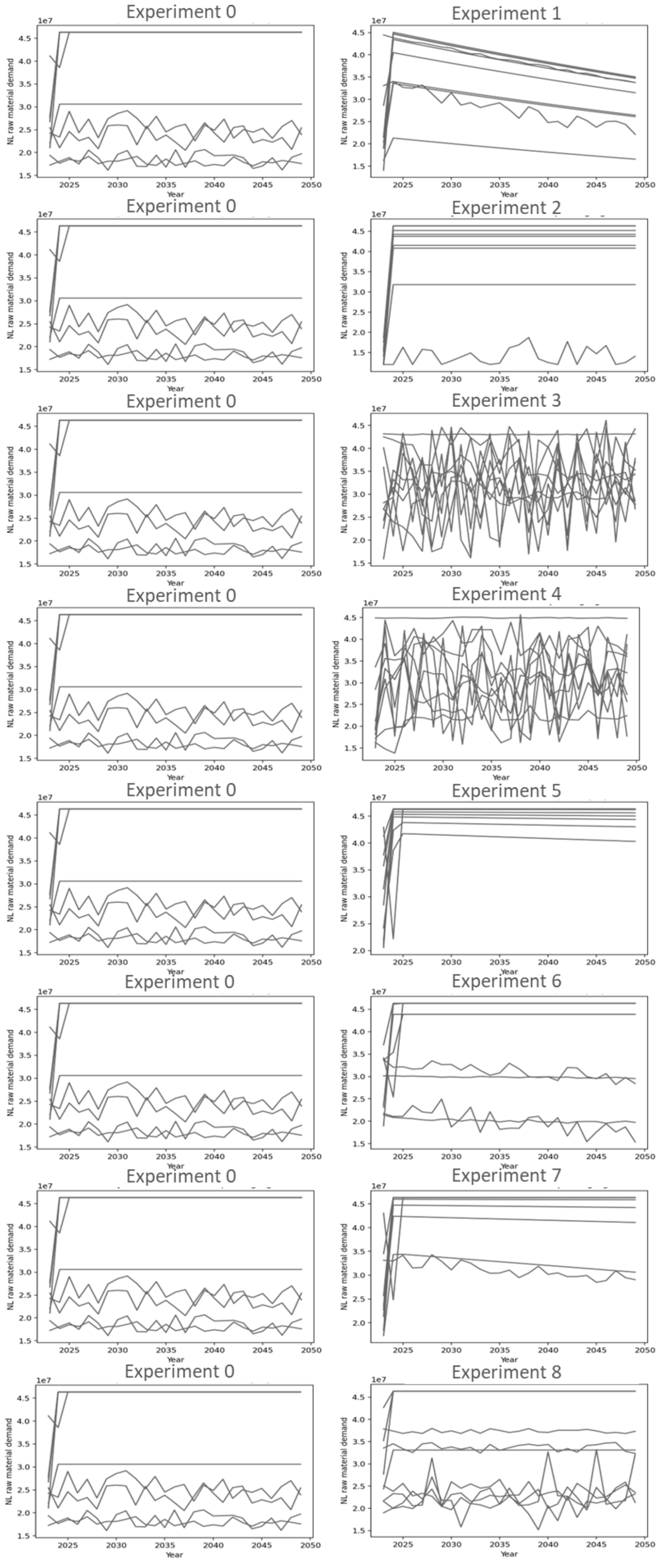
F.5 Variable experimentation – Recycled content in 2050 boxplots



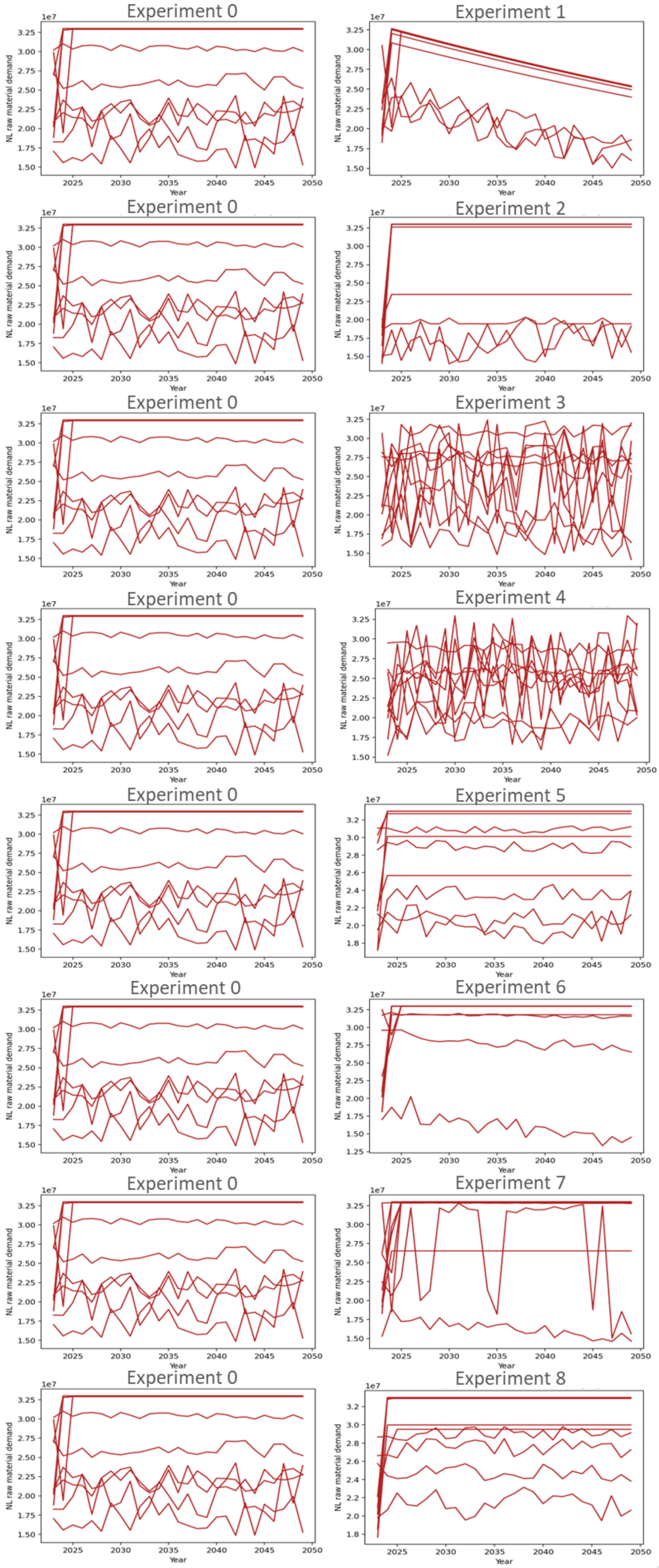
F.6 Variable experimentation – Raw material demand time series



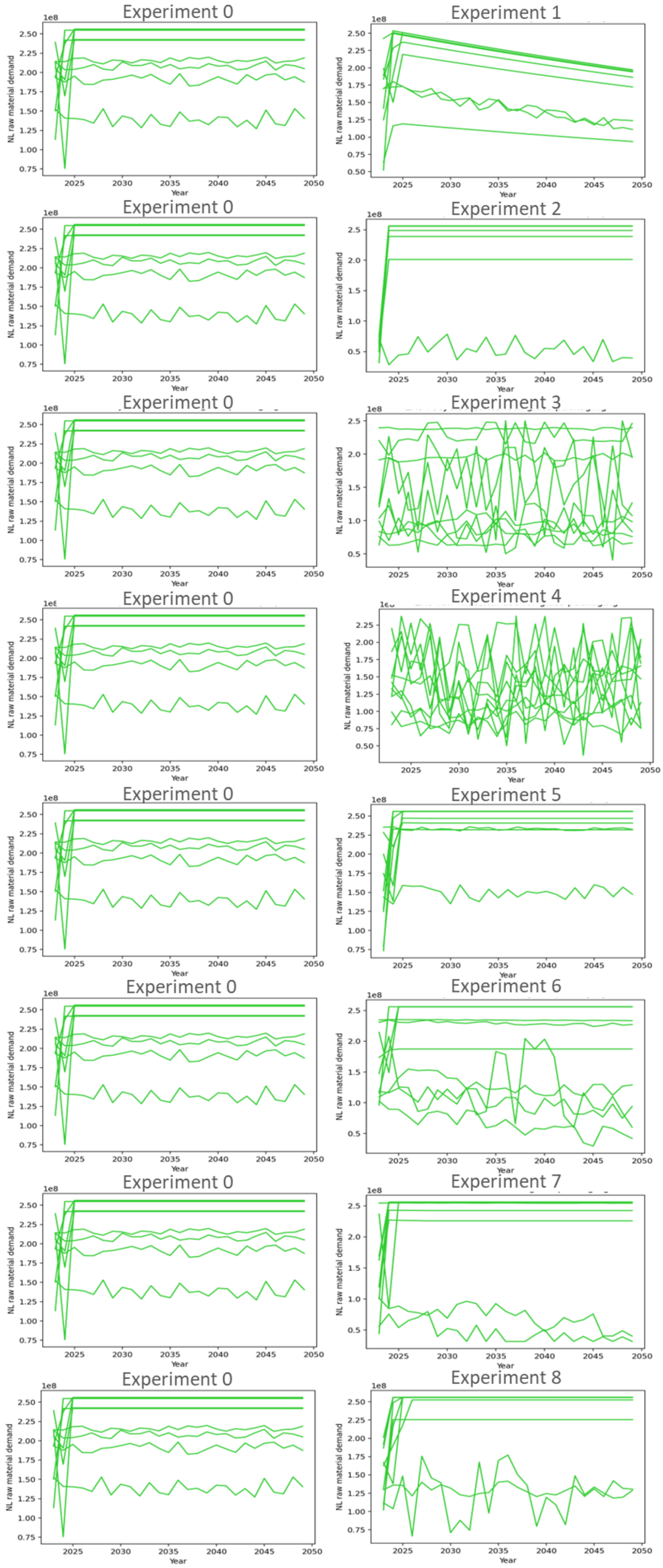
Raw material demand for aluminium can



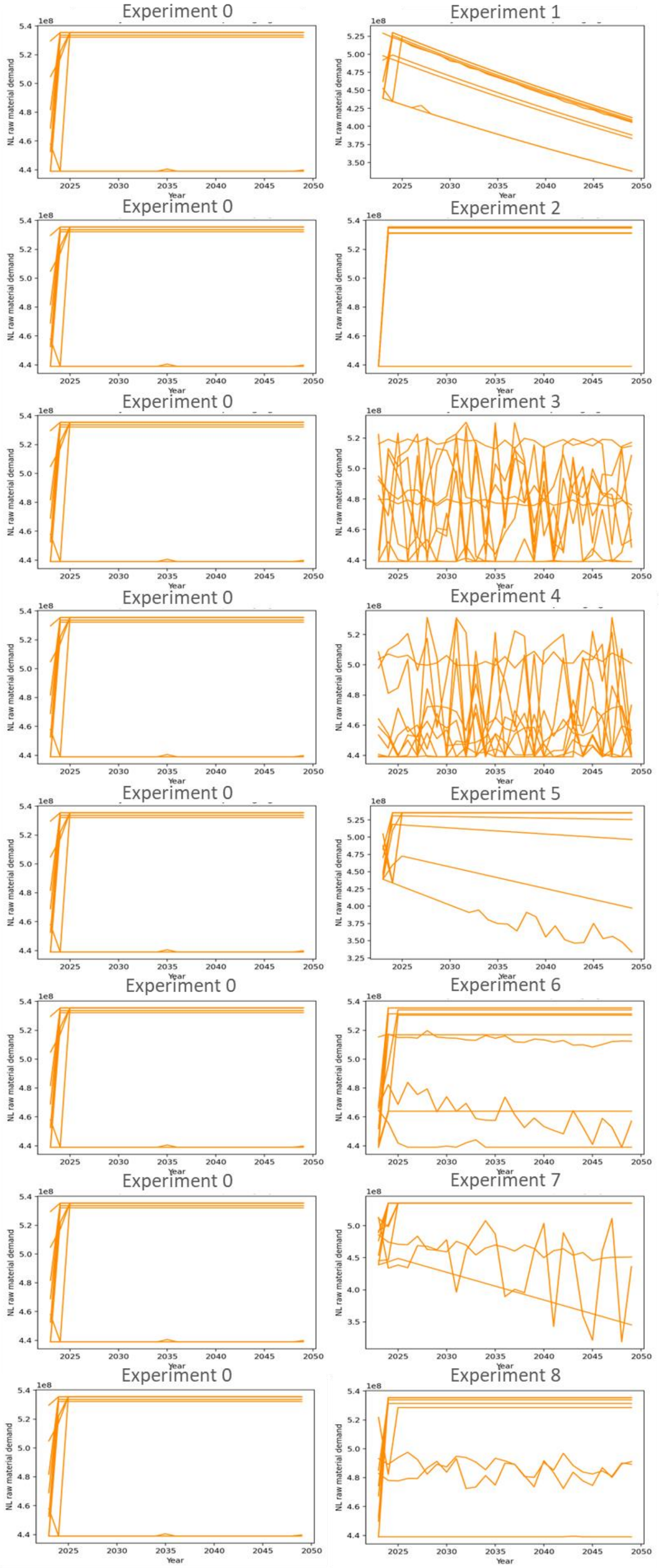
Raw material demand for PET bottles



Raw material demand for glass bottles



Raw material demand for Bag in Box



Appendix G – ABM NetLogo file

See attached file: ABM_AnnoekReitsema_Circular_Ecosystems.nlogo

Appendix H – ABM NetLogo interface