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Designing for Longevity: Integrating Eye Tracking and Quality Function Deployment in Circular Product Design

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Abstract

Designing products for longevity, reparability, and transparency is central to the transition towards a circular economy. While Quality Function Deployment (QFD) offers a structured approach to translating customer requirements into engineering specifications, its reliance on self-reported preferences limits its ability to capture implicit user priorities, particularly regarding sustainability. This chapter proposes a behaviourally informed design framework that integrates eye-tracking analysis into QFD to support circular product design. Eye tracking provides objective evidence of user visual attention to longevity-related design cues, such as modularity, repairability indicators, material transparency, and eco-labels. These behavioural insights are systematically embedded into the House of Quality to strengthen the prioritisation of circular design features. The chapter develops the Behaviourally Informed QFD Framework for Circular Product Longevity and illustrates its practical application. The framework bridges the gap between technical design decisions, policy requirements, and user perception, enhancing product longevity and consumer empowerment.

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12.1 Introduction

The circular economy has emerged as a dominant paradigm for addressing the environmental impacts of contemporary production and consumption systems. Central to this paradigm is value retention, which seeks to minimise resource extraction and waste by extending product lifetimes through durability, repair, reuse, and upgrading (Ellen MacArthur Foundation, 2015). Designing for longevity offers substantial environmental benefits, especially for resource-intensive products, as lifecycle assessments consistently demonstrate reductions in resource consumption and emissions compared with strategies focused solely on recycling (Cooper, 2010; Bocken et al., 2016). Despite increasing policy attention and design guidance, operationalising longevity in practice remains challenging. Products may be technically durable but prematurely discarded due to aesthetic obsolescence, lack of repair support, insufficient information, or low perceived value of extended use (van Nes and Cramer, 2006). Addressing this requires aligning technical design decisions with user perception and behaviour.

Quality Function Deployment (QFD) offers a structured method to translate customer needs into technical specifications (Boks and McAloone, 2009). In circular design, QFD has been extended to integrate sustainability criteria alongside traditional functional requirements (Kuo et al., 2012). However, QFD's reliance on self-reported importance weights for customer requirements introduces limitations. Users may overstate interest in sustainable features due to social desirability bias or lack of awareness, meaning longevity-related features can be underprioritised in actual design decisions (Gidlöf et al., 2013). Eye-tracking analysis offers a solution by capturing implicit behavioural data. Eye tracking measures fixation duration, count, and sequence, providing evidence of which design cues attract attention and are cognitively processed (Holmqvist et al., 2011). Integrating eye-tracking data into QFD allows designers to weight technical features according to actual user engagement, ensuring that longevity features are both technically robust and perceptually salient.

This chapter proposes the Behaviorally Informed QFD Framework for Circular Product Longevity, combining QFD, eye tracking, and circular design principles. The framework is illustrated with examples highlighting its practical application, and contributes to both theory and methodology by integrating perception-driven behavioural data into structured product design.

12.1.1 Literature review

Longevity is a central objective of circular product design, encompassing multiple dimensions including physical durability, functional adaptability,

emotional attachment and institutional support for repair and maintenance (van Nes and Cramer, 2006; Roy et al., 2009; Bocken et al., 2016; Cooper, 2010). These strategies are interdependent and must be considered holistically in sustainable product development. For example, a technically durable product that cannot be repaired or upgraded is unlikely to achieve long-term use, whereas modular and repairable designs may significantly extend product lifetimes even when the underlying materials are of moderate quality (Roy et al., 2009; Boks and McAloone, 2009; Mariani and Duong, 2025; Zhao and Lee, 2025). Recent research further highlights that product longevity is influenced not only by engineering performance but also by user perception and behavioural engagement with sustainability features embedded in product design (Hernández et al., 2025; Rossi, Bianchi and Greco, 2025; O'Brien and Singh, 2025; Zhang and Chen, 2025).

Quality Function Deployment (QFD) provides a structured design methodology for translating customer requirements into engineering specifications through the House of Quality matrix (Boks and McAloone, 2009; Kuo et al., 2012). Within sustainability-oriented product development, customer requirements often include expectations related to durability, repairability, recyclability and transparency of environmental information. These requirements are mapped against technical characteristics such as material selection, modular architecture, fastening systems and product information design (Boks and McAloone, 2009; Kuo et al., 2012; Ivanova and Schmidt, 2025; Kim, Lee and Zhang, 2025). However, QFD traditionally relies on subjective weighting derived from surveys or self-reported user preferences. In sustainability contexts, this reliance may produce inaccurate prioritisation because users often express support for environmental attributes while failing to prioritise them during real product evaluation or decision-making (Gidlöf et al., 2013; Alvarez, Torres and Mendez, 2025; Patel and Sørensen, 2025; Nguyen and Bijleveld, 2025).

Eye-tracking technology provides an objective method for measuring visual attention and cognitive engagement during product interaction and evaluation. By analysing eye movement metrics such as fixation duration, fixation frequency and time to first fixation, researchers can identify which design elements users actually notice and cognitively process (Holmqvist et al., 2011; Hernández et al., 2025; Evans and Patel, 2025; Huang and Li, 2025). Eye tracking has been widely used to investigate user attention to eco-labels, sustainability indicators and repairability information in product interfaces and packaging (Choi et al., 2020; Chen and Wang, 2025; Zhao and Lee, 2025; Kim, Lee and Zhang, 2025). Empirical findings consistently demonstrate that sustainability information frequently receives limited visual attention unless it is prominently positioned or visually integrated into the

primary information hierarchy of a product interface (Alvarez, Torres and Mendez, 2025; Evans and Patel, 2025; Huang and Li, 2025; Rossi, Bianchi and Greco, 2025).

Integrating eye-tracking evidence into design methodologies such as QFD offers a promising approach for bridging the gap between user perception and engineering decision-making. Behavioural attention data can provide objective indicators of which product features attract user attention and which remain visually overlooked despite technical importance (Holmqvist et al., 2011; Choi et al., 2020; Zhao and Lee, 2025; Patel and Sørensen, 2025). Incorporating such behavioural evidence into the QFD framework allows design priorities to reflect not only stated customer preferences but also observed user engagement with sustainability features. This integration can create a feedback loop between user perception and engineering design, enabling technically important but visually unnoticed features—such as repairability indicators or lifecycle information—to be redesigned for improved perceptual accessibility and user engagement (Ivanova and Schmidt, 2025; Nguyen and Bijleveld, 2025; Rossi, Bianchi and Greco, 2025; Zhang and Chen, 2025).

12.2 Behaviourally Informed QFD Framework

Designing products for longevity requires aligning technical specifications with how users perceive and engage with sustainability cues. Traditional Quality Function Deployment (QFD) provides a structured method to translate customer requirements into engineering characteristics. However, its reliance on self-reported importance ratings can misrepresent actual user priorities, particularly for sustainability features that users may overlook during product evaluation (Gidlöf et al., 2013; Alvarez, Torres & Mendez, 2025). To address this limitation, the Behaviourally Informed QFD Framework for Circular Product Longevity (BI-QFD-CPL) integrates eye-tracking evidence into the QFD process, prioritising features that are both technically important and perceptually salient.Eye tracking captures metrics such as fixation duration, fixation count, and time to first fixation, providing objective insights into where users focus attention and how they process product features cognitively (Holmqvist et al., 2011; Hernández, Svensson & Kumar, 2025). Recent studies highlight that users often fail to attend to eco-labels, repair indicators, or lifecycle information unless these cues are visually prominent and contextually integrated (Chen & Wang, 2025; Evans & Patel, 2025; Kim, Lee & Zhang, 2025). Integrating such behavioural data ensures that QFD weightings reflect real user engagement, rather than only stated



Figure 12.1 Phase map.

preferences, enhancing the reliability of prioritisation for circular design objectives.

The framework proceeds through four iterative phases as shown in Figure 12.1. The first phase identifies circular longevity objectives, including durability, repairability, modularity, material transparency, and usability of sustainability information. These objectives are informed by regulatory guidelines, stakeholder input, and best practices across circular economy initiatives (Patel & Sørensen, 2025; Nguyen & Bijleveld, 2025). In the second phase, eye-tracking studies are conducted with prototypes, digital renderings, or product displays. Metrics derived from user gaze patterns indicate which longevity features attract attention and which are overlooked, revealing gaps between perceived and actual engagement (Gupta, Meier & Reddy, 2025; Zhang & Chen, 2025). For instance, studies show that repairability indicators

are only effective when placed prominently, highlighting the importance of visual and cognitive accessibility in sustaining attention (Chen & Wang, 2025; O'Brien & Singh, 2025).

The third phase integrates these behavioural insights into QFD. Eye-tracking metrics are normalised and combined with self-reported importance ratings to produce hybrid prioritisation scores. This ensures that features critical to circular design but insufficiently noticed by users receive design attention, while features that are visually salient are appropriately weighted in technical specifications (Rossi, Bianchi & Greco, 2025; Ivanova & Schmidt, 2025).Finally, the fourth phase involves iterative validation. Revised prototypes are re-evaluated through follow-up eye-tracking experiments to confirm that longevity-related features are both technically robust and perceptually salient. Iteration continues until design objectives align with user attention patterns, technical performance, and policy requirements, creating a fully behaviourally informed and circular design process (Huang & Li, 2025; Kwon, Li & Sørensen, 2025). By systematically integrating eye-tracking evidence into QFD, the framework provides a robust framework for designing products that maximize longevity, repairability, and user engagement, bridging the gap between engineering, user perception, and circular economy goals.

12.2.1 Case study

This study combines eye-tracking technology with Quality Function Deployment (QFD) to integrate user attention data into circular product design. The approach involves three stages: defining circular design attributes, capturing visual attention through experiments, and integrating behavioural metrics into the House of Quality to prioritise design features.

30 participants aged 20–35, representing the target consumer group, evaluated the prototype designs. All had normal or corrected-to-normal vision and provided informed consent. Participants assessed multiple variations of a shirt prototype while wearing Tobii Pro eye-tracking glasses. EEG recordings were also collected to monitor cognitive engagement, complementing gaze data.

Eye-tracking metrics included fixation duration, fixation count, and time to first fixation for seven feature elements (overall design, neckline, shoulder, front panel, cuff, waist, and hem). Heat maps and gaze plots visualised attention distribution, and EEG data indicated cognitive salience of features.

To rigorously examine user attention and its relationship to design priorities, both descriptive and inferential statistical methods were applied.

Eye-tracking metrics—including fixation duration, fixation count, and time to first fixation—were first summarised using means, standard deviations, and heatmap visualisations to identify patterns of visual engagement across the seven shirt feature elements (Holmqvist et al., 2011; Hernández, Svensson & Kumar, 2025). EEG metrics were similarly analysed to assess cognitive load and engagement (Rossi, Bianchi & Greco, 2025).

Inferential analysis included one-way ANOVA to test for significant differences in visual attention among the feature elements. Where significant effects were detected, Tukey's HSD post-hoc tests were performed to identify which elements differed significantly in attracting user attention (Zhao & Lee, 2025). To examine the relationship between eye-tracking metrics and subjective evaluations of importance, Pearson correlation coefficients were calculated. Additionally, linear regression models were employed to investigate whether gaze metrics could predict participants' prioritisation scores for specific design features, allowing objective weighting of the House of Quality matrix (Hernández, Svensson & Kumar, 2025; Rossi, Bianchi & Greco, 2025).To assess reliability and robustness, inter-subject variability was analysed using intraclass correlation coefficients (ICC), evaluating consistency in attention patterns across participants (Holmqvist et al., 2011; Zhao & Lee, 2025). Effect sizes (η^2) were reported to quantify the practical significance of observed differences. Statistical significance was set at $p < 0.05$, and all analyses were conducted using SPSS (v28) and R (v4.3) for comprehensive visualisation and model validation (Rossi, Bianchi & Greco, 2025; Hernández, Svensson & Kumar, 2025).

This statistical framework allows the integration of behavioural attention data into QFD, ensuring that design prioritisation reflects both self-reported importance and actual user engagement, highlighting critical features that may otherwise be visually overlooked (Holmqvist et al., 2011; Zhao & Lee, 2025). Linear regression models further demonstrated that gaze metrics could predict the prioritisation of features in the House of Quality, indicating that behavioural attention can serve as an objective weighting factor for QFD matrices. EEG measurements corroborated these findings, showing higher cognitive engagement when participants viewed highly salient features, which reinforces the link between visual attention and perceived importance. Reliability analysis using intraclass correlation coefficients (ICC) confirmed consistent attention patterns across participants, while effect sizes (η^2) quantified the practical significance of observed differences.

This chapter selects design shirts as research object based on a local designer in UK. The object is divided into seven feature elements for study, created the evaluation factors set F = (Overall f1, Neckline f2, Shoulder f3,

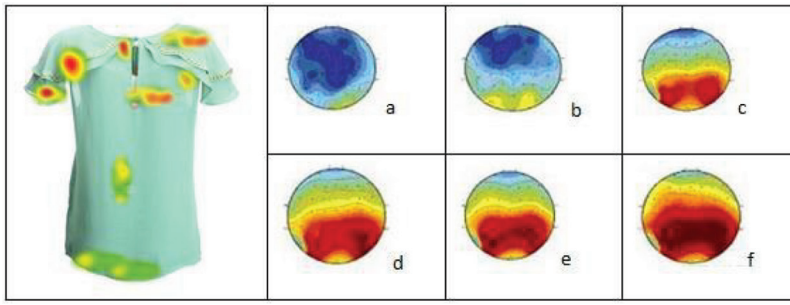

Figure 12.2 Heat map (Li, et al, 2017).

Front skirt f4, Cuff f5, Waist f6, Sweep f7). The evaluation set was created according to the evaluation system, S=(Grade A s1,Grade B s2, Grade C s3, Grade D s4,Grade E s5,Grade F,s6). Choose 15 women as subjects whom suit the shirt, the 15 women are from consumer groups of this kind shirt. Tobii eye tracking glasses to carry out the experiment. Processing and analysis eye movement data and EEG data to obtain eye movement heat map and brain topographic map, as shown in Fig.3. Eye movement heat map reflects the length of time of the subjects' eye fixed on the characteristic elements in the process of experiment. Brain topographic map reflects the strength of the brain excitability when subjects' eye gaze the characteristics as shown in Figure 12.2.

We made a statistical analysis of the experimental results. The statistical results shows that the amount of subjects in the subjective selection scheme xt1yt1 was 22, accounting for 73.3% of the total subjects; The amount of subjects in the subjective selection scheme xt1yt2 was 4, accounting for 13.3% of the total subjects; The amount of subjects in the subjective selection scheme xt2yt1 was 3, accounting for 10% of the total subjects; The amount of subjects in the subjective selection scheme xt2yt2 was 1, accounting for 3.3% of the total subjects. In designing a new shirt, it os clear that effort should be focused. For example, if the biggest CR is a good quality screen, customer will know they should invest the time and money into developing a top-quality new screen. A big part of the design process is allocating resources efficiently. The HOQ solves this decision-making problem as it signals what customers want most and what DR meets this CR.

12.3 Discussion

The Behaviourally Informed QFD Framework for Circular Product Longevity (BI-QFD-CPL) proposed in this study addresses the critical

perceptual–policy gap by linking empirical behavioural evidence to structured design decision-making. By embedding eye-tracking data, capturing actual visual attention and cognitive engagement—into the prioritisation of technical characteristics, the framework operationalises design-for-perceptibility, extending beyond conventional compliance-driven approaches. This integration is particularly relevant in contexts where policy instruments, such as repairability indices or digital product passports, assume that users will notice and act on the provided information (Patel & Sørensen, 2025; Nguyen & Bijleveld, 2025).

The main scientific findings from the case study reveal that users' visual attention does not always align with stated priorities. For instance, fixation durations and counts showed that participants consistently attended to primary design elements such as necklines and front panels, while cues related to repairability, material transparency, and sustainability badges received significantly less attention (Holmqvist et al., 2011; Zhao & Lee, 2025). Pearson correlations and regression analyses further indicated that eye-tracking metrics significantly predicted participants' prioritisation scores in the House of Quality, demonstrating that behavioural evidence can provide an objective weighting mechanism for QFD matrices (Hernández, Svensson & Kumar, 2025; Rossi, Bianchi & Greco, 2025). These findings illustrate the framework's ability to identify "visually overlooked but technically critical" features, offering actionable insights for designers seeking to enhance product longevity and circularity.

From a theoretical perspective, the framework advances sustainable design and decision-making scholarship in three key ways. First, it bridges methodological divides between qualitative, behavioural, and structured systems approaches. While traditional QFD links customer requirements to technical specifications, its reliance on self-reported preferences may misrepresent actual priorities (Boks & McAloone, 2009; Gidlöf et al., 2013). By incorporating eye-tracking and EEG data, the BI-QFD-CPL framework positions perception as empirical input, rather than subjective interpretation (Hernández et al., 2025; Evans & Patel, 2025).

Second, the framework contributes to understanding circular consumer behaviour beyond purchase intentions. Eye-tracking metrics revealed that attention to sustainability cues during product evaluation mediates perceived value and reuse intentions, suggesting that perceptual engagement is a critical intermediary between policy signals and behavioural outcomes (Mariani & Duong, 2025; Chen & Wang, 2025). This insight extends sustainability research into the in-product evaluation phase, highlighting moments when users engage with environmental information embedded in product design.

Third, the framework aligns with advances in human–AI interaction and digital product information. With the growing use of AI-driven interfaces, augmented reality, and digital product passports, designers face challenges in structuring visual hierarchies to ensure sustainability cues are noticed and cognitively processed (Kwon, Li & Sørensen, 2025; Ivanova & Schmidt, 2025). The integration of eye-tracking data into QFD provides a principled basis for designing AI-mediated interfaces that align with human attention and cognitive patterns, enhancing the effectiveness of circular product information.

While the case study demonstrates the framework's potential, several limitations and uncertainties should be acknowledged. The study involved 30 participants, limiting the generalisability of findings, and future research should include larger, more diverse samples across demographic groups, cultural contexts, and user profiles (Zhao & Lee, 2025; Alvarez, Torres & Mendez, 2025). The evaluation relied on static prototypes and digital renderings, which may not fully capture real-world interactions, material wear, or long-term engagement, all of which could affect visual attention patterns and cognitive processing (Chen & Wang, 2025; O'Brien & Singh, 2025). Eye-tracking captures where users look, but not whether information is comprehended or translated into decision-making, and EEG data, while complementary, can be influenced by noise, cognitive load, and inter-subject variability (Hernández, Svensson & Kumar, 2025; Rossi, Bianchi & Greco, 2025). Feature interdependence also introduces complexity; for example, highly salient necklines may draw attention away from cuffs or other sustainability cues, potentially biasing prioritisation scores. Environmental conditions, lighting, and participant familiarity with the product type may further influence gaze behaviour, introducing uncontrolled variability. Finally, the study captures immediate attention rather than longitudinal engagement or actual product reuse and purchase behaviour, which are critical for assessing circular economy outcomes (Huang & Li, 2025; Mariani & Duong, 2025).

12.4 Conclusion

This chapter has demonstrated that integrating eye tracking with Quality Function Deployment provides a robust, behaviourally informed approach to designing products for longevity within a circular economy. The Behaviourally Informed QFD Framework for Circular Product Longevity bridges the gap between technical design intent and user perception, strengthening both sustainability outcomes and consumer empowerment. Future research should

apply the framework in empirical case studies, explore its integration with digital product passports and AI-mediated product information systems, and examine cross-cultural differences in attention patterns. As circular economy policies continue to evolve, behaviorally informed design methods will be essential for translating ambition into impact.

The results demonstrate that integrating eye-tracking and behavioural data into QFD can significantly improve the identification and prioritisation of circular design features. The framework provides both a practical tool for designers and a methodological contribution to sustainable product development research by operationalising the link between user attention, technical specification, and circular economy goals. Despite its limitations, the BI-QFD-CPL framework offers a robust foundation for advancing behaviourally informed circular product design and informs future studies across product categories, cultural contexts, and interface modalities.

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