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The selection of CONAI eco-design levers of packaging through Bayesian networks to improve environmental performance

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1. Introduction

The linear economy model, in which goods are produced, consumed, and discarded, is globally fueling the depletion of non-renewable resources and environmental pollution due to the generation of a huge amount of waste (Minelgaitė and Liobikienė, 2019). In this framework, a significant share of the total municipal waste generated is packaging waste. In fact, in developing countries packaging waste represents about 15-20% of total municipal waste and in developed countries packaging waste represents about 30-35% of total municipal waste (Wiesmeth et al., 2018 cited in Afif et al., 2022). In 2020, European Union (EU) countries generated about 79,5 million tons of packaging waste, of which: about 19,4% in plastics; about 41,1% in paper and cardboard; about 5% in metals such as aluminum and steel; about 19,1% in glass; about 15,2% in wood; and a residual part in other materials[1]. In particular, plastics packaging waste represents about 60% of the total plastics waste generated by EU countries (European Commission, 2018 cited in Joltreau, 2022). Plastics waste has extremely negative impacts on the environment and human health because it is generally not managed properly but is accumulated in landfills and dispersed in ecosystems (Rai et al., 2021).

To counter the waste problem, a transition from the linear economy model to the circular economy model is needed (De Giovanni and Folgiero, 2023). The circular economy is a production and consumption model that aims to create closed loops of material and energy in which the consumption of production inputs, release of emissions, and generation of waste are minimized (Geissdoerfer et al., 2016 cited in Sharma et al., 2021). The 10R model explains how the circular economy achieves these goals (Morseletto, 2020 cited in Sharma et al., 2021). In the product design and production stages, the circular economy is based on the following practices: "refuse" unnecessary and unsustainable products, materials, and production processes; "rethink" the entire product design from a circular and sustainable perspective; and "reduce" the consumption of production inputs. During the life cycle of products, the circular economy is based on the following practices: "reuse" products several times in their life cycle; "repair" defective products so that they continue to perform their original function; "refurbish" old products to modernize them; "remanufacture" parts of discarded products to produce new products with the same original function; and "repurpose" discarded products or their parts to produce new products with a different function from the original one. In the end of the life cycle of products, the circular economy is based on the following practices: "recycle" waste to produce recycled materials and "recover" energy by incinerating waste. Therefore, the circular economy model (refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle, recover), unlike the linear economy model (produce, consume, dispose), allows to design and produce products in a sustainable way, to extend the life cycle of products and to enhance the value of products that have reached the end of their life cycle. The circular economy practices not only have a positive impact on the environmental performance of companies, but also

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[1] Eurostat; last update 21/03/2023; Packaging waste by waste management operations; https://ec.europa.eu/eurostat/databrowser/view/env_waspac/default/table?lang=en

on their long-term economic performance. In fact, companies can save on raw material costs, increase process efficiency, take advantage of new business opportunities, and access to green financing. In addition, such practices increase innovation, cooperation with different actors, competitiveness and reputation of companies (Maranesi and De Giovanni, 2020).

The circular economy model is at the heart of directives issued by the EU to counter the waste problem. Lorang et al. (2022) report that in 2008 the European Commission (EC) with the Waste Framework Directive 2008/98/EC determined a hierarchy of strategies to be pursued in waste management prior to disposal, in order of preference: prevention, reuse, recycling, and recovery. In particular, they report that the issue of packaging waste attracted the interest of the EC since 1994 with the implementation of the Packaging and Packaging Waste Directive (PPWD) 94/62/EC, which was amended in 2018 in Directive 2018/852/EU. The latter directive of the European Parliament set minimum recycling targets to be mandatorily achieved by 2025 and 2030 for packaging waste in general and for specific packaging materials (Sazdovski et al., 2021). In particular, the targets for 2025 and 2030 are respectively: 65 and 70% for packaging waste in general; 50 and 55% for plastics packaging; 75 and 85% for paper and cardboard packaging; 50 and 60% for aluminum packaging; 70 and 80% for ferrous metals packaging such as steel; 70 and 75% for glass packaging; 25 and 30% for wood packaging[2]. In addition, regarding plastics packaging, the EU in 2018 also set a target to make all plastics packaging reusable or recyclable by 2030 (Lorang et al., 2022).

The packaging design phase, from the generation of the product idea to its production, is crucial to reduce the packaging waste problem. In fact, Ahmad et al. (2018) report that the design phase is responsible for about 80% of the sustainability impacts of products. Therefore, the main efforts should not be directed at the treatment of existing packaging and packaging waste but should be directed at the design of new packaging, a stage where key decisions are made in terms of circularity and sustainability such as the materials to be used, the production processes to be implemented, and the activities to be undertaken at the end of the life cycle (Zhu et al., 2022). Ahmad et al. (2018) report that product design that incorporates the principles of circularity and sustainability can be called "eco-design" and is aimed to produce products with a low environmental impact and also with better economic and social performance. In addition, they report that several methods can be used to support eco-design of products, the most popular of which is Life Cycle Assessment (LCA), which allows the assessment of the impacts of products on different environmental categories during their entire life cycle, from the extraction and production of materials to the end of the life cycle.

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[2] Official Journal of the European Union; L 150; 14/06/2018; Directive (EU) 2018/852 of the European Parliament and of the Council of 30 May 2018 amending Directive 94/62/CE on packaging and packaging waste (Text with EEA relevance); p. 141-154; https://eur-lex.europa.eu/eli/dir/2018/852/oj

Governments in many developed countries implement various tools to incentivize companies to packaging eco-design and to reduce the packaging waste problem. They refer that these tools are part of the Extended Producer Responsibility (EPR) policy, based on the "polluter pays" principle, which makes producers organizationally or financially responsible for the products made also when they become waste (Afif et al., 2022). In this way, producers internalize the costs associated with the disposal of the packaging waste they generate because they are responsible for the collection, sorting, and preparation for recycling. This incentivizes producers to packaging eco-design because to reduce their waste management costs they must prevent waste formation by designing packaging that are optimal in terms of materials and size and reduce recycling costs by designing packaging that are easily recyclable. Moreover, collective EPR policies are adopted in most cases for economies of scale reasons. In collective EPR generally producers pay an advance disposal fee based on weight and packaging material to a producer responsibility organization, which takes legal responsibility from its members and is responsible for the collection, sorting, and recycling of the waste produced by its members (Joltreau, 2022).

In the Italian packaging industry, collective EPR policy is implemented through CONAI, the National Packaging Consortium (Lorang et al., 2022). CONAI is a non-profit consortium established in 1997 with 736.000 packaging producers and users as members and which performs various tasks related to packaging waste management and the achievement of statutory recycling and recovery targets[3]. CONAI coordinates seven private non-profit consortia that manage specific packaging materials: plastics are managed by CO.RE.PLA; bioplastics are managed by BIOREPACK; paper and cardboard are managed by COMICO; aluminum is managed by CIAL; steel are managed by RICREA; glass is managed by CO.RE.VE; and wood are managed by RILEGNO[3]. Rigamonti et al. (2015) study the role of CONAI in packaging waste management in Italian industry. CONAI is financed through the CONAI Environmental Contribution (CAC), which is calculated on packaging sold from the last producer to the first user. A portion of the CAC is retained by CONAI, while the remainder is transferred to the reference consortium for the specific packaging material. CONAI handles both packaging waste that comes from separate collection and packaging waste that comes from private individuals. Regarding the first ones, local authorities that adhere to the agreement between CONAI and National Association of Italian Municipalities (ANCI) manage the collection of urban packaging waste and its transportation to the reference consortium for the specific packaging material. The latter pays a fee to local authorities for collection and is responsible for managing packaging waste by sending it for recycling and/or recovery. In 2021, CONAI contributed to 50% of the packaging waste recycling rate achieved by Italy (73,3%) and achieved the following recycling rates for packaging materials: 55,6% for plastics and bioplastics packaging; 85,1% for paper and cardboard packaging; 67,5% for aluminum packaging; 71,9% for

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[3] CONAI; June 2022; General program for prevention and management of packaging and packaging waste; Final general report 2021; https://www.conai.org/chi-siamo/risultati/

steel packaging; 76,6% for glass packaging; and 64,7% for wood packaging[3]. Therefore, the recycling rates achieved by CONAI are above the targets for 2025 and 2030 set by PPWD after the 2018 amendment[2].

Mattia et al. (2021) observe in the Italian packaging industry, one of the most important in the world in terms of production which a sale of 7,6 billion USD in 2018, a strong focus on packaging eco-design. They recognize the importance of CONAI in the industry, which promotes innovation, communication, knowledge sharing, and collaboration along supply chains to support companies in packaging design, production, and disposal. In particular, Cozzolino and De Giovanni (2023) refer that CONAI identifies seven eco-design levers to incentivize companies to design circular and sustainable packaging: *"facilitation of recycling activities"*, *"logistics optimization"*, *"optimization of production processes"*, *"raw material saving"*, *"reuse of packaging"*, *"simplification of the packaging system"* and *"use of recycled material"*. Several practices can be implemented to eco-design packaging. The seven CONAI eco-design levers represent a comprehensive set of practices that can be adopted by companies on all types of packaging: packaging in different materials and packaging for different products.

However, in the literature on packaging eco-design, papers that study concrete cases of packaging eco-design analyze the environmental benefits of a single packaging eco-design practice or a few packaging eco-design practices. In addition, these papers focus on specific types of packaging: packaging in specific materials and packaging for specific products. To our knowledge, Cozzolino and De Giovanni (2023) are the only ones to consider a comprehensive set of packaging eco-design practices, packaging in different materials and packaging for different products, through the analysis of 603 concrete cases of success in which Italian companies have implemented CONAI eco-design levers on packaging to improve three environmental indicators: CO2 emissions, energy consumption and water consumption. Cozzolino and De Giovanni (2023) analyze the links among CONAI eco-design levers and identify the best eco-design levers for each environmental indicator. For example, they report that the best CONAI eco-design levers to reduce CO2 emissions are, in order of preference: *"reuse of packaging"*, *"facilitation of recycling activities"*, *"simplification of the packaging system"*, *"raw material saving"*, *"logistics optimization"*, *"optimization of production processes"*, and *"use of recycled material"*. However, companies need more precise guidance on which CONAI eco-design levers they should implement. In fact, companies would implement only one of the suggested eco-design levers to reduce CO2 emissions might achieve suboptimal environmental performance because some eco-design levers work better when combined with other levers to take advantage of synergies. Similarly, if they implemented multiple eco-design levers among those suggested to reduce CO2 emissions, they might incur high costs and achieve suboptimal environmental performance due to trade-offs among the levers. Therefore, companies should understand which eco-design levers are effective when implemented individually and which eco-design levers are effective combined in portfolios to exploit synergies. Our paper aims to provide companies a clear guidance for the selection of CONAI eco-design levers. Therefore, we ask the following three research questions (RQ).

RQ1. What are the links among CONAI eco-design levers, among environmental indicators, and among CONAI eco-design levers and environmental indicators? We build and analyze the complex network of relations that includes all possible links among CONAI eco-design levers, among environmental indicators, and among CONAI eco-design levers and environmental indicators. In this way we provide to companies a reference plan for the selection of CONAI eco-design levers.

RQ2. What is the impact of CONAI eco-design levers on environmental indicators when implemented individually? We model scenarios in which each eco-design lever is implemented individually to analyze its contribution to improving environmental indicators. In particular, we consider a CONAI eco-design lever effective when implemented individually if it improves environmental indicators relative to their benchmarks. The benchmark of each environmental indicator indicates its value in a scenario where companies do not implement any CONAI eco-design lever. In this way, we suggest to companies which CONAI eco-design levers are convenient to implement individually.

RQ3. What are the portfolios of CONAI eco-design levers that improve environmental indicators? We build different portfolios of CONAI eco-design levers that exploit synergies among CONAI eco-design levers to improve each environmental indicator relative to its benchmark. In this way, we suggest to companies the portfolios of CONAI eco-design levers best suited to their environmental goals

To pursue the research aim, we study the same sample used by Cozzolino and De Giovanni (2023), consisting of 603 successful cases in which Italian companies implemented CONAI eco-design levers on different types of packaging to improve three environmental indicators: CO2 emissions, energy consumption and water consumption. In particular, following De Giovanni et al. (2022), we implement Bayesian Networks (BN) and modern Machine Learning (ML) tools on the sample to create sophisticated decision supports for companies.

Our paper is organized as follows: in Section 2 we conduct an extensive literature review on packaging eco-design; in Section 3 we show the sample and procedure used in the analysis; in Section 4 we present the results of the analysis; in Section 5 we discuss the contributions provided by our results; in Section 6 we conclude the paper.

2. Literature review

2.1. Packaging overview

The term packaging refers to any object that externally covers products (Wyrwa and Barska, 2017). Packaging assumes different functions (García-Arca and Carlos Prado Prado, 2008), is composed of different levels (Twede, 1992), and can be made of different materials (Ibrahim et al., 2022).

2.1.1. Functions

García-Arca and Carlos Prado Prado (2008) refer that Johansson et al. (1997) attribute three functions to packaging: the logistics function, the marketing function, and the environmental function. We explore the logistic and marketing function of packaging, while the environmental function of packaging is discussed in Subsection 2.2. Ahmad et al. (2022) state that packaging has a logistical function because it is involved in all activities in the supply chain of products from their packaging to their consumption, such as: transportation, distribution, storage, and handling. In particular, Lindh et al. (2016) state that in all these stages of the supply chain, packaging protects products, simplifies their handling, and communicates information. First, packaging performs a dual protective function during transportation, distribution, storage and handling: it protects the contents from the external environment and protects the external environment if the contents are hazardous. (Wyrwa and Barska, 2017). According to Lindh et al. (2016), the protective function of packaging depends on: mechanical properties, which protect products from impacts; barrier properties, which protect products from spoilage agents such as gases, humidity, and microorganisms; thermal properties, which protect products from temperatures; and sealing properties, which protect products from leakage and contamination. Second, packaging facilitates product handling for all supply chain actors during transportation, storage, distribution, and facilitates product use for consumers (Wyrwa and Barska, 2017). The ease in handling products depends on physical elements of packaging such as volume and weight (Lindh et al., 2016). Third, packaging communicates information through words, symbols, and barcodes printed on its surface and/or on labels (Lindh et al., 2016). This allows all actors involved in the supply chain to share information about products, such as their fragility (Choi and Lee, 2019). Similarly, this provides information to consumers about the products, their use and their end-of-life treatment (Wyrwa and Barska, 2017). The logistical function of packaging is linked to its marketing function (García-Arca and Carlos Prado Prado, 2008). In fact, Lindh et al. (2016) report that packaging also communicates in order to promote products to consumers. Information provide by packaging and their design elements such as graphics, shapes, and colors perform the marketing function of products because they communicate information, values, and meanings that influence perceptions of consumer, differentiate products in their minds, and attract them to purchase (Rundh, 2016).

2.1.2. Levels

Twede (1992) report that packaging is a system composed of three levels of packaging: primary packaging, secondary packaging, and tertiary packaging. Primary packaging first covers products to protect them and facilitate their transportation, distribution, storage, and handling in the supply chain (Georgakoudis and Tipi, 2021). Primary packaging, being purchased by consumers (Wikström et al., 2014), also assumes the function of promoting products, providing information to consumers (Georgakoudis and Tipi, 2021), and simplifying the use of products. For example, a plastic bottle is a primary packaging. Secondary packaging groups multiple primary packaging together to further protect products and to further simplify their transportation, distribution, storage, and handling in the supply chain (García-Arca et al., 2020). For example, a corrugated cardboard box in which plastic bottles are stored is secondary packaging. Tertiary packaging groups multiple secondary packaging together to protect them and especially simplify their transportation in the supply chain (García-Arca et al., 2020). For example, the additional layer that allow corrugated cardboard boxes to be placed on a pallet is a tertiary packaging. Secondary and tertiary packaging also assume the function of communication because they allow supply chain actors to share various information such as the fragility of products (Lindh et al., 2016). The three levels of packaging are not always necessary because, for example, primary packaging can be stored directly in tertiary packaging (Ahmad et al., 2022). However, all levels of packaging should be designed simultaneously because changing one level could lead to changes on the other levels (Wikström et al., 2014). Therefore, all levels and their relationships should be considered in the LCA of packaging (Molina-Besch et al., 2019).

2.1.3. Materials

In packaging design, it is necessary to select the materials best suited to the needs of the products to be covered, because each material has different advantages and disadvantages in terms of cost and properties (Ibrahim et al., 2022). Varžinskas et al. (2020) refer that packaging can be made from a single material (mono-material packaging), from different materials combined in indistinguishable layers (multilayer packaging), or from different materials that can be separated manually. They state that the main materials used in packaging are plastics, paper/cardboard, metals, glass and wood. Specifically, the global packaging industry in 2019 consisted of plastics 43,2%, paper/cardboard 33,2%, metals 12,1%, glass 5,8%, and other materials 4,7%[4]. Moreover, in addition to these basic materials, packaging also includes auxiliary materials such as adhesives and inks (Li and Sun, 2020). Mendes and Pedersen (2021) refer that packaging is the main application of plastics, with 26% of total manufactured plastics used. The most commonly used plastics in packaging are polypropylene (PP), polyethylene terephthalate (PET), polyethylene (PE), and polystyrene (PS) (Salwa et al.,

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[4] Lucía Fernández; 10/03/2022; Distribution of packaging demand worldwide in 2019, by material type; Statista; https://www.statista.com/statistics/271601/packaging-materials-in-the-global-packaging-market-since-2003/

2019 cited in Mendes and Pedersen, 2021). Plastics offer significant advantages over other materials such as ease of processing, low cost, light weight, transparency, printability, and excellent protective properties (Yaroslavov et al., 2022). An alternative to traditional plastics are bio-based and/or biodegradable materials called bioplastics, which are discussed in Subsection 2.3. Paper and cardboard offer similar advantages to plastics such as low cost, light weight, and printability, but they have inferior protective properties to plastics such as poor barrier properties to humidity and water (Bandara and Indunil, 2022). The properties of paper and cardboard can be improved by combining them with other materials such as plastics and metals or by adding additives, but the latter can cause migration of hazardous substances from the packaging to the contents (Deshwal et al., 2019). Metals, for example, aluminum and steel, offer ease of processing, rigidity, and excellent protective properties such as barrier properties to light, gas, and humidity and thermal properties (Deshwal and Panjagari, 2020). In addition, they are 100% recyclable materials (Kazulytė and Kruopienė, 2018). However, metals are more expensive than other materials, corrode due to humidity, and can cause migration of hazardous substances from the packaging to the contents (Deshwal and Panjagari, 2020). Glass offers rigidity and excellent liquid and gas barrier properties, which ensure the quality of the contents, and chemical durability, which ensure the safety of the contents by preventing the migration of hazardous substances from the packaging (Guadagnino et al., 2022). Glass offers high recyclability, very close to 100% (Kazulytė and Kruopienė, 2018). However, glass is a heavy material with high mechanical and thermal fragility, which makes it dangerous in logistics activities (Ibrahim et al., 2022). Wood is a durable material that offers ease of processing, low cost, light weight, and rigidity (Andreolli et al., 2017). However, it requires the addition of chemicals to reduce the disadvantages of its biodegradation caused by microorganisms and its dimensional instability caused by humidity (Papadopulos et al., 2019). In Europe in 2020, the average recycling rates for packaging materials were 37,9% for plastics, 81,5% for paper/cardboard, 75,7% for metals, 75,9% for glass, and 31,9% for wood[5].

2.2. Eco-design for all types of packaging: the CONAI eco-design levers

Packaging has an environmental function (Johansson et al., 1997 cited in García-Arca and Carlos Prado Prado, 2008). In fact, it should be designed to perform its functions effectively while minimizing negative impact on the environment (Zhu et al., 2022). This subsection explores the environmental function of packaging using the CONAI eco-design levers of packaging. According to Cozzolino and De Giovanni (2023), CONAI identifies the following seven categories to incentivize companies to design circular and sustainable packaging: *"facilitation of recycling activities"*, *"logistics optimization"*, *"optimization of production processes"*, *"raw material saving"*, *"reuse of packaging"*, *"simplification of the packaging system"*, and *"use*

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[5] Eurostat; last update 21/03/2023; Recycling rate of packaging waste by type of packaging; https://ec.europa.eu/eurostat/databrowser/view/CEI_WM020__custom_354860/bookmark/table?lang=en&bookmarkId=bc39f400-65cd-40a8-bf14-c995c729e2a5

of recycled material". The CONAI eco-design levers represent a comprehensive set of practices that can be applied to all types of packaging: packaging in any material and packaging for any product. Starting from the definition of each eco-design levers provided by CONAI, we relate the reviewed studies to the appropriate category.

2.2.1. "Facilitation of recycling activities"

CONAI defines the eco-design lever *"facilitation of recycling activities"* as the design of packaging that simplifies all activities related to the recovery and recycling of packaging waste[6]. Okan et al. (2019) refer that waste recycling takes place in four modes: primary recycling, in which waste is recovered and reused without modification; secondary recycling, in which waste is mechanically processed; tertiary recycling, in which waste is chemically processed; and quaternary recycling, in which waste is incinerated in order to produce energy. In particular, we focus on mechanical recycling. According to Jeswani et al. (2021) in mechanical recycling, waste in collected, sorted, washed and shredded in plants to obtain recycled materials with which to make new products. They state that one of the main barriers to mechanical recycling is the recovery of waste suitable for mechanical processing. The improvement of packaging recycling requires not only downstream improvements in sorting and recycling plant processes and technologies, but also upstream improvements in packaging design by producers to reduce environmental pollution caused by the huge amount of packaging waste produced and discarded (Antonopoulos et al., 2021).

First, packaging should be designed to make recycling feasible. Eriksen and Astrup (2019) consider plastic packaging waste generated by households in Copenhagen and observe that packaging design does not optimize recycling activity. In fact, about 11% of packaging waste is represented by black plastic, which are not recyclable because they cannot be detected by near infrared technology in the sorting activities of recycling plants, and about 44% of the waste is represented by multilayer packaging, a significant portion of which is not recyclable because it cannot be mechanically separated. Bauer et al. (2021) state that multilayer packaging offers light weight packaging with excellent protective properties. However, currently these packaging that combine different materials into indistinguishable layers are not recyclable, and it is preferable to produce mono-material packaging. The same is also true for packaging composed of different materials that can be separated manually because they complicate recycling activities. In fact, Vazquez et al. (2022) report that the three parts that compose shampoo bottles (body, cap, and label) should be made of a single plastic material, such as high-density polyethylene (HDPE), to improve the recyclability of the products. In fact, they report that different types of plastic have different characteristics that complicate recycling operations. Keller et al. (2022) provide recommendations to improve recyclability of packaging such as avoiding fillers, making labels in the same material of the other parts to simplify sorting, producing water-soluble labels that can be easily

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[6] ECO TOOL CONAI; The levers of eco-design; https://www.ecotoolconai.org/index.php?r=site/page&view=ecopacking

removed during washing, and opting for transparent packaging to increase material recovery because near infrared technology cannot identify intense colors in sorting.

Second, packaging should be designed to incentivize consumers to separate waste properly. Williams et al. (2018) and Nemat et al. (2022) study the preferences of Swedish consumers and identify the types of packaging that hinder the conduct of proper waste separation. Specifically, these are packaging that are perceived to be of low value by consumers for the following reasons: they require time and water for the cleaning process because they are complicated to empty, clean and disassemble due to their design and/or contents; they are composed of parts made of different materials that make sorting more time-consuming and complicated; they are associated with less material waste because they are low in volume and weight; they are unable to retain their odors inside because they are difficult to reseal; and they do not provide visible, clear, and complete information on how they should be sorted. The importance of the information provided by packaging also emerges from the study of Norton et al. (2022), in which British consumers do not know that black plastic are not recyclable. Wikström et al. (2016) compare a tube of ground meat and a tray of ground meat. They show that the tray, being larger in size and easier to empty and clean, is considered more valuable by consumers and is more likely to be recycled. Therefore, the reduction of packaging size may lead to material savings in the short term, but hinder material recovery in the long term and increase the waste problem.

2.2.2. “Logistics optimization”

CONAI defines the eco-design lever *“logistics optimization”* as the design of packaging that optimizes all logistics operations, loads transported by vehicles, and the relationship between the three levels of packaging[6]. García-Arca et al. (2014) introduce the concept of “sustainable packaging logistics” to refer to the design of packaging that simplifies supply chain activities, reducing their relative costs and environmental impacts. García-Arca et al. (2017) identify packaging redesign interventions to optimize logistics such as the simplification of materials used in packaging, the reduction of packaging size, the redesign of the relationship between the three levels of packaging, and the variation of packaging elements such as shape. This optimizes the size of packaging and the loading capacity of vehicles used by companies to transport products. In fact, a higher number of products transported on each vehicle implies a lower number of trips made by the vehicles. This results in a reduction in the costs and environmental impacts, such as the release CO2 emissions, of transportation (Ahmad et al., 2022). The sustainable practices adopted on packaging to optimize logistics activities can be supported with the implementation of new digital technologies. Romagnoli et al. (2023) report that a portfolio of digital technologies that includes a transportation management system, Internet of Things, ML, robotics, and 3D printing allows companies to obtain a huge amount of information to be used in the decision-making process to plan logistics activities efficiently. In this way, the environmental and economic performance of logistics achieved by the sustainable practices can be maximized. In this regard, Vishkaei and

De Giovanni (2023) propose a multi-depot, multi-product, multi-vehicle delivery model that can reduce the environmental impacts and costs of logistics activities with the support of digital technologies. Ahmad et al. (2022) refer that packaging redesign to optimize logistics occurs mainly on secondary packaging such as corrugated cardboard boxes. In fact, interventions on primary packaging are riskier because they can alter consumer perceptions and behaviors (Georgakoudis et al., 2018). While interventions on tertiary packaging are little considered because the equipment used in transportation, such as pallets, are generally standardized (Ahmad et al., 2022).

Georgakoudis et al. (2023) consider the modification of the shape of a PET bottle from cylindrical to rectangular without changing its capacity. They show that this change in bottle shape reduces secondary packaging containing 20 bottles by about 19%, carries about 27% more bottles on each pallet, reduces logistics costs, and reduces CO2 emissions. Georgakoudis et al. (2018) compare a corrugated cardboard box to transport two-stroke engine lubricant bottles with two alternative boxes. Specifically, the proposed third box is the better alternative because it allows to transport 2000 more bottles on each vehicle, to avoid the use of 117 boxes, to reduce logistics costs, and to reduce CO2 emissions. García-Arca et al. (2020) present three case studies in which they examine the relationship between corrugated cardboard box redesign and logistics optimization. In the first case study, several modifications on three boxes avoid the use of 300 boxes, reduce logistics costs by 120.000 EUR, reduce cardboard consumption by 70 tons, and reduce plastics consumption by 2.5 tons. In the second case study, the optimization of how products are placed in the boxes, the reduction in the length and width of the boxes because they do not need to be palletized, and the increase in the height of the boxes to contain more products, reduce logistics costs by about 25%. In the third case study, the implementation of three die-cut boxes to match the size of the packaging to the orders received from customers saves about 10% in logistics costs.

2.2.3. “Optimization of production processes”

CONAI defines the eco-design lever *“optimization of production processes”* as the implementation of packaging production processes that reduce the consumption of production inputs and the generation of production waste[6]. According to Molina (2021), production transforms raw materials into finished products through related processes that add value. Liu et al. (2021) report that production processes significantly impact the environment because they consume production inputs such as materials, energy, and water and because they emit production wastes such as scrap, waste gases, and wastewater. They state that optimization of production processes improves environmental and economic performance because it increases efficiency, reduces resource consumption, reduces waste generated, and reduces costs. We discuss the optimization of packaging production processes.

Poovarodom et al. (2015) analyze the production of HDPE films, linear low-density polyethylene (LLDPE) films, and PP films for packaging. They observe an increase in global warming potential of 19-67% after their production, mainly caused by the high energy consumption and significant CO2 emissions of printing and laminating production processes. Kliopova-Galickaja and Kliaugaite (2018) focus on the printing of PP films and PE films for packaging. They show the optimization of this production process through three interventions: the replacement of solvent-based inks with water-based inks, the implementation of heat recovery systems, and the implementation of LED lamps. These interventions reduce annual costs by about 130.000 EUR and reduce per ton of packaging produced the consumption of solvent-based materials by 34,74%, energy consumption by 21,5%, CO2 emissions by 24,6%, and volatile organic compound emissions by 92,5%. He et al. (2021) focus on the lamination of three-layer packaging bags combining biaxially oriented polypropylene (BOPP), vacuum metalized polyethylene terephthalate (VMPET) and PE. They compare the innovative solvent-free lamination process, which bonds the different layers of materials using a solvent-free adhesive that does not require drying, with the traditional dry lamination process, which bonds the different layers of materials using a solvent-based adhesive that requires drying. The innovative lamination method optimizes the production process because it reduces energy consumption by 74,1%, CO2 emissions by 86,37%, and volatile organic compound emissions by 94,5%. Molina (2021) shows that optimizing the production processes of a plastics packaging company reduced the production waste of the extrusion process from 3,43% to 3,39%, the lamination process from 0,93% to 0,44%, and the sealing process from 2,80% to 1,85%. They also report that the decrease in waste has reduced the time and cost of production processes. Mourad et al. (2014) consider the many interventions made by a plant to optimize production processes for kraft paper and folding carton for packaging such as using a more efficient production method, implementing biomass boilers and implementing ultrafiltration systems for wastewater treatment. They report that the interventions significantly reduced the impacts of production processes on the environmental categories considered and reduced per ton of kraft paper and folding carton produced wood consumption by 7,2% and 6,6% respectively, electricity consumption by 5 and 21% respectively, and water consumption by 8,5% for folding paper. Jiang and Zeng (2019) consider the production of wood composite plastic packaging boxes using bamboo as wood fiber and HDPE and PP as plastic resin. They compare the innovative extrusion-compression production process, which uses a four-cavity mold, and the traditional injection molding production process, which uses a single-cavity mold. The innovative method optimizes the production process because the four-cavity mold increases the number of boxes produced per hour from 40 to 288 and reduces energy consumption by 29,81%. In addition, boxes produced by the innovative method have better characteristics in terms of mechanical properties and deformation stability.

García-Arca et al. (2017) refer that packaging optimization can also concern the product packaging processes performed by companies to reduce costs and environmental impacts. Wang et al. (2021) consider the automated packaging process of a panel furniture producer. The company introduced software to computerize and optimize the packaging process that reduced the total amount of packaging used by 2,96% and the consumption of corrugated board per product by 12,4%. Manfredi and Vignali (2015) compare hot-fill and aseptic packaging systems for sterilizing and packaging PET juice bottles. Both systems significantly impact several environmental categories. However, hot-fill systems require heavier bottles to resist temperature changes. Therefore, overall, aseptic packaging systems are environmentally preferable because they generate lower environmental impacts by an average of about 20% in all categories considered. In addition to reducing environmental impacts, optimizing the packaging process offers benefits such as increased efficiency, increased productivity, reduced costs (Hakim and Istiyanti, 2015; Zhu et al., 2017; Xu, 2020), and reduced risks to workers (Teixeira et al., 2022).

2.2.4. "Raw material saving"

CONAI defines the eco-design lever *"raw material saving"* as the design of packaging of reduced weight, with the same packaged products and performance, in order to decrease raw material consumption[6]. Ulucak et al. (2020) state that sustainable and efficient management of inputs used in production processes, including materials, is necessary to reduce production costs, consumption of raw materials and waste. However, in the packaging industry, the consumption of materials is high because packaging are heavier than necessary (Georgakoudis and Tipi, 2021). Packaging should be optimized according to the needs of products (Licciardiello et al., 2014) to save costs and materials (Gustavo et al., 2018).

Packaging are heavy mainly to ensure the protection of products in the supply chain (Georgakoudis and Tipi, 2021). Innovative materials for packaging are available in the market that offer both smaller sizes and greater protection for products (Licciardiello et al., 2014). For example, advances in the production of wine bottles allow the manufacture of lighter and more protective bottles than heavier ones (Soares et al., 2022). Georgakoudis and Tipi (2021) consider the weight reduction of a corrugated cardboard box. Specifically, they show the change from a corrugated box with a weight of 630g and a maximum strength of 190kg to a corrugated box with a weight of 420g and a maximum strength of 104kg. This intervention provides a cost reduction of about 34,4%, a material reduction and, does not compromise the protection of the products (which have a strength requirement of about 96,4kg). Licciardiello et al. (2014) consider the reduction in thickness of a packaging in different plastics for sliced bread. Specifically, they compare the preservation properties of the original packaging, with a 275mm bottom film thickness and a 125mm top film thickness, with two lighter alternatives. The first alternative has a 225mm bottom film thickness and a 125mm top film thickness, while the second alternative has a 230mm bottom film thickness and a 121mm top film thickness. They observe several bread quality parameters and show that the lighter alternatives provide bread preservation comparable to the original packaging, reduce costs and save about 20% in materials. Therefore, the design of packaging heavier than the product requirements represents an unnecessary waste of money and materials. However, the reduction in packaging weight should not be excessive because the use of fewer materials in packaging could compromise their protective functionality, damage products, and cancel economic and environmental benefits (Georgakoudis and Tipi, 2021).

When companies change the weight of primary packaging, they should consider the impact on consumers (Gustavo et al., 2018). Herrmann et al. (2022) refer that consumers perceive the environmental problems of overpackaging, especially when the packaging is made of plastic. However, the study by Steenis et al. (2018) shows that consumers do not fully understand the environmental benefits of packaging weight reduction. In fact, consumers consider it a strategy that provides small and limited environmental benefits. In addition, consumers attribute little value to small packaging. For example, Monnot et al. (2019) consider two differently packaged organic yogurt substitutes placed on the same store shelf. Specifically, they observe that consumers are more likely to purchase the product with the larger packaging because they perceive it as more attractive and more protective. Similarly, Soares et al. (2022) analyze the Portuguese wine market and observe that consumers associate heavier glass bottles with more expensive and higher quality wines.

2.2.5. “Reuse of packaging”

CONAI defines the eco-design lever *“reuse of packaging”* as the design of packaging that can be used multiple times in its life cycle for the same original purpose[6]. The production of disposable packaging is popular in the packaging industry because it simplifies supply chain activities (Coelho et al., 2020). The short life cycle of disposable packaging increases the problem of packaging waste (Yuan, 2022). In fact, a significant amount of the plastic waste generated globally is represented by disposable packaging (Tan et al., 2023). In addition, disposable packaging increases the consumption of raw materials and the giving of Greenhouse Gas (GHG) emissions for the production of new packaging (Coelho et al., 2020). The main alternative to disposable packaging is reusable packaging (Yaroslavov et al., 2022). Greenwood et al. (2021) distinguish reusable packaging into two main categories: refillable packaging and returnable packaging.

The term refillable packaging refers to packaging that can be purchased by consumers (consumer ownership of the packaging) and, after consumption, can be reused because the contents can be refilled by consumers through the purchase of complementary products (refills) or by going to refill stations (Greenwood et al., 2021). Refills are covered with less heavy and less bulky materials than the main product contained in the refillable packaging (Lin et al., 2023). Lofthouse et al. (2017) consider the implementation of two alternative refill sachets for a refillable bottle of body cleanser. Both sachets contain a concentrate to be poured into the refillable bottle and mixed with water. They report that over a period of six months, the use of the system composed of the refillable bottle and refill sachets makes it possible to reduce the consumption of materials (consisting mainly of the water that has been replaced with the concentrate) by about 60%, the products transported by about 90%, the waste generated by about 80%, and the related costs. The suggestions provided by Lofthouse et al. (2017) should be considered in the design of refillable packaging. They state that the reuse function of refillable packaging should be clearly communicated, refills should always be available and cost-effective, and the refill process should be practical to perform

The term returnable packaging refers to packaging that can be rented by consumers (business ownership of packaging) and, after consumption, must be returned to their owners (Greenwood et al., 2021). The process of returning packaging makes returnable packaging different from refillable packaging and involves companies implementing systems to incentivize consumers to return packaging and implementing reverse logistics to recover returned packaging and prepare them for new use. Long et al. (2022) state that two alternative systems can be implemented to incentivize consumers to return packaging: deposit systems, in which consumers deposit a sum of money and receive a refund after return, or penalty systems, in which consumers are charged a sum of money if they fail to return. In particular, they report that consumers are more likely to adopt return packaging where there are fully refundable deposit systems. In this regard, Šuškevičė and Kruopienė (2020) evaluate incentives implemented in seven outdoor festivals in Lithuania to encourage consumers to return reusable cups. They show that fully refundable deposit systems are the best incentive because they allow about 97% of the cups to be recovered. The implementation of reverse logistics to recover returned packaging includes activities from the consumer to the producer as opposed to direct logistics (Coelho et al., 2020). In particular, different logistics systems are available in which the ownership of returnable packaging and responsibility for activities such as recovery, cleaning, repair, and storage vary (Mahmoudi and Parviziomran, 2020). Compared to direct logistics, the implementation of reverse logistics for the recovery of reusable packaging significantly increases the complexity and costs of logistics activities for companies (Salandri et al., 2022). Postacchini et al. (2018) consider the introduction of reuse in an Italian honey supply chain where there is a consortium of beekeepers. Specifically, they model three reuse scenarios in which the supply chain is reorganized differently, but in which there are common elements such as: the implementation of reverse logistics, the creation of a logistics center in each municipality to pick up used jars and deliver new ones, and the creation of a washing and packaging center at the consortium to prepare the jars for new use. The results show that the introduction of reuse in the supply chain can reduce emissions in the categories considered by an average of about 70% in five years. In fact, appropriate planning of reverse logistics in terms of distances traveled, vehicles used, loads transported can reduce the costs and environmental impacts of logistics. Among the activities that should be performed on returnable packaging, the cleaning is critical to ensure the quality and safety of the contents (Long et al., 2022). In fact, López-Gálvez et al. (2021) compare salmonella contamination in cauliflowers contained in reusable PP boxes, disposable corrugated cardboard boxes, and disposable wooden boxes and observe the presence of the highest contamination in the reusable box because it requires careful cleaning after each use. Junior et al. (2019) show that the use of quality control systems in a Brazilian soft drink industry using returnable PET bottles reduces the index of bottles rejected due to the presence of contamination during inspection and more than halves customer complaints about problems such as altered flavor of contents in two years. Hitt et al. (2023), considering a restaurant that uses reusable take-out packaging, state that rinsing of packaging by consumers and cleaning of packaging by companies, if excessive, can generate environmental impacts related to energy and water consumption that are greater than disposable packaging.

Reusable packaging, both refillable and returnable, have better environmental performance than disposable packaging only if they are used a minimum number of times, which depends on the characteristics of the packaging (Greenwood et al., 2021). In fact, Tan et al. (2023) show that if reusable packaging is used only once and is then recycled, it has a greater environmental impact than disposable packaging. Reusable packaging should be used a certain number of times to offset the higher energy and materials required to make it, because it must be bulkier and heavier than disposable packaging to be resistant to multiple uses (Greenwood et al., 2021). Camps-Posino et al. (2021) consider returnable packaging used for delivery service from a restaurant. Returnable packaging weighs 154,9g more than disposable packaging. In particular, they observe that reducing the weight of returnable packaging can further decrease emissions by about 20%. However, reducing the weight of returnable packaging also decreases its lifetime by about 30% and again increases emissions by about 14%. In fact, Gatt and Refalo (2022), comparing different versions of a refillable cosmetic packaging, observe that the original three times refillable version is more sustainable than the lighter refillable version, because the latter is less durable and offers fewer reuses.

2.2.6. "Simplification of the packaging system"

CONAI defines the eco-design lever *"simplification of the packaging system"* as the elimination of superfluous elements of packaging in order to simplify it[6]. As seen in category *"raw material saving"*, the problem of overpacking is widespread in the packaging industry. Superfluous materials used in packaging represent up to 65 percent of the cost of packaging (SEVADEC, 2015 cited in Georgakoudis and Tipi, 2021). They also increase the negative environmental impacts of packaging production and transportation (Georgakoudis and Tipi, 2021; Yuan et al., 2022). For example, larger packaging do not allow vehicles to move fully loaded, increase the number of trips made by vehicles, and increase CO2 emissions. Therefore, the removal of superfluous elements of packaging provides different benefits, including logistics optimization.

Postacchini et al. (2021) show the simplification of a kitchen hood packaging. The original packaging included a corrugated cardboard box in which were placed four cardboard corners, an expanded polystyrene (EPS) base, a chimney protector, and four airbags to protect the product. They refer that optimizing the size of the corrugated cardboard box and toughening the EPS with a new design base made it possible to remove the four cardboard corners and four internal airbags without compromising product protection. The simplification facilitated the assembly process, reduced costs, material consumption, and impacts on all environmental categories considered by about 30% on average. Bassani et al. (2022) evaluate strategies to simplify blisters, bottles, and sachets for pharmaceutical products. Specifically, they propose optimizing blisters and bottles to reduce void space and removing superfluous sachet components such as boxes and package inserts to lighten the system. These interventions result in significant reductions in costs, materials, and environmental impacts in the categories considered because the volume of blisters is reduced by up to 1,9 times, that of bottles by up to 1,7 times, and that of sachets by up to 2,9 times. As seen in the category *"raw material saving"*, the removal of unnecessary packaging elements should not compromise product protection (Georgakoudis and Tipi, 2021) and should consider potential impacts on consumers if done on primary packaging (Gustavo et al., 2018).

Varžinskas et al. (2020) refer that the selection of material is critical to reduce the complexity of packaging. They state that simple packaging is made from only one material in order to simplify recycling. Hafsa et al. (2022) refer that unnecessary and non-recyclable packaging elements should be removed to simplify packaging. Foschi et al. (2020) show the simplification of a resealable cardboard box for condiments. Specifically, the plastic cap is removed and replaced with a cardboard opening system integrated into the box. The new mono-material packaging reduces material consumption, waste generation, and facilitates recycling. Vergnano et al. (2016) consider the simplification of a wooden box consisting of three modules (base, folding sides and lid) used in logistics. The three modules are retained but the folding sides are simplified. In fact, the metal hinge for the folding sides is removed and replaced by an interlocking system made of an innovative material composed of 99% lignin. The mono-material and easily disassembled solution facilitates recycling and reduces waste generation.

2.2.7. "Use of recycled material"

CONAI defines the eco-design lever *"use of recycled material"* as the partial or total replacement of virgin raw materials with recycled ones to reduce the consumption of virgin materials[6]. The use of materials obtained after recycling as raw materials to make new products reduces the waste problem because it transforms waste into resources and reduces the environmental impacts associated with virgin material production processes (Rajesh and Subhashini, 2021). Civancik-Uslu et al. (2019) show the redesign of a tube-shaped cosmetic packaging. Specifically, they report that packaging in which 40% LLDPE is replaced with post-consumer recycled HDPE is the best among the proposed alternatives in terms of both cost containment and reduction of environmental impacts related to packaging production. Bandara and Indunil (2022) focus on the production of recycled paper, which significantly reduces wood consumption, water consumption and the giving of emissions to the atmosphere. Specifically, they test the properties of three different types of recycled paper and observe that they can be used in the production of food packaging, but there is a need to improve water resistance and reduce lead and cadmium content. The study of Ruokamo et al. (2022) on Finnish consumers shows that individuals are generally inclined to purchase packaging made of recycled material that are functional, durable, and safe, regardless of price, dark color, and other physical defects.

However, the use of recycled materials in packaging increases the complexity and costs of production and logistics activities for companies. In fact, recycled materials involve changes in production processes, products redesign and their integration with virgin materials in inventory management (Salandri et al., 2022). Moreover, virgin materials used in products cannot be totally replaced by recycled materials due to quality, property and costs issues (Tallentire and Steubing, 2020). Therefore, the benefits of the use of recycled materials in terms of lower consumption of production inputs are complex to capture. In fact, Geueke et al. (2018) refer that glass and metal packaging can be recycled countless times because the material retains its quality and properties after each recycling, while the recycling of plastic and paper/cardboard packaging is more limited because the material loses its quality and properties after each recycling. In fact, plastic cannot be recycled more than seven times (Solis and Silveira, 2020 cited in Zhu et al., 2022) and paper/cardboard cannot be recycled more than five to seven times (Soni et al., 2020 cited in Bandara and Indunil, 2022). According to Etxabide et al. (2022), the production of recycled plastic and paper/cardboard materials requires the addition of a high amount of virgin materials to maintain an acceptable quality of the recycled material and additives and other chemicals that make the material hazardous to the environment, complex to recycle again in the future, and unsafe for human health when it comes into close contact with food. In addition, Kazulytė and Kruopienė (2018) observe that only 15% of packaging producer in Lithuania use exclusively recycled materials because quantities are insufficient, prices are high, and the composition of recycled materials is unknown. Therefore, they report that ensuring complete traceability of the life cycle of packaging and the chemicals used on it can increase the share of recycled material used in packaging manufacturing. Afif et al. (2022) show the impacts of the higher price of recycled materials compared to virgin materials on Quebec food packaging producer and retailers. Specifically, the price of recycled materials impacts producer more than retailers because the first ones not only have to bear the higher cost but also the greater technical difficulties relating to incorporating recycled materials into packaging. Therefore, producers are willing to pay more for recycled materials that are cheap and simple to incorporate such as recycled glass, while they are more likely to purchase virgin materials if the recycled materials are expensive and complex to incorporate such as recycled PET.

2.3. Eco-design for specific types of packaging: food packaging and plastics packaging

In the literature on packaging eco-design, two topics are widely discussed: the reduction of food waste caused by food packaging and the reduction of environmental impacts of plastics packaging through the use of bio-based and/or biodegradable materials. However, these packaging eco-design practices refer to specific types of packaging, food packaging and plastics packaging, and they are not part of the seven categories proposed by CONAI. Therefore, we discuss this part from a theoretical point of view to complete the literature review on packaging eco-design, but we do not use it in the empirical analysis. This subsection provides interesting insights on sustainable food packaging design and on the use of innovative bio-based and/or biodegradable materials in packaging.

2.3.1. Food waste reduction

Food losses and waste represent about one-third of the food for consumption produced in the world (Gustavsson et al., 2011 cited in Molina-Besch et al., 2019). In particular, food loss and waste occurs within food supply chains. In fact, according to Verghese et al. (2015), the agricultural production, post-harvest handling, post-harvest storage, processing and packaging stages are responsible for food losses, while the distribution, retail and consumption stages are responsible for food waste. In this framework, after the packaging of the food product, packaging can provide a significant contribution to the reduction of food waste because its main function is to ensure the proper preservation of food. However, packaging is not currently designed appropriately for food needs because it is considered more of an economic and environmental cost to reduce than a means to reduce food waste (Guillard et al., 2018). Therefore, the eco-design of packaging focuses mainly on reducing direct environmental impacts, such as those related to packaging production, rather than reducing food waste, which are relevant indirect environmental impacts of packaging because wasted food corresponds to the wasted resources for its production (Wikström et al., 2014). In fact, Molina-Besch et al. (2019) observe that indirect environmental impacts related to food waste are poorly considered in LCAs of packaging.

Silvenius et al. (2014), conducting LCA of different packaging for sliced black bread, ham, and soy beverage, report that indirect environmental impacts of packaging related to food waste should be included in packaging LCAs because they are more relevant than direct environmental impacts of packaging. For example, Casson et al. (2022) evaluate the life cycle of three different types of beef packaging: overwrap packaging, modified atmosphere packaging, and vacuum skin packaging. Specifically, considering only the direct environmental impacts of packaging, overwrap packaging is the packaging with the best environmental performance because it is the simplest and lightest, while modified atmosphere packaging has the worst environmental performance. However, when the indirect environmental impacts of packaging related to food waste are included in the analysis, the results are reversed because modified atmosphere packaging, due to its weight and complexity, provides greater product preservation, reduces food waste, and generates a lower overall environmental impact than overwrap packaging. Similarly, Dilkes-Hoffman et al. (2018) evaluate the life cycle of biodegradable packaging made with a combination of polyhydroxyalkanoates (PHA) and thermoplastic starch (TPS) and PP packaging for meat and cheese. Considering a scenario where methane is not captured in landfills and beef food waste is identical, PHA-TPS packaging gives 7% more GHG emissions to landfills than PP packaging.

However, PHA-TPS packaging may become the preferable alternative if it is redesigned to reduce food waste by 6% because this offsets its higher GHG emissions than PP packaging.

Therefore, according to Wikström et al. (2014), the inclusion of the indirect environmental impact of packaging related to food waste in the LCA of packaging may lead to the selection of packaging with a higher direct environmental impact but a lower overall environmental impact as a more sustainable alternative because it can provide better food preservation. This is especially when the food considered has a high ratio of food impact to packaging impact as in the case of beef and cheese rather than when the food considered has a low ratio of food impact to packaging impact as in the case of ketchup (Williams and Wikström, 2011). In particular, packaging that can extend the shelf life of foods but is costly and has a greater direct environmental impact due to issues of complexity and recyclability are innovative active packaging, containing active components that improve food preservation, and intelligent packaging, containing the technologies needed to monitor the condition of food and its environment and communicate them to all supply chain actors and consumers (Yan et al., 2022). However, consumers are not very conscious of the existence of solutions to extend food shelf life such as active packaging and intelligent packaging, as revealed in studies by Cammarelle et al. (2021) on a sample of Italian consumers and Stoma and Dudziak (2022) on a sample of Polish consumers.

In general, consumers perceive packaging as waste to be reduced, do not understand its role in the reduction of food waste, and underestimate the problem of food waste (Langley et al., 2021). Zeng and Durif (2020) investigate consumers behavior regarding food waste and report that it depends on the complex interaction between psychological determinants, packaging perceptions, consumption management and sociocultural determinants. Therefore, if consumers' perceptions of packaging affect their food waste behavior, packaging can be designed to induce consumers to reduce food waste indirectly. In fact, the study of Williams et al. (2012) on a sample of Swedish households shows that about 20-25% of food waste caused by consumers depends on packaging design. Packaging attributes that can influence consumer behavior and reduce food waste are summarized by Wikström et al. (2014) and include, for example, packaging that contains an adequate portion of food for consumers, packaging that can be easily emptied, packaging with a dispensing function, packaging that can be resealed conveniently and effectively after opening, and packaging that clearly informs consumers about the shelf life and storage of food. Specifically, Zeng et al. (2021), conduct two experiments on a milk cardboard and a cheese bag involving a group of consumers and observe that the physical features offered by packaging provide a greater contribution to reducing food waste in consumption than the verbal features, that inform consumers about the environmental sustainability of packaging. Williams et al. (2020), considering a sample of Swedish households, observe that the packaging features most relevant to avoid food waste are the presence of an adequate amount of food inside the packaging, because larger packaging sizes lead smaller and smaller households to waste food that they cannot consume before expiration, and the presence of accurate information about the shelf life of products, because labels often create confusion among consumers.

2.3.2. Use of bio-based and/or biodegradable materials

Plastics are polymers, which are macromolecules composed of monomers (Okan et al., 2019). Petroleum-based polymers such as PP, PET, PE, and PS are commonly used in plastics packaging because they are available at low cost and offer excellent properties (Mendes and Pedersen, 2021). However, petroleum-based polymers are derived from non-renewable sources, have a negative impact on the environment, and are not degradable. In fact, the production of petroleum-based plastics causes significant GHG emissions into the atmosphere (Mendes and Pedersen, 2021). While waste from petroleum-based plastics is not properly managed, but is accumulated in landfills, and dispersed in ecosystems (Rai et al., 2021). To reduce the environmental impact of petroleum-based plastics packaging, Reichert et al. (2020) state that it is necessary to design renewable and biocompatible packaging with bio-based and/or biodegradable materials. According to Sid et al. (2021), bioplastics are bio-based and/or biodegradable materials and can be distinguished into three categories: bio-based and non-biodegradable plastics, bio-based and biodegradable plastics, and petroleum-based and biodegradable plastics. Petroleum-based and biodegradable plastics are not considered bioplastics by Ibrahim et al. (2021) because they are derived from non-renewable sources.

First, the concept of biological origin must be distinguished from that of biodegradability. Bio-based plastics are partially or fully derived from the biomass of plants, animals, or microorganisms (Sid et al., 2021). First-generation biomass includes edible raw materials, second-generation biomass includes residues such as agricultural wastes, and third-generation biomass includes algae (Reichert et al., 2020). Sid et al. (2021) include among bio-based plastics: plastics that derive from natural polymers such as starch and cellulose; plastics that derive from bio-based polyesters such as polylactic acid (PLA) and PHA; and primitive bio-based plastics such as Bio-PE, Bio-PP, and Bio-PET. While biodegradable plastics degrade through a chemical process that involves a variety of microorganisms and generates an environmentally and human health friendly end product that includes natural substances such as biomass, carbon dioxide, methane and water (Guo C. and Guo H., 2022). Biodegradation of plastics does not always occur in the natural environment because it may require industrial composting, in which plastics are subjected to specific conditions that promote their biodegradation (Mendes and Pedersen, 2021). Shaikh et al. (2021) include among biodegradable plastics: plastics that derive from natural polymers such as starch and cellulose; plastics that derive from polymers chemically synthesized from bio-based monomers such as PLA, polybutylene succinate (PBS), polycaprolactone (PCL), and polybutylene adipate terephthalate (PBAT); and plastics that derive from polymers produced by natural or genetically modified organisms such as PHA.

Bio-based plastics are not all biodegradable and biodegradable plastics are not all bio-based (Juikar and Warkar, 2022). For example, starch is a bio-based polymer and biodegradable both in the natural environment and in industrial composting, PLA is a bio-based polymer and biodegradable only in industrial composting, and bio-PE is a bio-based polymer but not biodegradable. (Sid et al., 2021). Huang et al. (2022) evaluate the effects of three different types of degradation (PBS, UV and soil) on three films made from different materials (cellulose, PBAT and PE). They show that the bio-based and biodegradable cellulose film achieves the best performance in all three experiments. Specifically, after 98 days in the soil, the cellulose film loses 99,1% of its weight, while the petroleum-based and biodegradable PBAT film loses only 2,1% of its weight and the petroleum-based and non-biodegradable PE film loses only 1,7% of its weight. In fact, among biodegradable plastics, bio-based plastics tend to biodegrade faster than petroleum-based plastics (Reichert et al., 2020).

The environmental impacts of bioplastics are generally considered lower than those of petroleum-based plastics (Mendes and Pedersen, 2021). Nejad et al. (2021) compare the CO2 emissions produced and energy consumed in the life cycle of PLA and petroleum-based plastics trays. They report that petroleum-based plastics trays generate higher environmental impacts especially in the raw material production and end-of-life stages. Specifically, trays combining virgin and recycled PET produce 49% more CO2 emissions than PLA trays. Similarly, Cappiello et al. (2022) evaluate the life cycle of long-life milk packaging made of PET, HDPE, multilayer cardboard, glass, and PLA. The results indicate that PLA packaging has the best environmental performance and glass packaging the worst, both considering the end-of-life recycling option and not considering it. However, Atiwesh et al. (2021) say that bioplastics are not free of environmental impacts because: the cultivation of the raw materials requires a change in land use, consumes water, and produces pollutants due to the use of pesticides and fertilizers; the chemical treatments required to transform the raw materials into plastics are polluting; and bioplastics that require industrial composting to be biodegraded produce methane gas and contribute to the climate change problem. Second-generation biomass has less impact on the environment than first-generation biomass because it does not create land-use competition between raw materials for bioplastics production and those for human consumption (Mendes and Pedersen, 2021). The use of fruit and vegetable waste in food packaging is an economical and attractive alternative that reduces agricultural waste and environmental impact and offers excellent food preservation properties (Sani et al., 2022).

Bioplastics represent a very small share of plastics produced at the European level (Reichert et al., 2020) because they are more expensive (Mehta et al., 2021) and have fewer properties than petroleum-based plastics, so they require treatments and additives to improve their properties, such as barrier to water and oxygen (Juikar and Warkar, 2022). Bioplastics are used in various types of packaging, especially food packaging (Ibrahim et al., 2021). Hawthorne et al. (2020) compare trays combining PLA and cellulose and petroleum-based plastics trays for meat products. In particular, PLA and cellulose trays are a sustainable and functional alternative because they provide similar food preservation to conventional trays. Lorite et al. (2017) compared PLA packaging with nanoclays and surfactants, PLA packaging, and PET packaging for fresh-cut melons. PLA packaging with additives has superior properties to PLA packaging and comparable to PE packaging in terms of food preservation. Bioplastics packaging must be approved for food contact because raw material processing substances and additives to improve properties can cause migration of hazardous particles from the packaging to the food (Mendes and Pedersen, 2021).

Leal Filho et al. (2021), considering European consumers, show that consumers are conscious of the environmental impacts caused by packaging made from petroleum-based plastics and are likely to purchase bioplastics packaging, although they are not widely available in the market and are expensive. However, Dilkes-Hoffman et al. (2019), focusing on Australian consumers, observe that consumers are uninformed about bioplastics because they believe that bio-based plastics are also biodegradable and do not fully understand the meaning of biodegradability. In fact, Taufik et al. (2020) state that consumers, due to unfamiliarity with bioplastics packaging and unclear labels, handle bio-based and/or biodegradable packaging waste incorrectly. For example, they report that consumers place bio-based plastics packaging in the same waste stream as non-biodegradable plastics for recycling, rather than in the organic waste container. Both bio-based and non-biodegradable plastics can be collected and recycled together with conventional plastics, while biodegradable plastics should not enter into the conventional plastics waste stream because they complicate the sorting step and can contaminate the final output (Fredi and Dorigato, 2021), but should be destined to composting (Sid et al., 2021).

2.4. Research gaps

In the literature review on packaging eco-design performed in Subsection 2.2 we identified some research gaps, which we summarize in Table 1. In the table we link the packaging eco-design practices covered by each paper to the most appropriate CONAI eco-design levers to make them easily comparable. In addition, in the table we show the materials analyzed, the products analyzed, the environmental impacts analyzed, and the implications for companies in the selection of the CONAI eco-design levers of the reviewed papers.

Table 1. Reviewed papers on packaging eco-design

Reviewed papers	CONAI eco-design levers analyzed	Materials analyzed	Products analyzed	Environmental impacts analyzed	Implications for companies in the selection of CONAI eco-design levers
Licciardiello et al. (2014)	Raw material saving	Plastics	Films for sliced bread	-	-
Mourad et al. (2014)	Optimization of production processes	Paper, Cardboard	Packaging materials	LCA (Abiotic depletion; Acidification; Eutrophication; Global warming potential; Human toxicity; Photochemical ozone creation potentials)	-

Manfredi and Vignali (2015)	Optimization of production processes	Plastics	Juice bottles	LCA (Climate change; Freshwater ecotoxicity; Fossil depletion; Freshwater eutrophication; Human toxicity; Ionizing radiation; Marine ecotoxicity; Marine eutrophication; Metal depletion; Ozone depletion; Particulate matter formation; Photochemical oxidant formation; Terrestrial acidification; Terrestrial ecotoxicity; Water depletion)	-
Vergnano et al. (2016)	Facilitation of recycling activities, Simplification of the packaging system	Metals, Wood	Boxes for heavy industry products	-	-
Lofthouse et al. (2017)	Reuse of packaging	Plastics, Metals (aluminum and steel)	Refillable bottles and refill sachets for body cleanser	Eco-indicator 99 (ecosystem quality; human health; resource)	-
Georgakoudis et al. (2018)	Logistics optimization	Cardboard	Corrugated cardboard boxes for two-stroke engine lubricant bottles	-	-
Kliopova-Galickaja and Kliaugaite (2018)	Optimization of production processes	Plastics	Flexible packaging films	Environmental indicator (Inks, thinners, and other materials; GHG; Natural gas consumption; Total air emissions; Total energy consumption; Total waste production; VOC emissions)	-
Postacchini et al. (2018)	Logistics optimization, Reuse of packaging	Glass	Reusable jars for honey	LCA (Aquatic ecotoxicity; Global warming; Land occupation; Terrestrial acid/nutria; Terrestrial ecotoxicity)	-
Civancik-Uslu et al. (2019)	Use of recycled material	Plastics	Tubes for cosmetic products	LCA (Acidification; Climate change; Eutrophication freshwater; Eutrophication marine; Human health; Petrochemical ozone formation; Resource depletion, fossils and, renewables; Resource depletion water), Primary energy from non-renewable, Primary energy from renewable sources	-
Jiang and Zeng (2019)	Optimization of production processes	Plastics, Wood	Packaging boxes	Energy consumption	-
Foschi et al. (2020)	Facilitation of recycling activities, Simplification of the packaging system	Plastics, Cardboard	Boxes for condiments	LCA (Acidification; Climate change; Freshwater ecotoxicity; Freshwater eutrophication; Human toxicity cancer effects; Human toxicity non cancer effects; Ionizing radiation E; Ionizing radiation HH; Land use; Marine eutrophication; Mineral, fossil, and renewable resource depletion; Ozone depletion; Particulate matter; Photochemical ozone formation; Terrestrial eutrophication; Water resource depletion)	-
García-Arca et al. (2020)	Logistics optimization	Plastics, Cardboard	Boxes for food and clothing products	-	-
Camps-Posino et al. (2021)	Reuse of packaging	Plastics	Reusable packaging for food delivery	LCA (impact of climate change)	-
Georgakoudis and Tipi (2021)	Raw material saving	Cardboard	Corrugated cardboard boxes	-	-
Greenwood et al. (2021)	Reuse of packaging	Plastics, Metals (steel)	Reusable take-out containers	LCA (environmental footprint)	-
He et al. (2021)	Optimization of production processes	Plastics	Flexible packaging bags	LCA (Acidification potential; Global warming potential; Photochemical oxidant formation potential; Primary energy demand; Respiratory inorganics; Water use)	-
Molina (2021)	Optimization of production processes	Plastics	Flexible packaging	-	-
Postacchini et al. (2021)	Raw material saving, Simplification of the packaging system	Plastics, Cardboard	Packaging for kitchen hood	LCA (Fossil resource scarcity; Freshwater ecotoxicity; Freshwater eutrophication; Global warming; Human carcinogenic toxicity; Land use; Marine ecotoxicity; Marine eutrophication;	-

				Stratospheric ozone depletion; Terrestrial acidification; Terrestrial ecotoxicity; Water consumption)	
Wang et al. (2021)	Optimization of production processes	Cardboard	Corrugated cardboard boxes for panel furniture	-	-
Bassani et al. (2022)	Logistics optimization, Raw material saving, Simplification of the packaging system	Plastics, Paper, Metals (aluminum)	Blisters, bottles and sachets for pharmaceutical products	LCA (Abiotic depletion; Abiotic depletion – mineral and metal; Acidification; Eutrophication freshwater; Eutrophication marine; Eutrophication terrestrial; Global warming; Ionizing radiation; Land use; Ozone depletion; Particulate matter; Photochemical ozone formation; Water use)	-
Gatt and Refalo (2022)	Facilitation of recycling activities, Raw material saving, Reuse of packaging, Simplification of the packaging system	Plastics, Metals (aluminum and steel), Glass	Packaging for cosmetic products	LCA (Ecosystem endpoint; Human health endpoint)	-
Keller et al. (2022)	Facilitation of recycling activities	Plastics	Packaging for hygiene products	LCA (impact of climate change)	-
Yuan (2022)	Facilitation of recycling activities	Metals	Packaging for cookie	-	-
Georgakoudis et al. (2023)	Logistics optimization	Plastics, Cardboard	Corrugated cardboard boxes for water bottles	CO2 emissions	-
Hitt et al. (2023)	Reuse of packaging	Plastics	Reusable packaging for take-out food	LCA (GHG; Primary energy consumption; Water consumption)	-
Lin et al. (2023)	Raw material saving, Reuse of packaging	Plastics, Cardboard, Metals (steel), Glass	Packaging for food, beverage and home products items	Carbon footprint, Waste	-
Tan et al. (2023)	Reuse of packaging	Plastics	Reusable packaging for express delivery	LCA (Acidification potential; Chemical oxygen demand; Eutrophication potential; Freshwater aquatic ecotoxicity potential; Global warming potential; Marine aquatic ecotoxicity; Nitric oxides; Particulate matter; Primary energy demand)	-
Cozzolino and De Giovanni (2023)	Facilitation of recycling activities, Logistics optimization, Optimization of production processes, Raw material saving, Reuse of packaging, Simplification of the packaging system, Use of recycled material	Plastics, Paper/Cardboard, Metals (aluminum and steel), Glass, Wood	Packaging for the food, beverage, health care, home products and industrial sectors	LCA (CO2 emissions; energy consumption; water consumption)	Companies can understand: • The best CONAI eco-design levers to improve each environmental indicator • The effects of CONAI eco-design levers portfolios on each environmental indicator
This paper	Facilitation of recycling activities, Logistics optimization, Optimization of production processes, Raw material saving, Reuse of packaging, Simplification of the packaging system, Use of recycled material	Plastics, Paper/Cardboard, Metals (aluminum and steel), Glass, Wood	Packaging for the food, beverage, health care, home products and industrial sectors	LCA (CO2 emissions; energy consumption; water consumption)	Companies can understand: • The links among CONAI eco-design levers • The links among environmental indicators • The links among CONAI eco-design levers and environmental indicators • The effects of CONAI eco-design levers when they are implemented individually for each

					environmental indicator • The effects of CONAI eco-design levers portfolios on each environmental indicator

In the literature on packaging eco-design, papers that study concrete cases of packaging eco-design analyze the environmental benefits of only one packaging eco-design practice or a few packaging eco-design practices. Therefore, they do not consider a complete set of packaging eco-design practices and ignore synergies and trade-offs among packaging eco-design practices. In addition, these papers focus on specific types of packaging: packaging in specific materials and packaging for specific products. Therefore, they do not provide companies a general guidance for the selection of packaging eco-design practices. To our knowledge, Cozzolino and De Giovanni (2023) are the only ones to consider a comprehensive set of packaging eco-design practices (CONAI eco-design levers), packaging in different materials (plastics, paper/cardboard, metals such as aluminum and steel, glass and wood) and packaging for different products (from the food, beverage, health care, home products and industrial sectors), through the analysis of 603 concrete cases of success in which Italian companies have implemented CONAI eco-design levers on packaging to improve three environmental indicators: CO2 emissions, energy consumption and water consumption.

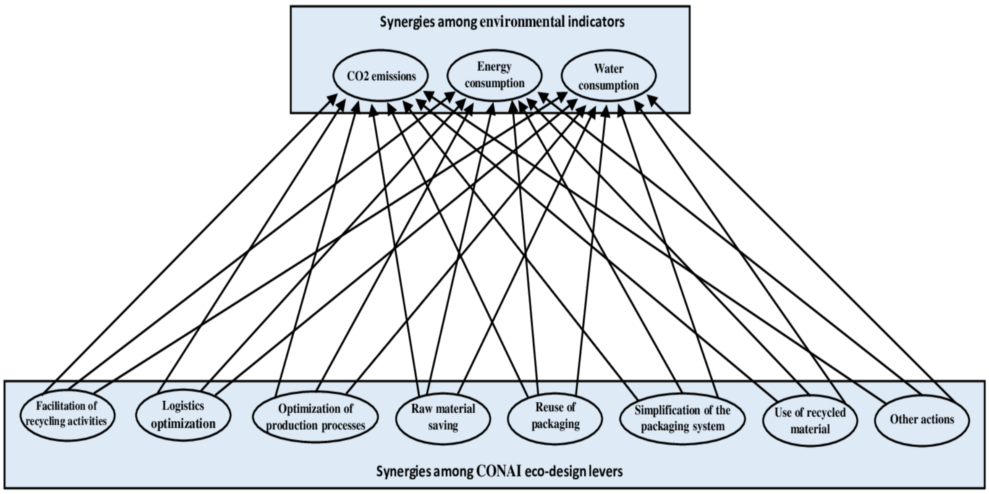
Cozzolino and De Giovanni (2023) analyze the links among CONAI eco-design levers. They identify the following significant links between the levers: trade-off between *"facilitation of recycling activities"* and *"raw material saving"* because the implementation of facilitators for recycling does not reduce the consumption of materials; synergy between "*logistics optimization"* and *"raw material saving"* because the reduction of material consumption allows for better organization of logistics; synergy between *"logistics optimization"* and "*simplification of the packaging system"* because light wight packaging optimize all logistics activities; trade-off between "*optimization of production processes"* and *"use of recycled material"* because the replacement of virgin materials with recycled materials is difficult to implement; trade-off between *"reuse of packaging"* and "*raw material saving"* because reusable packaging consume a lot of materials to be durable; trade-off between "*reuse of packaging"* and *"use of recycled materials"*; trade-off between "*use of recycled material"* and *"logistics optimization"* because the sourcing of recycled materials increases logistical complexity; trade-off between *"use of recycled material"* and *"raw material saving"* because the replacement of virgin materials with recycled materials is difficult to implement. In addition, Cozzolino and De Giovanni (2023) identify the best CONAI eco-design levers to improve each environmental indicator. To reduce CO2 emissions, companies should implement in order of preference: *"reuse of packaging"*, *"facilitation of recycling activities"*, *"simplification of the packaging system"*, *"raw material saving"*, *"logistics optimization"*, *"optimization of production processes"*, and *"use of recycled material"*. To reduce energy consumption, companies should implement in order of preference: *"reuse of packaging"*, *"simplification of the packaging system"*, *"facilitation of recycling activities"*, *"raw material saving"*, *"optimization of* *production processes”*, *“logistics optimization”* and *“use of recycled material”*. To reduce water consumption, companies should implement in order of preference: *“reuse of packaging”*, *“simplification of the packaging system”*, *“use of recycled material”*, “*raw material saving”*, and *“optimization of production process”*.

However, companies need more precise guidance on which CONAI eco-design levers they should implement. In fact, if they implemented only one of the eco-design levers suggested by Cozzolino and De Giovanni (2023) to reduce an environmental indicator, they may achieve suboptimal performance because some eco-design levers work better when combined with other levers to take advantage of synergies. Similarly, if companies implement multiple eco-design levers among those suggested by Cozzolino and De Giovanni (2023) to reduce an environmental indicator, they may incur high costs and achieve suboptimal performance due to trade-offs among the levers. Therefore, companies should understand which eco-design levers are effective when implemented individually and which eco-design levers are effective when combined in portfolios to exploit synergies. Our paper aims to provide companies a clear guidance for the selection of CONAI eco-design levers. To achieve this aim, we investigate the three research questions formulated in Section 1. To answer *RQ1*, we build and analyze the complex network of relations that includes all possible links among CONAI eco-design levers, among environmental indicators, and among CONAI eco-design levers and environmental indicators. In this way we provide companies a reference plan for the selection of CONAI eco-design levers. To answer *RQ2*, we model scenarios in which each CONAI eco-design lever is implemented individually to analyze its contribution to improving environmental indicators. Specifically, we consider a CONAI eco-design lever effective when implemented individually if it improves environmental indicators relative to their benchmarks. The benchmark of each environmental indicator indicates its value in a scenario where companies do not implement any CONAI eco-design lever. In this way, we suggest to companies which CONAI eco-design levers are convenient to implement individually. To answer *RQ3*, we build different portfolios of CONAI eco-design levers that exploit the synergies among CONAI eco-design levers to improve each environmental indicator relative to its benchmark. In this way, we suggest to companies the portfolios of CONAI eco-design levers best suited to their environmental goals. To pursue the research aim, we study the same sample used by Cozzolino and De Giovanni (2023), consisting of 603 successful cases in which Italian companies implemented CONAI eco-design levers on different types of packaging to improve three environmental indicators: CO2 emissions, energy consumption and water consumption. In particular, following De Giovanni et al. (2022), we implement BN and modern ML tools on the sample to create sophisticated decision supports for companies.

3. Methodology

To pursue the research aim, we develop an expert system tool through a BN to study the relationships among CONAI eco-design levers and environmental indicators. Following the paper of De Giovanni et al. (2022), we begin with a general expert system implemented in the form of a BN to identify all possible relationships among CONAI eco-design levers and environmental indicators. The BN involves a chain of conditional probabilities related to the impact of CONAI eco-design levers on environmental indicators. Therefore, starting from some initial beliefs and intuitions, we model the starting BN, shown in Figure 1, that will be refined later through a ML algorithm to identify the hidden relationships in the network among CONAI eco-design levers, among environmental indicators, and among CONAI eco-design levers and environmental indicators.

Figure 1. Starting Bayesian network



3.1. Data collection and sample description

To establish all the connections of the starting BN shown in Figure 1, we used a secondary dataset of Italian companies that have implemented CONAI eco-design levers on packaging. This dataset was used in the paper of Cozzolino and De Giovanni (2023) and collects data of the "eco-design for prevention" project from the platform created by CONAI. In fact, CONAI incentivizes companies to design circular and sustainable packaging and publicly reports on its platform the packaging redesign interventions implemented by companies.

The dataset includes 603 different successful cases of packaging eco-design. For each case, the dataset contains information about the intervening company such as: company name, number of company employees, and company sales. In addition, for each case, the dataset contains information about the redesigned packaging such as: name of the packaging or packaged product, sector of the packaging or packaged product, and packaging materials. Finally, for each case, the dataset contains information on the redesigned intervention such as: description of the intervention, year of the intervention, CONAI eco-design levers implemented in the intervention, and environmental performance of the intervention. The CONAI eco-design levers implemented in each intervention are selected from the seven categories discussed in Subsection 2.2: *“facilitation of recycling activities”, “logistics optimization”*, “*optimization of production processes”*, *“raw material saving”*, *“reuse of packaging”*, *“simplification of the packaging system”*, and *“use of recycled material”*. In addition, there is also a residual category called *“other actions”*, which includes, for example, companies that have a certified environmental management system. The environmental performance of each intervention is calculated using the LCA method and considering three environmental indicators: CO2 emissions, energy consumption, and water consumption. For each environmental indicator, its percentage change after the implementation of the intervention is shown, obtained from the difference between the percentage value of the pre-intervention environmental indicator and the percentage value of the post-intervention environmental indicator.

First, we describe the sample companies. The 603 packaging redesign interventions were performed by 258 companies, of which 8 collaborated with other companies in 8 cases. Table 2 shows the distribution of companies by number of interventions, by number of employees and by sales.

Table 2. Number of interventions, number of employees and sales

Number of interventions (258 companies)	Number of employees (247 companies)	Sales (242 companies)
< 2: 145 companies (56,20%)	< 50: 93 companies (37,65%)	< 7.000.000 EUR: 52 companies (21,49%)
2-5: 88 companies (34,11%)	50 - 249: 75 companies (30,36%)	7.000.000 - 19.999.999,99 EUR: 44 companies (18,18%)
6-10: 19 companies (7,36%)	250 - 500: 28 companies (11,34%)	20.000.000 - 80.000.000 EUR: 53 companies (21,90%)
> 10: 6 companies (2,33%)	> 500: 51 companies (20,65%)	> 80.000.000 EUR: 93 companies (38,43%)

The number of companies (258) is smaller than the number of cases (603) because 43,80% of the companies performed more than one packaging redesign intervention. Following Cozzolino and De Giovanni (2023), we distinguish companies by number of employees and sales. The number of employees is available for 247 companies, of which: 37,65% have fewer than 50 employees; 30,36% have between 50 and 249 employees; 11,34% have between 250 and 500 employees; and 20,65% have more than 500 employees. Sales are available for 242 companies, of which: 21,49% have sales less than 7.000.000 EUR; 18,18% have sales between 7.000.000 and 19.999.999,99 EUR; 21,90% have sales between 20.000.000 and 80.000.000 EUR; and 38,43% have sales greater than 80.000.000 EUR.

Second, we describe the sample packaging. We distinguish packaging according to their material of composition and sector. Table 3 shows the distribution of packaging by number of materials, the distribution of materials by type of materials and the distribution of packaging by sectors.

Table 3. Number of materials, type of materials and sectors

Number of materials (603 packaging)	Type of materials (680 materials)	Sectors (603 packaging)
1: 531 packaging (88,06%)	Plastics: 333 materials (48,97%)	Food: 164 packaging (27,20%)
2: 67 packaging (11,11%)	Paper and cardboard: 256 materials (37,65%)	Beverage: 76 packaging (12,60%)
3: 5 packaging (0,83%)	Metals: 41 materials (6,03%); Aluminum: 17 materials (2,50%); Steel: 24 materials (3,53%)	Healt care: 50 packaging (8,29%)
-	Glass: 17 materials (2,50%)	Home products: 55 packaging (9,12%)
-	Wood: 33 materials (4,85%)	Industrial: 258 packaging (42,75%)

We identify 680 materials in the dataset. The number of materials (680) is greater than the number of cases (603) because in 11,94% of the cases, the packaging are made of more than one material. Specifically, packaging are composed with the following materials: 48,97% with plastics; 37,65% with paper and cardboard; 6,03% with metals, including 2,50% with aluminum and 3,53% with steel; 2,50% with glass; and 4,85% with wood. Following Cozzolino and De Giovanni (2023), packaging belong to the following sectors: 27,20% to the food sector; 12,60% to the beverage sector; 8,29% to the health care sector; 9,12% to the home products sector; and 42,75% to the industrial sectors.

Third, we describe the sample redesign interventions. Table 4 shows the distribution of cases by years, the distribution of eco-design levers by type of lever, and the distribution of cases by number of levers implemented simultaneously.

Table 4. Years, type of levers and number of levers

Years (603 cases)	Type of levers (1069 levers)	Number of levers (603 cases)
2011: 12 cases (1,99%)	Facilitation of recycling activities: 77 (7,20%)	1: 286 cases (47,43%)
2012: 6 cases (1%)	Logistics optimization: 206 (19,27%)	2: 201 cases (33,33%)
2013: 64 cases (10,61%)	Optimization of production processes: 78 (7,30%)	3: 86 cases (14,26%)
2014: 55 cases (9,12%)	Raw material saving: 429 (40,13%)	4: 27 cases (4,48%)
2015: 88 cases (14,59%)	Reuse of packaging: 29 (2,71%)	5: 3 cases (0,50%)
2016: 94 cases (15,59%)	Simplification of the packaging systems: 101 (9,45%)	-
2017: 89 cases (14,65%)	Use of recycled material: 121 (11,32%)	-
2018: 140 cases (23,22%)	Other actions: 28 (2,62%)	-
2019: 55 cases (9,12%)	-	-

The 603 interventions were performed between 2011 and 2019. In particular, most of the interventions (23,22% of the total) refer to the year 2018. The total number of CONAI eco-design levers implemented in the dataset is 1069, of which: 7,20% are *"facilitation of recycling activities"*; 19,27% are *"logistics optimization"*; 7,30% are *"optimization of production processes"*; 40,13% are *"raw material saving"*; 2,71% are *"reuse of packaging"*; 9,45% are *"simplification of the packaging system"*; 11,32% are *"use of recycled material"*; 2,62% are *"other actions"*. Therefore, the most implemented eco-design levers are *"raw material saving", "logistics optimization", "use of recycled material",* and *"simplification of the packaging system".* As reported by Cozzolino and De Giovanni (2023), companies tend to focus on CONAI eco-design levers related to logistics activities rather than those related to production activities such as *"optimization of production processes"* and *"facilitation of recycling activities"* because they have probably already intervened in production processes in the past. In addition, they refer that the *"reuse of packaging"* is poorly implemented due to the trade-off between the sustainability of reusable packaging and the increased durability of reusable material. The number of levers (1069) is greater than the number of cases (603) because in 52,57% of the cases, companies implemented more than one CONAI eco-design lever at the same time. Cozzolino and De Giovanni (2023) find that companies have implemented one or two CONAI eco-design levers at a time rather than a full portfolio of CONAI eco-design levers. In particular, they identify two pairs of CONAI eco-design levers with significant correlations: the first pair is *"logistics optimization"* and *"raw material saving"* and the second pair is *"logistics optimization"* and *"simplification of the packaging system".*

3.2. Procedure

Following De Giovanni et al. (2022), we use a procedure composed of eight steps. It allows us to identify the most important relationships among CONAI eco-design levers and environmental indicators. In addition, Bayesian learning also allows us to identify unknown relationships among CONAI eco-design levers, among environmental indicators, and among CONAI eco-design levers and environmental indicators.

Step 1) Import the dataset on BayesiaLab 9.1 and discretize the continuous variables with the OptRandom* algorithm to create a constellation of nodes consisting of X environmental indicators and Y CONAI eco-design levers, where X{CO2 emissions, energy consumption, water consumption} and Y *{"facilitation of recycling activities", "logistics optimization", "optimization of production processes", "raw material saving", "reuse of packaging", "simplification of the packaging system", "use of recycled material", "other actions"}*. This allows all data to be in the correct value type.

Step 2) Fix an element of X as a target goal and use supervised ML algorithms available in BayesiaLab 9.1. This allows to establish and fix the relationships among CONAI eco-design levers and environmental indicators.

Step 3) Identify the most significant relationships between the element of target X and the elements of Y by evaluating the Pearson correlation coefficient and relative p-value. This allows to construct a BN that maintains the significant relationships among CONAI eco-design levers and environmental indicators.

Step 4) Repeat steps 2 and 3 for all elements of X and use the corresponding outputs to fix the arcs in the final BN.

Step 5) Use the unsupervised algorithms available in BayesiaLab 9.1 to identify other relationships. Select the best algorithm based on the Minimum Description Length (MDL). This allows to identify all significant and unknown relationships and keep the most relevant ones by evaluating the MDL, which is a measure of the robustness of the BN.

Step 6) Perform some perturbation tests to check the robustness of the BN and identify the final BN using the node force, Pearson's correlation and Kullback-Leibler index. This allows to confirm the output of step 5 and strengthen the evidence about the robustness of the BN.

Step 7) Use a negative hard evidence analysis to create a benchmark case where all elements of Y are lacking. This allows to create a benchmark case composed of companies that have not yet implemented CONAI eco-design levers.

Step 8) Use a positive hard evidence analysis to learn from the BN. Evaluate the impact of the single element of Y and a portfolio of elements of Y and analyze the changes in the element in X in terms of mean and standard deviation, use the Wald test to check significant variations, and report the log-loss function to show the robustness of the BN.

4. Results

4.1. Joint probability distributions and Bayesian networks

The results of the joint probability distribution are shown in Tables 5 and 6. In particular, Table 5 presents the probability that sample companies implement a certain CONAI eco-design lever. For example, the sample companies implement the eco-design lever *"facilitation of recycling activities"* with probability 0,1277.

Table 5. Joint probability distributions for CONAI eco-design levers

CONAI eco-design levers	P(Y=1) (adopted)	P(Y=0) (not adopted)
Facilitation of recycling activities	0,1277	0,8723
Logistics optimization	0,3365	0,6635
Optimization of production processes	0,1294	0,8706
Raw material saving	0,7109	0,2891
Reuse of packaging	0,0481	0,9519
Simplification of the packaging system	0,1669	0,8331
Use of recycled material	0,2007	0,7993
Other actions	0,0464	0,9536

Similarly, Table 6 presents the probability that companies will improve a certain environmental indicator when they implement CONAI eco-design levers with the probabilities shown in Table 5. For example, companies will achieve a high improvement in the reduction of CO2 emissions with probability 0,2609 when they implement the eco-design levers: *"facilitation of recycling activities"* with probability 0,1277; *"logistics optimization"* with probability 0,3365; *"optimization of production processes"* with probability 0,1294; *"raw material saving"* with probability 0,7109; *"reuse of packaging"* with probability 0,0481; *"simplification of the packaging system"* with probability 0,1669; *"use of recycled material"* with probability 0,2007; and *"other actions"* with probability 0,0464.

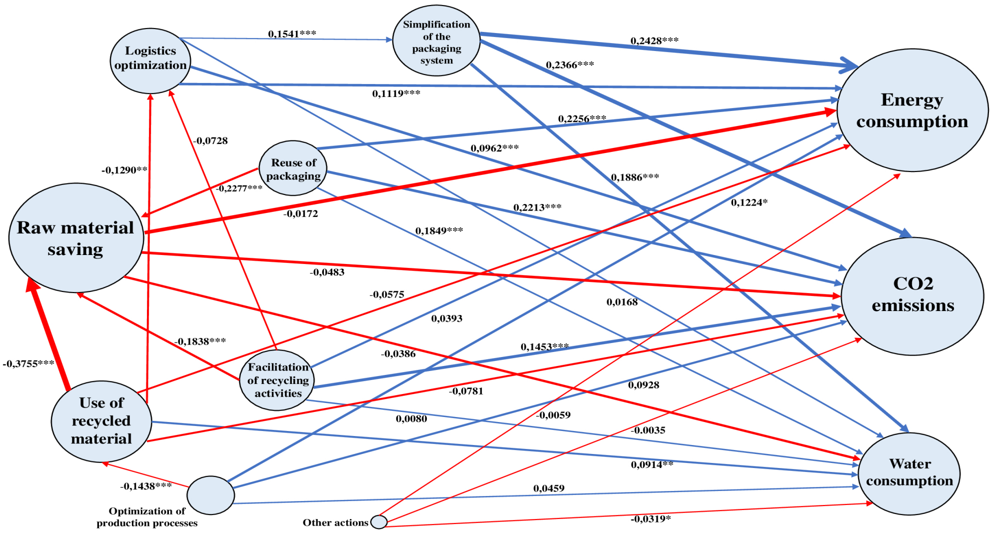
Table 6. Joint probability distributions for environmental indicators

Environmental indicators	P (X=High)	P(X=Low)
CO2 emissions	0,2609	0,7391
Energy consumption	0,2746	0,7254
Water consumption	0,2892	0,7108

We indicate with the symbol "∑" the joint probability distribution for CONAI eco-design levers shown in Table 5. While we indicate with the symbol "Φ" the joint probability distribution for environmental indicators shown in Table 6. Therefore, ∑ = P *("Facilitation of recycling activities"* = 1), P (*"Logistics optimization"* = 1), P (*"Optimization of production processes"* = 1), P (*"Raw material saving"* = 1), P (*"Reuse of* *packaging"* = 1), P (*"Simplification of the packaging system"* = 1), P (*"Use of recycled material"* = 1), P (*"Other actions"* = 1).

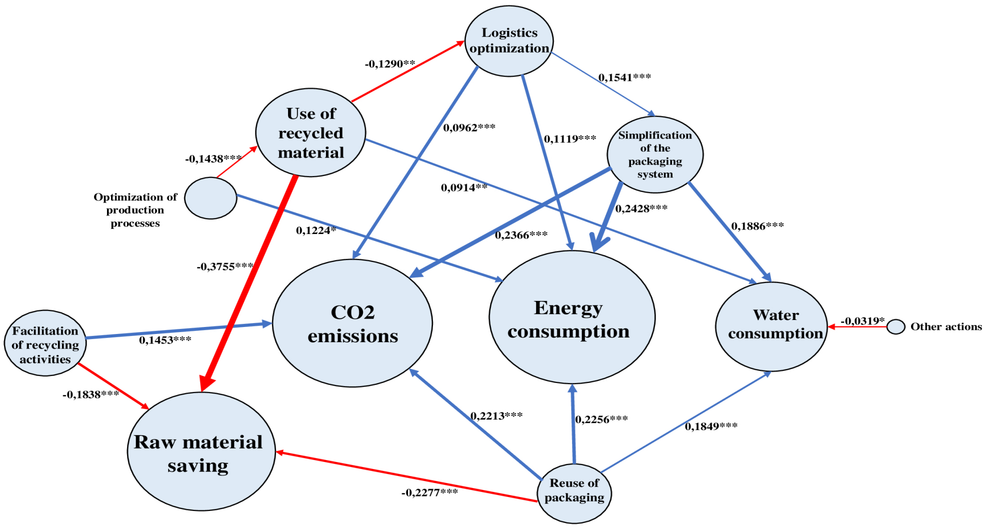
Steps 1 to 6 of the procedure explained in Subsection 3.2 allow us to identify the final BN, shown in Figure 2. The arcs that connect the CONAI eco-design levers to the environmental indicators were obtained by performing steps 1 to 4 of the procedure. They were drawn by the ML and exemplified by steps 5 and 6 of the procedure. The node force represents the size of a node. The larger the size of the node, the greater its importance in the analysis. The Kullback-Leibler index represents the thickness of the arcs. The greater the thickness of the arc, the smaller the difference between the original and the theoretical distribution. The Pearson correlation index represents the relationships between two arcs. In particular, blue arcs represent positive correlations, while red arcs represent negative correlations. In addition, asterisks indicate the statistical significance of correlations in terms of p-value: one asterisk indicates a p-value < 0,05; two asterisks indicate a p-value < 0,01; three asterisks indicate a p-value < 0,001. The closer the p-value is to zero, the higher the significance. Whereas correlations without asterisks have a p-value > 0,05, that is statistically non-significantly.

Figure 2. Final Bayesian network



The analysis of the final BN allows us to answer *RQ1*. In fact, we study peer-to-peer links between CONAI eco-design levers and environmental indicators to provide a reference plan that guides companies in the selection of CONAI eco-design levers. Figure 3 shows the final BN preserving only the most statistically significant relationships (p-value < 0,05).

Figure 3. Final Bayesian network (p-value < 0,05)



First, we examine the significant links among CONAI eco-design levers. The eco-design levers *"facilitation of recycling activities"* and *"raw material saving"* are negatively correlated (p-value < 0,001) because companies consume fewer materials without implementing facilitators for recycling (Cozzolino and De Giovanni, 2023). The CONAI eco-design levers *"logistics optimization"* and *"simplification of the packaging system"* are positively correlated (p-value < 0,001) because light weight packaging is easier to manage in all logistics activities (García-Arca et al., 2017; Georgakoudis and Tipi, 2021). The CONAI eco-design levers *"optimization of production processes"* and *"use of recycled material"* are negatively correlated (p-value < 0,001) because the replacement of virgin materials with recycled materials is difficult to achieve due to technical and economic issues (Kazulytė and Kruopienė, 2018; Afif et al., 2022). Therefore, companies fail to reap the benefits of the use of recycled materials. The eco-design levers *"reuse of packaging"* and *"raw material saving"* are negatively correlated (p-value < 0,001) because reusable packaging consumes more materials to be durable than disposable packaging (Greenwood et al., 2021). The eco-design levers *"use of recycled material"* and "*logistics optimization"* are negatively correlated (p-value < 0,01) because the sourcing of recycled materials requires more logistical complexity (Salandri et al., 2022). The CONAI eco-design levers *"use of recycled material"* and *"raw material saving"* are negatively correlated (p-value < 0,001) again due to the difficulty in the replacement of virgin materials with recycled materials (Kazulytė and Kruopienė, 2018; Afif et al., 2022). Furthermore, we identify insignificant negative correlation between the eco-design levers *"facilitation of recycling activities"* and *"logistics optimization"* (p-value > 0,05). Therefore, companies optimize logistics without implementing facilitators for recycling..

Second, we examine the links among environmental indicators. The study of correlation indices shows that there are not synergies among the reduction of CO2 emissions, the reduction of energy consumption, and the reduction of water consumption. Therefore, companies that want to achieve improvements in multiple environmental indicators should select appropriate eco-design levers.

Third, we examine the links among CONAI eco-design levers and environmental indicators. We divided CONAI eco-design levers into three clusters. The first cluster includes eco-design levers positively and significantly correlated with all environmental indicators: *"reuse of packaging"* and *"simplification of the packaging system"* (p-value < 0,001). Reusable packaging, by avoiding the production and purchase of new packaging, reduce the energy and water consumption of production and the CO2 emissions of direct logistics (Cozzolino and De Giovanni, 2023). While the design of light weight packaging reduces the consumption of production inputs such as water and energy in production and the CO2 emissions of logistics (García-Arca et al., 2017; Georgakoudis and Tipi, 2021). The second cluster includes eco-design levers positively and significantly correlated with some environmental indicators: *"facilitation of recycling activities"*, *"logistics optimization"*, *"optimization of production processes"*, and *"use of recycled material"*. The eco-design lever *"facilitation of recycling activities"* is positively and significantly correlated with the reduction of CO2 emissions (p-value < 0,001). Therefore, the production of easily recyclable packaging mainly reduces CO2 emissions related to packaging disposal (Cozzolino and De Giovanni, 2023). The eco-design lever *"facilitation of recycling activities"* is positively and insignificantly correlated with the reduction of energy and water consumption of recycling processes (p-value > 0,05). The eco-design lever *"logistics optimization"* is positively and significantly correlated with the reduction of CO2 emissions and energy consumption (p-value < 0,001). In fact, the main environmental impacts of logistics are precisely related to the release of CO2 emissions and energy consumption (Cozzolino and De Giovanni, 2023). The eco-design lever *"logistics optimization"* is also positively but insignificantly correlated with the reduction of water consumption, which has little relevance in logistics (p-value < 0,05). The eco-design lever *"optimization of production processes"* is positively and significantly correlated with the reduction of energy consumption (p-value < 0,05). Therefore, the efficiency and upgrading of production processes and machinery mainly affect the reduction of energy consumption (Kliopova-Galickaja and Kliaugaite, 2018; He et al., 2021). The eco-design lever *"optimization of production processes"* is also positively and insignificantly correlated with the reduction of CO2 emissions and water consumption of production (p-value > 0,05). The eco-design lever *"use of recycled material"* is positively and significantly correlated with the reduction of water consumption (p-value < 0,01). Therefore, the use of recycled materials mainly reduces the water used in the production of virgin materials (Cozzolino and De Giovanni, 2023). Whereas the eco-design lever *"use of recycled material"* is negatively and insignificantly correlated with the reduction of CO2 emissions and energy consumption (p-value > 0,05). In fact, the use of recycled material increases the production and logistical complexity of companies (Salandri et al., 2022). The third cluster includes eco-design levers that do not have relevant links with environmental indicators: *"raw material saving"* and *"other actions"* (p-value > 0,05). Both levers are negatively and insignificantly correlated with environmental indicators.

At this point, we have derived a reference plan for companies. Since there are no synergies among environmental indicators, companies should select the environmental indicators on which to act.

Consequently, they should select the most appropriate CONAI eco-design levers for the target environmental indicators, also paying attention to synergies and trade-offs among levers.

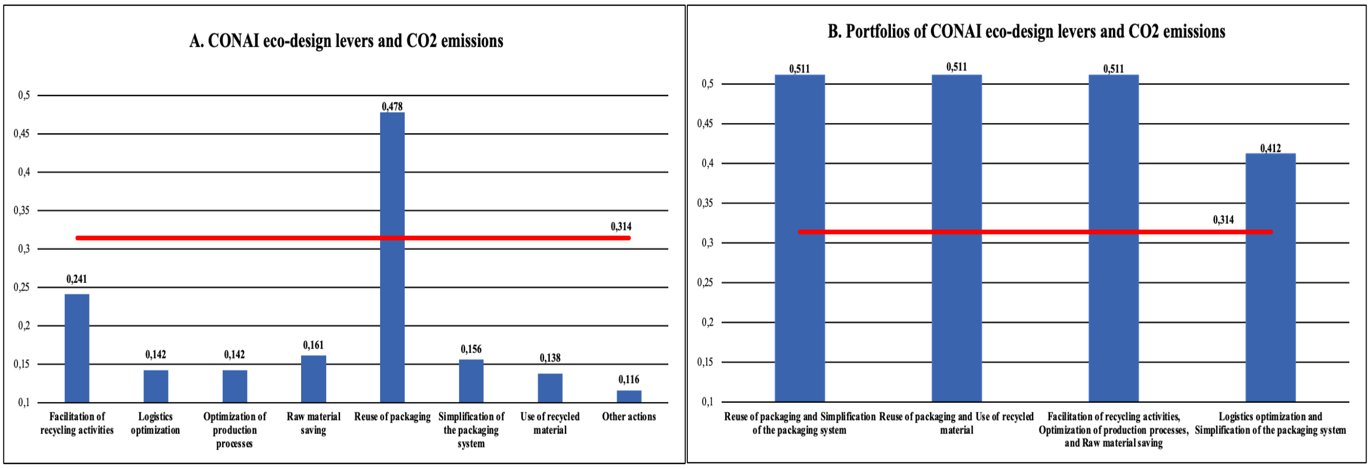
4.2. Bayesian network analysis with positive and negative outcomes

Steps 7 and 8 of the procedure explained in Subsection 3.2 allow us to draw two figures for each environmental indicator. Figure A allow us to answer *RQ2* because shows the improvements that companies can achieve in an environmental indicator when they implement CONAI eco-design levers individually. Figure B allow us to answer *RQ3* because identifies the best portfolios of CONAI eco-design levers to implement to improve an environmental indicator. Both figures are compared to the benchmark value of the environmental indicator. This indicates the value of the environmental indicator when companies do not implement any CONAI eco-design levers.

4.2.1. CONAI eco-design levers and CO2 emissions

Figure 3 shows that the reduction of CO2 emissions is positively and significantly correlated to the eco-design levers *"facilitation of recycling activities"* (p-value < 0,001), *"logistics optimization"* (p-value < 0,001), *"reuse of packaging"* (p-value < 0,001), and *"simplification of packaging system"* (p-value < 0,001). The negative hard evidence analysis allows us to learn more from our BN and discover the value of the reduction of CO2 emissions when companies do not implement any CONAI eco-design levers. The positive hard evidence analysis allows us to discover the contribution made to the reduction of CO2 emissions by each lever implemented individually and build portfolios of eco-design levers to improve the reduction of CO2 emissions. Companies that set a goal to reduce CO2 emissions without implementing CONAI eco-design levers achieve a reduction of CO2 emissions of 0,314. Starting from the original joint probability distribution, $\sum$ and Φ, and imposing positive hard evidence on the eco-design levers, we observe the probability of further reducing CO2 emissions. Figure 4A shows the reduction of CO2 emissions achieved when companies implement each eco-design lever individually and compares it with a benchmark of 0,314 (horizontal line in Figure 4A), which is the value of reduction of CO2 emissions when companies do not implement any CONAI eco-design levers.

Figure 4. Improvements in the reduction of CO2 emissions considering individual CONAI eco-design levers (A) and portfolios of CONAI eco-design levers (B)

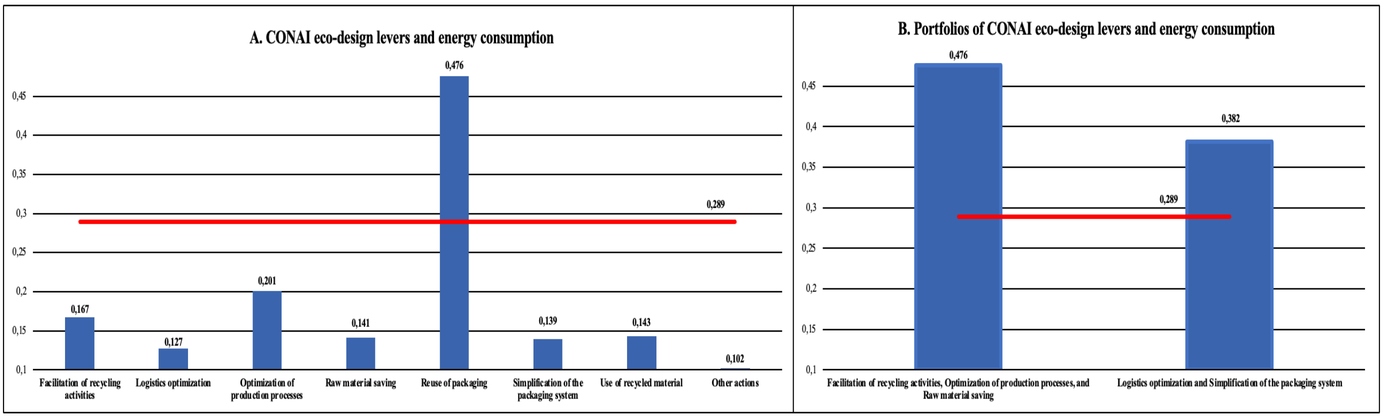


Therefore, we observe that the eco-design lever *“reuse of packaging”* is the only one that if implemented individually further reduces CO2 emissions from 0,314 to 0,478 (p-value < 0,001). While if the other CONAI eco-design levers are implemented individually, the reduction of CO2 emissions is always below the benchmark. Since almost all CONAI eco-design levers are not effective if implemented individually, we consider the construction of portfolios of CONAI eco-design levers to improve the reduction of CO2 emissions. The results of positive hard evidence to identify such portfolios are shown in Figure 4B and are compared with the same benchmark used previously (horizontal line in Figure 4B). In particular, three portfolios can be constructed to achieve the highest level of reduction of CO2 emissions from 0,314 to 0,511. The *“reuse of packaging”* is part of two of these portfolios. In the first portfolio, reuse is combined with *“simplification of the packaging system”*. Both levers positively influence the reduction of CO2 emissions (p-value < 0,001). Reusable packaging reduces CO2 emissions from the production and purchase of new packaging. While light weight packaging optimizes all logistics activities to reduce CO2 emissions. In fact, the lever *“simplification of the packaging system”* is positively correlated with the lever *“logistics optimization”* (p-value < 0,001). In the second portfolio, reuse is combined with the lever *“use of recycled material”*. The use of recycled materials increases the logistics complexity of companies, as evidenced by the negative link with *“logistics optimization”* (p-value < 0,01). However, the benefits of reuse more than offset the logistical disadvantages associated with the use of recycled materials and capture all the benefits of their use such as the reduction of CO2 emissions from production. The third portfolio is composed of *“facilitation of recycling activities”, “optimization of production processes”,* and *“raw material saving”*. In this portfolio, the lever *“facilitation of recycling activities”* is the one that most significantly influences the reduction of CO2 emissions (p-value < 0,001). In fact, the other two levers influence CO2 emissions insignificantly (p-value > 0,05) and are negatively correlated to each other (p-value < 0,001). However, if implemented all three contribute significantly to the reduction of CO2 emissions related to packaging production and disposal. In addition, we identify a portfolio to further reduce CO2 emissions from 0,314 to 0,412 composed of the eco-design levers *"logistics optimization"* and *"simplification of the packaging system"*. These eco-design levers positively influence the reduction of CO2 emissions (p-value < 0,001) and are positively correlated to each other *(*p-value < 0,001). The production of light weight packaging optimizes all logistics activities, reducing their CO2 emissions.

4.2.2. CONAI eco-design levers and energy consumption

Figure 3 shows that the reduction of energy consumption is positively and significantly correlated to the eco-design levers *"logistics optimization"* (p-value < 0,001), *"optimization of production processes"* (p-value < 0,05), *"reuse of packaging"* (p-value < 0,001), and *"simplification of packaging system"* (p-value < 0,001). The negative hard evidence analysis allows us to learn more from our BN and discover the value of the reduction of energy consumption when companies do not implement any CONAI eco-design levers. The positive hard evidence analysis allows us to discover the contribution made to the reduction of energy consumption by each lever implemented individually and build portfolios of eco-design levers to improve the reduction of energy consumption. Companies that set a goal to reduce energy consumption without implementing CONAI eco-design levers achieve a reduction of energy consumption of 0,289. Starting from the original joint probability distribution, ∑ and Φ, and imposing positive hard evidence on the eco-design levers, we observe the probability of further reducing energy consumption. Figure 5A shows the reduction of energy consumption achieved when companies implement each eco-design lever individually and compares it with a benchmark of 0,289 (horizontal line in Figure 5A), which is the value of reduction of energy consumption when companies do not implement any CONAI eco-design levers.

Figure 5. Improvements in the reduction of energy consumption considering individual CONAI eco-design levers (A) and portfolios of CONAI eco-design levers (B)



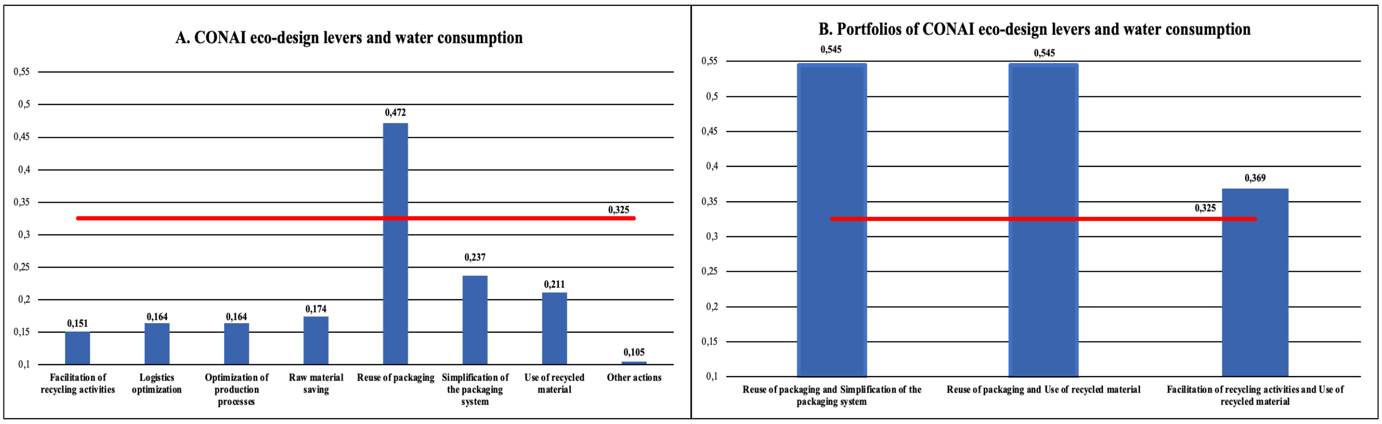
Therefore, we observe that the eco-design lever *"reuse of packaging"* is the only one that if implemented individually further reduces energy consumption from 0,289 to 0,476 (p-value < 0,001). While if the other

CONAI eco-design levers are implemented individually, the reduction of energy consumption is always below the benchmark. Since almost all CONAI eco-design levers are not effective if implemented individually, we consider the construction of portfolios of CONAI eco-design levers to improve the reduction of energy consumption. The results of positive hard evidence to identify such portfolios are shown in Figure 5B and are compared with the same benchmark used previously (horizontal line in Figure 5B). In particular, the portfolio that achieves the highest level of reduction of energy consumption from 0,289 to 0,476 is composed of *"facilitation of recycling activities", "optimization of production processes",* and *"raw material saving"*. The eco-design lever *"optimization of production processes"* is central in this portfolio because it is the only one that significantly influences energy consumption (p-value < 0,001). Whereas the other two levers influence energy consumption insignificantly (p-value > 0,05) and are negatively correlated to each other (p-value < 0,001). However, if the three levers are implemented at the same time, they significantly reduce the energy consumption of recycling processes and production processes. In addition, we identify a portfolio to further reduce energy consumption from 0,289 to 0,382, composed of the levers *"logistics optimization"* and *"simplification of the packaging system"*. Both levers are positively correlated with the reduction of energy consumption (p-value < 0,001) and to each other (p-value < 0,001). In fact, the production of light weight packaging optimizes all logistics operations, reducing their energy consumption.

4.2.3. CONAI eco-design levers and water consumption

Figure 3 shows that the reduction of water consumption is positively and significantly correlated to the eco-design levers *"reuse of packaging"* (p-value < 0,001), *"simplification of packaging system"* (p-value < 0,001), and *"use of recycled material"* (p-value < 0,01). The negative hard evidence analysis allows us to learn more from our BN and discover the value of the reduction of water consumption when companies do not implement any CONAI eco-design levers. The positive hard evidence analysis allows us to discover the contribution made to the reduction of water consumption by each lever implemented individually and build portfolios of eco-design levers to improve the reduction of water consumption. Companies that set a goal to reduce water consumption without implementing CONAI eco-design levers achieve a reduction of water consumption of 0,325. Starting from the original joint probability distribution, Σ and Φ, and imposing positive hard evidence on the eco-design levers, we observe the probability of further reducing water consumption. Figure 6A shows the reduction of water consumption achieved when companies implement each eco-design lever individually and compares it with a benchmark of 0,325 (horizontal line in Figure 6A), which is the value of reduction of water consumption when companies do not implement any CONAI eco-design levers.

Figure 6. Improvements in the reduction of water consumption considering individual CONAI eco-design levers (A) and portfolios of CONAI eco-design levers (B)



Therefore, we observe that the eco-design lever *"reuse of packaging"* is the only one that if implemented individually further reduces water consumption from 0,325 to 0,472 (p-value < 0,001). While if the other CONAI eco-design levers are implemented individually, the reduction of water consumption is always below the benchmark. Since almost all CONAI eco-design levers are not effective if implemented individually, we consider the construction of portfolios of CONAI eco-design levers to improve the reduction of water consumption. The results of positive hard evidence to identify such portfolios are shown in Figure 6B and are compared with the same benchmark used previously (horizontal line in Figure 6B). In particular, two portfolios can be constructed to achieve the highest level of reduction of water consumption from 0,325 to 0,545. Reuse is part of both portfolios. In the first portfolio, reuse is combined with *"simplification of the packaging system"*. Both levers are positively correlated with the reduction of water consumption (p-value < 0,001). In fact, reusable packaging, by avoiding the production of new packaging, reduce water consumption in production. Similarly, light weight, by reducing material consumption, reduce water consumption in production. In the second portfolio, reuse is combined with the lever *"use of recycled material"*. The latter is positively correlated to the reduction of water consumption (p-value < 0,01). The same discussion performed above applies to reuse. Whereas the use of recycled materials reduces the water consumption for the production of virgin materials. In addition, we identify a portfolio to further reduce water consumption from 0,325 to 0,369, composed of the eco-design levers *"facilitation of recycling activities"* and *"use of recycled material"*. The lever *"facilitation of recycling activities"* positively influences water consumption (p-value > 0,05). This portfolio maximize the benefits of reduction of water consumption from the use of recycled materials. In fact, the simplification of recycling activities allows more recycled material to be produced and used to replace virgin materials..

4.2.4. CONAI eco-design levers and environmental indicators

We consider the impact of CONAI eco-design levers on all three environmental indicators: CO2 emissions, energy consumption, and water consumption. The positive hard evidence analysis showed that the only eco-design lever that can be implemented individually to achieve environmental improvements compared to benchmarks is *"reuse of packaging".* In fact, compared with the benchmarks, it reduces CO2 emissions by 0,164 (Figure 4A), energy consumption by 0,187 (Figure 5A), and water consumption by 0,147 (Figure 6A). In addition, the positive hard evidence analysis showed that four portfolios of eco-design levers can be constructed to improve multiple environmental indicators simultaneously. In particular, two portfolios reduce CO2 emissions and energy consumption at the same time. The first portfolio, composed of the eco-design levers *"facilitation of recycling activities"*, *"optimization of production processes"*, and *"raw material saving"*, reduces CO2 emissions by 0,197 (Figure 4B) and energy consumption by 0,187 (Figure 5B). The second portfolio, composed of the eco-design levers *"logistics optimization"* and "*simplification of the packaging system",* reduces CO2 emissions by 0,098 (Figure 4B) and energy consumption by 0,093 (Figure 5B). Therefore, the first portfolio is the most effective in the reduction of CO2 emissions and energy consumption. Whereas two portfolios reduce CO2 emissions and water consumption at the same time. The first portfolio, composed of the eco-design levers *"reuse of packaging"* and *"simplification of the packaging system",* reduces CO2 emissions by 0,197 (Figure 4B) and water consumption by 0,220 (Figure 6B). The second portfolio, composed of the eco-design levers *"reuse of packaging"* and *"use of recycled material"*, reduces CO2 emissions by 0,197 (Figure 4B) and water consumption by 0,220 (Figure 6B). Therefore, the two portfolios reduce CO2 emissions and water consumption in the same way. However, we do not identify portfolios to reduce energy consumption and water consumption simultaneously. We also do not identify portfolios to reduce all three environmental indicators simultaneously. In fact, companies that want to achieve these goals should implement the lever *"reuse of packaging"* alone.

5. Discussion

The main aim of our paper is to support companies in the selection of CONAI eco-design levers to be implemented to improve their environmental performance. The CONAI eco-design levers are *"facilitation of recycling activities"*, *"logistics optimization"*, *"optimization of production processes"*, *"raw material saving"*, *"reuse of packaging"*, *"simplification of the packaging system"*, and *"use of recycled material"*. The environmental performances are analyzed through three environmental indicators: CO2 emissions, energy consumption and water consumption. To achieve this aim, we use a sample composed of 603 concrete cases of success in which Italian companies have implemented CONAI eco-design levers on packaging. In particular, following De Giovanni et al. (2022), we implement a methodology based on BN and modern ML tools on the sample. First, we build and analyze all possible links among CONAI eco-design levers, among environmental indicators, and among CONAI eco-design levers and environmental indicators to provide companies a reference plan for the selection of CONAI eco-design levers. Second, we study the impact of each CONAI eco-design lever when implemented individually relative to benchmarks of environmental indicators. The benchmark of each environmental indicator indicates its value in the case where companies do not implement any CONAI eco-design levers. In this way, we suggest to companies the most effective CONAI eco-design levers if implemented individually. Third, we construct different portfolios of CONAI eco-design levers to improve environmental indicators relative to their benchmarks. In this way, we suggest to companies the most effective CONAI eco-design lever portfolios. In the next subsections we discuss the research and managerial contributions provided by our results.

5.1. Research contributions

Our paper provides different research contributions. The seven CONAI eco-design levers represent a comprehensive set of different eco-design practices that can be implemented on all types of packaging: packaging in any material and packaging for any product. However, in the literature on packaging eco-design, papers that study concrete cases of packaging eco-design analyze the environmental benefits of only one packaging eco-design practice or a few packaging eco-design practices. In addition, these papers focus on specific types of packaging: packaging in specific materials or packaging for specific products. To our knowledge, Cozzolino and De Giovanni (2023) are the only ones to consider a comprehensive set of packaging eco-design practices (CONAI eco-design levers), packaging in different materials (plastics, paper/cardboard, metals such as aluminum and steel, glass and wood) and packaging for different products (from the food, beverage, health care, home products and industrial sectors), through the analysis of 603 concrete cases of success in which Italian companies have implemented CONAI eco-design levers on packaging to improve three environmental indicators: CO2 emissions, energy consumption and water consumption. Cozzolino and De Giovanni (2023) analyze the links among CONAI eco-design levers and identify the best CONAI eco-design levers for each environmental indicator. However, companies need more precise guidance on which CONAI eco-design levers they should implement. In fact, if they implement only one of the eco-design levers suggested by Cozzolino and De Giovanni (2023), they may achieve suboptimal performance because some eco-design levers work better when combined with other levers to exploit synergies. Similarly, if companies implement multiple eco-design levers among those suggested by Cozzolino and De Giovanni (2023), they may incur high costs and achieve suboptimal performance due to trade-offs among levers. Therefore, companies should understand which eco-design levers are effective when implemented individually and which are effective when combined in portfolios to exploit their synergies. The novelty of our paper lies precisely in the creation of guidance to help companies in the selection of CONAI eco-design levers to implement to improve environmental performance. To achieve this aim, we use the same sample of Cozzolino and De Giovanni (2023) and implement an innovative methodology in the area of packaging eco-design, based on BN and modern ML tools. This methodology allows us to create sophisticated supports to assist companies in the decision-making process. First, we show to companies all the possible links among CONAI eco-design levers, among environmental indicators, and among CONAI eco-design levers and environmental indicators, to provide them a reference plan for the selection of CONAI eco-design levers. As stated in Subsection 2.4, Cozzolino and De Giovanni (2023) analyze the links among CONAI eco-design levers. In Table 7 we compare the significant links between eco-design levers identified by Cozzolino and De Giovanni (2023) with those identified in our paper. Synergies are indicated with a plus sign, while trade-offs are indicated with a minus sign.

Table 7. Synergies and trade-offs among CONAI eco-design levers (p-value < 0,05)

Cozzolino and De Giovanni (2023)	This paper
Facilitation of recycling activities and Raw material saving (-)	Facilitation of recycling activities and Raw material saving (-)
Logistics optimization and Raw material saving (+)	-
Logistics optimization and Simplification of the packaging system (+)	Logistics optimization and Simplification of the packaging system (+)
Optimization of production processes and Use of recycled material (-)	Optimization of production processes and Use of recycled material (-)
Reuse of packaging and Raw material saving (-)	Reuse of packaging and Raw material saving (-)
Reuse of packaging and Use of recycled material (-)	-
Use of recycled material and Logistics optimization (-)	Use of recycled material and Logistics optimization (-)
Use of recycled material and Raw material saving (-)	Use of recycled material and Raw material saving (-)

Differently from Cozzolino and De Giovanni (2023), we do not identify the synergy between *"logistics optimization"* and *"raw material saving"* and we do not identify the trade-off between *"reuse of packaging"* and *"use of recycled material"*. In fact, in our portfolios *"raw material saving"* is not combined with *"logistics optimization"* but with *"optimization of production processes"*. While "*reuse of packaging"* is combined with *"use of recycled material"*. Therefore, we believe that the reduction of material consumption impacts production more than logistics, while reuse and use of recycled materials are compatible. Second, we suggest to companies CONAI eco-design levers that can be implemented individually to improve each environmental indicator relative to its benchmark. Third, we suggest different portfolios of CONAI eco-design levers that companies can implement to improve each environmental indicator relative to its benchmark. In Table 8 we compare the suggestions provided to companies for the selection of eco-design levers by Cozzolino and De Giovanni (2023) with those provided in our paper. For example, Cozzolino and De Giovanni (2023) suggest that companies interested in the reduction of CO2 emissions should implement the following eco-design levers, in order of preference: *"reuse of packaging"*, *"facilitation of recycling activities"*, *"simplification of the packaging system"*, *"raw material saving"*, *"logistics optimization"*, *"optimization of production processes"*, and *"use of recycled material"*. While in our paper we suggest that companies interested in the reduction of CO2 emissions should implement one of these alternatives: only *"reuse of packaging"*; a portfolio composed of *"reuse of packaging"* and "*simplification of the packaging system"*" a portfolio composed of *"reuse of packaging"* and *"use of recycled material"*; a portfolio composed of *"facilitation of recycling activities"*, *"optimization of production processes"* and *"raw material saving";* or a portfolio composed of *"logistics optimization"* and *"simplification of the packaging system"*. Our suggestions improve the reduction of CO2 emissions compared to its benchmark, which indicates the value of the environmental indicator when companies do not implement any CONAI eco-design levers. In this way, unlike Cozzolino and De Giovanni (2023), companies can identify the eco-design levers best suited to their corporate strategies and environmental goals.

Table 8. Guidance for the selection of CONAI eco-design levers

Environmental indicators	Cozzolino and De Giovanni (2023)	This paper
CO2 emissions	Reuse of packaging, Facilitation of recycling activities, Simplification of the packaging system, Raw material saving, Logistics optimization, Optimization of production processes, Use of recycled material	Reuse of packaging
	-	Reuse of packaging and Simplification of the packaging system
	-	Reuse of packaging and Use of recycled material
	-	Facilitation of recycling activities, Optimization of production processes and Raw material saving
	-	Logistics optimization and Simplification of the packaging system
Energy consumption	Reuse of packaging, Simplification of the packaging system, Facilitation of recycling activities, Raw material saving, Optimization of production processes, Logistics optimization, Use of recycled material	Reuse of packaging
	-	Facilitation of recycling activities, Optimization of production processes and Raw material saving
	-	Logistics optimization and Simplification of the packaging system
Water consumption	Reuse of packaging, Simplification of the packaging system, Use of recycled material, Raw material saving, Optimization of production processes	Reuse of packaging

	-	Reuse of packaging and Simplification of the packaging system
	-	Reuse of packaging and Use of recycled material
	-	Facilitation of recycling activities and Use of recycled material

5.2. Managerial contributions

Our paper provides different managerial contributions. In fact, we offer to companies sophisticated supports to guide them in the selection of CONAI eco-design levers to implement to improve environmental performance. Our paper can also support the achievement of the goals set by the EU for packaging circularity and sustainability. First, we provided companies a reference plan for the selection of CONAI eco-design levers. Based on this reference plan, we provide companies different suggestions. Companies should initially identify environmental indicators on which to act. Consequently, they should select CONAI eco-design levers based on their links with environmental indicators and other levers. Synergies and trade-offs among the CONAI eco-design levers are shown in Table 7. Companies should exploit the synergy between *“logistics optimization”* and *"simplification of the packaging system”*. In fact, light weight packaging are easier to manage in all supply chain activities (García-Arca et al., 2017; Georgakoudis and Tipi, 2021). Whereas companies should pay attention to different trade-offs. There is a trade-off between “*facilitation of recycling activities”* and *“raw material saving”* because facilitators for recycling do not reduce the consumption of raw material (Cozzolino and De Giovanni, 2023). There is a trade-off between *“reuse of packaging”* and *“raw material saving”* because reusable packaging consume a lot of materials to be durable (Greenwood et al., 2021). There is a trade-off between *“use of recycled material”* and *“logistics optimization”*, *“optimization of production processes”* and *“raw material saving”* because recycled materials increase the production and logistical complexity of companies and are difficult to use in replacement of virgin materials. (Kazulytė and Kruopienė, 2018; Afif et al., 2022; Salandri et al., 2022).

Second, we suggest to companies CONAI eco-design levers to implement to improve each environmental indicator against its benchmark, which indicates the value of the environmental indicator when companies do not implement any CONAI eco-design levers. The suggested CONAI eco-design levers are shown in Table 8. The eco-design lever *“reuse of packaging”* is the only one that when implemented individually improves each environmental indicator relative to its benchmark. Reuse avoids all environmental impacts associated with the production and purchase of new packaging (Cozzolino and De Giovanni, 2023). We provide some recommendations for companies to maximize the benefits of reuse. Reusable packaging must be used a certain number of times to be effective in order to offset the higher production inputs they require to be durable (Greenwood et al., 2021). In addition, the effectiveness of reusable packaging also depends on the organization of reverse logistics, to save on CO2 emissions, and the efficiency of cleaning activities, to save on water consumption (Postacchini et al., 2018; Hitt et al., 2023). While it is not convenient for companies to implement the other CONAI eco-design levers individually. For this reason, we also suggest different portfolios of CONAI eco-design levers in Table 8. In this way, companies can select the portfolio that best suits their corporate strategies and environmental goals. Companies interested in improving the reduction of CO2 emissions and/or energy consumption should select from two portfolios. The first portfolio combines *"facilitation of recycling activities"*, *"optimization of production processes"*, and *"raw material saving"*. The production of packaging that is easy to recycle makes recycling processes efficient. This reduces the energy consumption of recycling processes and the CO2 emissions of packaging disposal (Cozzolino and De Giovanni, 2023). The reduction of material consumption makes production processes more efficient. This reduces the energy consumption and CO2 emissions of production (Yuan et al., 2022). The second portfolio combines *"logistics optimization"* and *"simplification of the packaging system*". As mentioned above, the production of light weight packaging saves on energy consumption and CO2 emissions of production and logistics activities (García-Arca et al., 2017; Georgakoudis and Tipi, 2021). Companies interested in improving the reduction of CO2 emissions and/or water consumption should select from two portfolios. The first portfolio combines *"reuse of packaging"* and *"simplification of the packaging system"*. Reuse, by avoiding the production and purchase of new packaging, significantly impacts the water consumption of production and CO2 emissions of direct logistics (Cozzolino and De Giovanni, 2023). Similarly, light weight packaging reduce water consumption in production and CO2 emissions of logistics (García-Arca et al., 2017; Georgakoudis and Tipi, 2021). Reverse logistics optimization, crucial for reusable packaging, can be pursued through this portfolio. The second portfolio combines *"reuse of packaging"* and *"use of recycled material"*. Recycled materials increase the production and logistical complexity of companies, impacting CO2 emissions and energy consumption (Salandri et al., 2022). However, the benefits of reuse more than offset the logistical problems of recycled materials and exploit their advantages in terms of lower water consumption for the production of virgin materials (Civancik-Uslu et al., 2019). Companies interested in improving only the reduction of water consumption should implement a portfolio that combines *"facilitation of recycling activities"* and *"use of recycled material"*. The production of packaging that is easy to recycle reduces water consumption for waste treatment and, more importantly, allows the production of more recycled material, which we have seen is strongly linked to the reduction of water consumption for virgin material production (Keller et al., 2022; Civancik-Uslu et al., 2019). Companies interested in improving the reduction of all environmental indicators simultaneously should implement only *"reuse of packaging"* for the reasons already discussed. From our paper, the importance of reuse emerges. This practice is effective both when implemented individually and when combined with other levers in portfolios. Moreover, it is the only practice that can improve all three environmental indicators relative to their benchmarks. Therefore, we believe that companies should reconsider reuse and increase its implementation.

5.3. Limits and directions for future research

Our paper offers original and useful insights on packaging eco-design. However, it is not without limitations, which we discuss here to inspire future research in the same direction. First, we limit our analysis to the seven CONAI eco-design levers *"facilitation of recycling activities"*, *"logistics optimization"*, *"optimization of production processes"*, *"raw material saving"*, *"reuse of packaging"*, *"simplification of the packaging system"*, *"use of recycled material"* and the residual category *"other actions")* and three environmental indicators (CO2 emissions, energy consumption, and water consumption). Future research could include other packaging eco-design practices in the analysis. For example, in Subsection 2.3 we discussed the reduction of food waste caused by food packaging and the use of bio-based and/or biodegradable materials to reduce the environmental impacts of plastics packaging. However, this theoretical part of our paper was not empirically analyzed. In fact, our empirical analysis focused on eco-design for all packaging types (packaging in any material and packaging for any product) using the seven categories proposed by CONAI. Future research could also consider eco-design practices for specific types of packaging such as food packaging and plastics packaging. In addition, future research could include other environmental indicators than CO2 emissions, energy consumption, and water consumption in the analysis. Future research could also consider social and economic indicators using the same approach. Second, our paper focuses on a sample composed of 603 concrete cases of success in which Italian companies have implemented CONAI eco-design levers on packaging. Therefore, our results may be influenced by the composition of the sample, which includes only Italian companies registered to CONAI. Future research could replicate this analysis on a sample of companies from other countries or specific sectors to test the generalizability and the validity of our results.

6. Conclusion

The seven CONAI eco-design levers are a comprehensive set of the different eco-design practices for all types of packaging. However, there is a lack of papers in the literature on packaging eco-design that provide guidance for companies in the selection of CONAI eco-design levers to improve environmental performance. In fact, most papers study one or a few packaging eco-design practices and focus on specific types of packaging. Cozzolino and De Giovanni (2023) are the only ones to consider CONAI eco-design levers and different types of packaging, through the analysis of 603 cases in which Italian companies implemented CONAI eco-design levers on packaging to improve three environmental indicators: CO2 emissions, energy consumption and water consumption. However, even Cozzolino and De Giovanni (2023) do not indicate to companies which eco-design levers are effective when implemented individually and which eco-design levers can be combined into portfolios. Therefore, the novelty of our paper lies in the creation of sophisticated decision supports for companies to select CONAI eco-design levers. To achieve this aim, we implement on the same sample of Cozzolino and De Giovanni (2023) an innovative methodology based on BN and modern ML tools. First, we build a reference plan for the selection of CONAI eco-design levers that includes all possible links among CONAI eco-design levers, among environmental indicators, and among CONAI eco-design levers and environmental indicators. Second, we indicate to companies the CONAI eco-design levers that are most effective when implemented individually to improve environmental indicators. Third, we suggest different portfolios of effective CONAI eco-design levers to companies to improve environmental indicators. Based on the reference plan, companies should first identify the target environmental indicators and then select eco-design levers based on their links to environmental indicators and other levers. The only effective lever if implemented individually is *"reuse of packaging"* for all environmental indicators. Companies interested in the reduction of CO2 emissions and/or energy consumption can implement one of these two portfolios: "*facilitation of recycling activities"*, *"optimization of production processes"* and *"raw material saving"*; or *"logistics optimization"* and *"simplification of the packaging system"*. Companies interested in the reduction of CO2 emissions and/or water consumption can implement one of these two portfolios: *"reuse of packaging"* and *"simplification of the packaging system"*; or *"reuse of packaging"* and *"use of recycled material"*. Companies interested in the reduction of water consumption can implement a portfolio composed of *"facilitation of recycling activities"* and *"use of recycled material"*. In particular we show the relevance of reuse, the only practice that improves all environmental indicators and effective both individually and in portfolios. Overall, our paper provide all the tools there is a need for companies to design circular and sustainable packaging, to improve environmental performance, and to achieve the packaging goals set by EU.

Notes

1. Eurostat; last update 21/03/2023; Packaging waste by waste management operations; https://ec.europa.eu/eurostat/databrowser/view/env_waspac/default/table?lang=en

2. Official Journal of the European Union; L 150; 14/06/2018; Directive (EU) 2018/852 of the European Parliament and of the Council of 30 May 2018 amending Directive 94/62/CE on packaging and packaging waste (Text with EEA relevance); p. 141-154; https://eur-lex.europa.eu/eli/dir/2018/852/oj

3. CONAI; June 2022; General program for prevention and management of packaging and packaging waste; Final general report 2021; https://www.conai.org/chi-siamo/risultati/

4. Lucía Fernández; 10/03/2022; Distribution of packaging demand worldwide in 2019, by material type; Statista; https://www.statista.com/statistics/271601/packaging-materials-in-the-global-packaging-market-since-2003/

5. Eurostat; last update 21/03/2023; Recycling rate of packaging waste by type of packaging; https://ec.europa.eu/eurostat/databrowser/view/CEI_WM020__custom_354860/bookmark/table?lang=en&bookmarkId=bc39f400-65cd-40a8-bf14-c995c729e2a5

6. ECO TOOL CONAI; The levers of eco-design; https://www.ecotoolconai.org/index.php?r=site/page&view=ecopacking

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Thesis summary

1. Introduction

The linear economy model, in which goods are produced, consumed, and discarded, is globally fueling a huge amount of waste (Minelgaitė and Liobikienė, 2019). Packaging waste represents a significant share of municipal waste, about 15-20% in developing countries and 30-35% in developed countries (Wiesmeth et al., 2018 cited in Afif et al., 2022). To counter the waste problem, a transition from the linear economy model to the circular economy model is needed, which aims to create closed loops of materials and energy in which the consumption of production inputs, release of emissions, and generation of waste are minimized (Geissdoerfer et al., 2016 cited in Sharma et al., 2021; De Giovanni and Folgiero, 2023). The circular economy allows to: design and produce products sustainably through the practices of "refuse", "rethink", and "reduce"; extend the life cycle of products through the practices of "reuse", "repair", "refurbish", "remanufacture", and "repurpose": enhance the value of products that have reached the end of their life cycle through the practices of "recycle" and "recover" (Morseletto, 2020 cited in Sharma et al., 2021). Such practices not only positively impact the environmental performance of companies, but also their long-term economic performance (Maranesi and De Giovanni, 2020). The circular economy model is at the heart of directives issued by the European Union (EU) to counter the waste problem. In particular, the issue of packaging waste attracted the interest of the European Commission (EC) since 1994 with the implementation of the packaging and packaging waste Directive 94/62/EC, amended in 2018 in Directive 2018/852/EU (Lorang et al., 2022). The latter set minimum recycling targets to be mandatorily achieved by 2025 and 2030 for packaging waste in general and for specific packaging materials (Sazdovski et al., 2021). The packaging design phase is crucial to reduce the packaging waste problem. In fact, design is responsible for about 80% of the sustainability impacts of products. The design of environmentally friendly products can be called “eco-design” and can be supported by several design methods, the most popular of which is Life Cycle Assessment (LCA) (Ahmad et al., 2018). To incentivize companies to eco-design packaging, governments in many developed countries implement various Extended Producer Responsibility (EPR) tools, which makes producers organizationally or financially responsible for the products made also when they become waste (Afif et al., 2022). In most cases, collective EPR policies are adopted, in which producers pay an advanced disposal fee to a producer responsibility organization, which takes legal responsibility from its members and is responsible of managing the waste they produce (Joltreau, 2022). In the Italian packaging industry, collective EPR policy is implemented through CONAI, the National Packaging Consortium (Lorang et al., 2022). CONAI promotes innovation, communication, knowledge sharing and collaboration along supply chains to support companies in packaging design, production and disposal. (Mattia et al., 2021). In particular, CONAI identifies seven eco-design levers to incentivize companies to design circular and sustainable packaging: *“facilitation of recycling activities”*, “*logistics optimization”*, *“optimization of production processes”*, *“raw material saving”*, *“reuse of* *packaging"*, *"simplification of the packaging system"*, and *"use of recycled material"* (Cozzolino and De Giovanni, 2023). The seven categories identified by CONAI represent a comprehensive set of different eco-design practices that can be applied to all types of packaging: packaging in any material and for any product. However, in the literature on packaging eco-design, papers that study concrete cases of packaging eco-design analyze the environmental benefits of a single practice or a few practices and focus on specific types of packaging. To our knowledge, Cozzolino and De Giovanni (2023) are the only ones to consider a comprehensive set of packaging eco-design practices, packaging in different materials and packaging for different products, through the analysis of 603 concrete cases of success in which Italian companies have implemented CONAI eco-design levers on packaging to improve three environmental indicators: CO2 emissions, energy consumption and water consumption. Cozzolino and De Giovanni (2023) analyze the links among CONAI eco-design levers and identify the best CONAI eco-design levers for each environmental indicator. However, they do not indicate to companies which eco-design levers are effective when implemented individually and which eco-design levers are effective when combined in portfolios to exploit their synergies. Our paper aims to provide companies a clear guidance for the selection of CONAI eco-design levers. Therefore, we ask the following three research questions (RQ). *What are the links among CONAI eco-design levers, among environmental indicators, and among CONAI eco-design levers and environmental indicators?* (RQ1). We build all possible links among CONAI eco-design levers, among environmental indicators, and among CONAI eco-design levers and environmental indicators to provide companies a reference plan for the selection of CONAI eco-design levers. *What is the impact of CONAI eco-design levers on environmental indicators when implemented individually? (RQ2).* We model scenarios in which each eco-design lever is implemented individually to analyze its contribution to improving environmental indicators. We consider a lever effective when it improves environmental indicators relative to their benchmarks, which indicate the value of environmental indicators when companies do not implement any CONAI eco-design levers. *What are the portfolios of CONAI eco-design levers that improve environmental indicators? (RQ3).* We build different portfolios of CONAI eco-design levers that exploit synergies among CONAI eco-design levers to improve each environmental indicator relative to its benchmark. To pursue the research aim, we implement on the same sample of Cozzolino and De Giovanni (2023) a methodology based on Bayesian Networks (BN) and modern Machine Learning (ML) tools to create sophisticated decision supports for companies. Our paper is organized as follows: in Section 2 we conduct a literature review on packaging eco-design; in Section 3 we show the sample and procedure used in the analysis; in Section 4 we present the results of the analysis; in Section 5 we discuss the contributions provided by our results; in Section 6 we conclude the paper.

2. Literature review

2.1. Packaging overview

The term packaging refers to any object that externally covers products (Wyrwa and Barska, 2017). Packaging has three functions: logistics function, marketing function, and environmental function (Johansson et al., 1997 cited in García-Arca and Carlos Prado Prado, 2008). Packaging has a logistic function because it is involved in all activities in the supply chain of products from their packaging to their consumption, such as: transportation, distribution, storage, and handling (Ahmad et al., 2022). In all these stages of the supply chain, packaging: protects the contents from the external environment (Wyrwa and Barska, 2017); facilitates products handling for all supply chain actors, and product use for consumers (Wyrwa and Barska, 2017); and communicates information to all actors in the supply chain (Choi and Lee, 2019) and to consumers (Wyrwa and Barska, 2017). Packaging has a marketing function because the information communicated to consumers and its design elements also enable product promotion (Lindh et al., 2016). Packaging has an environmental function because it must be designed to perform its functions effectively while minimizing negative impact on the environment (Zhu et al., 2022). The environmental function of packaging is discussed in more detail in Subsection 2.2. Packaging is a system composed of three levels: primary, secondary, and tertiary packaging (Twede, 1992). Primary packaging first covers products to protect them, facilitate their transportation, distribution, storage, and handling in the supply chain, promote them, provide information to consumers, and simplify the use of products (Georgakoudis and Tipi, 2021). Secondary packaging groups more primary packaging to further protect products and to simplify their transportation, distribution, storage, and handling in the supply chain (García-Arca et al., 2020). Tertiary packaging groups more secondary packaging to protect them and especially simplify their transportation in the supply chain (García-Arca et al., 2020). Secondary and tertiary packaging also assume the function of communication because they allow supply chain actors to share information (Lindh et al., 2016). In packaging design, it is necessary to select the materials best suited to the needs of the products to be covered (Ibrahim et al., 2022). Varžinskas et al. (2020) refer that packaging can be made from a single material (mono-material packaging), from different materials combined in indistinguishable layers (multilayer packaging), or from different materials that can be separated manually. They state that the main materials used in packaging are plastics, paper/cardboard, metals, glass, and wood. In particular, the global packaging industry in 2019 consisted of plastics 43,2%, paper and paperboard 33,2%, metals 12,1%, glass 5,8%, and other materials 4,7%[4].

2.2. Eco-design for all types of packaging: the CONAI eco-design levers

CONAI identifies seven eco-design levers to incentivize companies to design circular and sustainable packaging: *"facilitation of recycling activities"*, *"logistics optimization"*, *"optimization of production* *processes"*, *"raw material saving"*, *"reuse of packaging"*, *"simplification of the packaging system"*, and *"use of recycled material"* (Cozzolino and De Giovanni, 2023). CONAI eco-design levers represent a comprehensive set of practices that can be applied to all packaging: packaging in any material and for any product.

CONAI defines the eco-design lever *"facilitation of recycling activities"* as the design of packaging that simplifies all activities related to the recovery and recycling of packaging waste[6]. In fact, one of the main barriers to recycling is linked to the recovery of waste that can be mechanically processed (Jeswani et al., 2022). The improvement of packaging recycling requires not only improvements in sorting and recycling plants, but also in packaging design by producer in order to reduce the huge amount of packaging waste produced and discarded (Antonopoulos et al., 2021). First, packaging should be designed to make recycling feasible. For example, packaging with intense colors should not be designed because the near infrared technology used in recycling plants during sorting cannot identify such colors (Eriksen and Astrup, 2019; Keller et al., 2022). In addition, multilayer packaging and packaging composed of different material that can be separated manually not be designed because they currently complicates recycling operations, but mono-material packaging should be preferred (Eriksen and Astrup, 2019; Bauer et al., 2021; Keller et al., 2022; Vazquez et al., 2022). Second, packaging should be designed to incentivize consumers to separate waste properly. Williams et al. (2018) and Nemat et al. (2022) refer that consumers do not properly separate packaging that they perceive to be of low value such as packaging that are complicated to empty, clean, and disassemble, packaging that are composed of different materials, packaging that are small in size, packaging that cannot be resealed, and packaging that do not provide adequate information on how they should be sorted.

CONAI defines the eco-design lever *"logistics optimization"* as the design of packaging that optimizes all logistics operations, loads transported by vehicles, and the relationship between the three levels of packaging[6]. García-Arca et al. (2014) introduce the concept of "sustainable packaging logistics" to refer to the design of packaging that optimizes supply chain activities. In particular, García-Arca et al. (2017) identify packaging redesign interventions to optimize logistics such as the simplification of materials used in packaging, reduction of packaging size, redesign of the relationship between the three levels of packaging, and variation of packaging elements such as shape. Packaging redesign to optimize logistics occurs mainly on secondary packaging because tertiary packaging are generally standardized (Ahmad et al., 2022) and primary packaging can alter consumer perceptions (Georgakoudis et al., 2018). These interventions reduce the weight and volume of packaging to transport more product on each vehicle and reduce the number of trips made by vehicles (Georgakoudis et al., 2018; García-Arca et al., 2020; Ahmad et al., 2022; Georgakoudis et al., 2023). This reduces costs, material consumption, and CO2 emissions associated to logistics activities. The sustainable practices adopted on packaging to optimize logistics activities can be supported by the implementation of new digital technologies to increase environmental and economic performance. (Romagnoli et al., 2023; Vishkaei and De Giovanni, 2023).

CONAI defines the eco-design lever *"optimization of production processes"* as the implementation of packaging production processes that reduce the consumption of production inputs and the generation of production waste[6]. The optimization of packaging production increases the efficiency of processes, reduces the consumption of resources such as materials, energy, and water, reduces waste such as scrap, waste gas, and wastewater, and reduces costs (Mourad, 2014; Poovarodom et al., 2015; Kliopova-Galickaja and Kliaugaite, 2018; Jiang and Zeng, 2019; He et al., 2021; Liu et al., 2021; Molina, 2021). García-Arca et al. (2017) refer that packaging optimization can also concern the product packaging processes performed by companies to reduce costs and environmental impacts.

CONAI defines the eco-design lever *"raw material saving"* as the design of packaging of reduced weight, with the same packaged product and performance, in order to decrease raw material consumption[6]. Generally, packaging are made heavier than necessary to ensure the protection of products in the supply chain (Georgakoudis and Tipi, 2021). However, packaging should be adapted to the needs of the products to avoid unnecessary waste of money and materials (Licciardiello et al., 2014; Georgakoudis and Tipi, 2021). The reduction in packaging weight should not be excessive to not compromise product protection (Georgakoudis and Tipi, 2021). In addition, the impact on consumers should be considered when changing the weight of primary packaging (Gustavo et al., 2018). In fact, consumers generally place little value on small packaging (Steenis et al., 2018; Monnot et al., 2019; Soares et al., 2022).

CONAI defines the eco-design lever *"reuse of packaging"* as the design of packaging that can be used multiple times in its life cycle for the same original purpose[6]. Reusable packaging represent the main alternative to disposable packaging (Yaroslavov et al., 2022), which can be used only once in their life cycle and increase the environmental impacts linked to the production of new packaging (Coelho et al., 2020) and the generation of packaging waste (Yuan, 2022). Greenwood et al. (2021) distinguish reusable packaging into two categories: refillable packaging and returnable packaging. Refillable packaging can be purchased by consumers (consumer ownership of the packaging) and, after consumption, can be reused because the contents can be refilled through the purchase of complementary products (refills) or by going to refill stations. Returnable packaging can be rented by consumers (company ownership of the packaging) and, after consumption, must be returned to its owners. The return process implies that companies implement systems to incentivize consumers to return packaging (Long et al., 2022) and reverse logistics to recover packaging and prepare them for new use through activities such as cleaning, repair, and storage (Coelho et al., 2020; Mahmoudi and Parviziomran, 2020). Greenwood et al. (2021) refer that reusable packaging, both refillable and returnable, have better environmental performance than disposable packaging only if they are used a minimum number of times to offset the higher energy and materials required to produce them. In fact, reusable packaging must be bulkier and heavier than disposable packaging to be durable.

CONAI defines the eco-design lever *"simplification of the packaging system"* as the elimination of superfluous elements of packaging in order to simplify it[6]. The removal of superfluous packaging materials optimizes their weight and volume, reduces material consumption and costs (Postacchini et al., 2021; Bassani et al., 2022). It can also provide different benefits in logistics because light weight packaging are easy to handle in logistics activities. The elimination of unnecessary packaging elements should not compromise product protection (Georgakoudis and Tipi, 2021) and should consider potential impacts on consumers if done on primary packaging (Gustavo et al., 2018). Packaging simplification can also involve the removal of non-recyclable packaging elements (Varžinskas et al., 2020; Hafsa et al., 2022). For example, the design of mono-material packaging by removing superfluous parts made of different materials facilitates recycling activities and reduces waste generation (Vergnano et al., 2016; Foschi et al., 2020).

CONAI defines the eco-design lever *"use of recycled material"* as the partial or total replacement of virgin raw materials with recycled ones in to reduce the consumption of virgin materials[6]. The use of materials obtained after recycling as raw materials for new packaging transforms waste into resources and reduces environmental impacts linked to the production of virgin materials (Rajesh and Subhashini, 2021). However, recycled materials increase the production and logistical complexity of companies and cannot completely replace virgin materials due to quality, property and cost issues (Tallentire and Steubing, 2020; Salandri et al., 2022). Glass and metal packaging can be recycled countless times because the material retains its characteristics after each recycling, while recycling of plastics packaging and paper/cardboard is more limited (Geueke et al., 2018). Therefore, the production of recycled materials in plastics and paper/cardboard requires the addition of a high amount of virgin materials to maintain an acceptable quality of the material and additives and other substances that make the material hazardous to the environment, human health, and complex to recycle again in the future (Etxabide et al., 2022). Packaging producers do not use only recycled materials because the quantities are insufficient, prices are high, and the composition of materials is unknown (Kazulytė and Kruopienė, 2018).

2.3. Eco-design for specific types of packaging: food packaging and plastics packaging

Two topics are widely discussed in the literature on packaging eco-design: the reduction of food waste caused by food packaging and the reduction of the environmental impact of plastics packaging through the use of bio-based and/or biodegradable materials. These eco-design practices refer to specific types of packaging and are not part of the seven categories proposed by CONAI. Therefore, this part is covered theoretically to complete the literature review on packaging eco-design but is not used in the empirical analysis.

Food losses and waste represent around one-third of the food for consumption produced in the world (Gustavsson et al., 2011 cited in Molina-Besch et al., 2019). In food supply chains, after the packaging of the food product, packaging can provide a significant contribution to the reduction of food waste because its main function is to ensure proper preservation of food. However, eco-design of packaging focuses mainly on the reduction of direct environmental impacts such as those linked to packaging production, rather than on the reduction of indirect environmental impacts linked to food waste caused by packaging, which are more relevant because wasted food corresponds to wasted resources for its production (Wikström et al., 2014). Therefore, the indirect environmental impact linked to food waste must be considered the design stage to produce overall sustainable packaging (Silvenius et al., 2014; Dilkes-Hoffman et al., 2018; Casson et al., 2022). In addition, about 20-25% of food waste caused by consumers depends on packaging design (Williams et al., 2012). Packaging that can influence consumer behavior and reduce food waste are those that contain an adequate portion of food, those that can be easily emptied, those with a dispensing function, those that can be resealed, and those that provide clear information about the shelf life of food (Wikström et al., 2014).

Petroleum-based polymers, commonly used in plastics packaging due to cost and property considerations, are derived from non-renewable sources, their production negatively impacts the environment, and they are not degradable (Mendes and Pedersen, 2021). In addition, when they become waste they are not properly managed, but are accumulated in landfills and dispersed in ecosystems (Rai et al., 2021). To reduce the environmental impacts of petroleum-based plastics packaging, it is necessary to design renewable and biocompatible packaging with bio-based and/or biodegradable materials (Reichert et al., 2020), called bioplastics (Sid et al., 2021). Bio-based plastics are partially or fully derived from the biomass of plants, animals, or microorganisms (Sid et al., 2021). Biodegradable plastics degrade through a chemical process that involves a variety of microorganisms and generates an environmentally and human health friendly end product composed of natural substances (Guo C. and Guo H., 2022). Biodegradation of plastics does not always occur in the natural environment because it may require industrial composting, in which plastics are subjected to specific conditions that promote their biodegradation (Mendes and Pedersen, 2021). Bio-based plastics are not all biodegradable and biodegradable plastics are not all bio-based (Juikar and Warkar, 2022). The environmental impacts of bioplastics are generally considered lower than those of traditional plastics (Mendes and Pedersen, 2021). However, bioplastics are not without impacts due to raw material cultivation, raw material processing, and industrial composting (Atiwesh et al., 2021). Bioplastics represent a very small share of plastics produced at the European level (Reichert et al., 2020) because they are more expensive (Mehta et al., 2021) and have fewer properties than petroleum-based plastics, so they require treatments and additives (Juikar and Warkar, 2022). Consumers, due to unfamiliarity with bioplastics packaging, handle bio-based and/or biodegradable packaging waste incorrectly (Taufik et al., 2020).

3. Methodology

3.1. Data collection and sample description

In our paper we use a secondary dataset of Italian companies that have implemented CONAI eco-design levers on packaging. The dataset collects data of the "eco-design for prevention" project from the platform created by CONAI. In fact, CONAI incentivizes companies to design circular and sustainable packaging and publicly reports on its platform the packaging redesign interventions implemented by companies. The dataset includes 603 successful cases of packaging eco-design. For each case, the dataset contains information about the intervening company such as: company name, number of company employees, and company sales. Then, for each case, the dataset contains information about the redesigned packaging such as: name of the packaging or packaged product, sector of the packaging or packaged product, and packaging materials. The 603 interventions occur on packaging for different products: food sector (27,20%), beverage sector (12,60%), health care sector (8,29%), home products sector (9,12%), and industrial sectors (42,75%). In addition, the 603 interventions occur on packaging in different materials: plastics (48,97%), paper/cardboard (37,65%), metals such as aluminum (2,50%) and steel (3,53%), glass (2,50%), and wood (4,85%). Finally, for each case, the dataset contains information on the redesign intervention such as: description of the intervention, year of the intervention, CONAI eco-design levers implemented in the intervention, and environmental performance of the intervention. In addition to the seven CONAI eco-design levers, we have a residual category called *"other actions"* that includes, for example, companies that have a certified environmental management system. Environmental performance is measured in terms of reduction of CO2 emissions, energy consumption and water consumption using the LCA method.

3.2. Procedure

To pursue the research aim, we develop an expert system tool through BN and ML to study the relationships among CONAI eco-design levers and environmental indicators. Following De Giovanni et al. (2022) we use a procedure composed of eight steps.

Step 1) Import the dataset on BayesiaLab 9.1 and discretize the continuous variables with the OptRandom* algorithm to create a constellation of nodes consisting of X environmental indicators and Y CONAI eco-design levers, where X{CO2 emissions, energy consumption, water consumption} and Y *{"facilitation of recycling activities"*, *"logistics optimization"*, *"optimization of production processes"*, *"raw material saving"*, *"reuse of packaging"*, *"simplification of the packaging system"*, *"use of recycled material"*, *"other actions"*}. This allows all data to be in the correct value type.

Step 2) Fix an element of X as a target goal and use supervised ML algorithms available in BayesiaLab 9.1. This allows to establish and fix the relationships among CONAI eco-design levers and environmental indicators.

Step 3) Identify the most significant relationships between the element of target X and the elements of Y by evaluating the Pearson correlation coefficient and relative p-value. This allows to construct a BN that maintains the significant relationships among CONAI eco-design levers and environmental indicators.

Step 4) Repeat steps 2 and 3 for all elements of X and use the corresponding outputs to fix the arcs in the final BN.

Step 5) Use the unsupervised algorithms available in BayesiaLab 9.1 to identify other relationships. Select the best algorithm based on the Minimum Description Length (MDL). This allows to identify all significant and unknown relationships and keep the most relevant ones by evaluating the MDL, which is a measure of the robustness of the BN.

Step 6) Perform some perturbation tests to check the robustness of the BN and identify the final BN using the node force, Pearson's correlation and Kullback-Leibler index. This allows to confirm the output of step 5 and strengthen the evidence about the robustness of the BN.

Step 7) Use a negative hard evidence analysis to create a benchmark case where all elements of Y are lacking. This allows to create a benchmark case composed of companies that have not yet implemented CONAI eco-design levers.

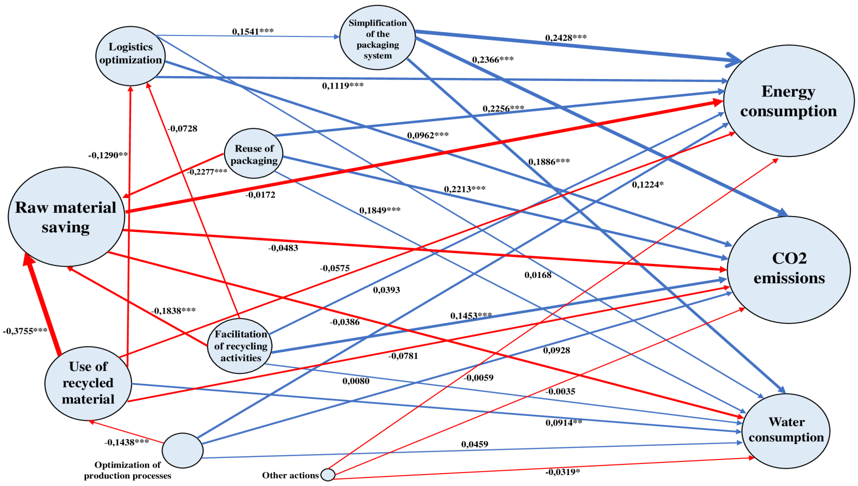
Step 8) Use a positive hard evidence analysis to learn from the BN. Evaluate the impact of the single element of Y and a portfolio of elements of Y and analyze the changes in the element in X in terms of mean and standard deviation, use the Wald test to check significant variations, and report the log-loss function to show the robustness of the BN.

4. Results

4.1. Bayesian networks

Steps 1 to 6 of the procedure allow identification of the final BN, shown in Figure 1. The node force represents the size of a node. The larger the size of the node, the greater its importance in the analysis. The Kullback-Leibler index represents the thickness of arcs. The greater the thickness of an arc, the smaller the difference between the original and theoretical distributions. The Pearson correlation index represents the relationships between two arcs. In particular, blue arcs represent positive correlations, while red arcs represent negative correlations. In addition, asterisks indicate the statistical significance of correlations in terms of p-value: one asterisk indicates a p-value < 0,05; two asterisks indicate a p-value < 0,01; three asterisks indicate a p-value < 0,001. The closer the p-value is to zero, the higher the significance. Whereas correlations without asterisks have a p-value > 0,05, that is statistically non-significantly.

Figure 1. Final Bayesian network



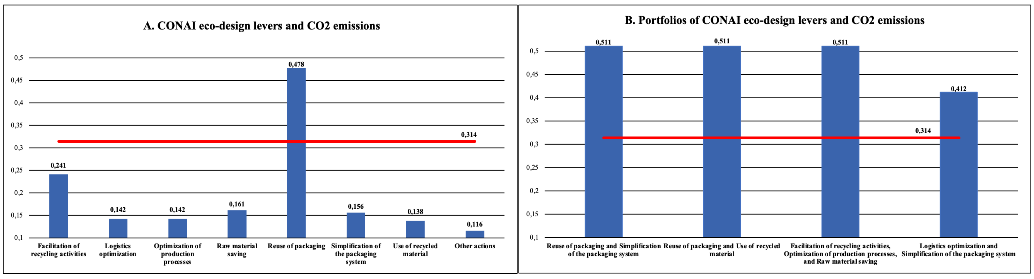
The analysis of the final BN allows us to answer *RQ1*. In fact, we study the peer-to-peer links among CONAI eco-design levers and environmental indicators to provide a reference plan to guide companies in the selection of CONAI eco-design levers. First, we examine the statistically significant links among CONAI eco-design levers. We observe only one synergy among CONAI eco-design levers, which is that between *"logistics optimization"* and "*simplification of the packaging system"*. While we identify several trade-offs between: *"facilitation of recycling activities"* and *"raw material saving"*; *"logistics optimization"* and *"use of recycled material"*; *"optimization of production processes"* and *"use of recycled material"*; *"reuse of packaging"* and *"raw material saving"*; and *"use of recycled material"* and *"raw material saving"*. The study of correlation indices shows that there are no synergies and trade-offs between the reduction of CO2 emissions, the reduction of energy consumption and the reduction of water consumption. Third, we examine the relationships among CONAI eco-design levers and environmental indicators. We divide the CONAI eco-design levers into three clusters. In the first cluster we include the CONAI eco-design levers that positively and statistically significantly influence all environmental indicators: *"reuse of packaging"* and *"simplification of the packaging system"*. In the second cluster we include the eco-design levers that positively and statistically significantly influence some environmental indicators: *"facilitation of recycling activities", "logistics optimization", "optimization of production processes", and "use of recycled material"*. In the third cluster we include CONAI eco-design levers that do not have particularly relevant links to environmental indicators: *"raw material saving"* and *"other actions"*. At this point, we have derived a reference plan for companies. Since there are no synergies among environmental indicators, companies should first select the environmental indicators on which to act. Consequently, they should select the most appropriate CONAI eco-design levers for the target environmental indicators, also paying attention to the synergies and trade-offs among levers.

4.2. Bayesian network analysis with positive and negative outcomes

Steps 7 and 8 of the procedure allow us to draw two figures for each environmental indicator. Figure A allows us to answer *RQ2* because it shows the improvements that can be achieved when only one CONAI eco-design lever is implemented. Figure B allows us to answer *RQ3* because it identifies the best portfolios of CONAI eco-design levers. Both figures are compared to the benchmark value of the environmental indicator, which is the value assumed by it when no CONAI eco-design levers are implemented.

Companies that aim to reduce CO2 emissions without implementing CONAI eco-design levers reduce it by 0,314 (benchmark). Figure 2A shows the reduction of CO2 emissions when companies implement each CONAI eco-design levers individually and compares it with the benchmark. Therefore, we observe that the eco-design lever *“reuse of packaging”* is the only one that when implemented individually further reduces CO2 emissions from 0,314 to 0,478. Since almost all eco-design levers are not effective in reducing CO2 emissions if implemented individually, in Figure 2B we construct portfolios of CONAI eco-design levers and compare them with the benchmark. In particular, three portfolios achieve the highest level in the reduction of CO2 emissions from 0,314 to 0,511: *“reuse of packaging”* and *“simplification of the packaging system”*; *“reuse of packaging”* and *“use of recycled material”*; and “*facilitation of recycling activities”, “optimization of production processes”,* and *“raw material saving”*. In addition, one portfolio reduces CO2 emissions from 0,314 to 0,412: *“logistics optimization”* and *“simplification of the packaging system”*.

Figure 2. Improvements in the reduction of CO2 emissions

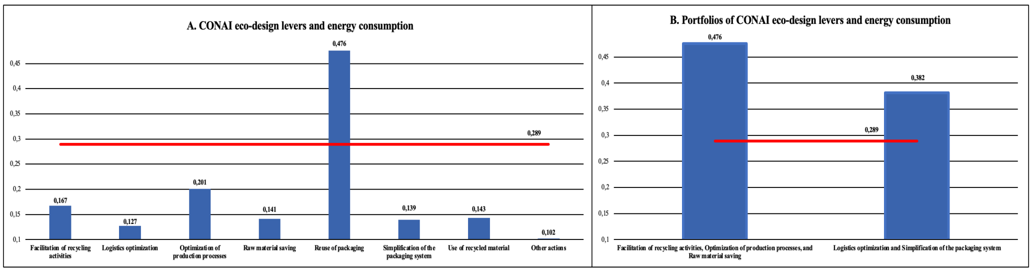


A. CONAI eco-design levers and CO2 emissions

B. Portfolios of CONAI eco-design levers and CO2 emissions

Companies that aim to reduce energy consumption without implementing CONAI eco-design levers reduce it by 0,289 (benchmark). Figure 3A shows the reduction of energy consumption when companies implement each CONAI eco-design levers individually and compares it with the benchmark. Therefore, we observe that the eco-design lever *“reuse of packaging”* is the only one that when implemented individually further reduces energy consumption from 0,289 to 0,476. Since almost all eco-design levers are not effective in reducing energy consumption if implemented individually, in Figure 3B we construct portfolios of CONAI eco-design levers and compare them with the benchmark. In particular, the portfolio that achieve the highest level in the reduction of energy consumption from 0,289 to 0,476 includes *facilitation of recycling activities”,* *"optimization of production processes",* and *"raw material saving"*. In addition, one portfolio reduces energy consumption from 0,289 to 0,382: *"logistics optimization"* and *"simplification of the packaging system"*.

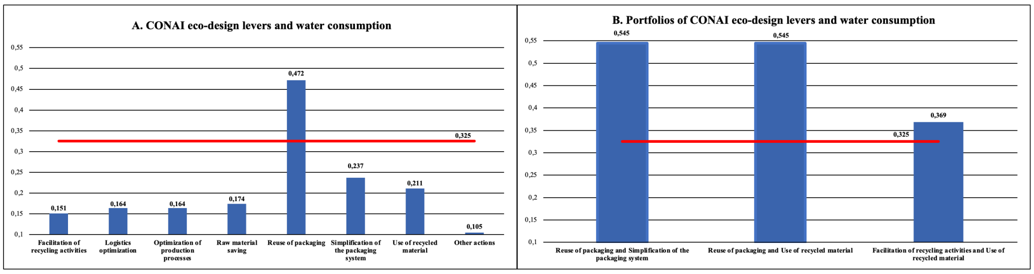
Figure 3. Improvements in the reduction of energy consumption


A. CONAI eco-design levers and energy consumption

B. Portfolios of CONAI eco-design levers and energy consumption

Companies that aim to reduce water consumption without implementing CONAI eco-design levers reduce it by 0,325 (benchmark). Figure 4A shows the reduction of water consumption when companies implement each CONAI eco-design levers individually and compares it with the benchmark. Therefore, we observe that the eco-design lever *"reuse of packaging"* is the only one that when implemented individually further reduces water consumption from 0,325 to 0,472. Since almost all eco-design levers are not effective in reducing water consumption if implemented individually, in Figure 4B we construct portfolios of CONAI eco-design levers and compare them with the benchmark. In particular, two portfolios achieve the highest level in the reduction of water consumption from 0,325 to 0,545: *"reuse of packaging"* and *"simplification of the packaging system"*; and *"reuse of packaging"* and *"use of recycled material"*. In addition, one portfolio reduces water consumption from 0,325 to 0,369: *"facilitation of recycling activities"* and *"use of recycled material"*.

Figure 4. Improvements in the reduction of water consumption


A. CONAI eco-design levers and water consumption

B. Portfolios of CONAI eco-design levers and water consumption

Our results show that the only CONAI eco-design levers that simultaneously reduces all environmental indicators relative to benchmarks is *"reuse of packaging"* when implemented individually. However, there are no portfolios of CONAI eco-design levers that simultaneously reduce all environmental indicators relative to benchmarks. In fact, two portfolios simultaneously reduce CO2 emissions and energy consumption compared to benchmarks: *"facilitation of recycling activities", "optimization of production processes"* and *"raw material saving"*; and *"logistics optimization"* and *"simplification of packaging system"*. While two portfolios simultaneously reduce CO2 emissions and water consumption compared to benchmarks: *"reuse of packaging"* and *"simplification of the packaging system"*; and *"reuse of packaging"* and *"use of recycled material"*.

5. Discussion

5.1. Research contributions

Our paper provides different research contributions. The seven CONAI eco-design levers represent a comprehensive set of different eco-design practices for all types of packaging. However, in the literature on packaging eco-design, none of the papers guide companies in the selection of CONAI eco-design levers to improve environmental performance. In fact, most papers consider only one or a few packaging eco-design practices and focus on specific types of packaging. Cozzolino and De Giovanni (2023) are the only ones to consider CONAI eco-design levers and different types of packaging, through their analysis of 603 cases in which Italian companies implemented CONAI eco-design levers on packaging to improve three environmental indicators: CO2 emissions, energy consumption, and water consumption. However, Cozzolino and De Giovanni (2023) do not indicate to companies which eco-design levers are effective when implemented individually and which are effective when combined in portfolios to exploit their synergies. The novelty of our paper lies precisely in the creation of guidance to help companies in the selection of CONAI eco-design levers to improve environmental performance. To achieve this aim, we use the same sample of Cozzolino and De Giovanni (2023) and implement an innovative methodology in packaging eco-design, based on BN and modern ML tools. This methodology allows us to create sophisticated supports to assist companies in the decision-making process. First, we show to companies all possible links among CONAI eco-design levers, among environmental indicators, and among CONAI eco-design levers and environmental indicators to provide them a reference plan for the selection of CONAI eco-design levers. Second, we suggest CONAI eco-design levers that companies can implement individually to improve each environmental indicator relative to its benchmark, which indicates the value of the environmental indicator when companies do not implement any CONAI eco-design levers. Third, we suggest different portfolios of CONAI eco-design levers that companies can implement to improve each environmental indicator relative to its benchmark. Each of these analyses is new in the literature on packaging eco-design and allows us to create comprehensive guidance for companies.

5.2. Managerial contributions

Our paper provides different managerial contributions. In fact, we offer companies sophisticated supports to guide them in the selection of CONAI eco-design levers to improve environmental performance. In addition, we support the achievement of the goals set by the EU for packaging circularity and sustainability. First, we provided companies a reference plan for the selection of CONAI eco-design levers. We recommend that companies initially identify the target environmental indicators and then select CONAI eco-design levers based on their links to environmental indicators and other levers. Companies should exploit synergies between *"logistics optimization"* and *"simplification of the packaging system"* because light weight packaging are easier to manage in all logistics activities (García-Arca et al., 2017; Georgakoudis and Tipi, 2021). Instead, companies should pay attention to different trade-offs. There is a trade-off between *"facilitation of recycling activities"* and *"raw material saving"* because facilitators for recycling do not reduce material consumption (Cozzolino and De Giovanni, 2023). There is a trade-off between *"reuse of packaging"* and *"raw material saving"* because reusable packaging consume a lot of materials to be durable (Greenwood et al., 2021). There is a trade-off between *"use of recycled material"* and *"logistics optimization"*, "*optimization of production processes"* and *"raw material saving"* because recycled materials increase the production and logistical complexity of companies (Kazulytė and Kruopienė, 2018; Afif et al., 2022; Salandri et al., 2022). Second, we suggest to companies CONAI eco-design levers to implement to improve each environmental indicator relative to its benchmark, which indicates the value of the environmental indicator when companies do not implement any CONAI eco-design levers. *"Reuse of packaging"* is the only eco-design lever that when implemented individually improves each environmental indicator relative to its benchmark. Reuse avoids all environmental impacts associated with the production and purchase of new packaging (Cozzolino and De Giovanni, 2023). We recommend that companies use reusable packaging a certain minimum number of times to offset the high inputs they require to be durable (Greenwood et al., 2021). In addition, reusable packaging to be effective also require optimization of reverse logistics and cleaning activities to save on CO2 emissions and water consumption, respectively (Postacchini et al., 2018; Hitt et al., 2023). Companies interested in improving the reduction of CO2 emissions and/or energy consumption should select from two portfolios. The first portfolio combines *"facilitation of recycling activities", "optimization of production processes"*, and "*raw material saving"*. Packaging that are easy to recycle reduce the energy consumption of recycling processes and the CO2 emissions of packaging disposal (Cozzolino and De Giovanni, 2023). The saving of materials reduces the energy consumption and CO2 emissions of production processes (Yuan et al., 2022). The second portfolio combines *"logistics optimization"* and *"simplification of the packaging system"*. Light weight packaging reduces energy consumption and CO2 emissions of production and logistics (García-Arca et al., 2017; Georgakoudis and Tipi, 2021). Companies interested in improving the reduction of CO2 emissions and/or water consumption should select from two portfolios. The first portfolio combines *"reuse of packaging"* and *"simplification of the packaging system"*. Reuse reduces the water consumption of new packaging production and the CO2 emissions of direct logistics (Cozzolino and De Giovanni, 2023). Light weight packaging reduce the water consumption of production and CO2 emissions of logistics (García-Arca et al., 2017; Georgakoudis and Tipi, 2021). The second portfolio combines *"reuse of packaging"* and *"use of recycled material"*. Recycled materials increase the production and logistical complexity of companies

(Salandri et al., 2022). However, the benefits of reuse more than offset the logistical problems of recycled materials and exploit their advantages in terms of lower water consumption for the production of virgin materials (Civancik-Uslu et al., 2019). Companies interested in improving the reduction of water consumption should implement a portfolio composed of *"facilitation of recycling activities"* and *"use of recycled material"*. The production of easily recyclable packaging reduces the water consumption of recycling processes and allows for more recycled material, which reduces the water consumption of the production of virgin materials (Keller et al., 2022; Civancik-Uslu et al., 2019). The importance of reuse emerges from our paper. This practice is the only one that can improve all environmental indicators relative to their benchmarks and is effective both individually and in portfolios.

5.3. Limits and directions for future research

Our paper is not without limitations, which we discuss here to inspire future research. First, we limit our analysis to the seven CONAI eco-design levers and three environmental indicators (CO2 emissions, energy consumption, and water consumption). Future research could include other packaging eco-design practices, other environmental indicators, and social and economic indicators in the analysis using the same approach. Second, our results may be influenced by the composition of the sample, which includes only Italian companies registered to CONAI. Future research could replicate this analysis on a sample of companies from other countries or specific sectors to test the validity of our results.

6. Conclusions

CONAI eco-design levers are a comprehensive set of different eco-design practices for all types of packaging. In the literature on packaging eco-design, no papers guide companies in the selection of CONAI eco-design levers to improve environmental performance. The novelty of our paper lies precisely in the creation of this guidance. To achieve this aim, we use a sample of 603 cases in which Italian companies have implemented CONAI eco-design levers on packaging to improve three environmental indicators: CO2 emissions, energy consumption and water consumption. Specifically, we implement on the sample an innovative methodology based on BN and modern ML tools to create sophisticated decision supports. First, we build a reference plan for the selection of CONAI eco-design levers that includes all possible links among CONAI eco-design levers, among environmental indicators, and among CONAI eco-design levers and environmental indicators. Second, we indicate to companies the CONAI eco-design levers that are most effective when implemented individually to improve environmental indicators. Third, we suggest different portfolios of CONAI eco-design levers that companies can implement to improve environmental indicators. In this way, we provide all the tools there is a need for companies to design circular and sustainable packaging, to improve environmental performance, and to achieve the packaging goals set by EU.