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Meeting Multi-User Needs in Early Design Stages: A Data-Driven Conceptual Framework for Smart and Sustainable Packaging

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Abstract

Effective design is becoming increasingly necessary to shorten product development times to meet evolving user demands. Thus, it is essential that designers uncover user requirements and translate them into tangible product specifications, but with the added endeavour of balancing functional and sustainability requirements. This poses several challenges to designers. In early design, designers must make important decisions based on limited knowledge, risking developing products which are rejected by users. A literature review determined that no available system is sufficient to balance multi-user requirements and design characteristics. Hence, the research goal is to address the gap in design support systems, which inspired the generation of the PRioritising and achIeving Multi-user rEquirements (*PRIME*) framework being proposed. The contribution of this work lies in the fusion of topic modelling, sentiment analysis, and conflict resolution techniques to enhance multi-user experience. The framework prioritises multi-user and design requirements, and translates them into product specifications. Furthermore, *PRIME* proposes and evaluates innovative design aspects to fulfil the established design targets. This research focuses on providing a knowledge-based framework applied in the early design stages to capture multi-user requirements and lays the foundation for concept generation. A case study of smart and sustainable packaging is considered to highlight the framework's applicability.

Keywords: user-centred design; design for X; sustainable design

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1. Introduction

A product's success is determined by user acceptance, so their perceptions of new products must be considered from the early design stages [1]. Due to rapid technological advancements, continuously rising user expectations, and product complexity, innovation in product design is critical to meet the modern market's demands for rapid and personalised design solutions. However, developing highly novel products may risk user rejection due to unfamiliarity, since users base their judgement on previous experience. This can be aided with trust in the product, supported by educational communication to inform users of its assets [2]. Thus, designers must elicit multi-user requirements from early design stages to ensure that users accept innovative products, hence ensuring the product's success.

Throughout a product's life cycle, from design to waste, multiple users interact with a product. *Users* are those who interact with the product throughout its life cycle, such as

personnel working at a manufacturing company. The *primary user*, i.e., the consumer or end-user, chooses to purchase the product, so it is essential that their needs are satisfied, as they ultimately determine the product's success. A *stakeholder* is the one who is directly impacted by the business, including the designer, who does not directly interact with the product but will also benefit from its success.

Previous research has shown that there is a semantic gap between designers and a product's life cycle users, which describes the difference between designers' perceptions of, and actual, user judgements [3], as illustrated in Figure 1. The sources of these deviations include a designer's insufficient setting of design specifications, inaccurate requirements and knowledge mapping, and an incomplete user profile, since designers underestimate the multi-dimensional approach to product evaluations by users [3]. Deviations between the product and the users' ideal solution can be minimised by designers precisely capturing the multi-user profile to generate satisfactory designs. While deviations are inevitable, feedback and understanding are essential. This is a continuous process, as design solutions converge with multi-user requirements, so real-time capturing of data is essential to develop design solutions which fully meet user requirements [3]. Correct knowledge mapping of requirements bridges the semantic gap between designers and users [4].

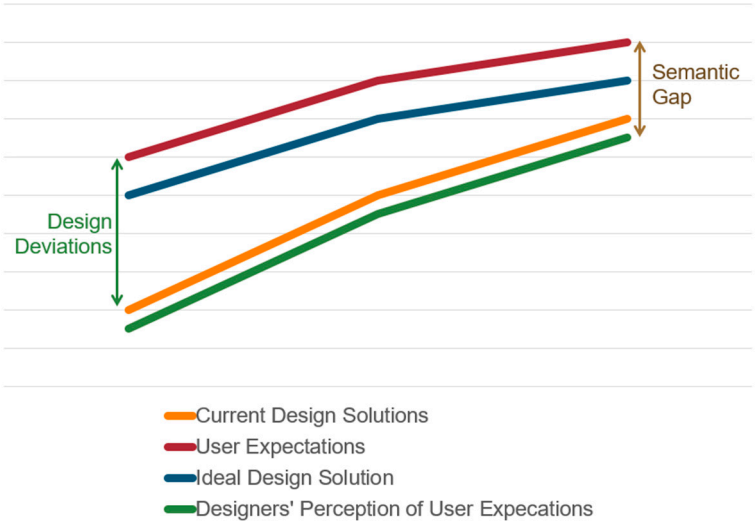


Figure 1. Illustration of the designer–user semantic gap, adapted from [3].

Conventional methods of user data collection, such as focus groups and surveys, are costly, and even when they are used, it is difficult to represent the complete user profile due to small sample sizes, often leading to the omission of useful information [5]. As an alternative, these approaches can be enriched by big data analytics to uncover correlations and trends to provide valuable insights to designers. Extracting multi-dimensional user data from online sources offers an effective, beneficial, and accessible resource in decision-making [6]. When employed, these methods expedite a responsive user-centred design (UCD) approach to capture dynamic user profiles in real-time in the design stage. This provides the additional benefit of allowing potential user requirements to be identified through predication models, and thus, designers are able to generate a more personalised and higher-quality design. The semantic gap between the designer and user is therefore reduced by providing an efficient approach to requirement elicitation and understanding and mapping to product design specifications. By adopting a data-driven approach, designers ensure that a user-centric innovative concept is developed.

While previous work has sufficiently captured consumer requirements from online reviews (e.g., [7,8]), a literature review revealed that, to the authors' knowledge, to date,

no available design support system captures and evaluates the multi-user profile in early design stages. Therefore, a gap in research has been identified, characterised by the lack of support designers have in minimising the semantic gap between themselves and multi-users, thus risking developing products which do not meet their needs. To address this research gap, this work aims to develop a framework which integrates data-driven approaches to multi-UCD to investigate correlations between multi-user requirements and functional aspects.

Domain-specific systems are advantageous as they utilise domain-specific lexicons and resources to gather knowledge, while independent systems make no specific assumptions and can be applied to design different types of products. Specific functional requirements need to be established in the early design stages, so a demonstration of the model's ability to develop a particular innovative product is critical in its eventual validation. The domain-independent part of the model is responsible for the decision-making and knowledge gathering and sharing, which, in this work, represents the capturing and resolving of multi-user requirements in early design stages. Furthermore, design opportunities are uncovered with topic modelling and sentiment analysis approaches and integrated into design concepts to meet established target specifications. The framework's modelling in a domain-specific application allows for visualisation and evaluation, which will be carried out in future work.

Smart and sustainable take-away (or take-out) food packaging was adopted as a case study to demonstrate this framework in a domain-specific application. Packaging is an integral aspect of a product's life cycle, as it serves its main functions of containment, protection, and preservation [9] throughout the supply chain. From a sustainable life cycle perspective, packaging supports the product and ensures that it reaches the use phase in good condition. However, these primary functions are no longer sufficient due to continuously rising user expectations and product complexity, with the demand of minimising environmental impacts [10]. Furthermore, COVID-19 induced global health and economic crises that had a major impact on consumer behaviour and perception of food safety and brought to light the limitations in the safety and traceability of conventional packaging [11]. Restaurant operators have reported that take-away sales have rapidly increased, and customers are more likely to order take-away compared to pre-COVID-19 [12], with consumption remaining consistently high post-COVID-19 [13]. Moreover, in today's global landscape, the rise in deliveries has resulted in more take-away food packaging use and disposal (due to the new trend ignited by COVID-19), with this having a significant impact, especially in relation to sustainability issues [14].

Despite its necessity, any packaging generates waste, and the single-use nature of take-away packaging leads to unsustainable growth [15], due to the relatively large impacts it induces throughout its life cycle, which comprises the following stages: raw material extraction, manufacturing, distribution, use phase, and end-of-life waste management [16]. Take-away packaging's use phase typically ranges from a couple of hours between order and consumption to a few days if leftovers are stored in a refrigerator. This is shorter when compared to other food items, such as frozen food, which can have a shelf life of a year [17]. Packaging loses its value after the consumer has used the product, as it is typically discarded immediately. For this reason, the material and energy resources used to develop the packaging are significantly larger than its use value, since the take-away packaging's use-time is comparatively very short. Thus, designers need to develop packaging systems more efficiently to ensure that its effective use phase compensates for the impact it induces. Designers should adopt a sustainable design approach to minimise its negative sustainability impacts by *extending* and *intensifying* its usage time, reduce

disposal due to obsolescence, and maximise end-of-life opportunities such as reuse and recycling [18].

For these reasons, smart packaging solutions which integrate innovative functions to enhance conventional packaging primary functions [19] are emerging and addressing weak points regarding sustainability. These supplementary attributes are based on useful interactions between the food, packaging, and user, with the main point of focus being to *extend* shelf life (via, for example, antimicrobial systems and active materials) and to *intensify* use by monitoring freshness and improving safety, quality, and integrity (by means of tamper-evident features and sensors). Smart packaging also adjusts to the user and is customised to their needs [20].

The rest of this paper is structured as follows: Section 2 describes the materials and methods utilised throughout this research. Section 3 reviews existing state-of-the-art design support systems which are applied to consider user requirements in early design stages. This is followed by an explanation of each module of the proposed *PRIME* framework in Section 4. Section 5 discusses the framework's strengths and limitations. Section 6 draws key conclusions, highlighting the contribution made.

2. Materials and Methods

This study's methodology is presented in Figure 2. Fifteen semi-structured interviews with food packaging designers were conducted as part of previous work [21] (Stage 1 in Figure 2). The aim of these interviews was to determine whether designers require support to capture the multi-user profile in early design and, if so, the areas in which they require support. The framework requirements established in this study were used as a basis for a literature review (Stage 2) to evaluate the extent to which state-of-the-art design support systems fulfil these requirements. Based on this, the proposed framework was developed (Stage 3).

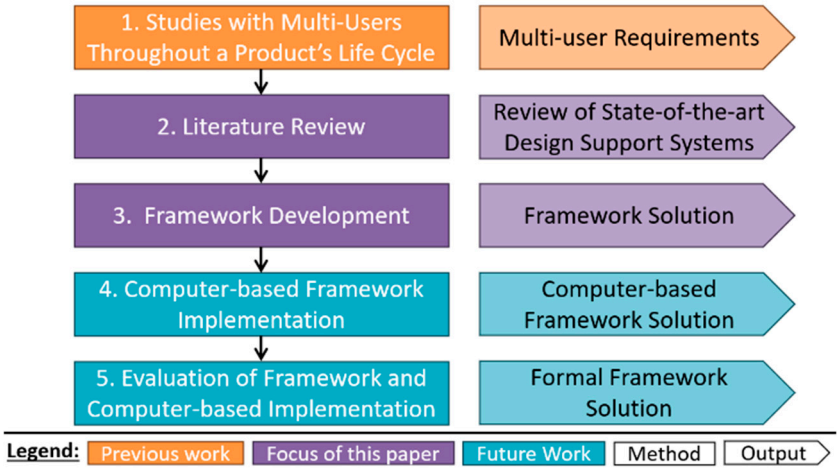


Figure 2. Methodology used to develop the *PRIME* framework.

Stages 1, 2, and 3 (discussed in this paper) contribute to answering RQ_1 and RQ_2, while Stages 4 and 5 will be carried out in future work to address RQ_3:

- **RQ_1:** To what extent do the correlations between the properties of smart and sustainable packaging influence the multi-user's experience with the packaging?
- **RQ_2:** What do designers require from a framework which adopts a multi-user-centred design approach to establish and prioritise design specifications in early design stages?
- **RQ_3:** How valid are the framework and its implementation in a computer-based proactive design system?

Based on the articulated research questions, the following research hypothesis is formulated, which binds this research work to research on the development of computer design support systems: "*Designers would benefit from a framework used to capture multi-user requirements, and identify innovative design aspects, through application in the sustainable smart take-away food packaging domain.*"

Additionally, studies with multi-users were conducted in Stage 1 to understand their perceptions of take-away food packaging. The participants included production personnel, restaurant owners and operators, consumers, and waste management personnel, as shown in Table 1. To analyse the qualitative data obtained in Studies 1, 2, and 4, a thematic analysis was conducted to identify themes to categorise the participants' responses. The qualitative data was analysed using the *NVIVO.12* [22]. The quantitative analysis performed on Studies 1 and 3 comprised of a three-stage process, where Stage 1 highlighted the overall rating for each question, in order to indicate the highly rated preferences, while Stages 2 and 3 explored the differences and relationships between each variable of the questions. The data was tested to understand the differences between every variable in each question and between each demographic group. The analysis from these studies provided insights into the correlations between the properties of smart and sustainable packaging, as well the extent to which they influence the multi-user's experience. The results were compared to uncover multi-user requirements, and designers' perceptions of their requirements, to understand where the discrepancies lie.

Table 1. Studies conducted to generate knowledge on sustainable smart take-away food packaging to utilise within the *PRIME* framework.

Study	Participants	Approach	Objective
Study 1	15 Food Packaging Designers	Mixed-Methods: Semi-Structured Interviews	To determine whether designers require support in the multi-UCD approach case study of take-away food packaging, and if so, to identify the areas in which designers require support when developing take-away packaging. To characterise sustainable smart food packaging by revealing the requirements for smart technologies, sustainable packaging, and multi-user-friendly food packaging.
Study 2	8 Stakeholders throughout Food Packaging Life Cycle	Qualitative: Focus Group	To establish multi-user requirements for sustainable, smart, and usable take-away food packaging.
Study 3	160 Consumers	Quantitative: Online Questionnaire	To quantify end-user requirements for sustainable smart take-away food packaging.
Study 4	7 Food Service Industry (FSI) Users;9 Consumers	Qualitative: 2 Usability Studies	To evaluate typical smart food packaging elements with multi-users.

It was found that safety/protection, usability, feasibility, and tamper evidence were essential multi-user requirements for sustainable smart take-away packaging. These requirements were found to have the potential to elicit a positive multi-UX in terms of desirability, usefulness, and credibility.

The knowledge gathered from these studies will be used to model the framework in an eventual computer-based implementation proof-of-concept tool in Stage 4 (refer to Figure 2). The validity of the framework will be tested through its evaluation by designers in Stage 5, and based on their feedback, a formal solution will be developed.

2.1. Study 1: Interviews with Food Packaging Designers

The life cycle of a product begins in the design process, where the designer is faced with the challenging task of adopting a multi-user-centred design approach when developing a product. For this reason, fifteen semi-structured interviews with food packaging designers were conducted. LinkedIn was used to recruit participants by searching for "food packaging designer", and those who disclosed and food packaging design experience were contacted. An equal representation of genders was achieved in the sample, with 47% male and 53% female designers. They had an average age of thirty-four, with an average experience of eight years in the food packaging design industry. Twelve participants (80%) were European, with the other three participants having Asian, North American, and South American nationalities (6.7% each).

The interview process was structured as follows: Firstly, designers were introduced to the study's aim and topics. The second part concerned questions on sustainable smart food packaging design, which aimed to characterise such a packaging. Then, queries on a framework were discussed, aimed at establishing the requirements for a system which provides support to designers when producing sustainable smart food packaging which enhances multi-UX. Each interview was held online via Google Meet and took, on average, 60 minutes. Both open- and close-ended questions were posed in presentation format, and participants were asked to indicate their degree of agreement using a Likert scale.

2.2. Study 2: Focus Group with Take-Away Packaging Life Cycle Stakeholders

Qualitative approaches applied in the early design stages allow designers to understand consumers' perceptions of smart packaging [23]. Eight food packaging life cycle stakeholders were asked to participate in a focus group to highlight any problems with the current take-away food packaging solutions with respect to multi-UX. This was followed by a discussion on how integrating smart functions and sustainability aspects improves the multi-UX of the food packaging. The main objective of this study was to establish multi-user requirements for sustainable, smart, and usable take-away food packaging. Production stakeholders had an average of nine years working in the food packaging industry, and a corporate caterer and consumer also participated. Participants were European, and there was an equal mix of males and females, with the average age of thirty-six.

The focus group followed a semi-structured approach, where open-ended questions were presented to participants via presentation slides. Eight professionals in the field of packaging production were asked to review the validity of the data collection instrument. These professionals were chosen to validate the data collection instrument as they had expertise in different life cycle stages, thus fully representing the participants' profile. Participants were asked to characterise smart food packaging, including questions such as "*what are the most important requirements for smart food packaging?*" Then, queries on a framework were discussed, aimed at establishing the requirements for a system which provides support to designers when producing sustainable smart food packaging which enhances multi-UX. This part included questions relating to which stage in the design would such a system be most useful (beginning or end), or whether it should be computer- or paper-based. The session lasted 90 min.

2.3. Study 3: Questionnaire with Take-Away Packaging Consumers

Study 3 was conducted to complement the themes identified in Study 2, the main objective of which was to quantify end-user requirements for take-away packaging. An online questionnaire was applied via Microsoft Forms and distributed to respondents via email and social media (LinkedIn and Facebook). A total of 160 consumers participated in this study. Likert scales and ranking data measures were employed to capture the participants' responses. The variables presented to every respondent for each ranking question were shuffled. Part 1 concerned demographics, which is relevant since these demographics influence consumers' preferences, asking for their age, gender, level of education, nationality, and location of residence. Then, questions were asked on their experience with current take-away packaging, including typical frustrations they encounter when handling take-away packaging, and areas of improvement. The next part concerned disposal and consumers' sustainability perceptions of take-away packaging. This part included questions such as "*Do you recycle the take-away packaging made from: (a) carton, (b) plastic, and (c) aluminium foil?*" Finally, questions related to their impressions of smart food packaging were presented, where mainly consumers were asked how much they are willing-to-pay for smart features in take-away packaging.

2.4. Study 4: Usability Studies with Take-Away Packaging Life Cycle Users

The interviews with food packaging designers (Study 1) revealed that consumers are generally not familiar with smart food packaging. For this reason, this study's objective was to evaluate typical smart food packaging elements with multi-users.

In Study 4, two sessions were carried out to comprehensively investigate the usability aspects of smart food packaging with users at different packaging life cycle stages. Seven stakeholders in the field of food packaging production reviewed the data collection protocol. One study was conducted with 9 consumers and the second with 7 life cycle users working in the food service industry (FSI). The sessions lasted 90 min each. In this study, a take-away pizza box was adopted as a case study, and smart aspects were integrated into the design concepts. A low-cost tamper evidence solution is a sticker, which is a visual indication that the packaging has not been previously opened prior to arriving at the user. This also promotes the provision of safety and protection, both to the user and to the food, as it eliminates the chances of the packaging being opened throughout delivery. However, the sticker can impede usability, so the take-away pizza box design was adapted with tabs to provide a sufficient area onto which the sticker can adhere and promote openability for the user. Participants were asked to describe their thoughts and concerns regarding such a packaging, in order to understand how they directly evaluate smart take-away food packaging.

3. Review of Design Support Systems

Based on the framework requirements established in previous work [21], a review was conducted on available state-of-the-art design support systems based on the following criteria:

- **RC_1:** Shows a domain-specific application;
- **RC_2:** Promotes a multi-UCD approach;
- **RC_3:** Establishes and prioritises design requirements;
- **RC_4:** Identifies and evaluates design opportunities to fulfil design requirements.

Relevant journal papers were extracted from *GoogleScholar*, *ProQuest*, *ScienceDirect*, and *Taylor&Francis* using the search query [*"multi-user" AND ("data-driven design" OR "early design") AND ("framework" OR "approach")*]. A total of 99 titles were extracted after automatic filtering. We filtered for papers published in the English language within the last ten years. Duplicates were removed, and each paper was thoroughly screened based

on relevance of contribution. A final 10 [7,8,20,24–30] were thus evaluated based on the review criteria.

Shao et al. [24] intended to resolve the designer–consumer semantic gap by developing a tool by collecting user reviews and design-related documents and applying topic modelling and sentiment analysis techniques to resolve user and design requirement conflicts. Furthermore, the optimal design concept was determined through regression methods, but its evaluation was only limited to a cost analysis.

Franz et al. [7] utilised customer feedback to identify the target areas for which a product's design can be optimised for device repairability. Their approach can be adopted in the early stages of product design to allow designers to understand consumers' common repairability concerns for devices on the market and leverage this knowledge to ensure that the repair-critical components in their designs are easily accessible and modular. By leveraging online reviews, designers gather insight on consumer-related design aspects, but they fail to generate knowledge on other life cycle user requirements (RC_2).

Yokokawa et al. [25] generated a framework for the early design stages of sustainable food packaging by quantifying the relationships between environmental packaging and consumers' functional preferences. A survey study was employed to represent consumers by recording their preferences for design concepts, and the results were examined using Choice-Based Conjoint Analysis techniques. However, this is a time-consuming approach, since the survey asked consumers to choose between each alternative. The authors' framework does not correlate consumer and environmental requirements, and the packaging's functional assessment is only based on consumer preferences.

In early design, a Quality Function Deployment (QFD) table is employed to balance engineering characteristics and user requirements, ensuring metrics are tabulated, and a market analysis is conducted [31]. The scope is to set target values which act as a benchmark for the subsequent design stages on which design concepts will be evaluated. Lee et al. [8] combined the QFD as a tool to establish product specifications with opinion mining to generate user requirements. Salwa et al. [26] have developed a model to promote the use of renewable and bio-compatible resources in take-away food packaging. These studies employ a QFD in their approach, and while this tool is sufficient to establish and prioritise design requirements (fulfilling RC_3), alone, it does not identify or evaluate design opportunities to fulfil these requirements (RC_4).

In the context of food packaging, which pertains to the domain-specific case study in this research (with respect to RC_1), Wei and Xiangbo [27] developed a parametric method for selecting the optimal food packaging solution based on a food's shelf-life by means of the fuzzy directivity approach to big data classification. Zhang et al. [29] employed natural language processing techniques applied to image semantic segmentation based on fully convolutional networks to improve packaging design. They developed a tool to optimise feature extraction through edge information knowledge. Wen et al. [28] propose a model for user experience evaluation for children's food packaging by representing packaging solutions on a two-dimensional model of functionality (utility) and emotional value (emotional). Adilah et al. [20] propose a design matrix utilising an axiomatic design approach to incorporate smart design aspects while maintaining circular economy principles.

Huang et al. [30] exploited the merits of knowledge graphs in the conceptual design phase in a tool to extract and represent design knowledge, capable of providing designers with visual representations of design concepts. The acquired design knowledge, involving user requirements, decision-making, and market research, is combined with case studies of existing products, serving as design inspiration. While the tool offers valuable insight into methods to identify new opportunities in design (fulfilling RC_4), their work contributes to providing a platform for design concept generation, but it does not provide a standard

design method for designers to establish specifications. Furthermore, the authors do not represent multi-user needs (RC_2), meaning the tool's outcomes only act as a reference for design inspiration and knowledge. So, their model does not support designers to prioritise design requirements (RC_3).

To address the design problem of a take-away food packaging which does not meet the sustainability and technological demands of multi-users, several design systems were reviewed based on the criteria established through *Study 1: Interviews with Food Packaging Designers*, as summarised in Table 2.

Table 2. Summary of the literature review of design support systems with full (✔), partial (■), and no (✘) fulfilment of the established review criteria.

Review Criteria	RC_1	RC_2	RC_3	RC_4
Shao et al. (2024) [24]	✘	■	✘	✘
Franz et al. (2024) [7]	✘	■	✘	✘
Yokokawa et al. (2021) [25]	✔	■	✘	✘
Salwa et al. (2021) [26]	✔	■	✔	✘
Wei and Xiangbo (2020) [27]	✔	✘	✘	✘
Wen et al. (2023) [28]	✔	■	✘	✘
Zhang et al. (2024) [29]	■	✘	✘	✘
Lee et al. (2024) [8]	✘	■	✔	✘
Adilah et al. (2023) [20]	✘	■	✔	✘
Huang et al. (2024) [30]	✘	■	✘	✘

QFDs and text mining product reviews and their sentiment analysis have previously been applied in engineering design to reduce the semantic gap between designers and the product users. While these notable approaches contribute to eliciting consumer requirements, these only represent the end-user, since these works only harvest consumers' online reviews, and alone, they cannot be employed to represent the multi-user profile. As shown in this section, from this review, we determined that none of the identified design support systems collectively satisfies all the criteria. Thus, this research will address this gap by proposing a conceptual framework inspired by these requirements.

4. Conceptual PRIME Framework

Based on the requirements established in Section 3, and in an attempt to extend our previous work [21], the PRioritising and achIeving Multi-user rEquirements (*PRIME*) framework is now proposed. *PRIME*, presented in Figure 3, is concerned with supporting designers to adopt a multi-UCD approach in early design by establishing design requirements and laying the foundation for concept generation by identifying design opportunities to meet these requirements.

At its core, the first module of the framework (*Frame 1: Knowledge Management*) captures data on users and product attributes from online sources (KM_1), and this data is pre-processed for analysis (KM_2). Topic modelling and sentiment analysis techniques identify topic models, their associated user sentiment, and frequency of occurrence within a corpus (KM_3). This knowledge is represented in a knowledge graph (KM_4).

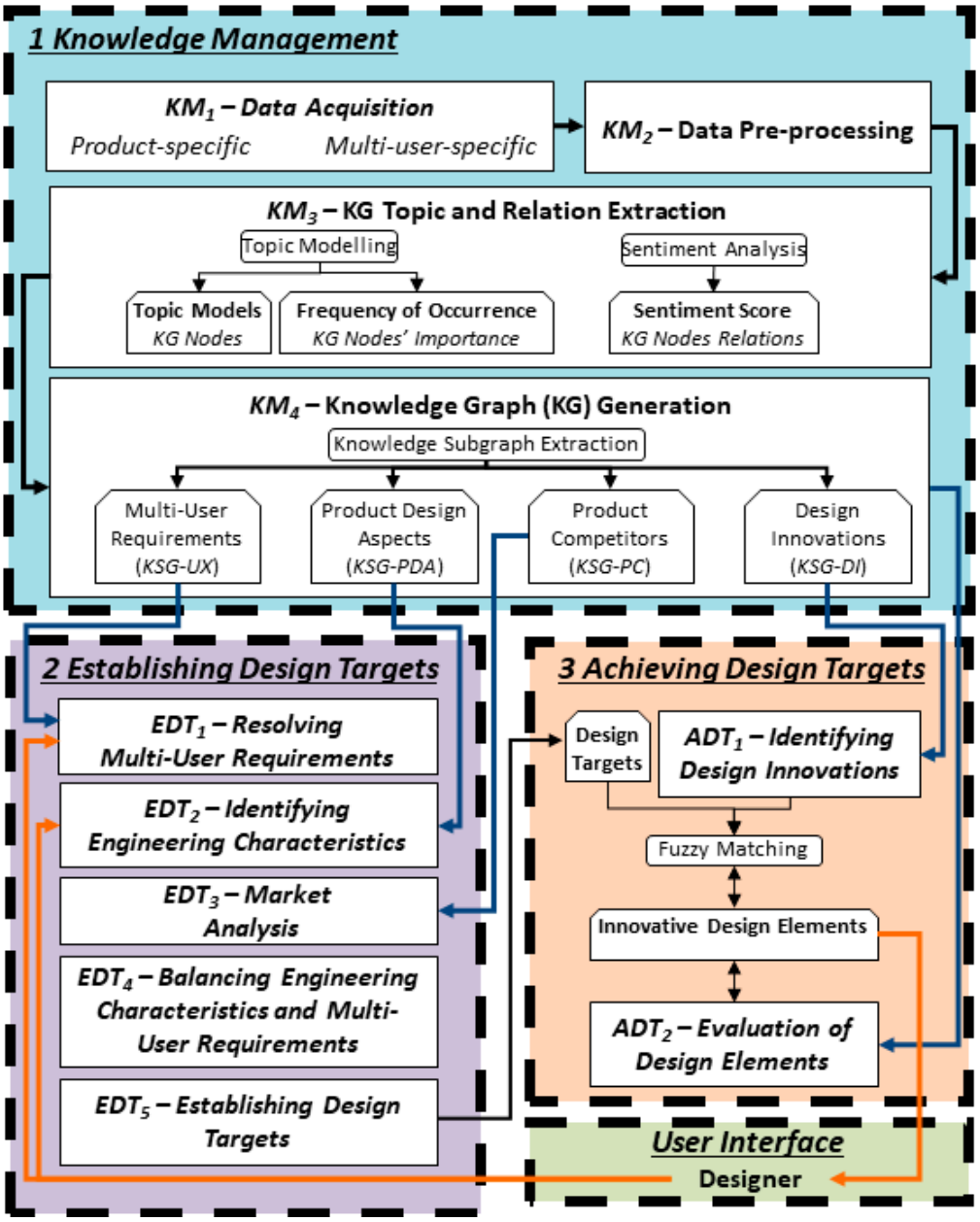


Figure 3. Conceptual *PRIME* framework.

The knowledge obtained from the first frame is then utilised within the framework, where, within the second module (*Frame 2: Establishing Design Targets*), design targets are established to set a benchmark for design concepts. The user requirements elicited, and their associated weightings, compose the voice of the users within the QFD, where conflict resolution methods resolve any contrasting multi-user requirements (EDT_1). Also, topic models representing product attributes formulate the engineering characteristics section (EDT_2). A market analysis is conducted (EDT_3) from the topic modelling and sentiment analysis knowledge by rating the extent to which similar products on the market meet user requirements. The multi-user requirements and engineering characteristics are evaluated (EDT_4), and the final design targets are established (EDT_5). Conflict resolution matrices are applied to eliminate conflicting targets, thus creating an overall design specification list.

The third module (*Frame 3: Achieving Design Targets*) focuses on matching design attributes and their intended function to the design targets (ADT_1). A prediction model

then evaluates the envisaged multi-user sentiment should they be integrated in the final design solution (ADT_2). The optimal design concept is chosen based on a weighting system.

Given the problem background described in Section 1, this framework can be applied to support take-away food packaging designers, where an apparent semantic gap is apparent due to the rapidly evolving multi-user requirements for food packaging. Conventional packaging fails to meet evolving user demands for increased safety, product integrity, and sustainability in food packaging [32], brought to light by the COVID-19 crisis. This motivated a shift towards sustainable food packaging, which can be further enhanced with smart functions. Sustainable food packaging is becoming increasingly important to minimise its burdens, due to the rapid increase in amount of waste generated compared to its use value. For these reasons, smart packaging solutions have the potential to accelerate sustainable development by offering innovative solutions to enhance product attributes, such as communication, product integrity, and an increase in shelf life. However, designers struggle with striking a balance between sustainability and smart functions in food packaging [21]. For example, consumers have shown a preference for recyclable packaging, and smart labelling devices can communicate the packaging's material composition to facilitate recycling. However, smart sensors typically pose a challenge to recycling [33], and a Life Cycle Assessment revealed that the environmental burden of conventional packaging is in the transportation phase, while these are relocated to smart packaging's intelligent system [34]. This emphasises the importance of incorporating a sustainable design approach to the initial design stages.

One aspect that separates take-away food packaging from other products is its role in the usage context. Typically for take-away food packaging, the consumer evaluates the packaging performance in relation to their experience with take-away food. It should serve its main functions and not negatively affect the overall eating experience of the consumer. So, it can only influence the user's experience negatively if it does not perform as intended and impacts on the food's condition, quality, and integrity. However, smart packaging provides supplementary benefits, due to the added functionalities in communication, protection, and handleability, over conventional packaging, thus contributing to a positive user experience. Likewise, it can also negatively impact if not designed according to consumers' requirements. This creates additional challenges for designers to uncover implicit user requirements from consumers, as they typically would not rate the packaging functionality. The food packaging designer is faced with the demanding task of striking a balance between sustainability and smart functions, while ensuring that the food packaging meets multi-user needs. Adopting the take-away food packaging domain as a case study, each module of the framework is explained hereunder within this context.

4.1. Frame 1—Knowledge Management

This first module, represented in Figure 4, contains all the data sources that may be utilised throughout the design process, in the form of structured and unstructured formats. Machine learning and natural language processing techniques create concepts and relations between the different data sources to build a cohesive domain-specific knowledge graph. In this research, the knowledge within the knowledge graph relates to sustainable smart take-away food packaging.

Online resources are exploited to gather a rich data set to provide designers with a stable foundation for detailed design [35], benefiting multi-UCD approaches via enabling access to data from multiple sources. Firstly, data is extracted using web crawlers and scrapers from data sources such as social media, academic studies, and articles to generate knowledge related to multi-user requirements. In terms of design aspects and existing packaging case studies, resources include design documents, internal and external stan-

dards, laws, policies, and databases. For example, in the food packaging field, journal papers and articles on existing smart packaging solutions provide insights into the novel approaches to food packaging design to identify innovations. This knowledge is exploited in subsequent stages.

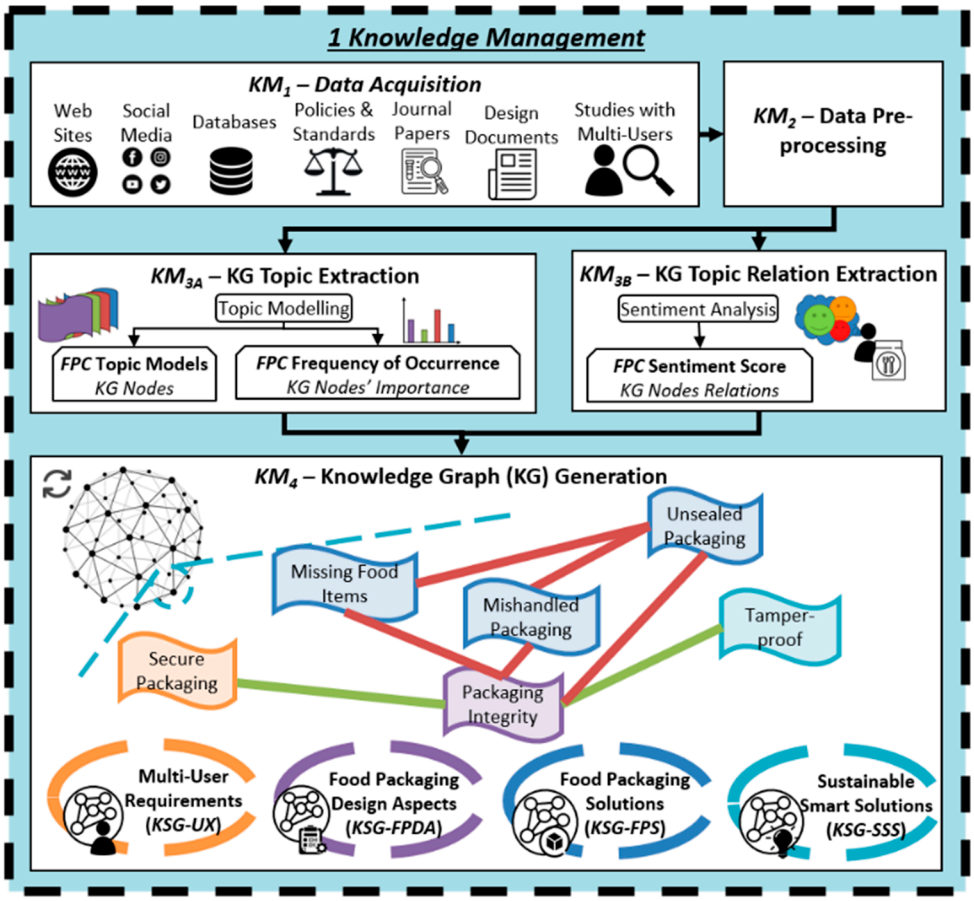


Figure 4. Frame 1—Knowledge Management of *PRIME*, adapted for the design of sustainable smart take-away food packaging.

Pre-processing methods are implemented to reduce noise in the data, including tokenisation based on bag-of-words indexing, which splits text into individual words to be included in the bagof-words; noise reduction, encompassing removal of punctuation and special symbols; conversion to lowercase characters; and lemmatisation, which reduces words to their root form. Despite being slower and more expensive to implement compared to stemming, lemmatisation is more suitable for applications where expressiveness and performance are important.

Once the data has been pre-processed, topics and keywords can be identified to obtain meaningful information from the data in relation to product design. One notable topic modelling technique is Latent Dirichlet Allocation (LDA), which is a flexible generative probabilistic model used to uncover latent topics and the frequency at which they appear in a corpus [36], and it can be easily embedded into complex models. Then, sentiment analysis techniques are applied on the keywords to extract the attitude expressed in topic models by assigning a positive, negative, or neutral emotional expression. The polarity of keywords is extracted, and predictions can be made by a text classifier model. It was shown that Support Vector Machine (SVM) is an effective classifier for transforming low-to-high-dimensional space with minimal overfitting [36]. To illustrate this, consider the review depicted in Figure 5 [37]. In this example, a consumer is complaining about unsealed and mishandled

packaging during delivery, which resulted in missing food items. The consumer also made note that a "*tamper-proof plastic bag*" will ensure that the delivery courier is held accountable whilst "*safeguarding the customer experience*". Through topic modelling techniques, the framework identifies the topic models from the review, which represent the knowledge graph (KG) nodes. The sentiment aspect extracted by means of sentiment analysis models provides the KG node relations.

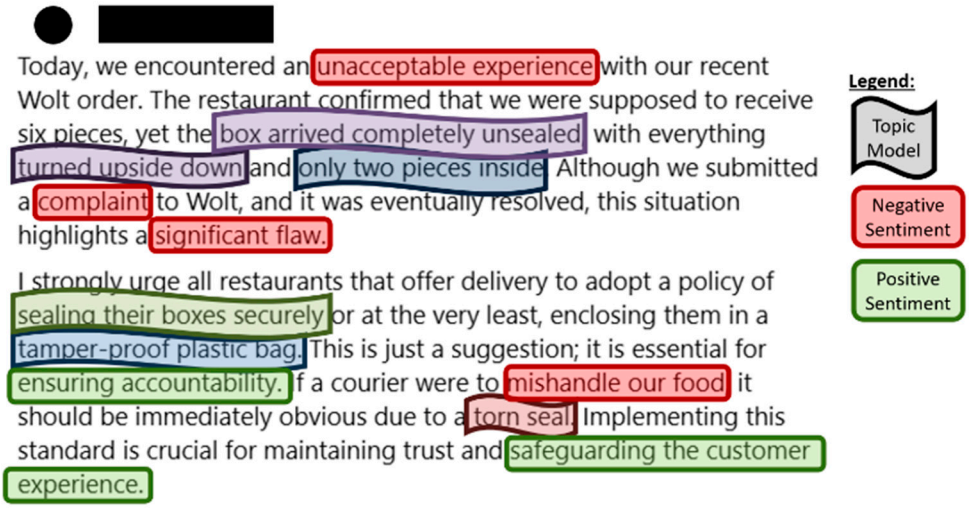


Figure 5. Consumer review with manual labelling of topic models and sentiment.

The identified topic models and their relationships are embedded and characterise the KG. Based on the prior extract, an example of the KG can be modelled (Figure 6). The topic models represent the nodes, whereas their associated sentiment indicates the relationships between them. Multiple knowledge sub-graphs (KSGs) are identified, depending on what knowledge is required to be extracted for the different steps of the framework. A KSG targets the relevant knowledge by pruning entities within the KG that are required for each stage of the framework. Reducing the search space, especially in large KGs, minimises computational time and improves new data integration by preventing unnecessary mapping [38].



Figure 6. Example of knowledge sub-graph.

4.2. Frame 2—Establishing Design Targets

The second module aims to establish design targets (Figure 7), beginning with a QFD table which tabulates metrics and evaluates market solutions [29]. The scope is to set target values which act as a benchmark for the subsequent design stages in which design concepts will be evaluated.

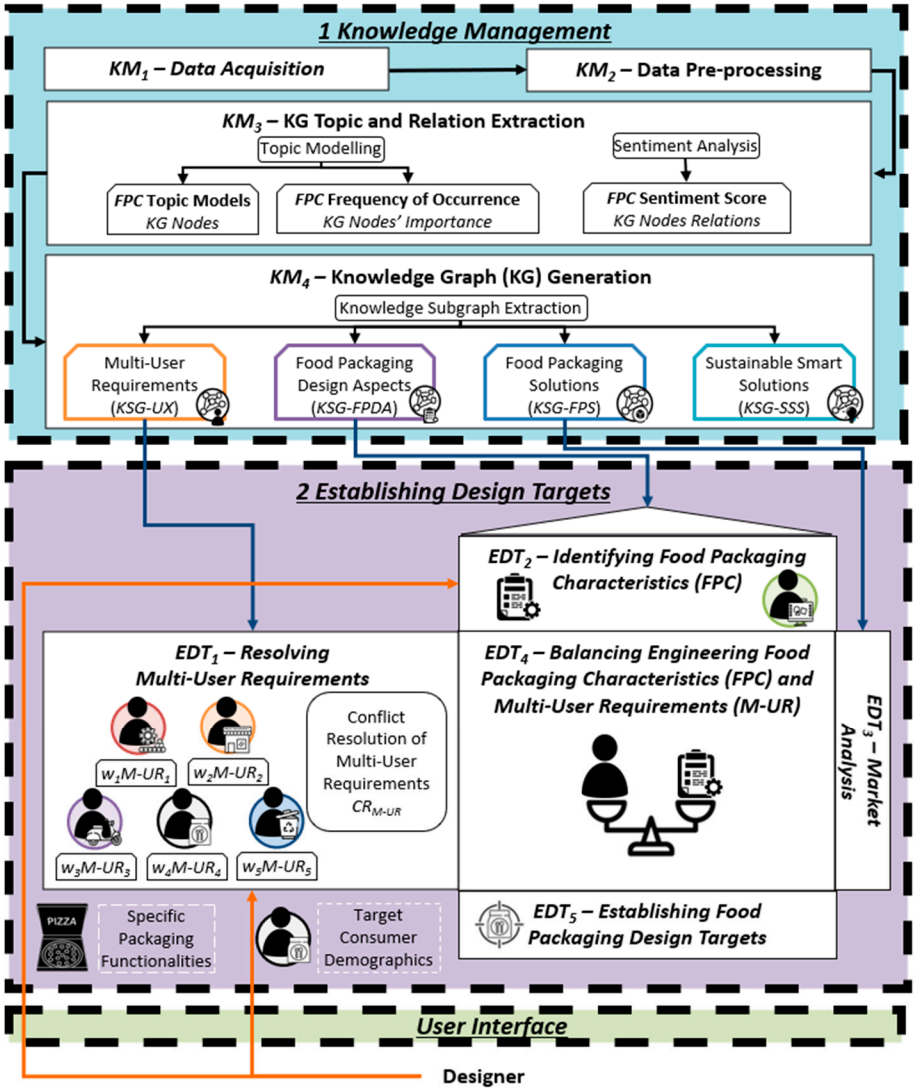


Figure 7. Frame 2—Establishing Design Targets of *PRIME*, adapted for the design of sustainable smart take-away food packaging.

The QFD is a structured approach for translating the "users' voice" into the engineering characteristics required to meet their expectations. The QFD assigns a measurable value to the user's wants through design requirements and also determines the relationships between them. It ensures that the design specifications are aligned with the 'wants' of the user, allowing for a multi-UCD approach. It is composed of five main elements, described by Stages EDT_1 to EDT_5.

1. Resolving Multi-User Requirements (EDT_1): The product is described in terms of what they require. In Stage EDT_1, multi-user requirements are identified from knowledge stored within the Multi-User Requirements sub-graph (*KSG-UX*), and any conflicts between the requirements are resolved. The designer inputs the target consumer demographics to target knowledge from this sub-graph to identify specific requirements for that consumer profile. For example, within the take-away food packaging

application, consumers of different demographics have varying requirements, such as differences in openability and handleability requirements, and recycling practices. Based on the user's demographic profile, probabilistic language analysis techniques are employed to extract the demographic-specific user requirements from the topic models obtained in the previous stage. Considering Figure 5, one such multi-user requirement would be "*secure packaging*", so as to ensure the packaging is not opened prematurely. The frequency of topic model occurrence in reviews is used to rank the user requirements in the QFD.

2. Identifying Engineering Characteristics (EDT_2): This stage represents how the user needs can be satisfied by the product. The engineering characteristics are extracted, also by means of probabilistic language analysis methods applied on the Food Packaging Design Aspects sub-graph (*KSG-FPDA*). From the knowledge graph in Figure 6, one such instance would be "*packaging integrity*". The designer can also input specific packaging functionalities in this step, for example, to choose what type of take-away packaging they need to develop.
3. Market Analysis (EDT_3): The performance of competitive take-away packaging solutions is compared with respect to the established multi-user requirements to further highlight the shortcomings of similar packaging used by other restaurants. This step makes use of knowledge stored in the Food Packaging Solutions sub-graph (*KSG-FPS*). The semantic relationships between the topic models present in *KSG-FPS* and *KSG-UX* indicate the level of fulfilment of competitive take-away packaging for each multi-user requirement. In Figure 5, it is shown that a take-away box arrived opened and with food missing, so for the "*secure packaging*" requirement, this take-away packaging would receive a relatively low score.
4. Balancing Engineering Characteristics and Multi-User Requirements (EDT_4): the relationship matrix indicates to what extent each engineering characteristic affects every user requirement. So, Engineering Food Packaging Characteristics are then analysed with respect to the Multi-User Requirements to attempt to strike a balance between the two sets of requirements. The Analytic Network Process is a typical model which is applied in criteria analysis and frequently adopted in QFDs to calculate the interrelationships between the consumer requirements and engineering characteristics, as well as the external relationships between the two [39].
5. Establishing Design Targets (EDT_5): The engineering characteristics are then translated and quantified into design targets with respect to the multi-user requirements. In the next stage, the designer would be provided with design opportunities to meet engineering characteristics, described below.

4.3. Frame 3—Achieving Design Targets

In order to fulfil the design targets established within the QFD, the third module, presented in Figure 8, identifies relevant design opportunities and evaluates these innovations with respect to the envisaged multi-user experience.

Stage ADT_1 aims to fulfil the design targets established in the previous frame by integrating smart elements within the take-away packaging design. In the domain-specific application of the framework, smart design technologies emerge in take-away food packaging solutions, and thus nodes contributing to knowledge on these innovations form the *KSG-SSS* (i.e., *KSG-DI*) sub-graph. Within the Sustainable Smart Solutions sub-graph (*KSG-SSS*), the smart technologies collated from existing packaging and literature are categorised according to their functionality and matched to the appropriate design target through fuzzy similarity matching techniques, such as n-gram matching. Thus, the im-

proved packaging concept is enhanced through smart elements to meet design targets set in the previous frame.

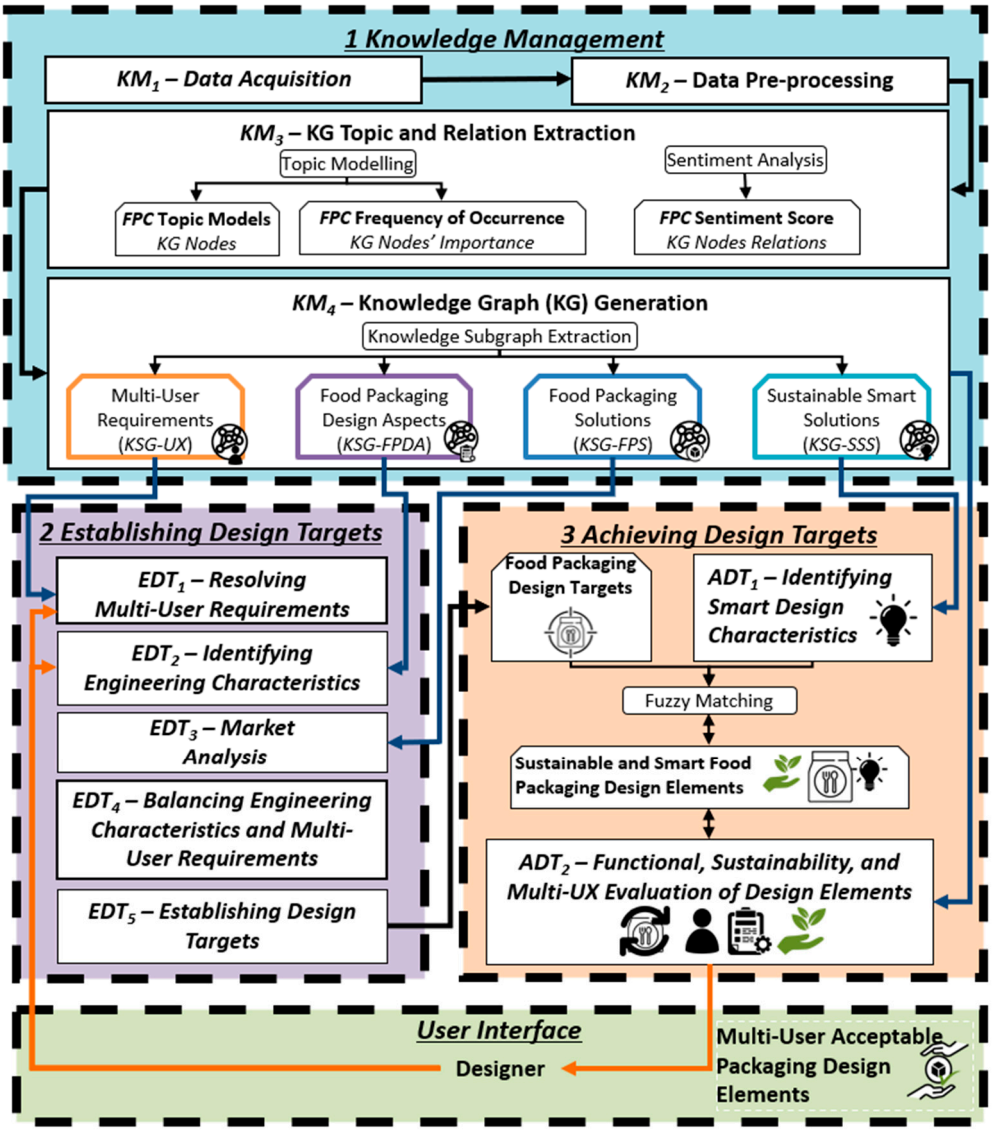


Figure 8. Frame 3—Achieving Design Targets of *PRIME*, adapted for the design of sustainable smart take-away food packaging.

Next, in Stage ADT_2, these smart elements are assessed with respect to sustainability, UX, and functionality. The sentiment analysis knowledge generated from *KSG-UX* is used to build a prediction model to anticipate the multi-users' sentiment towards the design improvements. The model will utilise sustainability-related data sources from Frame 1, such as carbon footprint databases and material use calculations, to predict the sustainability status of the packaging concept through a preliminary Life Cycle Assessment, a tool used to quantify the environmental impacts of a product throughout its life cycle. For example, to meet the "*packaging integrity*" design target, a "*tamper-proof plastic bag*" (Figure 6) can be integrated into the packaging design. However, the additional materials of these smart features will impact its sustainability status and the handleability of the take-away packaging. Thus, the framework would suggest other smart functional elements which strike a compromise between multi-user needs, functional requirements, and their sustainability implications.

5. Discussion

The *PRIME* framework supports the early design stages, found to be an area in which designers need most support [40–42]. The utilisation of big data analytics effectively supplements traditional user data collection methods, which are costly and time-consuming, to allow for real-time and large-scale analysis of rapidly evolving preferences. This aims to bridge the semantic gap between designers and multi-users by capturing actual multi-user needs, allowing designers to deeply understand their perceptions and requirements. Conflict resolution techniques are applied to balance functional aspects and multi-user requirements, thus equipping designers with an extensive resource to support their design practice. The framework contributes towards elevating the landscape of current design practice by empowering design innovation through the application of data-driven techniques to capture and resolve multi-user requirements, while guiding designers to establish and meet design targets. Design concepts are enhanced with innovative design aspects, identified through online sources.

In our previous work [21], interviews were held with designers, who established requirements for a framework to balance multi-user requirements in the early stages of design. Based on these outcomes, a literature review on available design support systems [7,8,20,24–30] identified a gap in multi-UCD support. Similarly to available design systems, the framework employs a QFD to balance engineering characteristics and user requirements. However, the resolution of multi-user requirements, together with Frame 3 of the model, are what elevates the framework from the state-of-the-art. So, *PRIME* distinguishes itself from these systems in adopting a multi-UCD approach aimed at closing the semantic gap between the designer and life cycle users.

Research indicates that domain-specific design systems enhance the overall efficiency in their design practice by inferring domain-specific knowledge [6] to meet the modern market's demands for rapid and personalised design solutions, which increases the complexity of big data analytics. For this reason, take-away food packaging is adopted as an application, where packaging design concepts are enhanced with smart functions, identified through online sources and literature, while maintaining sustainability aspects. The framework's application in the take-away food packaging industry delivers a domain-specific guideline to incorporate sustainability aspects and smart functionalities to contribute to a positive multi-user experience. Previous methods (e.g., [8,26]) have employed only a QFD to achieve a sustainable design while considering user requirements, but a QFD does not provide a holistic overview of the life cycle implications of product designs. Furthermore, *PRIME* provides an additional step to identify and evaluate innovative design aspects, such as smart packaging features, that can be integrated into design concepts to achieve the desired outcome from design targets established through the QFD. This contribution offers insights that could be beneficial across various applications by addressing the intricacies of a multi-user-centred approach in early design.

Research Question 1 (RQ_1) asked, "*To what extent do the correlations between the properties of smart and sustainable packaging influence the multi-user's experience with the packaging?*" We sought to uncover food packaging-related correlations between multi-users and functional attributes to generate a holistic and comprehensive multi-user profile of stakeholders. Thus, four studies were carried out with life cycle stakeholders of smart take-away food packaging, which helped to identify a semantic gap between designers and users. This creates challenges in smart take-away food packaging design since it risks concealing multi-user requirements. It was found that safety/protection, usability, feasibility, and tamper evidence were essential multi-user requirements for sustainable smart take-away packaging.

Study 1, where interviews were held with food packaging designers, addresses RQ_2: "*What do designers require from a framework which adopts a multi-user-centred design approach to*

establish and prioritise design specifications in early design stages?" The participants revealed that they struggle with striking a balance between sustainability and user requirements and are inexperienced in integrating smart functions in food packaging. Moreover, participants noted that they were not aware of a design support system which guides the development of smart take-away food packaging, even though they require it.

One merit of the *PRIME* framework is its representation of multi-user knowledge through knowledge graphs. Compared to ontological representations, KGs efficiently combine data from various sources and represent the semantic correlations between them [30]. KGs can be easily updated to integrate new data representing the real-time dynamic multi-user profile, which proved to be a challenge in existing domain ontologies due to their hierarchal nature [43]. KGs have been previously applied to minimise the semantic gap between users and designers (e.g., [30,44]).

Traditional Large Language Models rely on a static knowledge base embedded in their parameters during training, which makes them limited in accessing new information. Thus, due to memory constraints, the amount of knowledge that can be stored within the model is restricted. Without access to external information, such as online sources, the model risks being too generic or outdated. For these reasons, leveraging online sources within the knowledge graph offers a dynamic knowledge base, helping to retrieve information from an external corpus to utilise more up-to-date information within the model. This enhances its overall performance by generating more accurate and contextually appropriate knowledge. Furthermore, the retrieved documents can serve as evidence to increase transparency to the designer.

Despite these advantages, the quality of the KG is dependent on its data sources [45], so it is essential that the sources are consistent and reliable. Utilising data cleaning approaches tests the validity and consistency of web crawlers and scrapers. Furthermore, a weighting system will be applied on the online sources to segregate between sources which are known to be more reliable, for example, standards from verified sources. Also, the amount of interaction with a social media post (e.g., number of likes) will also contribute to its overall weight in determining reliability. To avoid overlooking implicit multi-user requirements, vector-based retrieval techniques complement the knowledge stored within the graph by covering gaps in the KG, while the KG context grounds the extracted information in verifiable relationships, thus reducing hallucinations. In the computer-based implementation, the results of Studies 1–4 will be used to model the multi-user profile of sustainable smart food packaging. Using the knowledge gained through these studies as a model bolsters confidence in the quality, reliability, and credibility of the KG, since the data was collected from primary sources. Also, knowledge graphs face latency issues as the real-time similarity computations across large-scale corpora affect retrieval time. Thus, efficient indexing methods for optimising real-time retrieval will be employed with algorithms such as FAISS, ANN, and HNSW. These optimise real-time search within the hierarchal subsets of vector embeddings in high-dimensional space, where the higher layers are utilised for global navigation, with the lower layers being used for a more detailed search. Furthermore, dimensionality deduction techniques reduce the size of embeddings, speeding up similarity calculations.

6. Conclusions

The *PRIME* framework distinguishes itself from the current state-of-the-art approaches by leveraging online resources to firstly elicit and resolve conflicts of multi-user requirements and subsequently identify design opportunities that can be integrated to optimise design concepts in order to strike a balance between design specifications and multi-user needs.

The results of Study 1 contributed to establishing requirements for such a framework, and based on these outcomes, a literature review on available design support systems

identified a gap. The life cycle stakeholder knowledge gained from Studies 1–4 further motivated the generation of the *PRIME* framework to address this gap.

In future work, the *PRIME* framework will be implemented into a computer-based tool to test its validity and reliability, as well as its practicality and feasibility in the smart take-away food packaging domain. The framework, and its implementation in a computer-based tool, will be evaluated by designers to assess accuracy, validity and practicality, and tests will be carried out to determine performance metrics such as precision, recall, and F1-score. Thus, interviews with food packaging designers will be conducted again to achieve these study objectives. This will address RQ_3: "*How valid are the framework and its implementation in a computer-based proactive design system?*"

Once completed, the framework, and its computer-based implementation in a tool, will expand on available design support systems, which currently only account for consumer needs in their analysis. One major advantage of the *PRIME* framework is its consideration of multi-user requirements (RC_2) when establishing and prioritising functional requirements (RC_3). Furthermore, the *PRIME* framework goes beyond the available systems in further evaluating product designs with respect to the multi-user requirements (RC_4) to ensure that a solution which is more mindful of their needs is developed. Its application in a domain-specific case study (RC_1), based on take-away food packaging, will allow for its eventual evaluation and verification by designers. These merits of the *PRIME* framework, relative to existing design support systems, offer a practical and effective approach to multi-UCD in the early design stages.

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Abbreviations

The following abbreviations are used in this manuscript:

RQ	Research Question
RC	Review Criteria
KG	Knowledge Graph
KSG	Knowledge Sup-graph
LDA	Latent Dirichlet Allocation
Multi-UCD	Multi-User-Centred Design
QFD	Quality Function Deployment
KM	*Frame 1: Knowledge Management*
EDT	*Frame 2: Establishing Design Targets*
ADT	*Frame 3: Achieving Design Targets*

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