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Design framework for circular and sustainable packaging design

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ABSTRACT: Packaging waste contributes significantly to resource depletion and pollution. Despite the crucial role of packaging in product preservation, its environmental impact has become a major issue. Addressing the circularity and sustainability (C&S) of packaging by design offers a route to mitigate these impacts and reduce waste. However, integrating C&S into the current packaging design process presents significant challenges, such as conflicts between C&S and functional requirements and inadequate tools to provide packaging-specific practical solutions. To address these challenges, this study proposes a novel packaging design framework developed through literature review, brainstorming sessions, and field visits. By incorporating iterative design strategies and leveraging past design knowledge, the framework empowers designers to create packaging solutions that meet C&S requirements.

KEYWORDS: packaging, circular, economy, sustainability, design, process, framework

1. Introduction

Packaging refers to products used for the containment, protection, handling, delivery, and presentation of goods as they move from manufacturer to consumer (*Packaging*, 2025). While packaging is essential for safeguarding goods throughout their journey from production to consumption, packaging waste, in the form of litter and landfill, creates a substantial negative impact on the environment and leads to a significant loss of resources (Pongracz, 2007). This problem of waste is driven by the current linear economy system of "take-make-dispose," which prioritises short-term resource use over long-term resource conservation (Murray, 2017).

One emerging way to tackle this problem is to transition towards a circular economy (CE). The CE is a restorative and regenerative system in which resource input, waste, emissions, and energy intake are minimised by employing CE principles, including slowing, closing, and narrowing the material loops (Geissdoerfer et al., 2017). The CE principles are realised by designing packaging solutions based on CE strategies, such as reduce, reuse, recycle etc. Notably, the CE strategies are also advocated by policies such as the *New Circular Economy Action Plan*, which aims to make packaging reusable and recyclable by 2030 (NCEAP, 2021). Additionally, regulations like the *Packaging and Packaging Waste Regulation* (PPWR) aims to promote reuse and high-quality recycling (PPWR, 2022).

Complementary to the CE, the field of sustainability provides tools to evaluate the eco-efficiency of a product, which is characterised by the balance between the value created or the function fulfilled by the product and the resource use or environmental impact incurred. Common sustainability indicators include global warming potential, greenhouse gas emissions, and energy and water consumption. Similar to the CE, sustainability is advocated by policies, such as the *United Nations 2030 Agenda* and the *UN Commission on Environment and Development* (Hauschild et al., 2020).

Despite these efforts, fulfilling circularity and sustainability (C&S) requirements in packaging design faces significant challenges. One key challenge is the conflict between CE strategies and functional requirements of packaging, such as product preservation, containment, and handling (Yokokawa et al., 2021). For example, in food packaging, protecting product from oxidation is essential, and Ethylene Vinyl Alcohol (EVOH) is commonly used as an oxygen barrier. However, EVOH material is often combined with other materials (e.g., PE) to create a multilayer packaging, which is difficult to recycle using traditional plastic recycling technologies. The chemical and thermal incompatibility of these layers complicates their separation and subsequent processing, making effective recycling infeasible (Walker et al., 2020). Another example is of the CE strategy of reduce, which focuses on lightweighting of packaging to minimise material usage. However, implementing this strategy may compromise the product stability and hinder fulfilment of functional requirements (Dillon, 2023). These challenges underscore the need to balance functional and C&S requirements in packaging design.

Existing design methods, such as CE guidelines (CEFLEX, 2024; RECOUP, 2024) and checklist-based methods, including CE Indicator Prototype (Cayzer et al., 2017), CE Toolkit (Bocken, N.M.P., 2013), NORDIC criteria (NORDIC, 2022) provide general guidance for designing circular and sustainable packaging solutions. These methods primarily focus on general circular design strategies (e.g., mono material). However, they often fall short in offering specific, practical solutions to address challenges during the packaging design process. Additionally, these methods frequently overlook the balancing of functional and C&S requirements in packaging design process.

To address these challenges, this research aims to develop a comprehensive design framework to support packaging designers in creating circular and sustainable packaging design solutions. It focuses on two key research questions:

1) What are the limitations of existing measurement methods, design frameworks, and design processes for circular and sustainable packaging?
2) What are the requirements and architecture of a design framework to support packaging designers?

The research focuses on primary packaging, which comes into direct contact with the product. Throughout this document, packaging refers to primary packaging unless stated otherwise.

2. Methodology

To comprehensively understand existing measurement methods and design frameworks for circular and sustainable packaging, a literature review was conducted. Additionally, a brainstorming session and field notes from site visits were utilised to gain insights into current design processes.

2.1. Literature review

A literature review was conducted using Scopus and Google Scholar databases. To identify relevant studies on design frameworks, the search employed combinations of keywords, including "Packaging", "Design", "Framework", "Sustainable", "Sustainability", "Circular", and "Circular Economy". A similar strategy was applied to identify literature on measurement methods, using keywords like "Sustainability", "Circularity", "Assessment", "Measurement", "Indicator", "Tool", and "Circular Economy". The search was restricted to documents published in English between 2009 and the submission date of this research. Duplicate and overlapping studies were removed, and papers without a clearly articulated design framework or measurement method and those unrelated to packaging applications were excluded.

2.2. Brainstorming session

A brainstorming session was conducted with experienced professionals from a multinational packaging company based in the EU. The session lasted four hours and explored existing design processes for C&S centred design of packaging. All participants were from the Packaging Design department of the partner company and held diverse technical roles with experience ranging from 5 to 25 years. During the session, participants discussed the current packaging design process within their organisation while focusing on the challenges encountered in the design of circular and sustainable packaging. Insights were gathered through direct observation and detailed notetaking.

2.3. Field visits

Field visits were conducted to gain practical insights into the packaging lifecycle, focusing on manufacturing and waste management practices. The first visit took place at a packaging manufacturing facility in the UK, where observations were documented through diary-keeping, supplemented by field notes from discussions with plant managers. The second visit was conducted at a waste sorting facility in the EU, where field notes were recorded based on conversations with plant managers. This facility separates waste into predefined material streams (e.g. glass, paper), after which the sorted material is sent to the recycling processing facilities.

3. Circularity and sustainability measurement methods in the literature

Material Flow Analysis (MFA) and Life Cycle Assessment (LCA) are widely recognised methods for measuring circularity and sustainability. MFA illustrates material flows within a system by analysing the amount and direction of material input and output (Gao et al., 2020). However, it does not account for the quality of recyclate and material losses, which are essential factors in addressing packaging circularity (Gonçalves et al., 2024). Indicators are also used to measure packaging circularity. Well-known circularity indicators include the "reuse index", "potential recycle index", "cyclical material use rate", "recyclability benefit rate" and "material circularity indicator (MCI)" (Mesa et al., 2018). MCI, the most widely cited indicator (Vadoudi et6al., 2022; Elia et6al., 2017), measures the maximisation of restorative flows and the minimisation of linear flows (EMF, 2021). However, it relies on general recycling rates based on material type (e.g. plastics, glass), overlooking the impact of key packaging characteristics like shape, size, and colour on recyclability, which significantly influence the recycling rates (CEFLEX, 2024).

In contrast, LCA is a standardised methodology for assessing potential environmental impacts associated with a product, process, or system throughout its lifecycle (ISO 14040, 2006). Despite its comprehensive approach, LCA is time-intensive, costly, and requires substantial input data for accurate analysis (Kiemel et al., 2022). A promising assessment tool, exclusive for packaging, is the Packaging Impact Quick Evaluation Tool (PIQET) (Verghese et al., 2010), that offers a streamlined LCA approach to assessment, making it faster and less data-intensive, though at the cost of accuracy and precision.

4. Packaging design frameworks in the literature

A design framework is intended as a structured approach to designing that integrates the packaging design process with guidance on the selection of appropriate design methods and tools. This ensures a systematic and coherent pathway for developing effective design solutions. In the literature, various efforts have been made to develop frameworks for C&S centred packaging design. Although at times authors refer to this work through alternative terms such as "lifecycle thinking approach" (Jagoda et al., 2023) and "design approach" (Zambujal-Oliveira & Fernandes, 2024a), these studies are included in our analysis as their contributions align with our understanding of a design framework. Based on the analysis of seven studies that proposed design frameworks, a key limitation is the absence of circularity assessment in all studies except one (Camilleri et al., 2023; Grönman et al., 2013; Jagoda et al., 2023; Liu et al., 2023; Santi et al., 2022; Zambujal-Oliveira & Fernandes, 2024b). While Zhu et al. (2022) include circularity requirements, their framework lacks an actionable implementation plan, a limitation shared with Liu et al. (2023), Santi et al. (2022), and Grönman et al. (2013). Another common gap in all studies is the omission of a redesign process, preventing iterative improvements to packaging solutions. Additionally, most frameworks primarily evaluate and rank existing packaging solutions rather than providing design guidance for resolving conflicts between functional and sustainability requirements. Addressing these gaps is essential to develop a more comprehensive and practical design framework for circular and sustainable packaging solutions.

5. Empiricial understanding of the current packaging design process

The brainstorming session and field visits provided valuable insights about the packaging design processes as shown in (Table 1). Insights from the brainstorming session indicate that designers primarily rely on experience and industry inputs, prioritising functional requirements over C&S requirements. Field visit to manufacturing plant highlight production constraints that limit the implementation of C&S

design aspects. Observations at sorting plant underscore the need to align C&S requirements with regional recycling infrastructure.

Table 1. Insights from brainstorming session and field visits

Research method	Insights
Brainstorming session	Design drivers: prior experience, existing designs, and inputs from material suppliers Primary design requirements: product protection, preservation, and handling (transport) Environmental assessment: LCA and recyclability assessments (physical tests at material recovery facilities (MRFs)) Redesign: packaging adjustments and prototype development are informed by hotspots emerged from assessment Design rationale: lack of documentation leads to reliance on baseline designs, limiting major innovation to avoid stability and shelf-life risks
Field visit - Manufacturing plant	Production constraints: equipment capabilities, filling line flexibility, and raw material availability limit circular and sustainable design
Field visit - Sorting plant	EOL infrastructural constraints: NIR technology detects and classifies packaging waste to target or reject (unrecoverable waste) streams. Sorting efficiency is affected by shape, size, colour, and material composition, emphasising the need to align design with regional recycling systems

6. A novel packaging design framework

6.1. Requirements for the framework

The key factors identified from the literature review, brainstorming session, and field visits highlight critical gaps in existing approaches to packaging design. These key factors are summarised in (Figure 1).

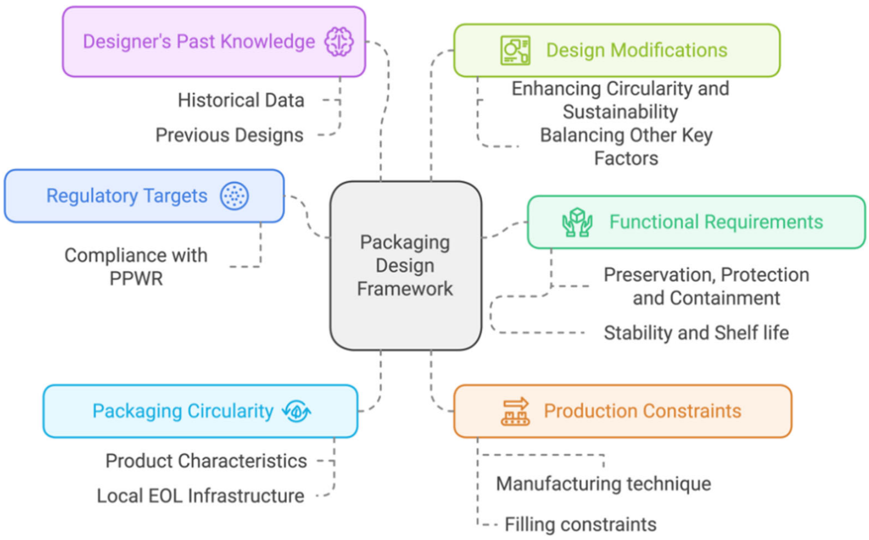

Figure 1. Key factors to be addressed by packaging design framework

Based on the key factors, the requirements for the packaging design framework are formulated as shown in the first column of (Table 2). These requirements will serve as driver for the development of the architecture of the proposed design framework presented in the next section.

Table 2. Mapping of requirements to stages

Requirements	Stages
Gather functional, circularity and sustainability requirements	Data Gathering
Gather data on existing packaging	Data Gathering
Gather past design knowledge, including historical data and previous designs	Data Gathering
Gather packaging characteristics data (e.g. shape, material, size)	Data Gathering
Gather production constraints	Data Gathering
Assess packaging functional and C&S performance	Assessment
Evaluate functional and C&S requirements of packaging	Evaluation
Redesign to fulfil functional and C&S requirements	Redesign

6.2. Framework architecture

The design framework proposed in this research has been developed to support packaging designers in the selection of suitable packaging characteristics (e.g. shape, material, size etc.) during the early stages of design. The requirements outlined in (Table 2) have been translated into the design framework, as shown in (Figure 2). The framework comprises of five process stages, each of which involves undertaking specific activities and using predefined methods and tools.

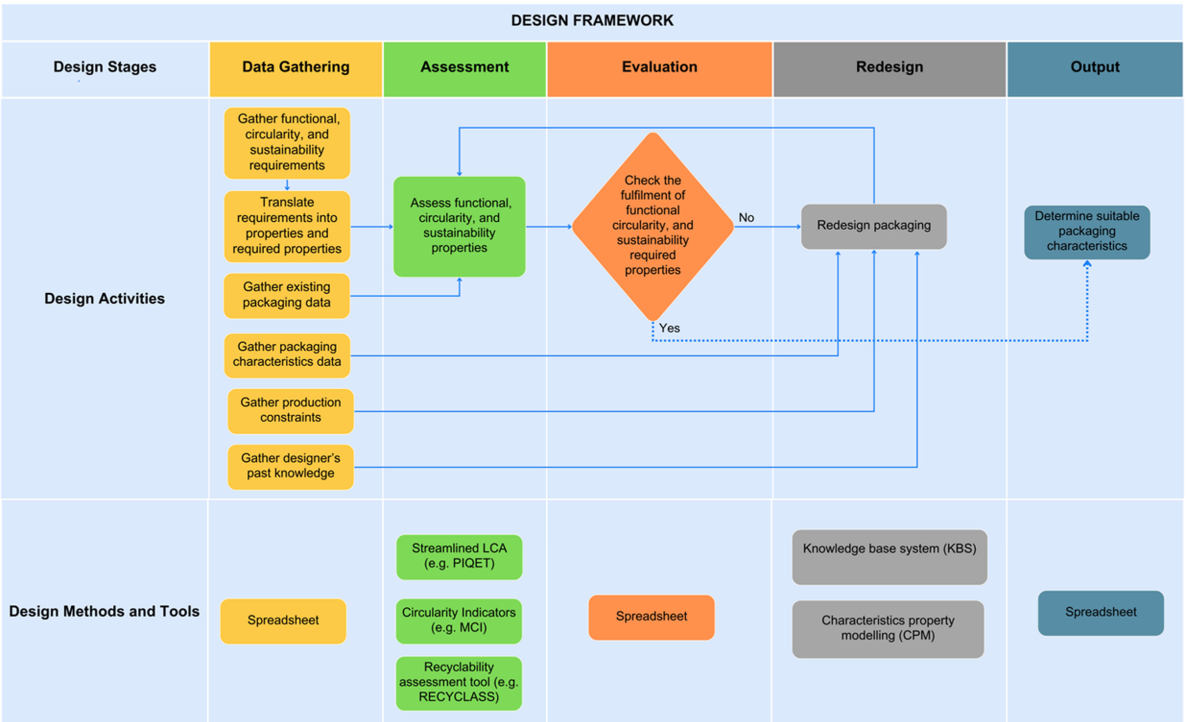

Figure 2. Design framework for circular and sustainable packaging

A detailed explanation of each stage, along with its activities and the corresponding methods and tools, is provided below.

1) ***Data Gathering***: In this stage, input data required for assessment is gathered while undertaking the following activities :
   a) Functional and C&S requirements: In this activity, the packaging functional and C&S requirements are formulated. The packaging functional requirements are based on protection (e.g. handling, transportation, impact resistance), preservation (e.g. oxygen and water vapour barrier, sunlight barrier), and containment (e.g. dose size). The C&S requirements are based

on regulations (e.g. PPWR), company targets, and CE and LCA indicators (e.g. minimum recycled content, recycling rate, global warming potential, water use). Next, based on the packaging designer's preferences, a list of requirements is selected for the subsequent activity.

   b) Translate requirements to properties (P) and required properties (Pr): In this activity, the requirements and their values are translated to P and Pr. A designer typically defines the product (in our case packaging) by means of requirements and then translate them into product properties (Mattmann et al., 2016). For example, the requirement that the packaging must protect from impact loads greater than 100 N translates into the property "impact strength (IS)" and required property "IS >100N".
   c) Existing packaging: In this activity, the initial packaging design characteristics, derived from previous design solutions, are defined. This serves as a foundation for conceptualising the shape and structure of the packaging.
   d) Packaging characteristics data: In this activity, data on packaging characteristics is gathered, including available choices for packaging materials, shapes, forms, and other characteristics based on material supplier input.
   e) Production constraints: In this activity, data on constraints is gathered, including available choices for manufacturing processes, filling processes and associated infrastructure.
   f) Designer's past knowledge: In this activity, data of designer's past knowledge is gathered, including both "structured knowledge", such as rules and design guidelines and "unstructured tacit knowledge", such as thumb rules, heuristics etc.
2) ***Assessment***: In this stage, the performance of the existing packaging is assessed by undertaking the following activities:
   a) Functional properties assessment: In this activity, the functional performance is measured by calculating the values of functional properties.
   b) C&S properties assessment: In this activity, the circularity of packaging is measured by considering packaging characteristics and its compatibility with the local sorting and recycling infrastructure. The data about regional sorting and recycling infrastructure can be gathered from online tools such as CEFLEX (CEFLEX, 2024) and RECYCLASS (Recyclass, 2024). The sustainability assessment utilises a streamlined LCA tool such as PIQET.
3) ***Evaluation***: In this stage, the fulfilment of all the required properties is evaluated. This process determines the extent of deviation from the Pr. The evaluation provides a critical reference for redesign efforts, as it identifies specific areas where the packaging fails to achieve the Pr.
4) ***Redesign***: In this stage, redesign strategies are employed to bridge the gap between the value of assessed properties and the required properties. These strategies may involve improving the existing design, modifying the structure of the current packaging, or conceptualising entirely new designs. The selection of redesign strategies is informed by the designer's preferences and previous packaging choices. Once a strategy is selected, packaging design alternatives are generated. A key challenge during redesign is balancing C&S requirements with functional requirements. To manage these trade-offs, the Characteristics Property Modelling (CPM) (Qureshi et al., 2011) and the Knowledge-Base System (KBS) (Sapuan, 2001) are employed. Additionally, throughout the redesign process, designers must consider *production constraints* to ensure that proposed modifications are technically feasible and economically viable within the limitations of existing manufacturing and filling process.Following stage 4, the generated design alternatives undergo reassessment to confirm their fulfilment of functional and C&S Pr; if they do not fulfil all the Pr, the iterative process is repeated until a satisfactory solution is achieved.
5) ***Output***: In this stage, the final suitable packaging characteristics are determined. The final output is defined in terms of packaging characteristics, including packaging material, form, dimensions, labels, additives etc.

7. Preliminary evaluation of the design framework

This section presents a case study developed in collaboration with a designer from the collaborating company to demonstrate the application of the design framework. The designer was tasked to develop a packaging solution meeting C&S requirements for a multivitamins (MV) product marketed in the EU.

The packaging must hold 60 tablets (1 g each), protect against UV light and impact loads, include a minimum recycled content, and meet EU recyclability targets. The design framework was implemented through its five stages as follows:

1) ***Data Gathering***:
   a) Functional and C&S requirements: The requirements for containment, preservation, protection, recyclability, and minimum recycled content were defined collaboratively and subsequently translated into specific product properties and required properties as shown in (Table 3). The first three requirements address the functions of the packaging, while the latter two focus on circularity. In the translation, moderate degree of preservation is defined based on the property "UV transmittance" (Coltro & Borghetti, 2007).

Table 3. Translation of requirements to properties

S. No	Requirements	Properties	Required Properties
1	Contain 60 tablets (each weighing 1 g)	Containment	Containment of 60 tb
2	Moderate degree of preservation against UV light	UV transmittance	UV transmittance less than 5 % (at 390 nm)
3	Protection from impact loads	Impact strength	Impact strength greater than $4 \frac{kj}{m^2}$
4	Fulfill 2030 PPWR recycling targets of B grade (equivalent to 90% recyclability (Recyclass, 2024))	Recyclability	Recyclability equal to 90%
5	Fulfill 2030 PPWR minimum recycled content target of 30%	Minimum recycled content	Minimum recycled content equal to 30%

   b) Existing packaging data: A previous bottle-based packaging design for the MV served as the starting point for the design process. The characteristics of this existing packaging are shown below in (Table 4).

Table 4. Characteristics of MV bottle packaging

Characteristics		
Bottle	Material	Polyethylene Terephthalate (PET)
	Shape	Cylindrical bottle
	Diameter	6 cm
	Height	15 cm
	Wall thickness	0.05 cm
	Additives	UV absorbers
	Colour	Opaque dark purple
Cap	Material	Polypropylene (PP)
Label	Material	Low density Polyethylene (LDPE)
	Adhesive	Water soluble adhesive

2) ***Assessment***
   a) *Containment*: Manual testing confirmed that the packaging could hold 60 tablets, occupying 80% of its volume.
   b) *UV protection*: The UV absorber additives inside the bottle provide a UV transmittance of 2% (at 390 nm), as verified by the designer.
   c) *Impact strength*: The PET material exhibits an impact strength of $4.6 \frac{kj}{m^2}$ (Olam, 2023).
   d) *Recyclability*: The packaging has 0% recyclability in the EU region (Recyclass, 2024). The Recyclass online tool was used to measure the recyclability. The tool considers the compatibility of packaging with the regional sorting and recycling infrastructure.
   e) *Minimum recycled content*: The packaging contains 0% recycled material.

3) ***Evaluation***: While the packaging fulfils Pr such as containment, UV transmittance, and impact strength it failed to achieve recyclability and minimum recycled content.
4) ***Redesign***: To address the shortcomings of the existing packaging, redesign strategies were implemented relying on the use of the CPM method and KBS tool as follows:
   a) To fulfill the recyclability, the CPM method is used to create a Characteristics Property (C-P) dependency matrix as shown in (Figure 3). The C-P matrix shows the dependency between the characteristics and properties as indicated by the blue shaded cells in (Figure 3). The rows show the dependency of each characteristic on all the properties, whereas the columns depicts the dependency of a property on all the characteristics. The KBS tool is used to extract the dependencies, for example, the sorting guidelines in the KBS mentions the dependency of colour, label, shape and dimensions on the recyclability of packaging. From the recyclability column in the C-P matrix, we can infer its dependant characteristics, namely bottle material, shape, diameter, height, additives, colour, cap material, label material and label adhesive. To improve recyclability, any of these characteristics can be modified. The KBS tool recommends making the bottle transparent, as opaque coloured PET bottles are not currently recyclable in the EU (Recyclass, 2024). To make the bottle transparent the additives must be removed as the colour is imparted by them (as shown by the double arrows in (Figure 3)). However, the UV transmittance is also dependent on additives as inferred from the C-P matrix. Hence, a design strategy must be devised, which solves these interdependencies. Two design strategies were proposed in consultation with the designer:
      – Add another characteristic, which fulfils the Pr of UV transmittance and remove the additives.
        For example, applying a UV-blocking coating to the inside or outside of the bottle surface.
      – Use an existing characteristic to fulfill the Pr of UV transmittance. For example, using a transparent UV resistant masterbatch for PET, such as PET UVA (*Ampacet Introduces PET UVA*, 2023).

   b) To fulfill the minimum recycled content, the PET masterbatch was replaced with a masterbatch containing 30% food-grade recycled PET. This substitution, compatible with existing production processes, allowed the bottle shape to remain unchanged.

Characteristics	Properties				
	Containment	UV transmittance	Impact strength	Recyclability	Minimum recycled content
Bottle Material			■	■	■
Bottle Shape	■		■	■	
Bottle Diamater	■			■	
Bottle Height	■			■	
Bottle Wall thickness		■	■		
Bottle Additives		■		■	
Bottle Colour				■	
Cap Material			■	■	■
Label Material				■	
Label Adhesive				■	

Figure 3. Characteristics and properties dependency matrix

   Using these strategies, two packaging alternatives were developed: (1) a transparent PET bottle with 30% recycled content and a UV coating, and (2) a transparent PET bottle with 30% recycled content incorporating a UV-resistant masterbatch. Both alternatives were reassessed and evaluated showing that they fulfill all the Pr.
5) ***Output***: The final packaging alternative out of the two suitable alternatives is determined based on additional factors such as material and manufacturing costs, as well as raw material availability in consultation with the designer.

8. Conclusion

This paper tackles the pressing need for a comprehensive framework to support packaging designers in addressing C&S in packaging design. The research highlights critical gaps in existing design frameworks and measurement methods for C&S in packaging. These include time-intensive, costly, and data-hungry sustainability assesments, the lack of circularity indicators that consider the entire lifecycle and packaging characteristics (e.g., shape, size, adhesives), the limited focus on CE strategies beyond recyclability, and the absence of practical implementation plans for redesign and iterative improvement in current design frameworks. Additionally, most design frameworks fail to address conflicting packaging functional and C&S requirements.

To bridge these gaps, a novel design framework is proposed, comprising of five process stages each of which involves undertaking specific activities and using predefined methods and tools. The framework is intended for use in the early stages of design, where there is greater flexibility to explore multiple packaging concepts that fulfil functional, sustainability, and circularity requirements, as opposed to the constraints typically encountered in the detailed design stage. The framework enables packaging designers to systematically address packaging requirements, while incorporating production constraints and regulatory targets. By providing iterative design strategies and leveraging design data, the framework equips designers to address C&S in packaging design. A preliminary evaluation of the framework is also presented with a case study of packaging design for a MV product.

The proposed framework contributes to advancing C&S in packaging design practice by integrating methods such as CPM and KBS to resolve conflicts between requirements. Leveraging insights from field observations and expert consultations, it emphasises the importance of considering regional EOL constraints from sorting and recycling infrastructure. Ultimately, this study offers a structured, actionable approach that bridges theoretical principles and industry practices, fostering the development of innovative and context-specific circular and sustainable solutions in packaging.

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