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Research Paper

To reuse or not to reuse: That is the question. Environmental trade-offs between reusable and recyclable packaging for large appliances

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ABSTRACT

This study aims to answer the Hamlet dilemma of packaging for large home appliances, i.e., to reuse or not to reuse, by evaluating the environmental trade-offs between recyclable and reusable packaging for large home appliances through a comparative life cycle assessment (LCA). Using washing machines as a case study, the research analyses four realistic distribution scenarios between Italy and France to determine under what conditions reusable packaging is environmentally preferable to recyclable packaging and vice versa. The LCA considers production, use, and end-of-life phases, with *Climate Change* as the reference impact category. Results show that recyclable packaging generally has a lower environmental impact, except for short transport distances (below 425 km for road transport and below 750 km for intermodal transport). A sensitivity analysis shows that these distance values may vary considerably depending on the impact category considered. Furthermore, additional sensitivity analyses on the number of reuse cycles and on the weight of the reusable packaging solution reveal that reusable packaging can be competitive with the recyclable option if used over 45–70 times or if its weight is reduced to approximately 9–11 kg, depending on the scenario. The study contributes to the literature in multiple ways. Firstly, it confirms that the environmental performance of packaging options depends on numerous factors and encourages data-driven decision-making to identify optimal solutions for large appliances. This outcome is demonstrated by applying a breakeven point analysis to the large appliances sector for the first time, supported by an extensive sensitivity analysis on the model parameters. Moreover, the study proposes a set of suggestions for policymakers, manufacturers, and retailers. Finally, the results of this study are highly sensitive to the choice of transport modes; therefore, these should be carefully evaluated, particularly in intermodal scenarios where multiple routing combinations are possible.

1. Introduction

The academic literature on the circular economy has increasingly sought to identify more robust operational principles to follow (Suárez-Eiroa et al., 2019). In this context, the R-hierarchy, for example, is one of such frameworks (Kirchherr et al., 2017; Potting et al., 2017). These studies have also shown that, in general, some R-actions are preferable and should be implemented before others (Kirchherr et al., 2017). The debate surrounding the R-hierarchy has not been limited to products alone, but has also extended to packaging; in this context, a reuse operation should be preferable to a recycling one. As a result, national and international policies (de Melo et al., 2022; EP, 2024) have begun to promote reuse, but they now face complex environmental trade-offs that arise in specific contexts. Among these policies, the EU Packaging and Packaging Waste Regulation (PPWR) is particularly relevant because it sets specific targets for reuse, which prioritise reuse and refill over recycling (EP, 2024). While the European regulatory framework promotes reuse as a primary option, some studies (e.g., Massarutto, 2023) have begun to warn that this perspective may be skewed by inaccurate or even absent impact assessments.

Packaging serves an essential role in protecting products during storage and transportation, ensuring they reach consumers in proper condition. Balancing these protective needs with environmental sustainability is a complex challenge. When comparing different recyclable

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packaging options, plastic often offers the lowest impact on *Climate change* across all packaging types, with a clear environmental hierarchy favouring localised recycling systems and discouraging open-loop processes and incineration due to their higher emissions (Hallberg et al., 2023). But when reusable packaging is also considered, it typically outperforms recyclable alternatives in terms of environmental performance after a certain number of reuse cycles (Greenwood et al., 2021; Tua et al., 2019). On the other hand, reusable packaging can pose significant environmental concerns when used to pack large-sized products requiring high protection during transport. In such cases, reusable packaging could be environmentally unfavourable compared to recyclable alternatives due to its higher weight. An increase in the amount of materials employed in reusable packaging is indeed necessary to protect products from damage, but it negatively affects environmental performance associated with transport (Chowdhury and Kabir, 2024), production, and disposal phases (Accorsi et al., 2014).

The performance comparison between reusable and recyclable packaging has been examined for small-sized industrial products such as food, including food products' packaging (Farrell et al., 2024; Kan and Miller, 2022), take-away food containers (Camps-Posino et al., 2021; Gallego-Schmid et al., 2019), and food transport packaging employed in the supply chain (Accorsi et al., 2022; Albrecht et al., 2013; Almeida et al., 2022; Singh et al., 2006; Levi et al., 2011). Outside the food sector, recyclable and reusable packaging have been compared in the chemicals and cosmetics industry (Raugei et al., 2009), and beauty and hygiene products (Civancik-Uslu et al., 2019; Gatt and Refalo, 2022; Goellner and Sparrow, 2014; Rathore et al., 2023; Ren et al., 2022). These studies generally suggest that the environmental sustainability of recyclable and reusable packaging depends on factors such as material composition, production processes, transportation distances, and end-of-life scenarios, underscoring the complexity of determining the most environmentally preferable packaging option. Bradley and Corsini (2023), through a recent literature review, show that the environmental performance of packaging is shaped by a complex interplay of 22 environmental, economic, social, and technical factors. Only careful management of these variables in relation to the specific context can determine whether reuse is actually preferable to recycling. However, a closer examination reveals that most studies on small-sized packaging are not primarily focused on comparing different packaging types. Instead, they tend to assess the environmental hotspots of recyclable (Kan and Miller, 2022) or reusable (Camps-Posino et al., 2021) transport packaging systems and networks separately. This results in a fragmented understanding of the topic, where the performance of different solutions cannot be directly compared. Consequently, the literature provides limited guidance for decision-makers seeking to identify the most environmentally sustainable packaging option across multiple alternatives.

Although the dilemma also applies to large-sized products – such as home appliances (e.g., washing machines, dryers, dishwashers, and ovens) – which generate significant amounts of packaging waste, including polystyrene, polyethylene, and cardboard (Landi et al., 2020), this issue has received considerably less attention in the literature (Bielecki, 2023). The comparison between reusable and recyclable packaging is strongly influenced by the selection of the packaging materials, which depends on the characteristics and the size of the products (Chowdhury and Kabir, 2024). Therefore, extending the analysis to large-sized products is important. Moreover, the performance of reusable packaging systems for bulky products also depends on the efficiency and structure of the reverse logistics network. In the case of electrical and electronic equipment, transportation efficiency, vehicle utilisation, and network design significantly affect both costs and environmental impacts, making reverse logistics a non-negligible contributor to the overall life cycle performance of the system (Govindan et al., 2015). Focusing both on the packaging and the system in which it is designed and transported is therefore essential to move beyond the many fragmented analyses conducted on small products, which often address the issue less systematically. The research gap we aim to address is supported by findings from previous studies that have highlighted several practical challenges complicating environmental assessments in the packaging sector. These include limited monitoring by material consortia, low participation from companies, and difficulties in obtaining accurate data (Rigamonti et al., 2018).

The importance of comparing reusable and recyclable packaging for large household products lies not only in academic inquiry but also in practical application. The growing pressure to reduce environmental impacts along supply chains has been reflected in policy developments, particularly concerning the recyclability and reusability of packaging systems. In this context, the Circular Economy Action Plan (EC, 2020) and the European Parliament's 2021 resolution (EC, 2021) aimed to make all packaging reusable or recyclable by 2030, leading to the PPWR. The initial proposal (EC, 2022) required 90% reusable transport packaging for large household appliances, facing industry opposition due to feasibility concerns. However, this target faced strong industry opposition due to specific and significant feasibility barriers. As highlighted in critical analyses of the regulation's assessment (e.g. Massarutto, 2023) and various industry consultation responses, the main obstacles included: the lack of an adequate reverse logistics infrastructure capable of efficiently handling bulky returns on a large scale; the prohibitive economic and environmental costs associated with transporting heavy empty packaging over long distances; and the technical challenges related to the standardization of packaging. The final regulation (EP, 2024) maintains reuse targets only for specific areas (e.g., food and beverages) while removing requirements for large appliances. The PPWR's initial promotion and subsequent withdrawal of reusable packaging requirements show uncertainty on this topic and need objective clarification. Which packaging system provides better environmental benefits remains unclear, especially for large items. Thus, a comparative analysis for large appliances can assess environmental impacts across packaging life cycles, providing insights to inform future regulations.

Aiming to address this research and operational gap, this study evaluates the environmental trade-offs between recyclable and reusable packaging for washing machines through a comparative Life Cycle Assessment (LCA). In more detail, the central research questions of this paper are the following:

RQ1. Under what conditions are reusable packaging systems environmentally preferable to recyclable alternatives (and vice-versa) for washing machines?

RQ2. "How do sales channels (direct vs. retail) and transport modes (road vs. intermodal rail) affect environmental trade-offs between reusable and recyclable packaging for washing machines?"

RQ3: "How do the choice of environmental impact category, the number of reuse cycles, and the weight of the reusable packaging affect the breakeven points?"

In addressing these research questions, this paper provides recommendations for policymakers, designers, and manufacturers. These recommendations should be interpreted considering that the comparative analysis presented here focuses on environmental sustainability only, whereas techno-economic and socio-economic aspects (e.g., costs, logistical feasibility, consumer behaviour, and infrastructure constraints) should also be evaluated when developing operational policy frameworks.

To address these research questions using LCA, the study employs scenario analysis to identify a breakeven distance at which the environmental impacts of reusable packaging are offset by the reduction of waste and emissions over multiple transport cycles. This distance is first calculated using *Climate Change* as the reference impact category, and then it is reassessed for other impact categories as part of a sensitivity analysis. In addition, sensitivity analyses on the number of reuse cycles of reusable packaging and on the mass of reusable packaging materials are presented. The findings of this study are particularly relevant to a range of stakeholders, including washing machine manufacturers seeking more sustainable logistics solutions, packaging designers aiming to develop effective reusable systems, and logistics providers interested in optimising transport and return strategies.

2. Materials and methods

This section provides a detailed description of the materials and methods used in the analysis. As outlined in the following subsections, the approach adopted in this study consists of three main steps: (i) case study and scenario development, (ii) definition of the material composition of recyclable and reusable packaging, and (iii) LCA. Following these steps, the environmental impacts of reusable and recyclable packaging solutions are assessed across the considered scenarios within a breakeven-point analysis framework. Specifically, the results are interpreted to determine whether a given scenario falls within the distance range in which reusable packaging outperforms recyclable packaging, or vice versa.

2.1. Case study and scenarios development

This study adopts a case study approach, which is well-suited for analysing real-world systems (Yin, 2018). The methodology integrated two data collection phases: desk research and stakeholder interviews. First, we collected and analysed information from the websites, supplementary documents, and patents of major Italian home appliance manufacturers. Second, we conducted semi-structured interviews. The involvement of a major European consortium of home appliance producers was instrumental in facilitating this process and overcoming the industry participation challenges previously noted by Rigamonti et al. (2018). To ensure the study's robustness, the consortium convened key industry stakeholders who provided technical insights on logistics and packaging (both recyclable and reusable). Furthermore, all scenarios were discussed and validated in collaboration with this consortium. Due to confidentiality agreements established before the data collection phase, the names of the participating companies, as well as the specific interview transcripts, have been anonymized. Nevertheless, to highlight the representativeness of the collected data, it is important to note that the two specific manufacturing companies interviewed account for approximately 17% of the total home appliance market revenue, ensuring a highly representative sample of the sector's operational reality.

For the analysis, scenarios were created in which the appliance is manufactured in Italy and shipped to France, as data show that France is one of the largest markets for washing machines in Europe (Statista, 2025; Michel et al., 2016). The choice of France as the target market provides a realistic, cross-border distribution scenario with a transport distance long enough to meaningfully test the environmental trade-offs. This choice does not limit the generalizability of the results; rather, France serves as a representative market, enabling the analysis of key logistics configurations and sales channel structures that are widely applicable across other European countries. As shown in the Supporting Information files, the breakeven point analysis presented here is based on European-level inventory datasets for freight transports. A case study is conducted to assess whether reusable packaging outperforms recyclable packaging, or vice versa, under French market conditions, but alternative European countries may also be considered within this framework. Furthermore, this setup allows for the evaluation of different, complex logistics dynamics, including both road-only and intermodal (road-rail) transport.

Information on the reusable packaging was obtained from a patent by one of the participating companies and a subsequent interview, both specifically related to this type of product. In parallel, data on traditional recyclable packaging were derived from publicly available information on the websites of major European manufacturers.

To develop the case study and reproduce a credible map of the washing machine's journey from producer to consumer, four distinct scenarios were constructed, considering warehouses and stores in the consumer's country. The scenarios encompassed two distinct sales distribution channels: (i) direct sales (DS) through the company's subsidiaries operating in the destination country and (ii) retail distribution (RD) via established local washing machine retailers such as wholesalers and resellers, to facilitate sales and delivery. Furthermore, for each channel, two transport modes were assessed: (a) a road-only option relying exclusively on a lorry and (b) an intermodal configuration combining rail transport for long-distance segments with lorry transport for domestic delivery. Details about scenario development are explained in Fig. 1.

Further details on the configuration of the scenarios for logistics are provided in Appendix 1. The characteristics of the channel distribution system and the selected transport modes were key determinants in defining the kilometre distances across all scenarios. Moreover, both the channel distribution setup and the type of packaging – whether recyclable or reusable – played a crucial role in the LCA calculations. Distances and transport modes were defined to represent realistic freight and waste management routes consistent with the actual washing machine distribution system.

2.2. Material composition of recyclable and reusable packaging

The bill of materials of the two packaging solutions is significantly different. Recyclable packaging typically comprises standard materials and is designed to be supported by a EUR-pallet, whereas reusable packaging incorporates the pallet itself. The two types of packaging systems considered in this study are illustrated in Fig. 2.

2.2.1. Material composition of recyclable packaging

The recyclable packaging is based on data and quantities provided on the website of one of the participating companies, which allowed us to have details and quantities for recyclable packaging used for an 8 kg capacity washing machine. Based on these data, the materials composing the recyclable packaging considered for this study are corrugated board, polystyrene, and polyethylene. As underlined in Fig. 1, a EUR pallet is also necessary to sustain the recyclable packaging. Data about EUR-pallets are taken and adapted from Gasol et al. (2008), including details on the number of uses, dimensions, and weight of the pallets. Due to the dimensions of the EUR-pallet, it is assumed that two washing machines are placed on a single wooden pallet. Based on these assumptions, the overall mass of the recyclable packaging is set to 1.14 kg.

2.2.2. Material composition of reusable packaging

The reusable packaging is modelled on an actual example inspired by a prototype developed by a leading European manufacturer in the home appliance sector, which is part of a major European consortium of home appliance manufacturers. Even though it is no longer in use, this particular reusable packaging design for washing machines – previously evaluated by the company – may serve as a reference model if the adoption of reusable packaging is reconsidered in the future. A patent published in 2004 by this leading manufacturing company served as a foundational element in the conceptual development of the reusable packaging solution for large household appliances considered in this study. The patent primarily contains design and functional data for a stackable transport packaging system for large household appliances. The original patent delineates a robust, stackable transport system comprising two symmetrical shells with integrated centring and fastening mechanisms. It also includes information on geometrical properties and adaptability to different appliances and handling methods, but does not provide experimental or numerical data on technical characteristics of reusable packaging (e.g., density, tensile strength, elongation at break, charpy impact resistance, environmental resistance). To validate our approach and refine critical parameters such as load-bearing capacity and weight optimisation, with the support of

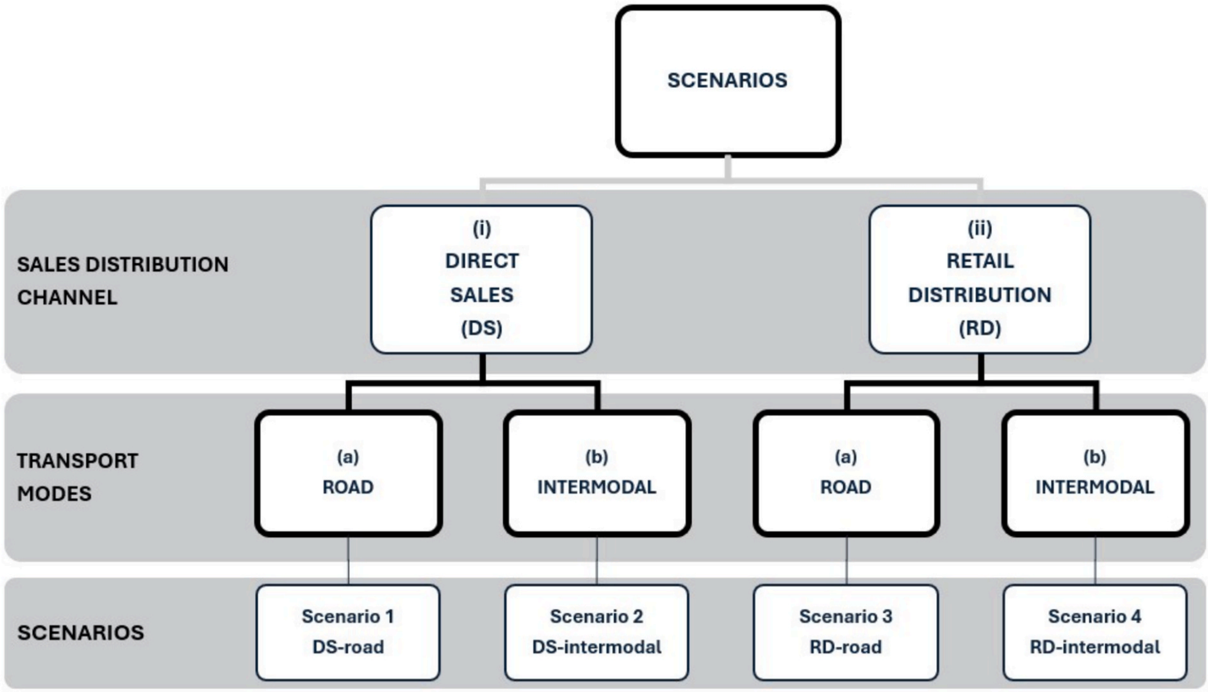

Fig. 1. Scenarios developed combining sales distribution channels and transport modes. DS = Direct Sales, RD = Retail Distribution.

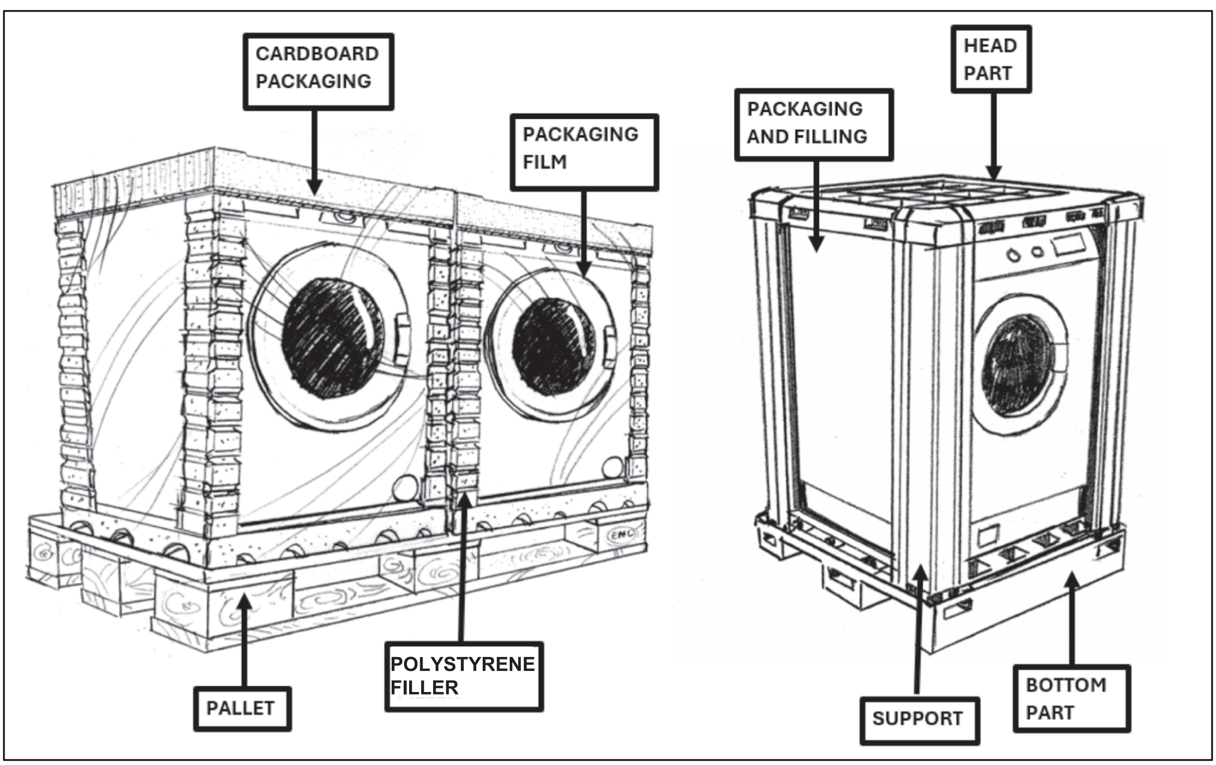

Fig. 2. Representation of the two types of packaging systems for transport of washing machines considered in this study: recyclable packaging (left) and reusable packaging (right).

the European consortium, we engaged directly with an engineer who had been actively involved in the washing machine packaging programs at the time the patent was filed. This collaboration was instrumental in understanding both the context that led to the conceptualisation of reusable packaging solutions and the factors underlying their limited adoption in recent years, primarily due to techno-economic and practical challenges related to the complex and costly management of packaging materials. On the other hand, this interview confirmed that our assumptions regarding weight distribution and stacking limits were consistent with practical, field-tested constraints and, more generally, indicated that the design of reusable packaging can, in principle, be compatible with modern logistics. Consequently, our solution preserves the structural logic of the original packaging while reinterpreting it – with the technical support of the specialist – in a simpler and more modular format that remains fully compatible with modern logistics systems. The accounted materials and quantities of the reusable packaging are glass fibre reinforced plastic (GFRP), polycarbonate, acrylonitrile–butadiene–styrene (ABS), and polyethylene. For each material, the LCA model incorporated data concerning the impact of production, transportation, and waste management. Based on the gathered data, the overall mass of the reusable packaging is set to 14.34 kg. The reusable packaging was designed to circulate at least 30 times before disposal, but the actual number of reuse cycles is highly uncertain because reusable packaging has not yet been deployed at a scale sufficient to generate reliable historical data on average lifespan. Consequently, its lifespan could be significantly higher than the minimum one set by design. In contrast, the lifespan of recyclable packaging is assumed to be limited to a single cycle, as no reuse by end users is considered.

2.3. Life cycle assessment

LCA is a standardised methodology to assess the potential environmental impacts across a product's life cycle, from raw material extraction, through manufacturing, use, and end-of-life stage. In this paper, we followed the LCA methodological framework defined by the ISO 14040 (ISO, 2006a) and ISO 14044 (ISO, 2006b) standards, which include four phases: i) goal and scope definition, ii) life cycle inventory (LCI), iii) life cycle impact assessment (LCIA), and iv) life cycle interpretation (Finkbeiner et al., 2006).

2.3.1. Goal and scope definition

The goal of this LCA study is to compare the environmental performance of reusable and recyclable packaging for a typical washing machine, depending on the transport distance. Specifically, we develop a methodological framework to identify the breakeven point between these options by calculating a distance at which the environmental impacts of recyclable packaging match those of reusable packaging. The distance corresponding to the breakeven point is hereafter referred to as the "breakeven distance." The scenarios described in Fig. 1 serve as test cases for applying this methodological framework, allowing the evaluation of whether reusable packaging outperforms recyclable packaging in some realistic scenarios, or vice versa. However, beyond the considered scenarios, the proposed methodology holds a more general value, as the breakeven distance calculated here can be used by suppliers as a benchmark to support decisions on the most suitable packaging option, also in alternative conditions from the ones proposed in the scenarios, depending on the logistics of the washing machine delivery.

The function of both recyclable and reusable packaging is to ensure the protection of the appliance during its delivery to the consumer. Consequently, the functional unit is defined as "*protecting 1 washing machine during its delivery to the consumer*".

The system boundaries, shown in Fig. 3, are from cradle to grave, because they include resource use and emissions to the environment across the production phase, use phase, and end-of-life. In Fig. 3, the background datasets represent all upstream and downstream processes (such as raw material extraction, energy supply, and waste management) that are connected to the packaging life cycle as part of the product system. The washing machine contained in the packaging is left outside the system boundaries. This decision was made to omit from the assessment any potential damage to the appliances that might result from the use of reusable or recyclable packaging, due to the unavailability of relevant data, which is a limitation of the study. The system boundaries in Fig. 3a are related to recyclable packaging, while Fig. 3b refers to the reusable one. The scheme illustrates which are the inputs

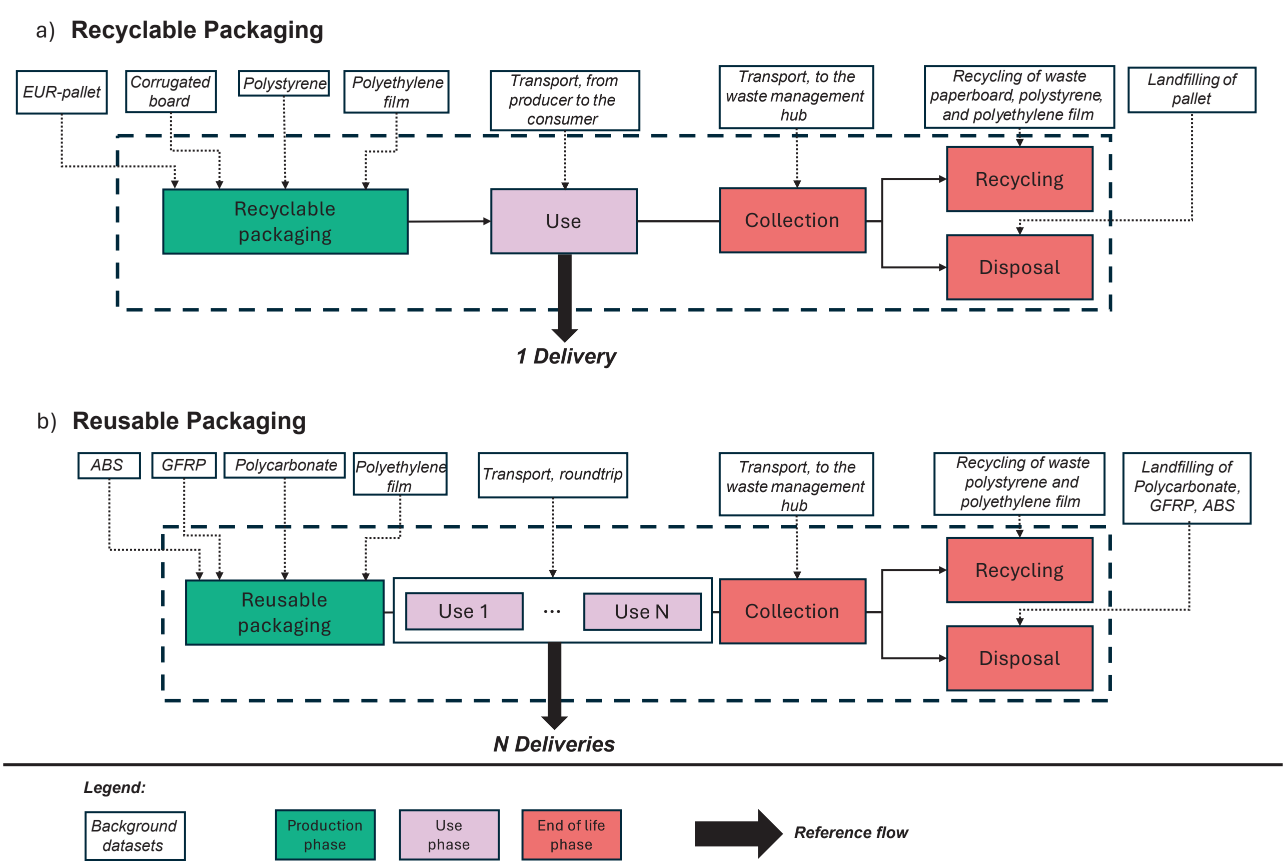

Fig. 3. Representation of the system boundaries considered in this LCA study, including production, use, and end-of-life phases for a) recyclable packaging and b) reusable packaging. ABS = acrylonitrile–butadiene–styrene; GFRP = Glass Fibre Reinforced Plastics; N = number of reuse cycles of reusable packaging.

and outputs considered when modelling the life cycle of the two packaging materials, specifying the materials and the processes that have been included in the system boundaries. We adopted the cut-off approach to model recycling, thus assuming that the recycled materials used in packaging production carry only the impacts associated with the recycling process, while no upstream burdens from the original material production are attributed to them (Hermansson et al., 2022). However, this approach also excludes the possibility of benefitting from any avoided burden from materials recycling and energy recovery (van der Harst et al., 2016).

As shown in Fig. 3, the main difference between the life cycle modelling of reusable and recyclable packaging lies in the use phase, since the former undergoes multiple reuse cycles. For this reason, the impact of the reusable packaging is allocated over various reuse cycles. Another difference related to the use phase is that, in case recyclable packaging is considered for the delivery, the transport of the washing machine starts at the producer's gate and concludes once the appliance is delivered to the consumer. Conversely, the delivery of a home appliance implies a round-trip travel of the transporter when reusable packaging is employed because once the appliance is delivered to the customer, the packaging must be returned to the producer for subsequent uses. In the modelling of the use phase, potential variations between different uses of the reusable packaging were not considered, under the assumption that identical transport routes are followed throughout all reuse cycles. Regarding the use phase of recyclable packaging, we assumed that one wooden EUR-pallet of standard dimensions (1.200 × 800 mm) and weight (25 kg) can carry two washing machines at a time. In addition, we assumed that a EUR-pallet can be reused 10 times, which is an intermediate assumption between the highest and the lowest reuse rates set by Gasol et al. (2008). In the end-of-life phase, we presume that once the washing machine is delivered, the recyclable packaging is collected and transported to a waste management hub where the recyclable parts (i.e., the plastic film, cardboard) are separated and sent to recycling. Concerning the reusable packaging, instead, the plastic packaging film can be recycled, but we suppose that the core structure is not recovered after multiple uses, and it is disposed of.

2.3.2. *Life cycle inventory*

The LCI is based on the background database Ecoinvent 3.9.1 cut-off version (Frischknecht, 2010) and on the primary data for the foreground modelling, collected in 2024. We developed a parametric LCI in which some quantities are expressed as formulas, as already performed in the packaging sector by Niero et al. (2014). Details about the parameters are listed in Table 1. Using formulas and parameters is fundamental in this analysis (Gao et al., 2025) because, in line with the goal of the study, we are applying variations to the transport distances travelled by lorry (d_l) and by train (d_t) and – as a sensitivity analysis – to the number of reuse cycles of reusable packaging (N), thus calculating results variations as function of these parameters. In particular, the parameter N is used to allocate the impacts of reusable packaging production and end-of-life on multiple deliveries, which are 30 by default. Another parameter varied in the sensitivity analysis is the weight of the reusable packaging, which is uncertain because the design dates to 2004. Accordingly, a dimensionless parameter, W, set to 1 by default, is introduced to scale the mass of reusable packaging material. In the sensitivity analysis, W is varied to represent changes in mass ranging from − 50% to + 50%.

As previously stated, EUR-pallets have been modelled considering a usability of 10 times and carrying two appliances for each use. A sensitivity analysis of this parameter is not reported in this paper; however, readers can explore its influence by applying parameter

Table 1
Parametric Life Cycle Inventory (LCI) referred to the functional unit of this study (1 appliance delivery), detailing the parameters used to model the life cycle of recyclable and reusable packaging. Data quality labels: A = primary data published online on recyclable packaging, B = industry estimates on reusable packaging, D = data generated during the case study design and validated by industrial partners, D = Data derived from the scientific literature or inventory databases.

Parameter	Description		
N	Number of reuse cycles of the reusable packaging		
W	Correction factor for the mass of reusable packaging		
d_l	Distance from the appliance producer to the consumer by lorry		
d_t	Distance from the appliance producer to the consumer by train		
Recyclable packaging			
Item	Unit	Amount	Data source
Cardboard packaging	kg	0.41	A
Polystyrene filler	kg	0.52	A
Packaging film	kg	0.21	A
Transport to the cardboard recycling facility: 132 km	kg * km	54.12	A/C
Recycling of cardboard	kg	0.41	A
Transport to the polystyrene and polyethylene waste management facility: 29 km	kg * km	21.05	A/C
Recycling of polystyrene	kg	0.52	A
Recycling of polyethylene	kg	0.21	A
EUR-pallet (single piece)	p	0.05	D
Transport to the pallet recovery centre: 29 km	kg * km	36.25	D/C
Average waste management of wood products in Italy	kg	1.25	A
Transport by train from the appliance manufacturer to the consumer	kg * km	1.14* d_t	A
Transport by lorry from the appliance manufacturer to the consumer	kg * km	1.14* d_l	A
Reusable packaging			
Item	Unit	Amount	Source
Head and bottom part	kg	4.90 / N / W	B
Head and bottom part	kg	2.10 / N / W	B
Support	kg	3.50 / N / W	B
Support	kg	3.50 / N / W	B
Filling	kg	0.13 / N / W	B
Packaging	kg	0.21 / N / W	B
Transport to the plastics recycling facility: 29 km	kg * km	415.80 / N / W	B/C
Average waste management of plastic materials in Italy	kg	9.10 / N / W	B
Recycling of polystyrene	kg	0.34 / N / W	B
Recycling of polyethylene	kg	4.90 / N / W	B
Transport by train from the appliance manufacturer to the consumer	kg * km	14.34 / W * d_t * 2	B
Transport by lorry from the appliance manufacturer to the consumer	kg * km	14.34 / W * d_l * 2	B

variations in the Excel files provided as Supporting Information. In addition, these calculation files can be used to increase the amount of materials consumed for some parts of reusable packaging (e.g., supports) in order to simulate the replacement of parts and components and to assess the resulting variations in the results.

A full parametric LCI – coherent with the functional unit definition – is made available in Table 1. In addition, Table 1 collects the data sources for the amounts: all the data referred to the mass of materials are taken from the producer. Differently, some amounts depend on assumptions that are defined during the case study and scenarios definition (e.g., transport distances, reuse cycles). More specifically, data sources were classified by distinguishing among: (i) primary data published online on recyclable packaging (labelled A); (ii) industry estimates on reusable packaging (labelled B); (iii) data generated during the case study design and validated by industrial partners (labelled C); and (iv) data derived from the scientific literature or inventory databases (labelled D). In line with the unit of measurement used in transport datasets (kg * km), two labels have been used to classify data sources: the first related to the mass of transported material, the second to the transport distance. For example, in the case of recyclable packaging, the mass of polystyrene and packaging option was published online (i.e., data source A); distances from waste management facilities were defined during the case study definition, as detailed in Appendix 1 (i.e., data source C). Therefore, the data source associated with "*Transport to the polystyrene and polyethylene waste management facility*" was classified as A/C. In contrast, for transport from the appliance manufacturer to the consumer, no data source label has been assigned to the distance, as it is treated as a parameter rather than a fixed value.

Some more details about the LCI and the background datasets used during its development are available as Supporting Information.

2.3.3. Life cycle impact assessment

In this study, the Environmental Footprint 3.1 (EF3.1) method is employed as LCIA method, as recommended in the context of the Product Environmental Footprint (PEF) initiative of the European Commission (Damiani et al., 2022). This LCIA method includes 16 environmental impact categories, which have all been calculated during the LCA. However, in the first stage, we decided to perform the breakeven point analysis using the *Climate Change* impact category. This impact category is particularly relevant for the packaging sector because, alongside Cumulative Energy Demand (CED) – which is not considered by the EF3.1 method – it reflects non-renewable resource use and correlates strongly with other impact categories such as fossil resource depletion, particulate matter formation, photochemical oxidant formation, and terrestrial acidification (Scipioni et al., 2013, Laurent et al. 2010). As reviewed in the study of Accorsi et al. (2014), there are indeed several examples in the literature of authors who previously used *Climate change* as a reference indicator, especially for ecodesign purposes (Sanyé-Mengual et al., 2014). The breakeven point analysis has been replicated for all other impact categories as a sensitivity analysis. Normalization and weighting of midpoint impact categories were performed to derive a single-score indicator, based on the EF 3.1 normalization and weighting approach. All calculations were carried out using SimaPro Craft v.10.2 (PRé Sustainability, 2025).

2.3.4. Life cycle interpretation

During the life cycle interpretation phase, results have been examined to evaluate the influence of the distance between the appliance producer and the consumer on the comparison between reusable and recyclable packaging. The LCA results are therefore interpreted through a breakeven point analysis, illustrating the environmental impact of reusable and recyclable packaging as a function of this distance (indicated in Table 1 as d_t for train transport, and d_l for lorry transport). The breakeven point is defined as the distance at which the environmental impacts of the two solutions are equivalent. This assessment is performed using *Climate change* as a reference indicator and considering 30 reuse cycles for reusable packaging (indicated as N in Table 1).

In addition, three sensitivity analyses have been conducted. The first sensitivity analysis is on the chosen environmental impact category used for the calculation of the breakeven point, underlining how this choice affects the results. The second sensitivity analysis is on the number of reuse cycles for the reusable packaging, and the third one on the mass of reusable packaging materials, and they are conducted to address the significant uncertainty of the parameters N and W. The number of reuse cycles of reusable packaging is indeed difficult to predict because it depends on various factors, such as accidental impacts during shipping and handling by operators. Therefore, variations in the assumed number of reuse cycles can be used to simulate the effects of damage to the reusable packaging.

The Supporting Information files contain the calculation of the breakeven distance for all impact categories proposed by EF3.1 (Damiani et al. 2022). These Excel files can be customized in order to change the model parameters (e.g., the number of reuse cycles), and the results will change accordingly.

3. Results

3.1. Case study results

Fig. 4 represents, for all scenarios considered in this study, how the *Climate Change* indicator varies as a function of the distance between the producer of the appliance and the consumer. As illustrated in Fig. 4, the *Climate Change* of reusable (in blue) and recyclable (in purple) packaging varies linearly with the distance. On the x-axis, we represent the distance from the producer to the consumer (from 0 to 2000 km), and on the y-axis, the *Climate Change* (expressed as kg CO_{2eq}). The breakeven points are represented in these charts as red dots, while triangles indicate the reference distances for all scenarios.

Fig. 4a represents the results for the Scenario 1 DS-road and Scenario 3 RD-road, in which all distances are entirely covered by lorry. Fig. 4b and Fig. 4c regard the scenarios involving intermodal transports, Scenario 2 DS-intermodal and Scenario 4 RD-intermodal, respectively.

Examining the profiles illustrated in Fig. 4a, it can be observed that the blue line exhibits a steeper slope than the purple one. This indicates that, as expected, transporting reusable packaging by lorry has a considerably higher impact than transporting recyclable packaging. The main reason is that reusable packaging entails a round-trip journey, meaning that the distances indicated on the x-axis must be covered twice by the transporter – once to deliver the washing machine and once to return the reusable packaging. Moreover, the substantially higher weight of the reusable packaging (14.34 kg) compared to the recyclable one (1.14 kg) further increases the environmental burden associated with transport. Fig. 4a shows that in the case where road transport is adopted, the breakeven point is 424.6 km (marked in red). This implies that for distances shorter than this, reusable packaging results as a more sustainable option than the recyclable one. Conversely, for longer distances, recyclable packaging is more favourable in terms of *Climate Change*. At a distance of exactly 424.6 km between producer and consumer, both packaging options result in the same impact, namely 4.3 kg CO_{2eq}. After determining the distance at the breakeven point, we compare it with the reference distances assumed in Scenario 1 DS-road and Scenario 3 RD-road. The triangles in Fig. 4a indicate that in both scenarios these distances (1481 km and 1749 km) far exceed the breakeven distance (424.6 km). Consequently, in these scenarios, recyclable packaging emerges as more advantageous compared to reusable packaging.

Regarding Scenario 2 DS-intermodal and Scenario 4 RD-intermodal, the involvement of intermodal transport alters the impact of the overall transport, thereby changing the slope of the blue and purple lines. For instance, in Scenario 2 DS-intermodal, 27% of the distance between producer and consumer is covered by a lorry, and 73.4% are covered by train. Since rail transport generally has a lower impact on *Climate Change*

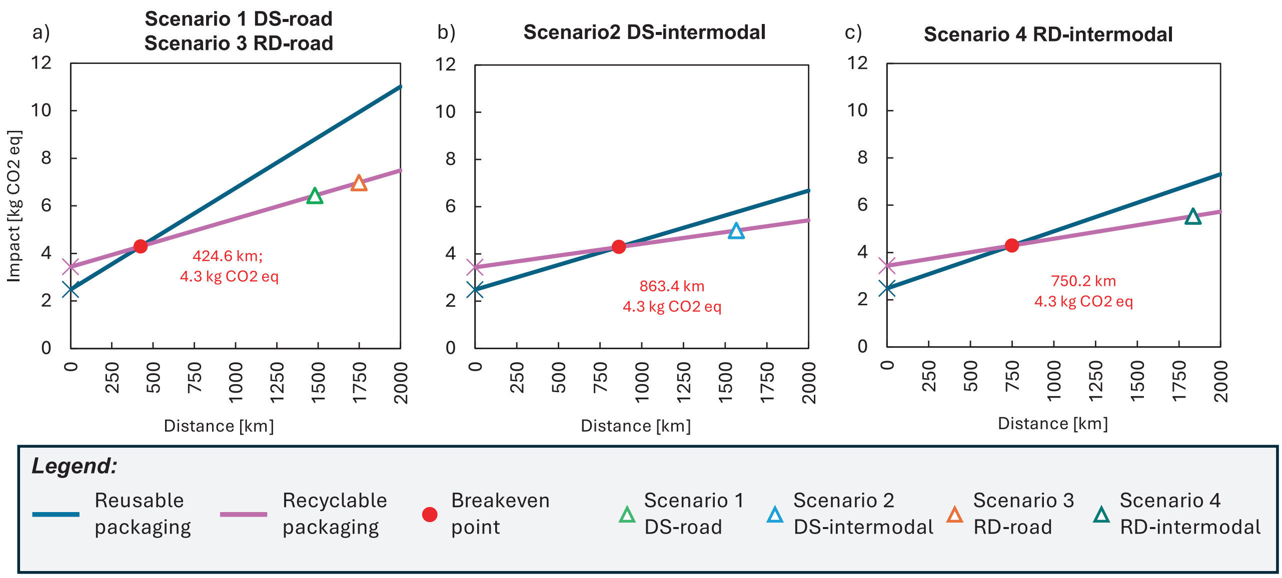

Fig. 4. Breakeven point analysis results referred to the functional unit of this study (1 appliance delivery), calculated considering Climate Change as the reference impact category. Results are illustrated for a) the Scenario 1 DS-road and Scenario 3 RD-road, b) the Scenario 2 DS-intermodal, and c) the Scenario 4 RD-intermodal.

compared to road transport, the slopes of both lines depicted in Fig. 4a decrease, thus determining an increase in the distance at the breakeven point from 424.6 km (valid for road transport only) to 863.4 km. Similarly, in Scenario 4 RD-intermodal, 37% of the distance travelled during the delivery is covered by lorry, and 63% by train. Accordingly, the distance at the breakeven point in Scenario 4 RD-intermodal is assessed to 750.2 km (Fig. 4c). Given that the reference distances assumed in Scenario 2 DS-intermodal and Scenario 4 RD-intermodal – namely 1567 km and 1835 km, respectively (marked as blue triangles in Fig. 4b and Fig. 4c) – it can be stated that also in these scenarios, recyclable packaging turns out as more environmentally sustainable than reusable packaging in terms of *Climate Change*.

It should be noted that the environmental competitiveness of reusable packaging would improve if packaging materials were also assumed to be recyclable, rather than being treated as disposed of at the end of life. Based on our calculations, the breakeven distance would consequently increase, but not to an extent sufficient to reverse the relative preference between reusable and recyclable packaging in the proposed scenarios.

Another potential variation of the proposed modelling framework involves adopting the avoided burden approach for recycling. By accounting for environmental credits from recycling, this approach would

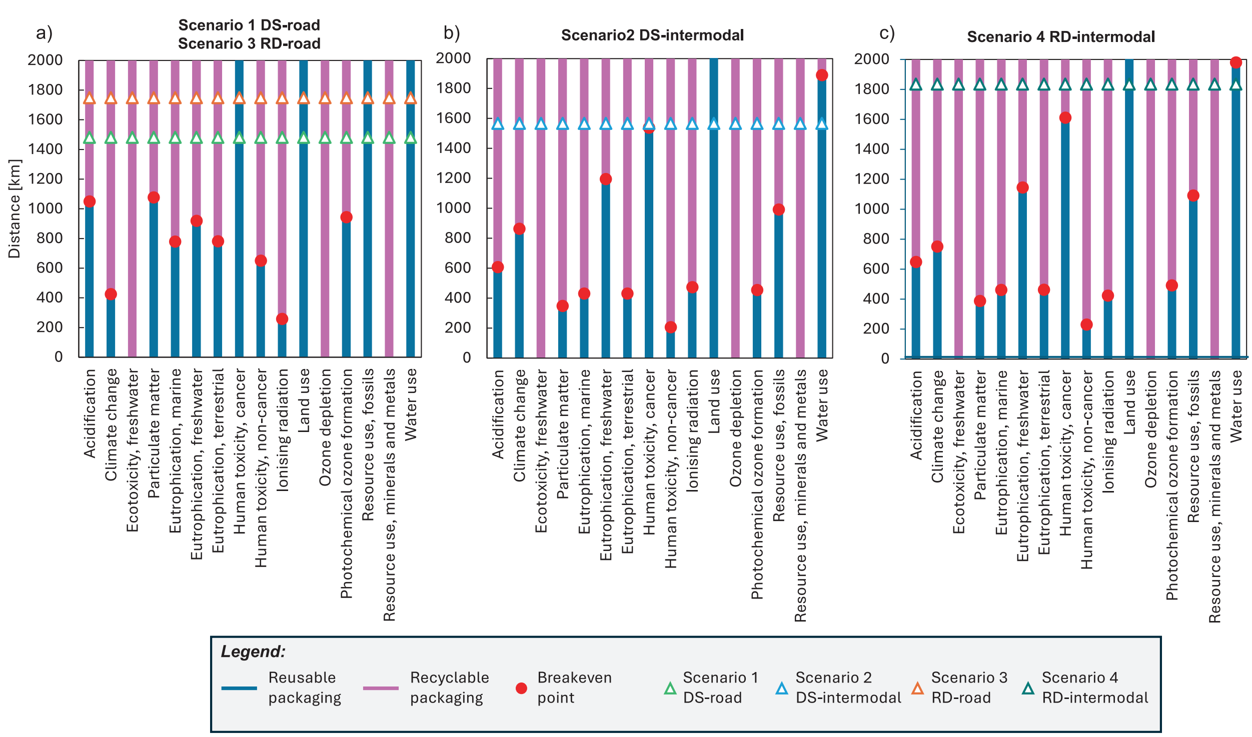

Fig. 5. Results of the sensitivity analysis on the reference impact category, calculated considering 30 reuse cycles. Results are referred to the functional unit of this study (1 appliance delivery) and illustrated for a) the Scenario 1 DS-road and Scenario 3 RD-road, b) the Scenario 2 DS-intermodal, and c) the Scenario 4 RD-intermodal.

further favour recyclable packaging, leading to a reduction in the breakeven distance. Consequently, the conclusions drawn for the analysed case studies would remain unaffected by this modelling choice, as recyclable packaging already emerges as the most environmentally favourable option for the *Climate change* impact category. Moreover, even if reusable packaging were also assumed to be recyclable, the overall conclusions would remain unchanged, since both packaging systems would benefit from reduced environmental impacts, resulting in a further decrease in the breakeven distance.

3.2. Sensitivity analyses

Using a sensitivity analysis we assessed how varying the environmental impact category the number of reuse cycles, and the mass of reusable packaging affects the breakeven distance.

Regarding the sensitivity analysis on the impact category, results are illustrated in Fig. 4, including a list of the impact categories on the x-axis and the distances on the y-axis. More specifically, the blue segments indicate the distance ranges for which the reusable packaging is the most environmentally sustainable solution, and the purple segments indicate the distances for which recyclable packaging outperforms the reusable one. The blue and the purple segments are separated by red dots, representing the breakeven distance. Tringles are instead used to mark the reference distances assumed in the test-case scenarios.

In particular, for Scenario 1 DS-road and Scenario 3 RD-road, the sensitivity analysis results are available in Fig. 5a. It is possible to observe from the chart that the breakeven distance is strongly dependent on the impact indicators. For several impact categories (*Acidification*, *Particulate Matter*, *Eutrophication, freshwater*, and *Photochemical Ozone Formation)*, it ranges between 800 and 1000 km. Differently, regarding the categories *Ecotoxicity, freshwater,* and *Ozone depletion*, no breakeven point exists because recyclable packaging maintains a lower impact regardless of distance. For these indicators, the environmental performance of reusable packaging is significantly penalized by the massive use of plastic materials such as polycarbonate. This indicates that reusable packaging has a lower environmental impact except in the case of extremely long-distance shipments, which are unlikely for a washing machine in Europe and are therefore not shown in the chart for clarity.

The above-mentioned considerations are valid for road transport (i.e., for Scenario 1 DS-road and Scenario 3 RD-road). However, similar patterns appear in Scenario 2 DS-intermodal (Fig. 5b) and Scenario 4 RD-intermodal (Fig. 5c). Indeed, similarly to Fig. 5a, these charts

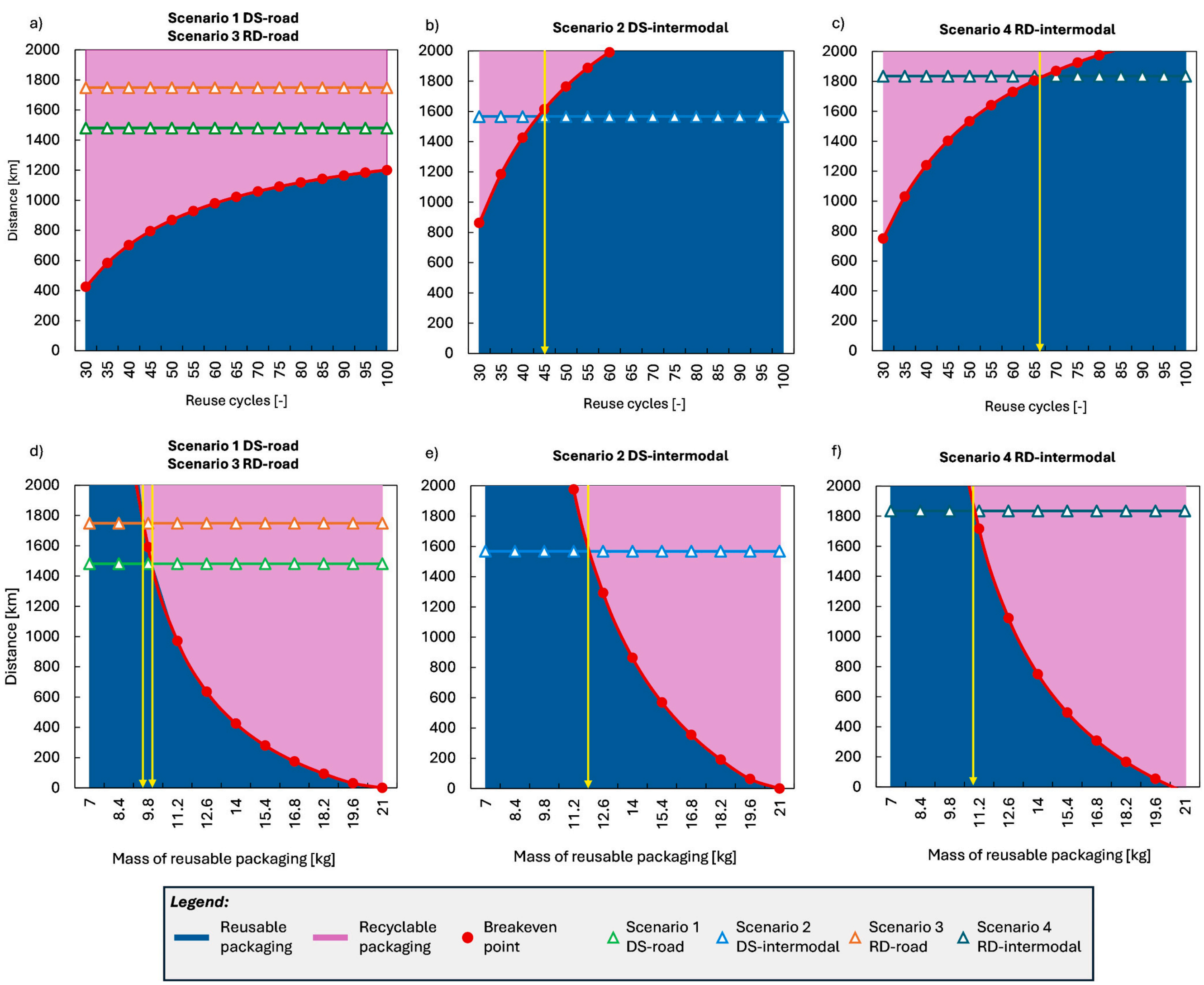

Fig. 6. Results of the sensitivity analysis on the number of reuse cycles and on the mass of reusable packaging for the impact category Climate Change. Results are referred to the functional unit of this study (1 appliance delivery). The results of the sensitivity analysis on the number of reuse cycles are illustrated for a) the Scenario 1 DS-road and Scenario 3 RD-road, b) the Scenario 2 DS-intermodal, and c) the Scenario 4 RD-intermodal. The results of the sensitivity analysis on the mass of reusable packaging are illustrated for d) the Scenario 1 DS-road and Scenario 3 RD-road, e) the Scenario 2 DS-intermodal, and f) the Scenario 4 RD-intermodal.

demonstrate that when intermodal transport is considered, the break-even point analysis is extremely sensitive to the impact category under evaluation. Based on the charts in Fig. 5, it is also possible to compare the reference assumed for each scenario (marked as triangles) with the breakeven distance. All the charts highlight that for most indicators, the triangles fall into the purple segments, which means that if the scenarios generated in this paper correspond to reality, recyclable packaging would be the winning solution for most environmental impact categories.

A more comprehensive comparison between reusable and recyclable packaging systems can be achieved by considering a single-score environmental impact indicator derived from the normalization and weighting of midpoint impact categories. Consistent with the *Climate Change* indicator and most other impact categories, the single-score results indicate that recyclable packaging is overall environmentally preferable to reusable packaging across all proposed scenarios. Further details on the breakeven transport distances calculated using the single-score indicator are provided in the Supporting Information. In addition, the Supporting Information includes summary tables reporting environmental impact values for all scenarios, as well as correlation matrices that describe, across all considered scenarios, the consistency of preference outcomes between reusable and recyclable packaging systems across different environmental impact categories.

An additional sensitivity analysis is conducted to estimate the influence of the number of reuse cycles, assuming that it could be reused more times than the minimum requirements set by design (30 reuse cycles). The breakeven point is therefore calculated for several reuse cycle values, ranging from 30 to 100. The environmental impact category *Climate Change* is again used as a reference metric for this purpose.

The results of this sensitivity analysis are reported in Fig. 6: the red curve in the charts indicates the breakeven distance as a function of the number of reuse cycles of reusable packaging. The area below the red line is painted in blue because, for distances lower than the breakeven, the reusable packaging outperforms the recyclable one; vice versa, the purple area above the red curve indicates that recyclable packaging is the winning solution for longer distances. However, in Scenario 1 DS-road and Scenario 2 DS-intermodal the reference distances are respectively set to 1481 km and 1749 km, the corresponding data points on the charts (depicted as triangles) fall into the purple area regardless of the number of reuses, which implies that the recyclable packaging turns out as the solution having the lower *Climate Change* in the reference conditions for these scenarios. In addition, since the red line representing the breakeven distance tends asymptotically to 1200 km, it is reasonable to assume that reusable packaging would not outperform the recyclable one even for extremely high reuse cycles.

By examining Scenario 2 DS-intermodal (Fig. 6b) and Scenario 4 RD-intermodal (Fig. 6c), some additional observations on intermodal transports can be made. In Scenario 2 (DS-intermodal), the breakeven distances represented by the red line increase more rapidly than in Fig. 6a, due to the combined use of train and lorry transport. This indicates that reusable packaging becomes competitive with recyclable packaging not only on short distances, but also across longer transport ranges. The reference distance selected for Scenario 2 DS-intermodal is 1567 km; as highlighted by the chart, if the number of reuse cycles exceeds 45, reusable packaging proves to be more advantageous than recyclable packaging at this distance and more. Similarly, in Scenario 4 RD-intermodal, 70 reuse cycles is the threshold to be achieved by reusable packaging in order to become competitive with the recyclable one. These outcomes can be useful as targets for reusable packaging designers, who are expected to develop a packaging that should be able to perform 45 – 70 cycles to be convenient in realistic distribution scenarios like the ones proposed here. Although it is not possible to compare these numbers of reuse cycles with empirical evidence for this reusable packaging, due to its currently limited deployment, the scientific literature indicates that similar levels of reusability (30–70 cycles) have been achieved in reusable crate systems (Coelho et al., 2020). Particular attention shall be paid to the transport way selection for the distribution, which may significantly alter the results.

Another option to increase the competitiveness of reusable packaging is to reduce material mass while preserving protective performance. The sensitivity analysis presented in Fig. 6 shows that even a moderate reduction – from 14.34 kg to 9.5 kg in road transport scenarios (Fig. 6d), or to 11 kg in intermodal scenarios (Fig. 6e and Fig. 6f) – would be sufficient to alter the preference between reusable and recyclable packaging. Below these mass thresholds, reusable packaging would emerge as the most environmentally sustainable option.

4. Discussion

Our research encourages further reflection on how these findings align with similar studies in other sectors where the focus on reusable packaging lies more in the reuse rate than in transport distances.

One of the main findings of this study is that recyclable packaging generally results in lower environmental impacts for large home appliances. In contrast, reusable options only become competitive under specific conditions: namely, high reuse cycles (45–70) or short transport distances (below 425 km for road transport). This is particularly significant as it contrasts with the conclusions of previous research focused on smaller, lighter packaging. For instance, earlier studies on food packaging often found that reusable options become environmentally preferable much sooner. A study on a national food supply chain found that food containers became environmentally advantageous after only 15 rotations (Accorsi et al., 2022). Other studies reported even lower break-even points, such as 8–13 uses for reusable takeout containers (Hitt et al., 2023) and 7–12 cycles for insulated reusable boxes in fresh food distribution (Kim et al., 2023). On the other hand, Coelho et al. (2020) report results consistent with those of the present study, showing that reusable crates are less impactful than recyclable alternatives at both 30 and 70 reuse cycles.

The study also identifies transport as a critical limiting factor for reusable packaging. This is due to the significantly higher weight of reusable containers (14.34 kg) compared to recyclable ones (1.14 kg), coupled with the need for reverse logistics. This conclusion is strongly supported by existing literature, which emphasizes the environmental relevance of logistics (Chowdhury and Kabir, 2024; Hallberg et al., 2023) and highlights how reusable systems require more complex transport arrangements than single-use alternatives (Accorsi et al., 2022). For small-scale Business-to-Consumer packaging, environmental performance also depends on additional trips made by customers to return the packaging (Hitt et al., 2023). Although this is not the case for large appliances, where the reusable packaging is returned by the delivery operator, this logistical setup does not sufficiently reduce the transport-related impact. On the other hand, reducing the weight of reusable packaging materials to approximately 9–11 kg, depending on the scenario, would be sufficient to make reusable packaging competitive with the recyclable alternative.

A comparison of our results with prior studies reinforces the view that no single packaging solution can be universally preferable (Accorsi et al., 2014; Gallego-Schmid et al., 2019; Kan and Miller, 2022; Gatt and Refalo, 2022; Goellner and Sparrow, 2014). Trade-offs must be evaluated case by case, and insights across sectors can help shape consistent sustainability metrics and support evidence-based decisions in packaging design and policy.

In detail, the study performs a breakeven point analysis focused on transport distances to identify environmental trade-offs between reusable and recyclable packaging and integrates validated, real-world logistics data from European industry partners. A central strength of our methodological framework is that, while it builds on well-documented case studies validated directly with industry partners, it also offers broader applicability. Our study demonstrates that our methodological framework is effective in highlighting how the conclusions of packaging environmental assessments can vary depending on the logistics of a product, which can be diverse and complex. By employing a breakeven point analysis, the methodology allows for the quantification of the critical distance at which the priority between reusable and recyclable packaging is reversed. This provides actionable guidance for decision-making across multiple stakeholders, including packaging designers, logistics providers, appliance manufacturers, and end consumers, underscoring its practical relevance and potential impact. The sensitivity analyses further highlight the influence of multiple environmental impact categories and reuse assumptions, confirming that results are not generalizable across all contexts but are highly dependent on material characteristics and operational conditions.

There are also implications from our study for both policymakers and businesses. It is acknowledged that these recommendations may be affected in the future by the increasing penetration of electric mobility in the freight transport sector, as well as by the decarbonization of energy sources supplying manufacturing industries and waste management facilities. Such developments are expected to be particularly favourable for reusable packaging systems, which would benefit more strongly from lower-impact transport modes. In addition, prospective, future-oriented analyses may consider the adoption of emerging packaging solutions, such as compostable packaging, which are currently predominantly applied in the food sector (Raźniewska, 2022).

From a policy perspective, the results suggest that universal mandates favouring reusable packaging, such as those initially proposed in the PPWR, may not be environmentally justified. In other terms, we provide empirical support for the theoretical criticisms expressed by Massarutto (2023) regarding the approach of the PPWR. One possible solution is to shift the focus of incentives to the system level, working on intermodal logistics infrastructure to reduce the overall environmental impact of transporting both products and packaging, or centralized return systems, and packaging standardization. Another key policy-related insight is that environmental policies should not focus on a single impact, such as CO_2 emissions. Instead, they should be based on multi-criteria assessments and comprehensive LCA evaluations to avoid shifting environmental burdens from one impact category to another.

For manufacturing companies, one recommendation emerging from this research is to map their logistics networks before considering the use of reusable packaging, even when driven by sustainability branding (Miao et al., 2023). Another implication is the importance of continued investment in research and development. Since packaging weight is identified as one of the main hotspots, companies should explore new materials to develop lighter reusable packaging that can still guarantee between 45 and 70 cycles. Moreover, investments in reusable systems are most effective when paired with intermodal or rail transport, which significantly extends the breakeven distance and enhances environmental performance. Given the growing sustainability demands from the retail sector (Midar et al., 2026), the research also suggests avoiding the inclusion of packaging reusability as a screening criterion for suppliers located far from distribution points. Some of the study's recommendations are also directed at trade associations, which could play a role in improving the sustainability of packaging design across companies. For example, by reducing material use in recyclable packaging or working towards the standardisation (Azzi et al., 2012) of reusable packaging to make it suitable for different products, thereby enabling the achievement of minimum reuse cycles even across various goods. In addition to extending the lifetime, another recommendation for reusable packaging producers is to design lightweight packaging structures to reduce the environmental impacts associated with transporting packaging materials, thereby making this solution environmentally favourable even over short transport distances. Further research and development are needed to identify lighter packaging architectures that preserve the required mechanical protective properties. Notably, combining weight reduction with the maximization of reuse cycles would represent the optimal strategy. Furthermore, manufacturers should consider that design choices are strongly influenced by the environmental impact category adopted as a reference for decision-making. Depending on the impact category under evaluation, LCA results may favour either recyclable or reusable packaging as the most environmentally sustainable option. In this context, the use of a single-score indicator – calculated through the normalization and weighting of all environmental impact categories – may represent a useful approach for comparing the two solutions.

5. Conclusions

This study provided a comparative LCA of recyclable and reusable packaging systems for large household appliances, focusing on washing machines as a representative product. By analysing four realistic European distribution scenarios and identifying breakeven transport distances, the research offers both methodological and practical contributions to understanding the environmental trade-offs between packaging strategies. The results confirm that recyclable packaging generally has a lower environmental impact, except in short-distance or intermodal transport conditions, where reusable packaging can become competitive if used for sufficient cycles. The answer to the Hamlet dilemma “to reuse or not to reuse?” is, as very often in comparative LCA studies, “it depends”. In the case of large appliances represented by washing machines, it depends on the transport distance and modes.

Although the study is relevant and advances research on the topic, certain limitations and future areas of investigation should be mentioned. One aspect not considered in this study relates to the standardisation of packaging. The variety of shapes and sizes of household appliances may hinder the adoption of standardised reusable packaging, increasing the risk of over-packaging and/or the need to include non-reusable materials to ensure a better fit. These factors may worsen the global performance of a return system for different types of products, leading to a natural increase in the number of reuse cycles required and a reduction in the distances within which reuse may perform better than recycling. Future research could take these aspects into account by analysing cross-compatible packaging solutions for different types of electronic products and assessing their environmental impact in both reuse and recycling scenarios.

Moreover, although our study identifies the minimum number of cycles and the weight required for reusable packaging to outperform the recyclable option, future research could focus on the factors that influence these thresholds. For instance, the rate at which reusable packaging is removed from the system and its breakage rates could further reduce the environmental performance of reuse.

Finally, future research should extend the analysis to include economic and operational feasibility assessments as well as the behavioural and organisational dimensions. Integrating customer communication strategies and information provision at the point of purchase with environmental and techno-economic assessments would support the development of more effective and operational reuse-oriented packaging policies. Comparative LCAs should also address other types of home appliances, explore alternative logistics routes such as maritime transport, and test new reusable packaging prototypes that incorporate innovative materials and modular designs. These directions will support a more comprehensive evaluation of packaging systems and guide policymakers and manufacturers in making informed, context-specific decisions toward more sustainable supply chains.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting Information

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wasman.2026.115522.

Data availability

The data that has been used is confidential.

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