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REVIEW ARTICLE

The role of traditional handcrafting in promoting sustainability: A literature review

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Abstract

The fashion industry is one of the largest and fastest-growing sectors of the global economy, with significant social and environmental impacts. However, the prevailing fast-fashion model leads to overconsumption and serious consequences for both the environment and industry workers. In response to this trend, the slow fashion movement has emerged, promoting a more conscious and sustainable approach to clothing production and consumption. This movement involves a variety of practices, including traditional techniques – such as weaving, embroidery, knitting, felting, and dyeing with natural dyes. In this study, a systematic literature review was conducted to explore how traditional techniques are incorporated into contemporary fashion design and production, and whether these techniques truly support local communities. The findings reveal that traditional techniques are linked to sustainability in the fashion industry; however, they require a significant investment of time compared to fast-fashion cycles, resulting in higher production costs. Thus, despite their promising potential, these techniques contradict the prevailing economic model of development followed in the fashion industry. Ultimately, this study highlights the important role of traditional techniques in promoting sustainability and advocates for integrating these practices in the fashion industry through an alternative economic model.

Keywords: We-economy; Anthropogeography; Clothing handcrafting; Slow fashion; Local communities

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1. Introduction

The fashion industry is one of the largest and fastest-growing sectors of the global economy, with significant social and environmental consequences. The term "fast fashion," which has gained widespread attention in recent years, refers to the rapid production of large volumes of affordable clothing within short timeframes. This approach leads to overconsumption and serious consequences for both the environment and garment industry workers.[1-3] Fast fashion is expanding at an exceptionally rapid pace globally, while simultaneously being criticized by the scientific community for its role in

increasing carbon emissions, depleting natural resources, generating large volumes of waste, and exploiting workers, especially in developing countries.[4-8]

In response to this trend, and as an effort to counteract it, the slow fashion movement has gained prominence in recent years. This concept has gained increasing attention in industry trends and marketing strategies, drawing interest from a wide range of scholars, designers, companies, and consumers. As part of the broader shift toward sustainability, both researchers and professionals across all sectors are paying greater attention to this issue, as they face the ongoing challenge of balancing environmental priorities with business needs.[9] It is difficult to fully describe the concept of sustainability, as it is a complex, multi-layered phenomenon with numerous aspects and interpretations, and lacks a single, universally accepted definition. According to Hethorn and Ulasewicz,[10] sustainable fashion means "no harm done to people or the planet, and that a thing or process, once put into action, can enhance the well-being of the people who interact with it and the environment it is developed and used within."

Sustainable fashion has been examined through several theoretical approaches, which can be categorized into the following three:

- Sustainable growth: The concept of sustainable development emphasizes the preservation of natural resources and the reduction of environmental footprints through responsible production and consumption methods. According to the United Nations Environment Programme's report, *Designing for Sustainability: A Step-by-Step Approach*, sustainability involves the creation of products and services that address societal needs while minimizing environmental impacts throughout their life cycle.[11] In slow fashion, this approach supports the use of natural and recyclable materials, as well as the preservation of local traditions, with the goal of ensuring long-term environmental and economic well-being.[12,13]
- Degrowth: The theory of degrowth rejects the idea of continuous economic growth and advocates for a radical and fair reduction in global production and consumption.[14] It seeks to redirect the current unsustainable trajectory toward a model centered on human well-being and broader visions of alternative futures.[15,16] In the context of slow fashion, this approach promotes small-scale production and the use of local raw materials while limiting overconsumption and the commodification of fashion.[17]
- Post-growth: The concept of post-growth refers to alternative frameworks for understanding development beyond traditional economic indicators, emphasizing well-being and sustainable resource management.[18] It advocates developmental alternatives, often in the form of communities that integrate elements of both "traditional" and "modern" cultures, in opposition to the global capitalist economy and dominant scientific rationalities.[19] In the context of slow fashion, this approach translates into strategies that foster social consciousness and environmental responsibility.

Both degrowth and post-growth share the assumption that continued economic growth is not necessary to achieve environmental integrity and human well-being.[20] They also share common themes – including a critique of the modern (Western) cultural model, an emphasis on autonomy, and a focus on the solidarity-based economy model.[21] Through these concepts, they diverge from the concept of sustainable development and support slow fashion from fundamentally different ideological and strategic perspectives.

In this context, the slow fashion movement has emerged as a growing response, promoting a more conscious and sustainable approach to clothing production and consumption. This movement falls under an umbrella category that encompasses a wide range of practices, along with other dominant movements in the field – such as the cradle-to-cradle principle, functional design based on human needs and ecological principles, alternative sustainable materials (e.g., eco-friendly fibers, recyclable materials), fiber processing methods (e.g., environmentally friendly dyeing techniques), sustainable production methods (zero-waste patternmaking and textile processes, and handcrafting), social responsibility (participatory design, ethical labor practices, activist movements), resource and energy conservation, and production transparency (garment traceability).[22,23] Slow fashion focuses on the quality and longevity of products, thereby enhancing their emotional durability, while also incorporating traditional techniques and handicraft methods that are closely tied to cultural heritage and local economies.[24] Traditional techniques such as weaving, embroidery, and dyeing with natural pigments have deep roots in human history and are increasingly coming to the forefront in response to growing demand and the urgent need for sustainable and ethical production.[25,26]

These techniques promote an alternative approach to the fashion value chain, linking production with the preservation of cultural identities and the support of local economic networks.[27] Many of these techniques originate in countries of the Global South (i.e., the world's developing and least developed countries), including India and various African nations, where local garment production relies on handcrafted work.[28,29] Through the revival of these techniques, slow fashion contributes to

the creation of a more collective economic model, known as the "we-economy," which is based on solidarity and cooperation among communities.[30] The we-economy arises from collaborative and decentralized production, community-based creation, and learning through practical engagement and collaboration, and it fosters social capital through local and global networking.[31]

The we-economy refers to non-sovereign economic relations among participants – including practices such as communing and small-scale, bottom-up production collectivities – that occur at the local level and are grounded in fair and ethical financial relationships among the inhabitants of a shared ecosystem. Several researchers have proposed business model templates that align with this approach, such as those illustrated in Figure 1.[32-34] This economic model promotes the concepts of social justice and economic empowerment for traditional local professions (e.g., artisans and weavers), who participate in all stages of the production process – from sourcing materials to manufacturing finished products.[35]

Although this economic model has gained increasing attention from researchers and policymakers alike, several gaps still remain in the existing literature:

(i) Lack of data on the long-term impact of traditional techniques on sustainability: Although numerous theoretical studies on slow fashion exist, only a few have examined the long-term socioeconomic and environmental impacts of traditional techniques
(ii) Lack of analysis on the integration of the we-economy into the fashion sector: Most studies focus on large brands pursuing ethical transitions, while paying limited attention to local production networks and their potential to contribute to sustainable value chains
(iii) The majority of existing studies on traditional techniques and sustainable fashion primarily focus on individual initiatives related to the circular economy, re-economy, or isolated sustainability strategies. These approaches, although valuable, do not situate traditional craftsmanship within a broader, self-managed framework encompassing economic, social, and ecological dimensions.

Therefore, this study aims to address this gap by incorporating all qualitative characteristics of craftsmanship, not only as a production technique but also as a social process with ethical and ecological implications within local ecosystems. Craftsmanship is not merely a production method – it is a process that shapes community relationships. In addition, local production should not be examined in isolation, but as part of an ecosystem that leverages local resources with minimal environmental impact.

The true challenge lies not merely in preserving craftsmanship but in integrating it into a self-managed, collaborative economic framework. The we-economy provides a foundation for local development where:

(i) Traditional techniques enhance sustainability from both environmental and social perspectives
(ii) Artisans maintain control over the means of production, free from dependence on large chains or commercial pressures

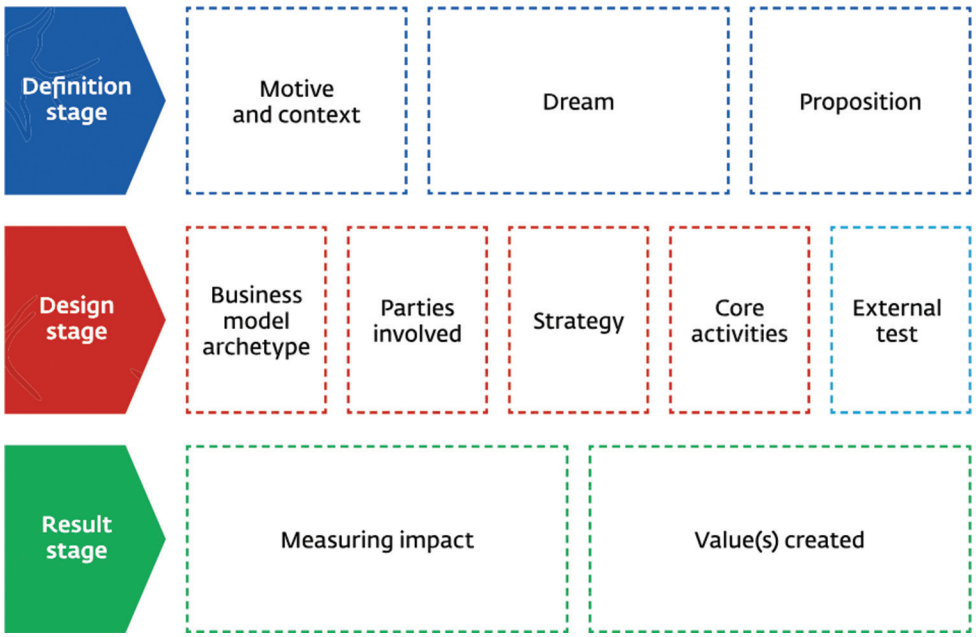

Figure 1. The proposed business model template[34]

(iii) Economic activities are retained within local communities, thereby reducing inequalities.

This study aims to map the utilization of traditional techniques and handicraft practices within the modern fashion industry, examining their connections to value chains, community economic empowerment, and their potential to support alternative economic models. Instead of simply examining how traditional techniques can survive, the study advocates for their integration into a comprehensive, community-organized production and economic management framework.

2. Research objectives

Based on the analysis of the existing literature, the specific objectives of this study are:

- To examine how traditional techniques – such as weaving, embroidery, and dyeing with natural pigments – are integrated into contemporary fashion design and production
- To explore the key regions and methods worldwide where traditional techniques are utilized, including the stages of the value chain and the types of fashion enterprises involved
- To analyze whether, and in what ways, traditional techniques support local communities and contribute to economic development, particularly in developing regions
- To investigate the challenges documented in existing literature, with a focus on those related to the incorporation of traditional techniques into modern fashion systems (e.g., feasibility of industrialization and mass production, cost factors, and the preservation of expertise and authenticity), to synthesize and assess proposed solutions and strategies
- To evaluate the potential of traditional handicrafts as an alternative economic model within the fashion industry, and to inform their role in promoting a more sustainable and ethical fashion sector.

3. Research methodology

3.1. Purpose

The main purpose of this study is to examine and analyze the literature concerning the integration of traditional techniques and handicrafts into contemporary fashion. It aims to evaluate this integration and its acceptance in the international literature, as well as to determine the extent to which this adoption has contributed – or is expected to contribute – to sustainability. This study employs a systematic literature review, a form of secondary research that involves the collection, evaluation, and interpretation of a large number of related studies on a specific topic.[36] The process includes planning, reviewing, analyzing, and presenting findings from the reviewed literature. The goal is to help researchers gain a better understanding of existing studies.[37]

A systematic review differs from traditional literature reviews in that it follows predefined criteria and methodologies for source selection and data analysis. This approach reduces the likelihood of bias and enhances the validity of the conclusions. According to Cooke *et al.*,[38] systematic reviews assist in identifying gaps in existing studies and contribute to developing a clear framework for future research.

The systematic review process includes the stages of defining the research question, formulating a review protocol, selecting sources, assessing the quality of studies, extracting and analyzing data, and finally presenting the findings.[39] This method was employed to produce a well-structured and comprehensive review of the international literature, providing insights into the domain and the trends in existing published research.

3.2. Selection of sources

For a comprehensive review, search, and analysis of sources, this study applied clearly defined inclusion and exclusion criteria to select articles from the vast amount of available literature. To ensure methodological validity and alignment with contemporary developments, only articles published between January 2000 and September 2024 were included. This time frame also served to reduce the scope of the extensive existing literature. Keywords relevant to the research topic were used, including:

(i) "We-economy and handcrafting in fashion." This keyword was utilized to identify studies analyzing how traditional handcrafting supports collaborative economic models. Specifically, the search focused on studies discussing:
   (a) Co-operative fashion and craft workshops
   (b) The role of local communities in sustainable production
   (c) Initiatives promoting ethical and socially equitable practices.

(ii) "Slow fashion and handcrafting techniques." This keyword was used to identify studies examining:
   (a) The integration of traditional techniques into contemporary slow fashion
   (b) Challenges in preserving these techniques amid increasing industrial automation
   (c) Collaborations between designers and traditional artisans to create sustainable and ethical collections.

(iii) "Sustainable textile production." This keyword was applied to identify articles examining:

(a) The impact of traditional techniques on sustainability
(b) Modern adaptations of these techniques (e.g., handmade dyeing with natural materials at an industrial scale)
(c) The role of small-scale producers in sustainable fashion compared to large fast-fashion chains.

(iv) "Collective action and fashion sustainability." This keyword was used to identify studies exploring:
(a) Movements and initiatives promoting sustainable fashion (e.g., Fashion Revolution and Fair Trade Fashion)
(b) Programs involving local communities in ethical fashion production
(c) Policy frameworks and regulations influence the development of the sustainable fashion industry.

(v) "Traditional textile techniques and local economies." This keyword was utilized to search for studies examining:
(a) The impact of traditional weaving on local economies
(b) The role of women's cooperatives and small producers in preserving these techniques
(c) The connection between cultural heritage and local economic development.

In addition, Boolean operators (e.g., AND, OR), date filters (2000 – 2024), and language restrictions (English only) were applied when searching for the relevant articles. Published articles were sourced from reliable and scientifically recognized databases, including Web of Science, Scopus, ScienceDirect, SpringerLink, and the Multidisciplinary Digital Publishing Institute.

To ensure research validity and relevance, specific inclusion and exclusion criteria were established.

- Inclusion criteria:
  (i) Scientific articles published between 2000 and 2024
  (ii) Studies focusing on sustainable fashion and traditional textile techniques
  (iii) Research presenting empirical evidence (e.g., case studies)
  (iv) Articles examining the relationship between local economies and the fashion industry.
- Exclusion criteria:
  (i) Studies not addressing the social and economic impacts of traditional techniques
  (ii) Non-scientific or secondary sources (e.g., blogs and non-scientific articles)
  (iii) Research is lacking analysis related to sustainability.

In addition, the snowballing technique was applied retrospectively, following the previously established methodology by Wohlin,[40] as well as by Jalali and Wohlin,[41] and the procedure demonstrated in Figure 2.[40-42]

(i) Backward snowballing: The bibliographic references of selected articles were analyzed to identify relevant earlier studies
(ii) Forward snowballing: Tools such as Google Scholar and Scopus were used to trace subsequent publications that cited the original studies, allowing the investigation of ongoing developments in related research areas.

This approach contributes to the identification of critical theoretical frameworks and research gaps, thereby enhancing the comprehensiveness of the study.

3.3. Data collection and analysis

Following an initial screening of article titles and abstracts, the selected articles were evaluated in detail based on the criteria established by Denyer and Tranfield[43] to determine their relevance to the study's topic. Data were collected from the selected articles and books to capture key concepts, theoretical frameworks, and findings related to the integration of traditional techniques into fashion and sustainability. The assessment of internal validity was guided by established research in the field.[44]

The inclusion and exclusion of articles were carefully discussed to resolve any discrepancies, enhance relevance and quality, reduce bias, and ensure overall reliability.

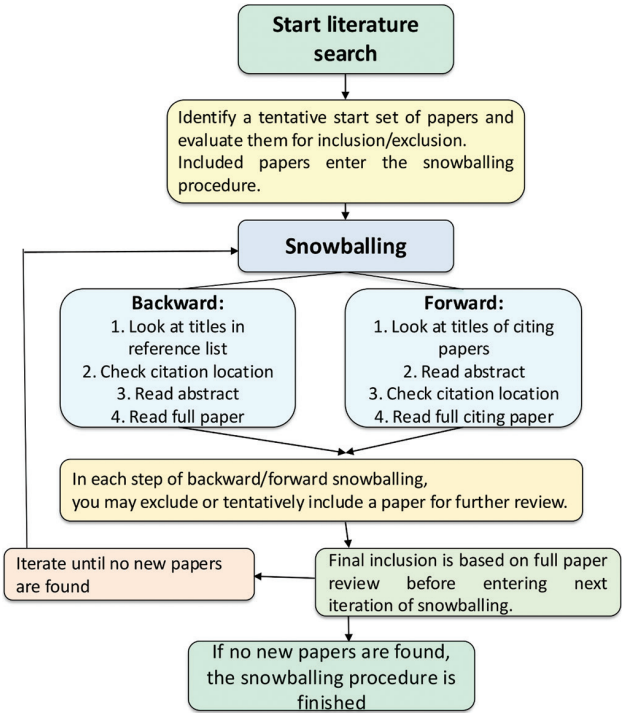

Figure 2. Snowballing procedure based on the methodology established by Wohlin[40]

The selected studies focus on cases in which traditional techniques and handicrafts constitute an integral part of the garment production process. They distinguish between techniques employed in the early stages of production and those applied during the transformation or decoration of garments – particularly in the context of reuse, recycling, and re-economy initiatives. These practices highlight the role of traditional crafts not only in the creation of new garments but also in extending the lifecycle of existing clothing through creative and sustainable methods.

The quality of the selected studies was assessed using the methodology proposed by Denyer and Tranfield,[43] which is based on clear and reproducible evaluation criteria. The studies were then categorized according to five key quality criteria:

(i) Clarity of the research question: Assessing whether the study clearly states a hypothesis or research framework
(ii) Methodological transparency: Examining whether the study clearly describes and justifies the methods employed
(iii) Analytical depth: Evaluating whether the study provides sufficient quantitative or qualitative analysis to support its findings
(iv) Empirical applicability: Determining whether the findings are supported by primary data or case study evidence
(v) Scholarly contribution: Identifying whether the study addresses existing gaps in the literature or suggests new research directions.

Each study was rated by two independent evaluators using a 1 – 5 scale, and those with an overall score above 3.5 were included in the systematic review. This strategy was adopted to ensure the reliability of the results and the validity of the conclusions.

Following the initial screening and quality assessment, relevant information from each included source was extracted using a structured form designed to capture:

(i) Type of technique or practice (e.g., weaving and dyeing)
(ii) Dimension of sustainability (e.g., environmental, social, and economic)
(iii) Demographic focus (e.g., women, elders, and minorities)
(iv) Connection to broader conceptual frameworks (e.g., we-economy, post-growth, and circularity).

The extracted data were subsequently analyzed using qualitative thematic synthesis, guided by an inductive coding process. An iterative, manual approach to open coding was then applied.

Emerging codes were grouped into higher-level themes aligned with the research questions, including:

(i) Environmental sustainability through natural techniques
(ii) Community-powered models and collective governance
(iii) Craft as economic infrastructure.

3.4. Literature review

A systematic method was applied to the literature review to achieve a comprehensive understanding of the study's topic. The review focuses on examining theoretical frameworks and current trends related to slow fashion and traditional handicrafts, while also gathering data from a diverse range of scholarly sources. In this section, the systematic literature review offers an in-depth understanding of the conceptual foundations of the slow fashion movement and its relationship with traditional techniques, including the ideological and economic aspects embedded within this context.

The following key trends and ideas were analyzed:

- Collectivity and locality: These are core principles of the slow fashion movement, emphasizing collaboration within communities and the promotion of local craftsmanship as essential for preserving cultural traditions. Local communities are reinforced through the promotion of products rooted in locally sourced materials and traditional production methods, thereby reducing dependency on large-scale industries.[45] Approximately 18.18% of the reviewed articles engage with the themes of "collectivity and locality," demonstrating the field's emphasis on reinforcing local economies and regional identities.
- Togetherness and the care economy: The concept of togetherness is linked to the creation of communities and collaborative networks, where producers and consumers engage collectively to promote sustainable practices.[46] The care economy emphasizes the importance of social and ethical responsibility, in which production and consumption occur with respect for both the environment and the local community.[13]. Approximately 18.18% of the reviewed articles are associated with the concept of "togetherness and the care economy," indicating a limited but increasing emphasis in the literature on the ethical dimensions of production.
- Community-powered solutions and the we-economy: Community-powered solutions and the concept of the we-economy promote the development of alternative economic models based on collaboration and solidarity, aiming to foster self-sustaining local economies. In the slow fashion movement, this is reflected in the

formation of small cooperative networks that support the production of high-quality products on a limited scale.[47] Table 1 outlines the traditional techniques used in slow fashion, their associated values, and key prerequisites. It highlights methods such as weaving, embroidery, and natural dyeing, and emphasizes principles such as quality, sustainability, cultural preservation, and local production. Approximately 22.73% of the selected studies pertain to themes related to "the we-economy and community-based solutions," reflecting a cautious yet meaningful shift in the literature toward alternative production models.

Approximately 21.21% of the reviewed studies engage with more than one thematic area, highlighting the interdisciplinary nature and conceptual interconnectedness evident in the relevant literature. In contrast, 19.7% of the selected articles do not align directly with any of the aforementioned categories, either due to a primary focus on technical or historical aspects, or a different theoretical perspective, such as a broader orientation toward sustainability. These distributions and thematic values are presented in Table 2 and illustrated in Figure 3.

3.5. Content analysis

In this study, content analysis focuses on identifying and categorizing thematic units related to traditional techniques and sustainable practices within the fashion industry. The systematic approach enabled the extraction of these thematic categories from the literature, with an emphasis on mapping sustainable practices across all stages of production – from raw materials to final products.

Table 1. Traditional techniques in slow fashion: Values and prerequisites

Traditional techniques in slow fashion	Values	Prerequisites
Weaving, embroidery, dyeing with natural colors, handmade garment construction, knitting, and felting.	Product quality, enhanced emotional durability, preservation of cultural heritage, the support of local economies, and the promotion of product longevity.	The use of natural, recyclable, or locally sourced materials; the practice of handicraft production; the incorporation of traditional techniques; engagement with local communities or production networks; and the implementation of upcycling methods.

Table 2. Bibliography trend categorization

Trend	Percentage
Collectivity and locality	18.18
Togetherness and the care economy	18.18
Community-powered solutions and we-economy	22.73
Multiple trends	21.21
No thematic match	19.7

The analysis highlights the connections between traditional handicraft techniques and sustainable development. These techniques are associated with practices such as the use of local and natural raw materials, waste reduction, and the reinforcement of local communities, while also challenging the traditional mass-production model in the garment industry.

The mapping of sustainable practices was organized according to the stages of the value chain, including raw materials, production, profit distribution, and consumption. The analysis also considered the need to align organizational and operational aspects to support the development of new business models that can effectively address sustainability challenges.[48]

To reduce the likelihood of bias in the analysis, the initial mapping results were revisited and adjusted, taking into account new parameters and data from diverse literature sources. This allowed for a more comprehensive and balanced approach, adapting the analytical methods to the specific needs of the research.

The quantitative classification of all case studies and academic references reveals distinct patterns regarding the types of traditional techniques most commonly highlighted in discussions of sustainable fashion. "Weaving" emerges as the most frequently cited technique (approximately 18.18%), reflecting its cultural depth, scalability, and ongoing relevance in both indigenous communities and contemporary sustainable design frameworks.

"Dyeing with natural colors" also holds a prominent place in the literature – appearing in approximately 13.72% of the reviewed articles – and is frequently associated with reduced environmental impact and the preservation of ancestral knowledge, particularly within South Asian and Andean contexts. "Handmade garment construction" and "embroidery" follow closely, underscoring their dual roles in cultural expression and value-added craftsmanship within slow fashion models.

While "knitting" and "felting" are less frequently discussed, they represent specialized practices often linked to elder artisans, local wool economies, and advanced material experimentation. In addition, approximately 19.15% of the selected studies engage with multiple techniques simultaneously, reflecting the hybrid and interdisciplinary nature of many sustainable fashion projects.

Finally, a notable portion of the literature (approximately 13.56%) does not explicitly focus on specific craft methods but instead examines broader supply chain models, design

philosophies, or systemic approaches to sustainability. These findings are summarized in Table 3 and illustrated in Figure 4.

3.6. Research limitations

This study is limited to the analysis of existing studies and does not include primary data collection or interviews. Therefore, the findings are based solely on published literature and may not fully capture the most recent developments or emerging practices in the field. Specifically:

(i) The scope of the study is limited to a qualitative, thematic synthesis of literature and case studies

Table 3. Craft technique representation

Craft technique	Percentage
Dyeing with natural colors	13.72
Embroidery	12.12
Weaving art	18.18
Multiple techniques	19.15
Handmade garment construction	12.67
Knitting	7.58
No specific craft	13.56
Felting	3.03

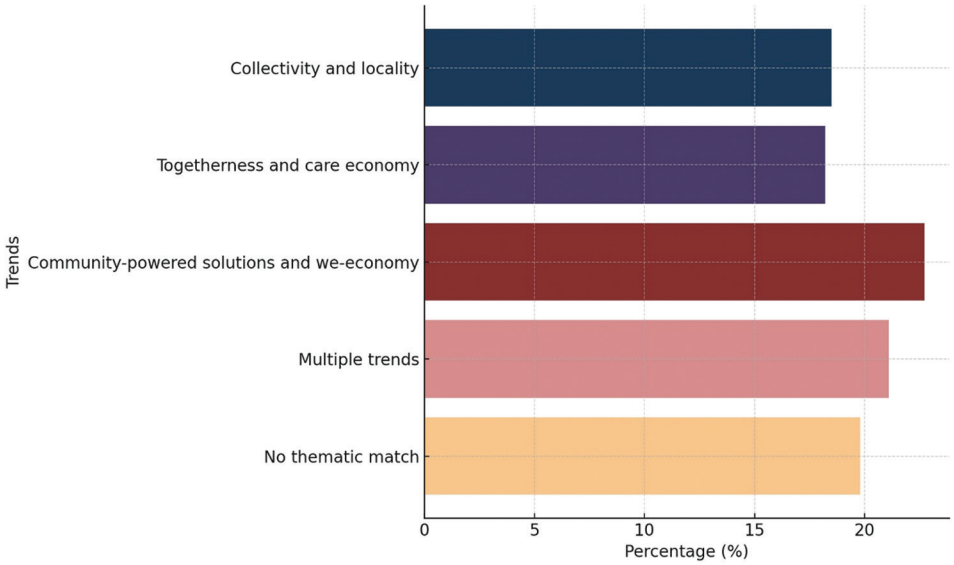

Figure 3. Graph of the bibliography trend categorization

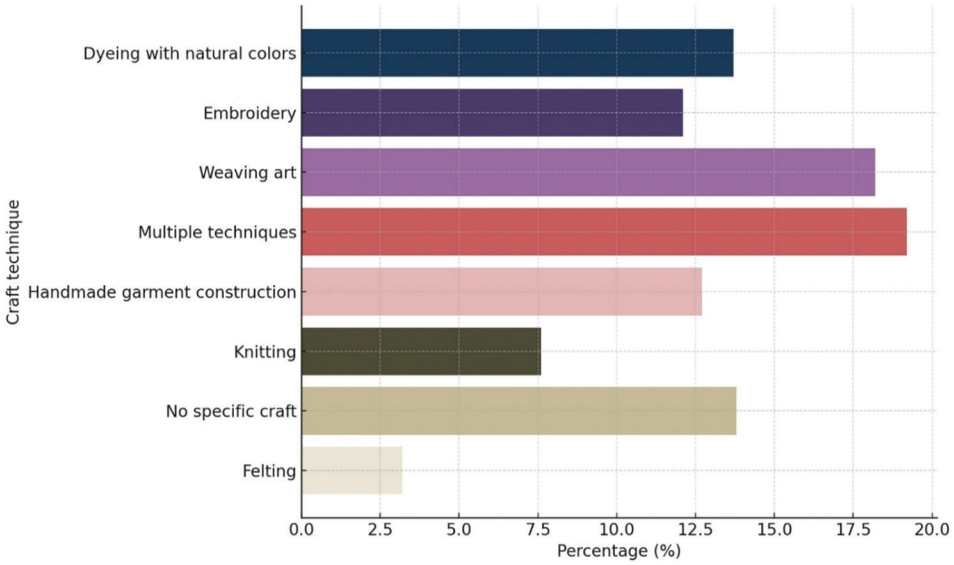

Figure 4. Craft technique representation graph

related to traditional textile techniques and their role in sustainable fashion systems and the we-economy

(ii) The analysis is restricted to English-language sources published between 2000 and 2024, potentially excluding relevant regional publications and non-academic perspectives

(iii) While a wide range of case examples is reviewed, the study does not include original fieldwork or empirical data and, as such, cannot offer generalized conclusions beyond the scope of the reviewed literature.

4. Content analysis and materials evaluation results

The content analysis conducted in this review focuses on the categorization and interpretation of the main themes that emerge from the examined sources. Traditional handicrafts – such as weaving, embroidery, and dyeing with natural pigments – are identified as key elements associated with sustainability in the fashion industry.

Quantitative data from the analysis confirm that traditional techniques significantly influence fashion sustainability, not only from an environmental perspective but also as instruments of social and economic empowerment. The presence of these themes in the literature demonstrates that sustainable fashion is intrinsically linked to local communities and their cultural traditions, serving as a mechanism for preserving these elements within the global market.

4.1. Sustainability and ethics in fashion

The connection between traditional handicrafts and sustainable, ethical fashion has been highlighted in numerous studies as an effective approach to achieving a more responsible and socially equitable production model. Traditional techniques – which often involve the use of local, natural materials and handmade production – offer alternative solutions to the dominant industrialized production system, promoting the concept of slow fashion.

According to Brown and Vacca,[49] traditional techniques contribute to reducing overconsumption and waste, as production is based on quality and the long-term use of products rather than rapid consumption and disposal (Figure 5).

Many traditional practices embody ethical values – such as the use of local raw materials and handmade production – which contribute to minimizing ecological impact. The research conducted by Karaosman *et al.*[50] notes that dyeing with natural colors and using renewable materials – such as cotton and linen – promote environmental sustainability. For example, the traditional art of fabric dyeing in India using natural dyes not only respects the environment but also supports local communities (Figure 6).[51,52]

Sustainability and ethics in fashion are critical issues in the modern industry, as consumers increasingly seek options that respect both the environment and local communities. The slow fashion movement promotes the

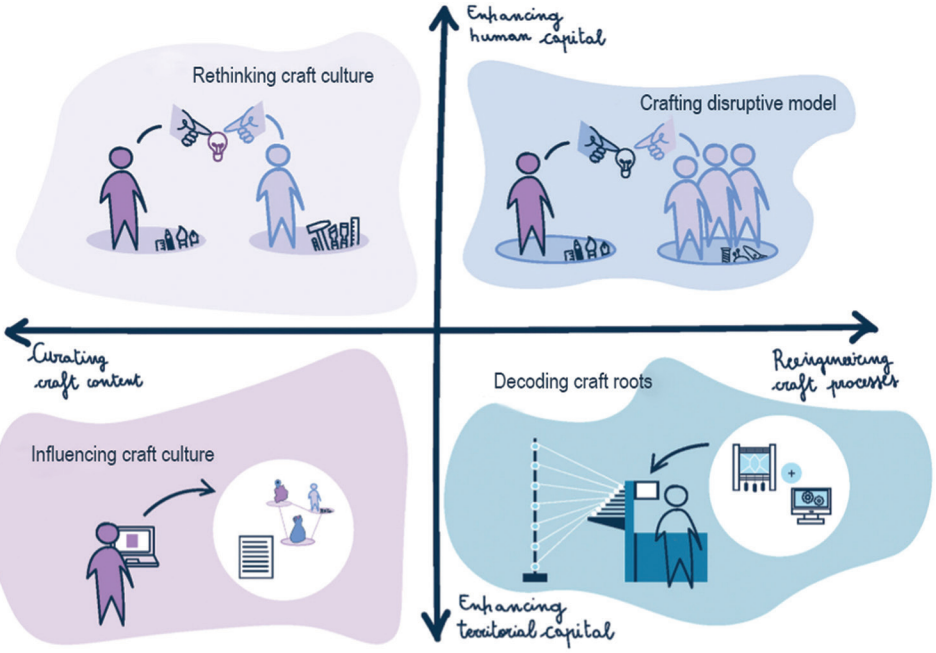

Figure 5. Cultural sustainability through craft: An interpretative model. Adapted from Brown and Vacca[49]

Mordant	K/S	L*	a*	b*	C*	H*	ΔE*
Unmordanted	0.6843	60.688	4.668	5.911	7.532	51.681	8.629
Alum	3.6043	62.878	9.504	15.036	17.788	57.68	5.909
Copper	3.0751	54.183	-1.4	-8.149	8.535	260.526	1.338
Iron	5.0298	51.815	-0.854	-8.953	8.994	264.517	1.317
Tin	3.7798	60.937	14.951	13.822	20.361	42.736	4.378

Figure 6. Absorption and scattering coefficients, along with colorimetric values of dyed cotton fabrics
Notes: CIELab color coordinates: L* indicates lightness value; a* represents lum- and tin-mordanted dyed fabrics support redness; b* signifies lum- and tin-mordanted dyed fabrics support slight yellowness; C* refers to Chroma (color intensity or saturation); H* represents Hue angle (the type of color – red, yellow, green, etc.); and ΔE indicates color difference (the perceived difference between two colors). Data were extracted from Kumbhar *et al.*[52]
Abbreviations: K: Absorption coefficient; S: Scattering coefficient.

idea that product quality and longevity are more important than overconsumption. The use of fabrics that foster collaboration and solidarity contributes to community building.[53]

Ethical consumption is also central to this discussion. Brown and Vacca[49] analyzed how traditional production techniques can contribute to sustainability by combining cultural heritage with contemporary fashion practices. The importance of consumer participation in supporting sustainable practices is also highlighted by Karaosman *et al.*,[50] who examined how localized production systems can enhance sustainability through conscious consumption.

Frater and Hawley[54] emphasize the importance of collaboration between designers and traditional artisans, demonstrating how such partnerships can create new products that respect cultural heritage while supporting environmental sustainability.

Moreover, international literature highlights the growing integration of traditional clothing techniques into contemporary fashion practices as a means of promoting ethical consumption. Gwilt and Rissanen[25] report cases in which international designers collaborate with local artisans, combining creative design with cultural heritage to produce unique products that appeal to sustainability-conscious consumers.

4.2. Traditional techniques and the fashion value chain

Traditional techniques and crafts in fashion are key components of cultural heritage and economic sustainability. These include:

- Weaving art: Techniques such as *ikat*, in which yarn is dyed before weaving, are well-established in many cultures, including Indonesian traditions[55]
- Embroidery: Traditional *kantha* embroidery from Bengal is renowned for its intricate craftsmanship[56]
- Natural dyeing: Techniques such as *shibori*, widely practiced in Japan, use natural dyes and reflect region-specific methods of textile coloring[57]
- Handmade garment construction: Techniques such as traditional hand sewing remain integral to garment-making in countries like India and Morocco[58,59]
- Knitting: Knitting continues to be a widely practiced craft associated with sustainable fashion, especially within the slow fashion movement. Small-scale producers employing this technique – both in developed and developing countries – often promote local production, material reuse, and the use of natural fibers such as organic cotton and recycled wool.[60-62] These practices not only support the economic sustainability of local communities but also integrate traditional values into the modern fashion industry
- Felting: Wool felting remains particularly important in regions such as Central Asia and the Alps and is recognized for its ecological benefits. This technique has re-emerged in sustainable fashion, emphasizing the use of natural raw materials while avoiding chemical processes in textile production.[63] In addition, designers now use felted fabrics to create products with high esthetic and cultural value, thereby enhancing sustainability and authenticity.[64,65]

The fashion value chain refers to the process that a product undergoes from production to consumer sale. It includes steps such as design, production, distribution, and retail.[66] A well-organized value chain can enhance economic sustainability by identifying ways in which traditional techniques can be integrated into contemporary practices (Figure 7).

According to Bassett,[67] the production of cotton fabric through traditional methods in West Africa not only promotes the local economy but also reinforces the cultural identity of the producers. These techniques create unique products that embody the collective voice of communities, strengthening the emotional connection between consumers and the products.

Similarly, Andorfer and Liebe[68] examined how ethical consumer practices are influenced by both product information and the ethical dimensions of production.

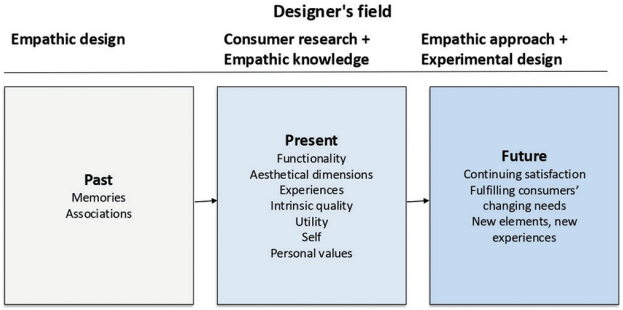

Figure 7. From disposable to sustainable: The complex relationship between design and consumption in the textile and clothing sector. Adapted from Andorfer and Liebe.[68]

Products derived from traditional techniques often have greater perceived value and are preferred by consumers seeking authenticity and quality.

Collaboration between contemporary designers and traditional artisans has led to the revitalization of old techniques. In the study by Hu *et al*.,[69] the importance of co-design is emphasized, in which traditional artisans collaborate with designers to create products that integrate innovation with tradition. This approach not only preserves traditional skills but also adapts them to meet modern market demands.

McQuillan[70] conducted research on zero-waste design, demonstrating how traditional techniques can contribute to reducing waste and creating sustainable products. These techniques offer alternative production methods that reduce the industry's ecological footprint.

Traditional production techniques – such as weaving, pottery, and handmade embroidery – enable local communities to maintain control over production activities, reducing reliance on large industries or intermediaries. For example, women's cooperatives in Bolivia producing handmade wool products engage directly with international markets, ensuring fair wages by bypassing intermediaries.[71,72]

Handicraft methods generally have lower production capacity compared to industrial fashion. However, through cooperative models and e-commerce, they can scale effectively without compromising quality or authenticity. Rather than integrating into existing fast-fashion chains, traditional techniques can facilitate the development of alternative, locally managed economic networks. In Sri Lanka, handmade embroidery (e.g., *batik*) entered the market through tourism businesses, generating employment and increasing local income.[73-75]

Communities that preserve traditional techniques tend to have higher employment rates and greater economic stability compared to those reliant on low-wage jobs in the fashion industry. Traditional techniques can offer viable business models with long-term resilience. They are not merely methods of production, but holistic ecosystems of economic, cultural, and social sustainability. A characteristic example is the Center for Traditional Textiles of Cusco in Peru, which preserves Andean weaving traditions while strengthening cultural identity and supporting local economies.[76-78]

4.3. Traditional handicrafts and sustainable production

Traditional techniques are essential for preserving the cultural identity of local communities and enhancing social cohesion. Handicrafts – such as weaving, knitting, embroidery, felting, and dyeing with natural pigments – form the foundation of sustainable production. They not only preserve cultural heritage but also offer a more sustainable alternative to mass industrial production. The use of local, natural materials and handmade processes contributes to reducing the environmental footprint while supporting local communities.

(i) Reduced water and energy consumption: Traditional dyeing techniques using natural extracts – such as indigo or plant-based colors – consume less water and fewer chemicals than industrial methods[79]
(ii) Reduced carbon dioxide emissions: The use of local raw materials minimizes the need for extensive transportation and imports, thereby lowering carbon footprints[80]
(iii) Biodegradable materials without environmental pollution: Local fabrics such as organic cotton, linen, and wool do not contain microplastics or toxic dyes, thus preventing water pollution[81]
(iv) Sustainable use of local resources: Many communities implement textile recycling techniques, such as patchwork or upcycling, which extend product life cycles[82]
(v) Increased local employment: Handmade production requires more skilled labor, thereby preserving and transmitting traditional skills[83]
(vi) Self-managed economic models: Local production enables communities to independently manage their resources, avoiding reliance on large supply chains.[84]

Almalki and Tawfiq[63] present a sustainable clothing design framework emphasizing the use of local wool to create women's garments using the felting technique. Their study investigates the potential of using local materials to reduce the environmental footprint and enhance the local economy. They also highlight the importance of sustainability in fashion by advocating for natural raw materials and ethical production practices. Surjit[85] explores the potential of wool recycling and

proposes strategies to enhance the sustainability of the process. Wool recycling contributes to reducing resource consumption and minimizing waste production – an aspect that is particularly important in the fashion sector, which increasingly promotes responsible consumption and circular economy principles.

Previous studies discussing the role of knitting and wool recycling within the context of sustainability, the circular economy, and Industry 4.0 provide valuable insights into the sustainable development of the garment and textile industry. Čuden[86] examines how knitting can be adapted to align with circular economy principles by incorporating smart technologies and Industry 4.0 processes to reduce the environmental footprint of textile products. Meanwhile, Maiti *et al.*[87] analyze the sustainability of knitting processes and resulting textile products, focusing on the use of eco-friendly materials, waste reduction strategies, and the optimization of production processes through advanced technologies.

Another example of a sustainable practice is dyeing with natural pigments. According to Niinimäki and Hassi,[88] natural dyes offer unique colors and are less harmful to the environment because they lack chemical additives. This method not only reduces environmental damage but also promotes creativity and authenticity in fashion. Their study investigates how sustainability influences consumer behavior in fashion and highlights the growing demand for ethically produced products.

Traditional techniques, such as embroidery, also provide significant economic opportunities for women in remote areas. A study by Li *et al.*[89] examines the potential for the sustainable development of traditional handicrafts through a design thinking-based approach. They analyze how design thinking can act as a catalyst for the revival and promotion of traditional techniques within a globalized and mass-production-driven context. The study proposes the development of a collaborative ecosystem involving designers, artisans, and consumers, aimed at integrating traditional techniques into modern markets in a way that ensures cultural preservation and economic empowerment of local communities (Figures 8-10).

Moreover, Niinimäki and Hassi[88] also emphasize that traditional techniques empower communities and enhance sustainability by combining cultural heritage with contemporary practices to promote sustainable fashion. Traditional handicrafts play a critical role in sustainable production, offering solutions that align cultural heritage with the needs of modern society. According to Raven,[90] the slow fashion movement incorporates traditional techniques and materials, thereby fostering community engagement around fabrics and garments that respect both the environment and the artisans who produce them, as shown in Figure 11.

Brown and Vacca[49] highlight the importance of cultural sustainability in fashion, emphasizing that traditional techniques can contribute to the preservation of cultural heritage and the promotion of sustainable development practices. They note that understanding cultural parameters can enhance appreciation for and demand for traditional products.

A study by Sandhu[91] analyzes sustainability strategies employed by designers such as Aneeth Arora, who integrate traditional techniques into contemporary design. This approach not only promotes ethical consumption but also creates opportunities for local communities, thereby enhancing the sustainability of production systems.

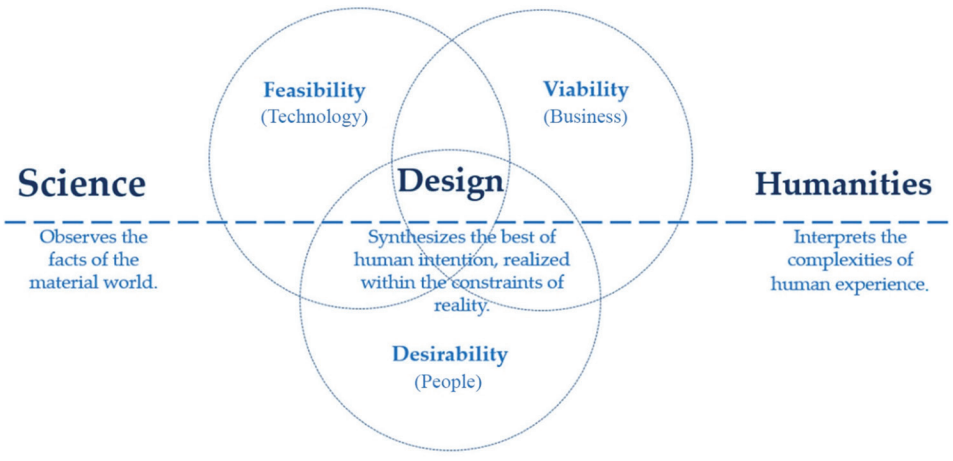

Figure 8. Design as a third culture: Positioned between science and the humanities, design addresses questions of feasibility, viability, and desirability. Adapted from Li *et al.*[89]

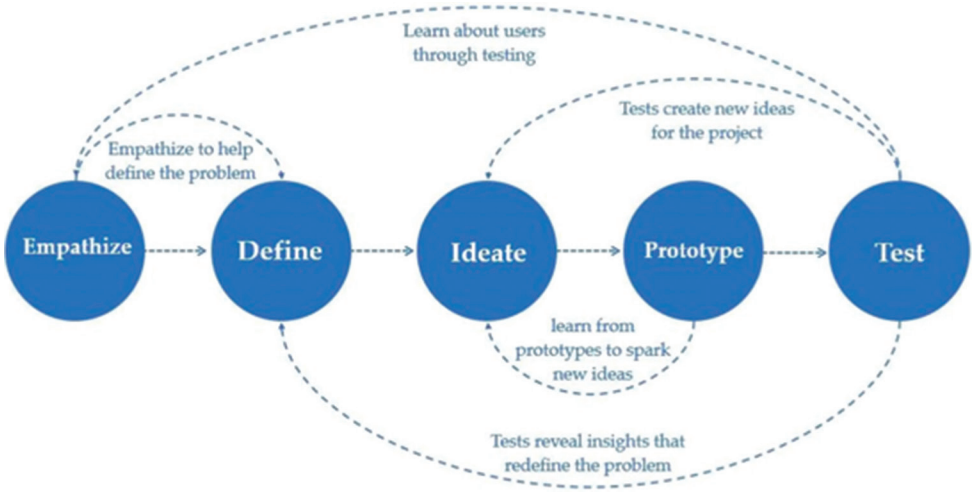

Figure 9. The proposed five-stage design thinking model: A non-linear process. Adapted from Li *et al.*,[89] based on the original model by Teo Yu Siang and the Interaction Design Foundation.

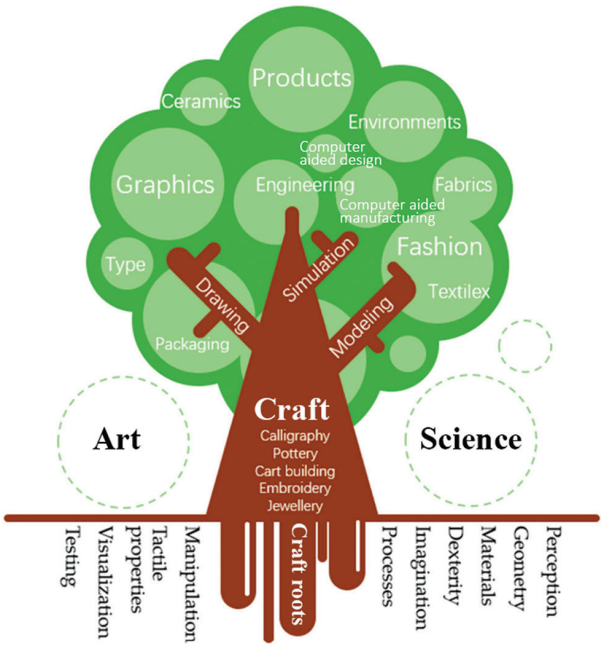

Figure 10. A tree diagram representing the structure and evolution of design. Adapted from Li *et al.*[89]

According to Wanniarachchi *et al.*,[92] the weaving industry in Sri Lanka showcases innovative production practices emerging from the combination of traditional and modern techniques. Several studies highlight that such practices can promote sustainability and strengthen local economies by ensuring fair compensation for producers. An illustrative example is the work of PBP International, whose mission centers on fostering sustainable livelihoods for Haitian artisans through locally rooted production, capacity building, and ethical partnerships – illustrating how design-led initiatives can support both cultural preservation and economic self-sufficiency (Figure 12).[93,94] Similarly, the brand "Maiwa" in Canada collaborates with artisans from India and Pakistan using natural dyes and traditional printing techniques to produce ethical fashion.[90] The United Nations' Ethical Fashion Initiative connects fashion designers with artisans from Africa, Asia, and Latin America, helping to preserve local techniques through fair trade practices.[95]

Xue *et al.*[96] analyze the consumption of traditional fashion by Chinese consumers, highlighting that authenticity and cultural heritage are significant factors influencing purchasing decisions. This study demonstrates how traditional techniques can be integrated with modern consumer preferences to promote sustainable products. Figure 13 presents the result of the study's questionnaire, which was administered to students as a pre-test to determine whether the items were well-designed and understandable.

The Self-Employed Women's Association (SEWA) in India is a notable initiative that provides employment to artisan women, thereby enhancing their economic autonomy. These women employ traditional weaving and embroidery techniques to produce sustainable clothing that is sold in international markets. SEWA's efforts have empowered numerous women artisans, enabling them to preserve cultural heritage while achieving financial independence.[97-99] A diagram of SEWA's proposed constitutional structure is presented in Figure 14.

Finally, the process of embroidery, as discussed by Dissanayake *et al.*,[100] can offer significant economic opportunities for women in remote areas. These practices encourage the development of new support networks and income streams, allowing women to actively participate in the

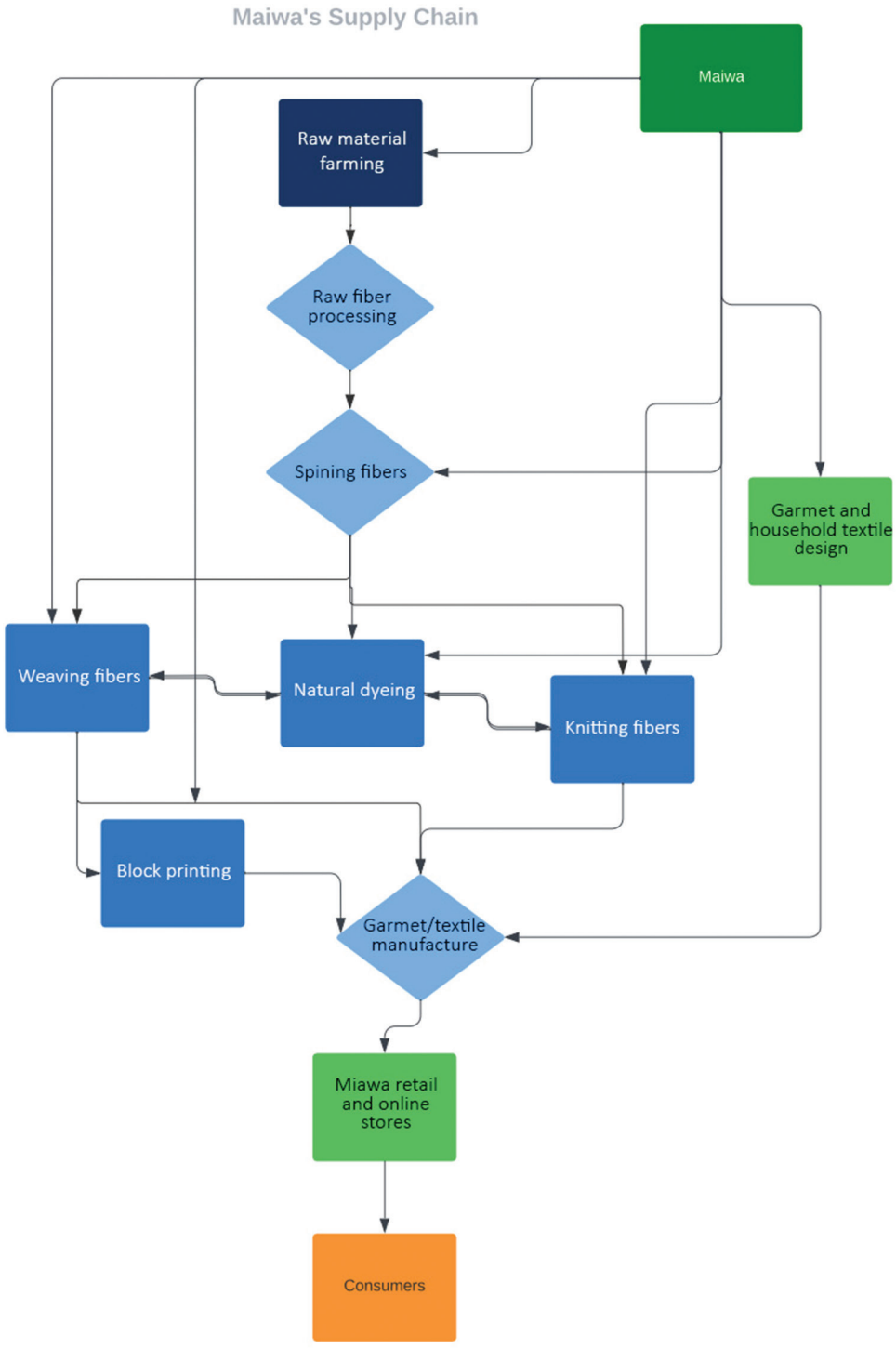

Figure 11. Textile production flow of Maiwa's supply chain. Adapted from Raven.[90]

economic life of their communities. Embroideries originating from local communities in Asia combine traditional craftsmanship with economic development, simultaneously promoting local cultural heritage and sustainability. Samples of these zero-waste-inspired works are shown in Figure 15.

4.4. Environmental sustainability

Environmental sustainability, as a foundation of sustainable fashion, is closely linked to traditional handicrafts that utilize local and natural materials. Dissanayake *et al.*[100] emphasize

Figure 12. Artisans and leatherworkers from Haiti.[94] Copyright © [2025], Deux Mains.

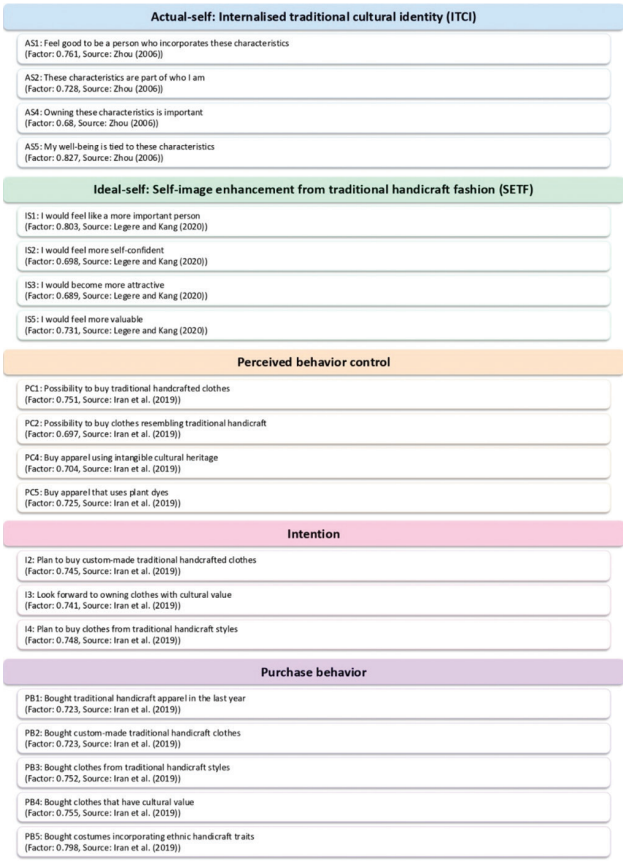

Figure 13. Results of a pre-test administered to 82 students to assess the clarity and design quality of questionnaire items. Adapted from Xue *et al.*[96]

the importance of adopting traditional techniques, which reduce dependence on chemicals and non-renewable resources. Indeed, as discussed by Cox,[101] the coexistence

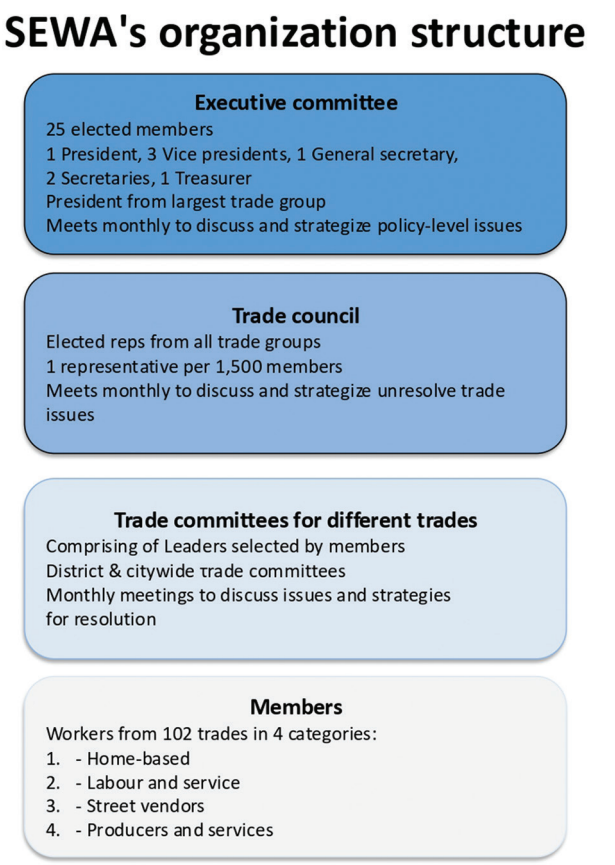

Figure 14. Organizational structure of SEWA. Adapted from the official SEWA website (https://www.sewa.org/about-us/sewas-structure/).[99] Abbreviation: SEWA: Self-Employed Women's Association.

of art and sustainable development can create new opportunities for local economies and communities.

The slow fashion movement highlights the value of traditional techniques. Several studies emphasize that products crafted using traditional methods possess greater durability, thereby contributing to the reduction of a culture of overconsumption. Beard[55] and Niinimäki[66] note that the consumption of ethical products, such as fair fashion, depends on consumers being informed about the broader impacts of their purchases.

The use of natural dyes and materials promotes sustainability and biodiversity while supporting local production. Sandhu[91] notes that engagement with local producers enhances not only product quality but also the conservation of natural resources. This approach is reflected in initiatives aligned with the principles of Fair Trade, which aim to strengthen producer networks and improve their quality of life, as demonstrated by Raynolds *et al.*[102]

Figure 15. Samples of zero-waste-inspired works[100]

Moreover, Lewis and Potter[103] highlight the social dimension of ethical consumption, emphasizing that consumers are often willing to pay more for products that are environmentally friendly and derived from equitable practices. This conscious choice, as shown in the study by Andorfer and Liebe,[68] is influenced by factors such as price, awareness, and ethical values.

Implementing sustainable practices through traditional handicrafts not only reinforces environmental sustainability but also promotes social cohesion. As Parker[104] states, initiatives that integrate tradition with contemporary sustainability principles can serve as models for a new approach to the fashion industry.

Dhingra *et al.*[66] note that the working conditions of artisans and their quality of life are critical to the development of sustainable handicraft industries. Traditional handicrafts, such as embroidery and weaving, contribute to the restoration of ecological balance.[105] For example, sustainable fashion initiatives rooted in local traditions create alternative economic models that prioritize environmental integrity and community reliance.

4.5. Social sustainability

Social sustainability is closely linked to fashion, as clothing production and consumption processes have direct impacts on the communities and workers involved. Ethical trade practices and the fair treatment of workers are key factors in achieving social sustainability. According to Dhingra and Dhingra,[105] the quality of life of workers in the handicraft industry significantly affects the social development of their communities.

Ensuring workers' rights and establishing fair working conditions are critical for social sustainability. As Dickson *et al.*[106] note, a lack of transparency in supply chains can lead to the exploitation of workers, affecting both individual and social well-being. Ethical trade, fair wages, and working conditions that respect human rights are prerequisites for achieving social justice in the fashion industry.

Moreover, social sustainability is directly related to strengthening the local economy and supporting community development by empowering small-scale producers and artisans. As discussed by Fletcher and Grose,[107] supporting local artisans and promoting traditional production methods enhances the local economy, thereby contributing to poverty reduction and fostering social stability, while providing communities with opportunities to develop sustainably.

According to Lundblad and Davies,[108] consumers also have a role in achieving social sustainability through their purchasing decisions. Increasing awareness of working conditions and corporate social responsibility encourages consumers to choose products produced in a socially responsible manner. This awareness creates pressure on businesses to improve their practices and promote social justice. The concept of social sustainability in fashion also ensures that the industry's social aspects – such as working conditions, equal opportunities, and community well-being – are maintained and adequately supported. Recent initiatives indicate that the fashion industry is increasingly focusing on integrating the social dimension into broader sustainability strategies.

Several studies explore the role of fashion design as a tool for social inclusion, particularly focusing on refugee

Figure 16. Bashir Salehi, a refugee from Afghanistan, started Palme Couture in January 2021 in La Rochelle, France, to provide tailoring services. Copyright © [2025], UNHCR/Benjamin Loyseau, the UN Refugee Agency, Content Production Section.

communities in Greece (Figure 16).[109,110] These studies investigate how design processes, within the broader context of social innovation, can create opportunities for marginalized groups – such as refugees – to integrate into local economies and societies. The research highlights the potential of fashion as a platform for empowerment, cultural expression, and skills development by engaging refugees in creative and collaborative design practices, which can lead to economic inclusion and social cohesion. Similar initiatives have emerged across Europe. For example, in Germany, a project supported by the United Nations High Commissioner for Refugees brings together refugee seamstresses from Syria and Afghanistan, helping them rebuild their lives and regain a sense of agency through a shared tailoring workshop.[111]

According to the United Nations' Fashion Industry Charter for Climate Action, renewed in 2021, the industry commits to achieving net-zero emissions by 2050 and publicly reporting its progress through scientifically substantiated targets (e.g., science-based targets). This initiative emphasizes corporate accountability and the publication of emission reduction plans, incorporating social responsibility as a key element of companies' commitments.[112]

Moreover, a report by the Global Fashion Agenda, presented at the 28th Conference of the Parties in 2023, highlights the need for a positive impact in the fashion sector by fostering safe and decent working conditions and promoting fairer wage systems. This report underscores social sustainability priorities, such as ensuring respect and safety in workplaces, improving wage structures, and adopting more sustainable material choices by collaborating with organizations like the Fair Labor Association and the Social and Labor Convergence Program.[113]

Social sustainability in fashion remains a significant challenge, as companies must balance sustainable development with the well-being of workers and communities affected by their activities. Efforts to align best practices and social performance continue, aiming to achieve the United Nations Sustainable Development Goals by 2030 and to limit global warming to below 1.5°C, as stipulated in the Paris Agreement.[112,113]

The systematic categorization of both practical case studies and academic sources reveals significant trends regarding the demographic focus of studies related to sustainability and traditional handcrafting. The group with the highest representation in the reviewed literature is women (approximately 31%), reflecting the long-standing connection between women's labor and production, empowerment through collective initiatives (e.g., SEWA), and the preservation of cultural heritage.

Minorities and local communities account for approximately 12%, primarily through examples such as the Nöl Collective, Andean artisans, and the incorporation of the *Nhat Binh* robe into fashion products for young consumers, as well as initiatives grounded in the solidarity economy.[114-116] Elders and youth are represented to a lesser extent (1% – 3%), indicating that the discussion around sustainable production often remains partially disconnected from the generational dimensions of knowledge – whether in terms of traditional transmission or youth-driven innovation, such as *Nhat Binh* robe's revival among younger consumers.

Previous research provides a comprehensive overview of how youth contribute to sustainability in the fashion industry and highlights young consumers' awareness, values, and behaviors related to sustainable fashion, while also identifying gaps in generational engagement (Figures 17 and 18).[117,118] Another example of ethical frameworks within sustainable fashion is the 3C Rule (Consent, Credit, Compensation ©2017) implemented by the Cultural Intellectual Property Rights Initiative® in a project developed in partnership with the Traditional Arts and Ethnology Centre in Laos and the Oma people of Nanam Village. This initiative emphasizes the importance of community-led free, prior, and informed consent, proper attribution, compensation, and control over how traditional designs are used and represented (Figure 19).[119,120]

Finally, approximately 50% of the reviewed articles follow neutral or systems-oriented approaches, focusing on sustainability at the level of supply chains, consumer behavior, technological innovations, or policy strategies, without targeting specific social groups.

These findings highlight the need for a more balanced

Figure 17. Designs from a local brand illustrate an effective and unique way of integrating traditional patterns into everyday fashion: (A) Application of *Nhat Binh* robe patterns in fashion products targeting young consumers; (B) Collaboration between Converse and La Quoc Bao's BARO[117]

Figure 18. Garment co-designed during a collaborative workshop, where participants altered and embellished existing clothing to address physical, emotional, and spiritual needs. (A) Hacked garment without bustle; (B) Hacked garment with removable bustle attached.[118]

Figure 19. Representatives of the Oma people of Laos at the Lao Handicraft Festival, 2020. Photo credits: Traditional Arts and Ethnology Centre, Laos. Reprinted with permission from OMA Māori LORE.[119] Copyright © [2025], Cultural Intellectual Property Rights Initiative®, TAEC, Oma People.[119,120]

demographic approach in future research, providing space for both traditional and marginalized populations, while also encouraging active youth participation and intergenerational connection. These findings are summarized in Table 4 and illustrated in Figure 20.

4.6. Economic sustainability

According to the globalized model of production and economy, exploitative relationships have emerged between the Global North (i.e., the world's developed countries) and the Global South within the fashion industry.[121] These challenges raise concerns about fair remuneration and value creation across different stages of production, particularly in relation to cultural appropriation. Traditional production techniques and methods can be linked to the ethical consumption of clothing, offering an alternative economic model of production networks. They also support the economic empowerment of local communities through alternative systems of economic management, production, and distribution. As noted by Beard,[55] ethical fashion may be considered a luxury, but it has the potential for broader appeal if consumers understand the values underpinning these products. According to Andorfer and Liebe,[68] ethical consumption is critical for economic sustainability, as consumers increasingly seek products that promote fair trade practices.

Bassett[122] and Ferraro *et al.*[123] highlight the importance of fair trade practices in agricultural sectors – such as cotton farming – as a means of alleviating poverty in regions such as West Africa. Ferraro *et al.*[123] examine the relationship between traditional techniques and sustainability, highlighting how local communities in Scotland integrate handicrafts to produce goods that are competitive in the international market. In addition, Parker[104] examines a case in Bangladesh where traditional fashion techniques have

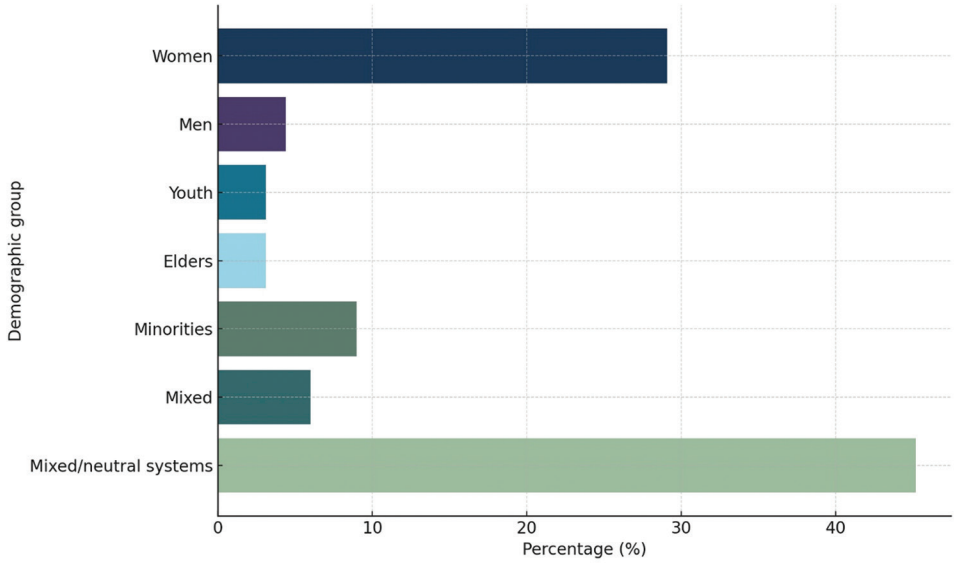

Figure 20. Graph of case study classification by demographic group

Table 4. Case study classification by demographic group

Demographic group	Percentage
Women	28.79
Men	4.55
Youth	3.03
Elders	3.00
Minorities	9.09
Mixed	6.00
Mixed/neutral systems	45.45

been revived through collaborations with international designers, leading to the development of alternative economic models that support sustainability.

The revival of traditional techniques contributes not only to environmental and cultural sustainability but also to enhanced consumer value. Niinimäki[66] argues that shifting from the consumption of disposable products to those that respect tradition can offer a new perspective in the market. The study highlights the importance of designing sustainable products that incorporate traditional techniques, thereby supporting economic sustainability in the fashion sector. Moreover, it demonstrates that education and investment in traditional skills can create new employment opportunities and strengthen local economies.

Recent studies, such as that of Imran *et al.*,[124] highlight the need for innovation and the growing importance of sustainability in the fashion industry, indicating that consumers are increasingly drawn to products that combine quality with social responsibility. Furthermore, Henninger *et al.*[125] demonstrate that modern consumers are willing to invest in sustainable products, thereby reinforcing the sector's long-term economic viability.

The development of ecological and social labeling systems, as discussed by Koszewska,[126] facilitates product differentiation and creates new opportunities for promoting traditional techniques. These labels can enhance the relationship between producers and consumers, contributing to a more equitable and sustainable economy.

In Sweden, the Reko-ring/Rejäl Konsumtion (REKO) program establishes closed-loop economic chains between producers and consumers by eliminating intermediaries. Although originally developed for agriculture, the REKO model is now being extended to the handicraft sector.[127,128]

In summary, economic sustainability in the fashion sector relies on the revitalization of traditional techniques and a commitment to ethical consumption, offering opportunities for local community growth and prosperity (Figure 21).

4.7. Application of traditional techniques and handicrafts in contemporary fashion

The application of traditional techniques and handicrafts in contemporary fashion has gained increasing significance as consumers become more aware of the social and environmental impacts of the industry. Some contemporary examples include:

- Clothing companies incorporating handicrafts: Companies such as Patagonia and Everlane incorporate traditional techniques into their manufacturing

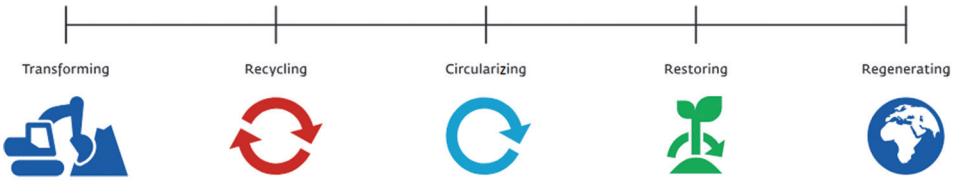

Figure 21. Five positions of value creation[34]

processes, thereby promoting sustainability and social responsibility.[129,130] Patagonia, for instance, collaborates with local artisans to produce environmentally friendly clothing using sustainable practices, while also carefully assessing the environmental impacts of fashion.[129,131]

- Artistic integration of handicrafts: The work of Celia Pym,an artist specializing in textiles and repair, is significant in this context. Her practice combines handicraft with artistic expression to explore themes such as decay, repair, and the value of objects through knitting and garment mending. Scholars have noted a shift in contemporary handicraft toward artistic curation and performative practice, as reflected in Pym's work, where the act of repair becomes a form of creative expression. Her work negotiates the concepts of wear and regeneration, highlighting the tension between the old and the new.[132,133] In Pym's approach, the repair and reuse of garments are examined within the broader context of circular fashion. Her emphasis on repair as both an artistic and ethical act aligns with the current trend in sustainable fashion and supports waste reduction through recycling and reuse (Figure 22).
- Fair compensation: Ensuring fair compensation for workers across production chains is critical to promoting social sustainability in the fashion industry. Companies such as People Tree implement fair trade practices that guarantee fair wages and safe working conditions.[134]
- Ethical platforms and artisan empowerment: Platforms such as XTANT promote ethical production, local sourcing, and artisan empowerment, aiming to bridge the gap between tradition and innovation. These initiatives not only support livelihoods but also contribute to the broader movement toward slow fashion and conscious consumerism. XTANT is a contemporary platform that celebrates and preserves traditional textile techniques, artisanal craftsmanship, and cultural heritage within the fashion industry. It connects global artisans with designers to foster collaborations that preserve and evolve traditional practices – as exemplified by designer Gabriela Martinez in Figure 23. XTANT seeks to elevate handcrafting techniques – such as weaving, embroidery, and dyeing – by integrating them into

Figure 22. Celia Pym: Double Denim, photographed by Michele Panzeri. Reprinted with permission from photographer Michele Panzeri. That is Not My Age[133] Copyright © [2025], Michele Panzeri.[133]

modern fashion, thereby supporting sustainable production and preserving cultural heritage.[135]

- Role of advocacy organizations: Advocacy organizations such as Fashion Revolution and the World Hope Forum play central roles in promoting sustainability in contemporary fashion. These organizations raise awareness of the need for transparency and ethical practices in the fashion industry, focusing on innovative economic models and collective solutions that contribute to a transition toward a more equitable and responsible system. Fashion Revolution was founded after the Rana Plaza tragedy in 2013 and campaigns for transparency, decent labor rights, and sustainable garment production practices. Through campaigns such as "Who Made My Clothes?," it urges the global fashion industry to recognize and protect the people and resources involved throughout the value chain.[136]
- Collective economic approach: The World Hope Forum incorporates the concept of the "we-economy" and emphasizes collective solutions to address global challenges such as overproduction and environmental degradation in fashion. It supports local communities by promoting the use of traditional techniques and handicrafts to enhance locality and foster solidarity through fashion.[137]
- Transparency in the production chain: Companies such as Stella McCartney, Ferragamo, and Vivienne

Westwood have committed to transparent production processes. They publish detailed reports on material sourcing and working conditions, thereby enhancing consumer trust.[138]

- Collaborations with designers: Initiatives such as Fashion for Good bring together creators, consumers, and businesses to promote sustainable fashion practices. By supporting innovative designers who incorporate traditional techniques, these initiatives contribute to sustainable development.[139]

The importance of fair compensation and transparency in production chains is crucial to advancing sustainable practices in fashion. Fair compensation ensures that workers are remunerated proportionally to their contributions, thereby supporting the economic sustainability of their communities. Transparency allows consumers to make informed purchasing decisions and fosters a culture of accountability within the industry.[140,141]

4.8. Challenges of integrating slow fashion and traditional techniques into the modern fashion model

Integrating slow fashion and traditional techniques into the modern fashion model presents numerous challenges related to both production processes and consumer perceptions. These challenges arise from the disparity between the demand for rapid, mass production and the need to preserve sustainable, culturally embedded practices.

- Commercial and operational challenges: Traditional techniques – such as hand weaving and natural dyeing – typically require more time and specialized labor, resulting in higher production costs and limited scalability (Figure 24). This creates a competitive disadvantage compared to fast fashion, which is driven by rapid production cycles and low pricing strategies.[102] Attempts to scale up traditional production may compromise the quality and authenticity of these practices, as pressure to increase output and reduce costs can negatively affect the handcrafted nature of products and the integrity of techniques.[68,142] Moreover, increased demand may lead to the industrialization of traditional techniques, making it difficult to maintain their authenticity and the cultural identity they embody.[143]
- Cultural preservation and appropriation: Integrating traditional techniques into slow fashion aims to preserve and revive these practices. However, their commercial exploitation may result in diminished authenticity or even cultural appropriation.[144] Recognition of, and respect for, cultural heritage and the contributions of local artisans by designers and businesses are critical to prevent the exploitation of these practices. Cultural appropriation – defined as the commercialization or extraction of traditional designs and techniques without the consent or participation

Figure 23. Intuitive embroidery by Gabriela Martinez, XTANT Craft Workshops. Reprinted with permission from XTANT (https://www.xtant.io/). Ref. XTANT.[135] Copyright © [2025], XTANT.[135]

Figure 24. Values context[142]

of the originating communities – remains a significant challenge to sustainable fashion.[62,107] It is essential to ensure that local artisans are actively involved and receive equitable compensation for the commercial use of their techniques, thereby safeguarding the continuity and integrity of their cultural heritage.[144]

- Changing consumer patterns: Slow fashion encourages consumers to prioritize product longevity and to reduce the overconsumption associated with fast fashion. However, this behavioral shift requires sustained education and awareness, as many consumers continue to be influenced by instant gratification and low-cost purchasing habits.[22,145] To facilitate this transition, companies must promote transparency by disclosing information about product origins and production processes, thereby supporting informed consumer decision-making.[146]
- Geographical inequality and the value chain: The fashion value chain often perpetuates structural inequalities between developing and developed countries. Lower wages and less stringent environmental regulations in the Global South have contributed to the systemic exploitation of workers and natural resources.[147] While slow fashion emphasizes ethical and sustainable production, its effectiveness as an alternative depends on collaborative efforts among value chain stakeholders to ensure decent working conditions and the protection of local communities.[48]
- Innovation and new technologies: Technological innovations – such as biomaterials and circular production systems – have the potential to reduce the environmental footprint of the fashion industry and foster more sustainable practices. The implementation of these technologies supports the development of new business models, such as the reuse and recycling of materials, thereby reinforcing circular economy principles.[147] Such transitions can enhance the industry's overall sustainability by reducing raw material consumption and limiting waste production.[131]

These challenges highlight the need for a comprehensive shift in the fashion industry's operational paradigm, emphasizing collaboration and continuous education for both consumers and producers. Promoting innovation within local craft communities and ensuring respect for human and environmental integrity are key to achieving sustainability in the fashion industry.

5. Prospects

The slow fashion sector presents significant prospects for the future, as increasing consumer awareness and evolving societal values highlight the need for sustainable and ethical practices.

- Rising consumer awareness: Consumers are becoming increasingly conscious of the environmental and social impacts of fast fashion and are opting for products that prioritize sustainability and quality. Studies indicate that the newer generation of consumers (e.g., Gen Z and Millennials) is shifting away from conventional fast fashion consumption patterns and is seeking alternatives that integrate product quality, supply chain transparency, and ethical production standards.[148]
- Emphasis on transparency and traceability: Consumers are placing greater emphasis on transparency across the supply chain and increasingly favor brands that provide information regarding material sourcing and labor conditions.[149] The integration of technologies such as blockchain can enhance traceability, thereby strengthening consumer trust and brand credibility.[150]
- Digitization and innovation: The digitization of production processes and the adoption of emerging technologies provide opportunities to enhance efficiency and sustainability. The use of three-dimensional printing and computer-aided design tools can reduce material waste and enable the production of customized garments with minimal waste production.[147]
- Reuse and the circular economy: The circular economy provides a framework for material reuse and recycling, thereby reducing the demand for newly extracted raw materials and mitigating environmental impacts.[151] Slow fashion businesses can implement practices such as upcycling and recycling to extend the lifecycle of garments and minimize textile waste.
- Collaborations and collective initiatives: Collaboration among diverse stakeholders – from designers and manufacturers to consumers and organizations – is critical for advancing the slow fashion movement. Initiatives such as the Fashion Revolution platform facilitate the exchange of knowledge and best practices, supporting efforts to improve transparency and sustainability across the fashion sector.[136]

This research aims to serve as a foundation for future studies and to connect local craft communities with the "we-economy" concept and the evolution of sustainable models in garment manufacturing.

Potential directions for future research include:

(i) Primary research in communities implementing the "we-economy" in fashion: Rather than relying solely on secondary literature, case studies can be conducted in local workshops that integrate traditional techniques to examine how workers' lives are affected
(ii) Quantitative and qualitative assessment of slow

fashion in relation to post-growth principles: This includes analyzing individual traditional techniques and processes within the framework of the circular economy

(iii) Exploration of consumer relationships with handmade fashion: Analyzing consumer preferences and investigating how traditional techniques can become more accessible through contemporary business models (e.g., social marketing).

6. Conclusion

This review highlights that traditional garment-making techniques are examined in the literature through the lens of human geography, as they are deeply embedded in local communities and reflect routine practices as well as the economic dynamics of specific ecosystems. Therefore, efforts to connect these techniques with contemporary garment production should be grounded in an alternative economic model that prioritizes local economies and aligns with the evolving movement from the local to the global.

By mapping traditional garment production techniques, it becomes evident how fashion value chains are created, emphasizing production methods, labor, and the individuals involved, thus shifting the garment's value away from brand names, which largely define the fast fashion industry. From the close connection between traditional techniques, craftsmanship, and communities, it is understood that these practices represent economic opportunities for local communities and a sustainable solution for the planet, viewed within the framework of slow fashion. In short, traditional techniques – as slow processes – compete with the fast cycles of fashion, introducing a new imaginary that challenges the prevailing model of perpetual growth.

To date, there has been no substantial convergence between the local economy (e.g., traditional techniques and craftsmanship) and the industry, in terms that are mutually beneficial for the entire value chain of garment production. Traditional techniques, being slow processes, often compete with the rapid cycles of the fashion industry. They require significant time investment, making them more expensive and primarily accessible to niche markets. This reflects the absence of a viable business model. Handmade products inherently carry the value of uniqueness and manual craftsmanship and, therefore, increase in value in market terms, positioning them as luxury products in the global high-fashion market.

The garment – as a product of traditional techniques and craftsmanship – represents an ethical and sustainable solution for the environment, people, and societies, though not necessarily for the global fashion economy. The global fashion economy faces persistent challenges in integrating traditional techniques into modern economic and business models. Labor inequality between countries of the Global South and the Global North continues to pose a significant barrier, particularly in relation to the production and distribution of traditional, local-economy products. Therefore, there is an urgent need to implement an alternative model, not solely economic, but also one that redefines ways of living, since ways of living are as closely linked to consumption patterns and actual human needs.

Most studies on traditional techniques focus either on their cultural dimension (as arts that must be preserved) or on their commercial potential (i.e., how they can be integrated into fashion). However, there is a lack of studies examining handcrafting as part of a self-sustaining economic system.

This study highlights that traditional techniques should not merely be preserved but also integrated into collaborative, alternative economic models. In addition, local production must be strengthened through the we-economy, enabling it to function as a self-sufficient and sustainable solution for communities. The we-economy could organize economic relations among all participants in the garment production process (e.g., designers, craftsmen, local artisans) in a more equitable and ethical way, thereby ensuring human and social well-being.

Moreover, this study underscores that the environmental footprint of handcrafting is significantly lower than that of industrial production, making it a credible strategy for sustainability. Rather than limiting itself to isolated examples, this research aims to connect the social, economic, and environmental dimensions of traditional handcrafting into a unified framework.

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ARTICLE

Stakeholder identification through participatory and speculative design: A case study

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Abstract

As organizations face increasingly complex and shifting stakeholder landscapes, innovative methods are needed to identify and engage with both present and future stakeholders. This article explores the integration of participatory and speculative design approaches for stakeholder identification. Our case study was conducted within an international organization focused on intellectual property protection, and it addressed a critical organizational task: Identifying actual and potential stakeholders. Traditional top-down approaches to stakeholder identification were found to be limiting due to the evolving nature of stakeholder relationships. Therefore, we proposed a design-led approach that involved participatory workshops and speculative thinking, empowering the organization to maintain a dynamic stakeholder list in the future. The project involved interviews with key staff, participatory workshops to identify and prioritize values, and a speculative approach – the Stakeholder Mapping Cone – to identify stakeholders and predict their future impact. By combining the creativity of speculative design with the inclusivity of participatory methods, the project allowed the organization to identify existing stakeholders and envision potential future stakeholders. This research demonstrates that speculative and participatory design are viable methods for stakeholder identification, offering innovative approaches that challenge conventional strategies and empower organizations to adapt to future challenges. It also introduces the need to explore how speculative design can evolve into operative speculative design thinking.

Keywords: Participatory design; Speculative design; Stakeholder identification; Strategy; Value

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1. Introduction

The constant transformation of society into a web of complex systems – where difficult-to-solve issues are the norm – has pushed the discipline and practice of design to change and evolve. In their 1973 seminal paper, Rittel and Webber[1] coined the term "wicked problems" to describe challenges that lack straightforward solutions and cannot be framed in terms of right or wrong. Over the past decades, the complexity of our societies, governments, and businesses has only increased due to technological advancements, globalization, and the growing demands of diverse social groups for

visibility and voice – factors that have multiplied both the number and intensity of wicked problems. Therefore, designers increasingly see themselves as responsible for shaping a better, more inclusive, sustainable, and ethical world.[2,3] This shift reflects a socially progressive view of the designed subject: design is not only tasked with meeting human needs but also with contributing to the improvement of society.[4,5] Since the 1970s, this orientation has given rise to various progressive and socially engaged design approaches, including participatory design, social design, critical design, design fiction, and speculative design.

These theories and practices share a common understanding that design can and should work to improve society and people's condition. However, they differ in their conceptual and practical approaches, methodologies, and motivation to act through design. This study focuses on two specific design practices: Participatory and speculative design. It presents our recent research in which these methods were implemented within an international non-profit organization to address a task that has been extensively studied by scholars from different fields, particularly management and public policy.[6] However, to the best of our knowledge, this task – the identification of an organization's stakeholders – remains relatively unexplored within design research and practice. This is the first step for an organization to understand and address complex, wicked challenges. To design for change, organizations must understand the actors who can benefit from it, as well as those who may facilitate or hinder it.

This study presents and analyzes research performed through an exploratory design case study: a stakeholder identification project conducted between November 2024 and January 2025 for an international non-profit organization in Europe involved in intellectual property (IP) protection. The organization addresses significant societal challenges by protecting innovations and promoting advancements that drive sustainable solutions for companies, workers, and society. The main mission of the organization is to receive and process IP registrations in its jurisdiction and to foster the development of a societal ecosystem where IP rights are valued and protected. The project focused on the identification of the organization's strategic, general stakeholders that influence and are involved in the overarching activities of the organization,[7] as opposed to specific project-related, operational stakeholders.

2. Literature review

According to the stakeholder theory, or the stakeholder approach to organizational management,[8] stakeholders' participation and engagement are key factors in the success of various planned activities. Therefore, organizations need to know their stakeholders for decision-making processes[9] and to design effective engagement strategies. The identification of stakeholders is the first step in this strategy, and it leads to a complete understanding of an organization's stakeholder community.[10-13]

Defining stakeholders is a taxing task, and several scholars have contributed to determining what constitutes a stakeholder. The present research relies on the classical definition of Freeman and Reed,[14] who identify a stakeholder as an individual or group that can affect, or be affected by, the achievement of an organization's objectives. It also builds upon the broad idea of actual or potential stakeholders proposed by Mitchell *et al.*,[15] which includes not only people, social groups, communities, and organizations, but also the natural environment.

To distinguish real stakeholders from potential stakeholders or non-stakeholders, in their seminal research paper published in 1997, Mitchell *et al.*[15] identified three criteria for stakeholdership: Power, legitimacy, and urgency. More recent scholarly works[16,17] identified other criteria, such as influence, attitude, interest, support, and contribution. The application of these criteria, however, poses practical problems because, for example, there may be stakeholders who do not have power but are nevertheless important for organizations and their managers.[15]

The claim that people or groups with no power, legitimacy, or urgency are not stakeholders and are not important to organizations' managers[15] is not entirely convincing. This is because it keeps emerging stakeholders who, in the near or far future, could be salient for the firm or have a broader societal impact off the managers' radar. Indeed, Mitchell *et al.*[15] recognized that people or groups that do not possess specific attributes are non-stakeholders or potential stakeholders. The project described in this article took a pragmatic approach consistent with the inclusive nature of design: stakeholder identification is understood to encompass both actual and potential stakeholders.

Extensive literature in the field of stakeholder theory claims that the objective of stakeholder management is to create value for stakeholders[18-20] – or with stakeholders through a process of joint value creation.[21] Value creation extends beyond the economic value that stakeholders may seek,[22] including financial and non-financial benefits.[18] This argument can be extended to the firm that creates value – indeed, a firm may seek to reach value beyond economic or financial benefit – and it applies with particular strength to non-profit organizations.

The research on stakeholder theory and value creation has a potential gap because it considers value creation for

stakeholders, or for and with stakeholders (joint value creation), while offering limited consideration of value creation for the stakeholders and the firm. Although filling this gap is beyond the scope of this article, it is acknowledged as a relevant research challenge. As stakeholder management practices that establish a fair relationship between the firm and its stakeholders – where interests are mutually considered and balanced – have been shown to positively affect organizational performance,[23-25] value creation for the firm should be included in more mature stakeholder management theories.

Given the strong connection between stakeholder management and values, stakeholder identification should be value-driven. The identification of an organization's stakeholders should create value for both the organization and its stakeholders. However, before identifying specific stakeholders, a firm should determine the common values it plans to create for or with them. In the research presented in this study, this step involved specific work with the organization to assess the values supporting the stakeholder identification process. These are the most important values that stakeholder identification (and, at a later stage, management) should create for the organization and its stakeholders collectively.[20]

Following the most common managerial approach in the literature and practices, stakeholder identification is typically done by a research team following a top-down approach (which relies exclusively on the team perception, thus potentially reflecting biases and with no involvement of stakeholders) or a bottom-up approach (where the assessment of potential stakeholders by the research team involves research methods, such as interviews and surveys with stakeholders, requiring a substantial investment of time and resources).[26,27] In both cases, the research team identifies stakeholders using the most appropriate criteria and delivers the results of their work to their supervisor(s) or client, who is not directly involved in the process. However, as suggested by Mitchell *et al.*,[15] static maps of an organization's stakeholders are useful as heuristics, but one should also consider stakeholders' impact and relevance change. This consideration was one of the foundations of the project described in this article to support the adoption of participatory and speculative design to identify stakeholders.

The participatory design emerged in the 1970s in Scandinavia – and concurrently in England, with a more multidisciplinary agenda[28] – to engage workers in the development of new systems for their workplace, merging the methodology and system knowledge of the designers and the experience and expertise of the workers affected by the new systems.[29-31] Participatory design is well-suited for projects where identifying, mapping, or engaging stakeholders is important. In this article, participatory design is understood as a process of collective creativity throughout the entire design process, in which designers and people with no education and training in design collaborate creatively in the design development process.[31]

Over the years, scholars and practitioners in marketing and business have endorsed participatory design as a practice that empowers firms to co-create value with customers.[32] The emergence and affirmation of participatory design within both design and business practices indicate that the scope of design practices extends beyond product design.[33] What legitimizes the use of the term "design" in a project is not solely the outcome of the creative process, but also the application of a design – and thus creative – mindset and way of thinking throughout the process. Participatory design can be effectively implemented to address business problems and challenges, which legitimately become design problems and challenges.

Some scholars suggest using the expression "co-creation" or "co-design" instead of participatory design. However, this article sticks to participatory design; not only because the expression participatory design has been commonly used for more than 50 years,[31] but also for semantic reasons. The term participatory design highlights with particular strength that creation happens in a participatory, thus democratic, way. Democratic participation is one of the key pillars of participatory design. For Manzini,[34] the process of co-designing means that everybody brings their ideas, regardless of the problems and tensions they may potentially generate, together with an attitude to listen to each other, change opinions, and converge toward a shared view on the results.

The importance of listening and exchanging ideas between co-designers implies that workshops play an extremely important role in participatory design, together with collective prototyping and prototypes, iterative development, and mock-ups.[30] The project described in this study relied extensively on participatory workshops – because they can help elicit valuable insights for creating interventions and fostering collective thinking among participants from diverse organizational units[35] – and on the iterative development of the stakeholder identification. The involvement of direct stakeholders within an organization can empower them, resulting in more coherent and resilient strategies that enable greater readiness for future and speculative outcomes.[36]

On the other hand, speculative design emerged in the 1990s as a form of critical design practice focused on socio-scientific and socio-technical concerns.[36] It evolved as a reaction against the neoliberal model of capitalism,

which turbocharged the emergence of liquid and flexible societies of individuals.[37-39] Due to its strong focus on technology and its impact on people's lives, speculative design corresponds to a form of speculative philosophy of technology that questions what technology means.[37] In Malpass's words,[36] speculative design maps alternative systems to challenge the dominant technological ideology and proposes different technological futures grounded on alternative values.

The project described in this article decoupled speculative design both from technology and from its more pungent socially critical dimension. Instead, it endorsed and highlighted other aspects of speculative design, in particular, the projection into the future of speculative design artifacts and its capability to stimulate creative and critical thinking – in this context, "critical thinking" should be understood as a form of reflection that goes beyond the specific situational status quo, but not necessarily with macro-social and ethical implications. Projection into the future is indeed a key characteristic of speculative and conceptual design practices, which are more concerned about designing for how things could and should be.[37]

Despite speculative designers criticizing several aspects of the relationship between technologies and society (and the impact of technologies on society) through their designs, they also want to have social usefulness.[37] In the research project presented here, usefulness played an important role. Speculative design was used to design a solution that could be accepted and understood by the organization. Imagination-based speculation is a powerful tool to change existing situations. Speculative design provides the opportunity for the organization to flexibly and iteratively shape the outcome of the stakeholder identification through speculations, not about how the future will be (like in other design approaches, such as design roadmapping[40]) but about how the future should be made – through activities, innovations, and processes that have a direct impact on the stakeholder identification.

Due to the limitations of traditional stakeholder identification strategies, our methodological approach incorporated established speculative design methods to address these shortcomings. In particular, we invited the organization's members to identify stakeholders critically and creatively through fictional (but possible), narrative-centered scenarios[41] built as thought experiments. The proposed scenarios, which are the core of a thought experiment,[42] partially follow the paradigm of thought experiments described by Dunne and Raby[37] – mental constructions based on ideas expressed through design that support thinking about challenging issues. The thought experiments used in the study stimulate critical and creative thinking, explore possible implications, and fully engage the imagination. What-ifs were also extensively used to explore ideas, encourage creativity, and potentially improve the quality of predictions about the impact of specific stakeholders. We challenged the organization's members to assess how the outcome of the identification process would change if, for example, specific actions were implemented (such as communication or awareness campaigns). This project included a dimension of realism to speculations, which are not merely possible and narrative abstract happenings, but realistic factors that may take place in the future, and not just by accident, but also because the organization decides so.

3. Research challenges

A stakeholder landscape is not static, but it evolves constantly. The traditional approach to stakeholder identification, discussed in greater detail in the literature review section above, often results in static stakeholder lists primarily generated through desktop analysis. This method makes it resource-intensive to keep the stakeholder list continuously updated. Furthermore, it may be challenging to plan stakeholder engagement strategies starting from complex lists of stakeholders.

Therefore, the directors of the organization were proposed to adopt a design-oriented approach for the project that allows iteration and staff participation. Based on a literature review and our experience as designers and researchers, participatory design and speculative design were identified as suitable design practices for the desired approach. Both approaches presented immediate challenges in identifying stakeholders. As pointed out in the previous section, speculative design is normally used with technologies and technological artifacts rather than management processes. In addition, speculative design is a form of critical design that focuses on socio-scientific and socio-technical issues, focusing on concerns related to possible futures. The main research challenge involved decontextualizing speculative design and using it to engineer a future-oriented process grounded in design thinking,[33] tailored to the specific needs and requirements of the organization. Another challenge was the implementation of participatory design methods within an organization with no prior experience. A further issue, discussed in the next section, was that organizations usually identify their stakeholders in a non-participatory way, leading to unsatisfactory results.

4. Research question and methodology

This article answers the following research question: Are participatory and speculative designs adequate methods to design a methodology and process to identify stakeholders?

This study aims to find and establish new connections between participatory and speculative design and stakeholder identification. Across the case study discussed in this paper, new knowledge is generated for design, both as practice and discipline. Moreover, the design also served as a means to develop a method, approach, and practice for addressing an unprecedented situation – the identification of stakeholders through participatory and speculative design.

Building upon a literature review on stakeholder management, participatory design, and speculative design, the research methodology consists of individual interviews, participatory workshops, and the critical assessment of the material collected and produced during the project. All individual interviews were recorded and transcribed to identify inputs for the project. For the workshops, the Miro platform and its digital notes were used to record participants' inputs, supported by ethnographic observation of the participants.

5. Case study: Participatory and speculative design for stakeholder identification

In this project, we aimed to identify the organization's stakeholders, and we acted as facilitators and enablers of the design process.[31,43-45] The case study involves an international non-profit organization with the mission to benefit companies and society through IP protection. However, the organization had no experience with participatory and speculative design processes. The literature reports some cases of projects where the research team conducted stakeholder mapping through co-creation; however, the participants were invited for their background and expertise in stakeholder mapping and co-creation[46] (which were both missing in the present project). The development of the project followed the chronological and methodological steps summarized in Figure 1.

5.1. Phase 1: Understanding needs and expectations and defining operational criteria

It was realized that engagement by the organization's team in the project was a key factor for the success of the project. After a series of frequent interactions with the project officer, the first step was to explain the project to all staff members working with stakeholders and collect their feedback, insights, and expectations. Twelve key staff members who commonly interact with the organization's stakeholders were identified and interviewed individually, in person or online. All interviews were recorded and transcribed using Microsoft Teams. Each interview included six questions, as reported in Table 1.

	Phase 1 Project preparation	Phase 2 Value definition	Phase 3 Design for stakeholder identification	Phase 4 Stakeholder identification and validation
Goal	Create awareness, collect feedbacks and insights	Define the overarching values for stakeholder identitication	Design a tool for the creative and participatory identification of stakeholders	Test the methodology, validate the findings of the research
Participatory design method	12 individual interviews in preparation of workshops	Participatory workshop with 12 staff members	Planning and design of the participatory workshop of phase 4	Participatory workshop with 7 staff members to identify stakeholders
Speculative design method		Use of thought exercises and what-ifs during the workshop to discuss about values	Design of the Stakeholder Mapping Cone; design of thought exercises and what-ifs	Use of the Stakeholder Mapping Cone through thought exercises and what-ifs
Other research method	Desktop research	Ethnographic observation	Desktop research	Ethnographic observation
Outcome	Knowledge of needs and expectations; 6 operational criteria	Identification of the values that support the stakeholder identification	The Stakeholder Mapping Cone	First iteration of the stakeholder identification, feedback to validate methodology

Figure 1. Overview of the project phases

Then, the transcription of the interviews was processed to assess the comments and topics discussed during the interviews and map them in thematic clusters, as reported in Table 2.

For each interview, the 20 most frequently used words and expressions were identified, excluding common ones. Then, the information was aggregated to determine the frequency ratio of these words across all interviews. The objective of this analysis (Figure 2) was to provide input for the participatory workshop in phase 2, where participants would be invited to reflect on these words, why they are frequently used in connection with stakeholder identification, and the values these words underpin.

Table 1. List of interview questions

No.	Question
1	Do you work with stakeholders in your position within the organization? Can you elaborate?
2	Based on your experience, what is a stakeholder?
3	The organization team defined a stakeholder as: "By stakeholders, we mean people, groups of people, organizations, or companies that have a direct or indirect interest in the organization and vice versa. They are affected in a positive or negative way by the organization and our activities." Would you change it or add something to it?
4	In your opinion, how can stakeholders add value to the organization?
5	Based on your experience, what is the value in the context of stakeholders?
6	Do you want to add any comments?

Table 2. Theme clusters emerged from the interviews

Theme No.	Description
1	Gaps and challenges
2	Opportunities and strengths
3	Visibility and awareness
4	The organization in the IP ecosystem
5	IP organizations as key stakeholders
6	The political dimension of stakeholdership
7	Stakeholders, customers, and accounts
8	Understanding and interacting with stakeholders
9	The value of reciprocity
10	The value of tier 1 stakeholders (and its limits)
11	Business rationale
12	The need to measure the stakeholder impact

Abbreviation: IP: Intellectual property.

5.2. Phase 2: Prioritizing values through participatory design

The second phase of the project relied extensively on participatory methods. A workshop was organized with all staff members interviewed in the first phase of the project, with two objectives:

(i) Introduce the most frequently used words in interviews as a trigger to collective thinking and discussion.
(ii) Identify, map, and prioritize the values that direct the stakeholder identification.

The core of the workshop was about identifying, mapping, and prioritizing values. To promote active participation from all attendees, each participant was individually asked to quickly and instinctively propose a value. Participants have identified diverse values, such as collaboration, efficiency, consultation, professionalism, income, understanding, empathy, and consistency. The exercise was repeated several times. The research team wrote all suggestions in digital notes using the Miro platform. In the next step, participants grouped the values per theme: entrepreneurs, customer, system, organization, business, contact, project, approach, interest, relationship, work, collaboration, partner, information, awareness, and operations.

Next, participants moved to the identification of the most important project values. The discussion led to the reflection that the overarching project values should relate to customers because the organization wants to be customer-centric. Indeed, "customer" ranked among the most frequently used words in interviews. Participants also decided that the project values should be consistent with the organization's statutory and legal missions. As evidenced in Figure 3, two values emerged from the final discussion: awareness (the organization should stimulate awareness about IP in its ecosystem) and conversion of the awareness into actual IP registrations. In practice, participants agreed that the stakeholders will be identified for their (potential) role in co-creating these values.

Figure 2. The most frequently used words in individual interviews

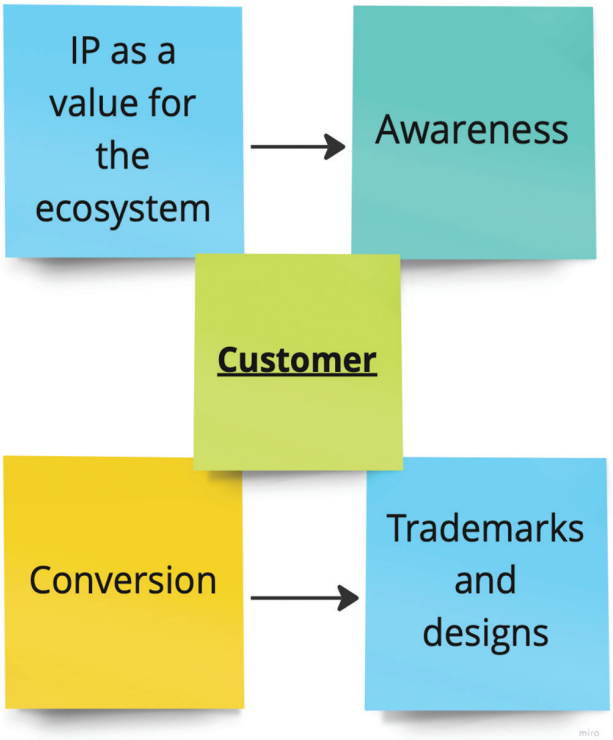

Figure 3. Identification of the overarching project values
Abbreviation: IP: Intellectual property.

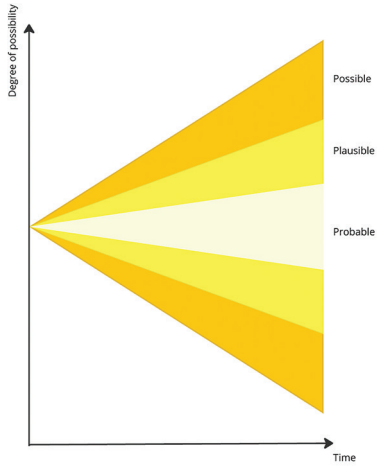

Figure 4. The Stakeholder Mapping Cone. Image created by the authors with Miro (https://miro.com/).

5.3. Phase 3: Designing a speculative design approach to map stakeholders

In this phase, principles and practices from both speculative design and participatory design were used to set up an approach to identify the organization's stakeholders. The approach was built upon Dunne and Raby's[37] diagram to illustrate different kinds of potential futures (the so-called PPPP diagram): Possible, plausible, probable, and preferable futures. We named our approach the Stakeholder Mapping Cone, as illustrated in Figure 4.

The Stakeholder Mapping Cone is designed for two purposes:

(i) Identify stakeholders.
(ii) Predict the future projection of the stakeholders' impact in terms of values.

The vertical axis represents the level of possibility, plausibility, or probability, while the horizontal axis refers to time. When identifying stakeholders, time may indicate when the organization expects that a stakeholder will generate value or when the organization will approach the identified stakeholders. The user of the cone can set a scale on the timeline for more accurate predictions. The key aspect to consider when identifying stakeholders with the cone is the expected creation of value for the organization (as identified by the organization) and its stakeholders. The Stakeholder Mapping Cone is both value-based and future-oriented. When identifying stakeholders with the cone, three groups of stakeholders emerge:

(i) Possible stakeholders: These are stakeholders that may potentially create value for the organization, its stakeholders, or the IP ecosystem of stakeholders. The notion of possibility refers to new situations supported by a credible series of events,[37] which are not impossible but difficult to foresee in the present. More pragmatically, a possible stakeholder is associated with an event that may happen at an unspecified point in the future. To explain the difference among the three areas, participants were invited to reflect on the following thought exercise: a design school, in general, may be considered a possible stakeholder. However, if the organization organizes a demonstration on trademark and design registration specifically for the school's final-year master's students, the design school shifts from a possible to a plausible, or even a probable, stakeholder.
(ii) Plausible stakeholders: These are stakeholders that plausibly will create value for the organization. Plausibility refers to outcomes that could happen[37] with a reasonable degree of likelihood.
(iii) Probable stakeholders: These are stakeholders that will probably create value for the organization. Probability indicates what is likely to happen in reality.[37]

In the next sub-section, the use of the cone to identify and map stakeholders is presented. Once stakeholders have been identified and categorized as possible, plausible, or probable, the cone plays a role in the prioritization process. Stakeholders classified by the organization as priorities are placed within a fourth area of the cone: the preferred stakeholders, that is, those considered central to

the stakeholder engagement strategy (Figure 5). During the prioritization process, selected stakeholders are moved into the cone of preferred stakeholders. This cone can ideally span across all other cones, with two, or even with only one, depending on the organization's strategic decision.

The Stakeholder Mapping Cone is also designed to predict and visualize the future projection of stakeholders' impact in terms of values. In this case, the organization can forecast whether a specific stakeholder will possibly, plausibly, or probably contribute to generating awareness and conversion in the future (or any other value identified by the organization). The Stakeholder Mapping Cone helps the organization make and represent the predictions. Discussion with participants revealed that, from a logical standpoint, awareness is created before it is converted into registrations. For example, a campaign targeted at product design students (where the main stakeholder is the design school) is likely to create immediate awareness about the importance of protecting their designs. However, actual conversion into design registrations may only happen later when the young designers have developed designs that can be registered.

Not all stakeholders have the same opportunity to contribute to the creation of shared values, nor do they do so at the same time or pace. These values may be assessed in combination or separately. In the thought experiment discussed earlier, where the organization arranges a demonstration on IP registration for design students ready for graduation, the Stakeholder Mapping Cone may appear as illustrated in Figure 6. In this scenario, IP awareness is immediate and classified as probable, while conversion is considered possible and projected into the future. However, the extent to which this future materializes depends primarily on specific conditions, such as the age and design maturity of the students.

Additional thought experiments and what-ifs were used to show that conversion may also be classified as plausible or even probable in the near future. For example, when students are launching their first product and are committed to registering their designs within weeks or months. Conversion can also be probable and immediate, for example, a campaign organized during a show of student's final projects may lead them to immediately register their IP. Owing to its flexibility and adaptability, the Stakeholder Mapping Cone offers significant potential to support the organization in envisioning future scenarios and designing targeted strategies and actions. The last step in Phase 3 involved the planning and design of the final participatory workshop of Phase 4.

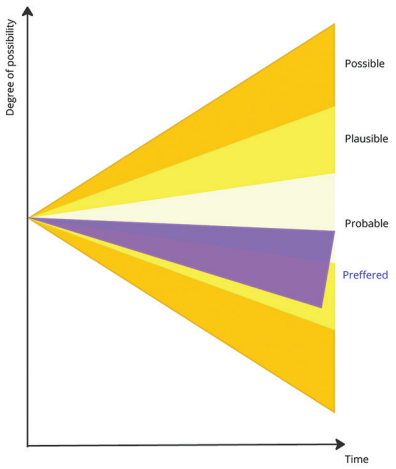

Figure 5. The Stakeholder Mapping Cone and its four cones. Image created by the authors with Miro (https://miro.com/).

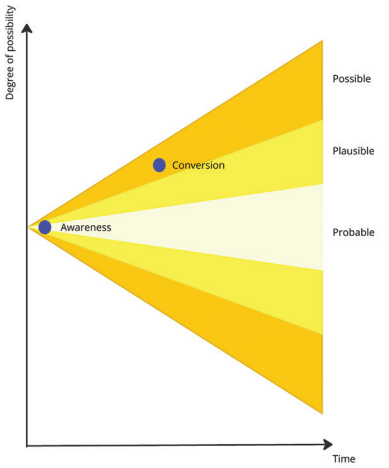

Figure 6. Example of use of the Stakeholder Mapping Cone to predict stakeholders' impact. Image created by the authors with Miro (https://miro.com/).

5.4. Phase 4: Identifying stakeholders through participatory design

The last phase of the project focused on the implementation of the Stakeholder Mapping Cone to identify stakeholders and validate its usability. First, a method for identifying stakeholders was identified and suggested through the cone: in participatory workshops, participants were invited to express their creative potential and identify as many stakeholders as possible. For testing and internal validation purposes, a participatory workshop was organized with seven staff members (including a member of the Board of Directors and two senior managers) working with stakeholders on a regular basis. The workshop had three consecutive sessions: introduction, identification, and mapping of stakeholders (the core session of the workshop),

and a final discussion to refine the identification and mapping. After an introduction to the methodology proposed for the workshop and the Stakeholders Mapping Cone, participants were invited to identify stakeholders and map them in the cone. A scenario-based workshop was chosen to facilitate participants' engagement. The scenario used for the workshop is the following thought exercise: "Amber is a young fashion designer. She just launched her brand and found her first resellers. In classes at the design school, a professor talked about the importance of protecting a brand identity. Amber starts looking around for advice on which is the best strategy to adopt."

All participants were seated around a table, where a printout of the cone, as shown in Figure 5, was laid out. The research team acted as facilitators and recorded all stakeholders identified by the participants on the cone. In the core session of the workshop, participants used the cone creatively and effectively to identify and map stakeholders. The method of starting the creative process from a speculative but realistic scenario triggered dynamic collective thinking. At the beginning of the workshop, participants revealed a need to get rules and guidelines, but once they understood that the workshop should not follow a rigid script, the creative process developed smoothly. At the end of the workshop, the cone was populated with several stakeholders, as shown in Figure 7.

Participants identified a total of 28 potential stakeholders, ranging from chambers of commerce and lawyers (which are not only probable, but also actual and established stakeholders) to healthy food shops, hair stylists, and yoga clubs as possible stakeholders. The Stakeholder Mapping Cone sparked creativity among participants, who identified stakeholders that otherwise would have been ignored. On average, each participant identified four stakeholders. After the final discussion, one stakeholder ("association of students") moved from probable to plausible stakeholder; two stakeholders ("Google" and "ChatGPT") moved from plausible to probable stakeholders; and two probable stakeholders ("magazines/journalists") were moved left in the cone because participants agreed that their potential impact and value creation are likely to occur sooner than initially expected.

In total, 12 stakeholders have been identified as probable, five as plausible, and 11 as possible. The method led participants to identify stakeholders across several industries: the majority (11 stakeholders) are from retail, industry, and commerce; six are service providers (which includes chartered professions); three represent digital platforms and the institutional and government sectors respectively, two are from the education sector and professional organizations, respectively; and one stakeholder is from the press and communication industry.

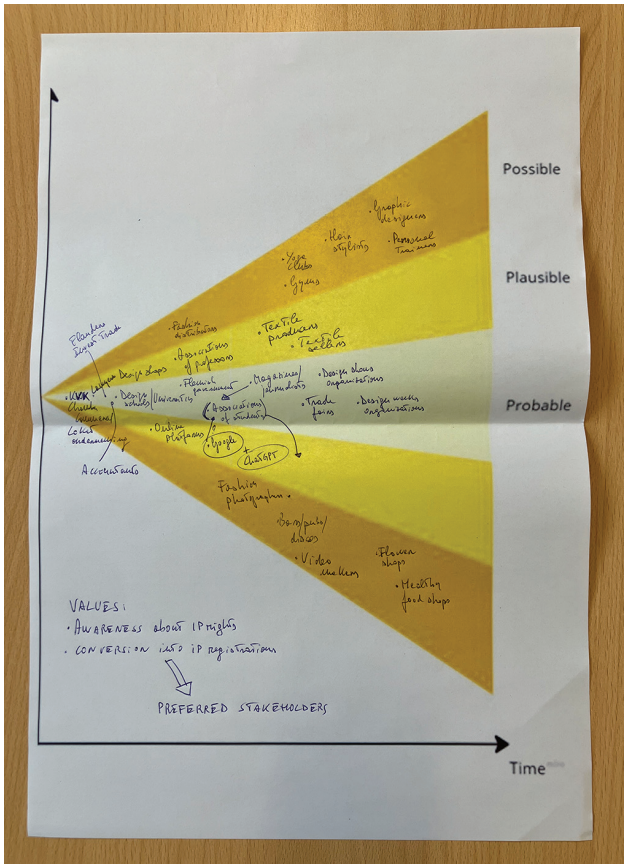

Figure 7. Identifying stakeholders in a participatory workshop using the Stakeholder Mapping Cone

5.5. Opportunities and limitations

Direct observation and final discussions among participants in the participatory workshops during Phases 2 and 4 revealed that all attendees actively and equally participated in the identification of the values underpinning the identification of stakeholders and in the identification of stakeholders. It was also observed that encouraging participants to empathize with the subject's perspective within the scenario effectively stimulated creative thinking. During the final workshop in Phase 4, the speculative thought exercise involved inviting all participants to play the role of Amber, the young fashion designer in the proposed scenario. They openly and freely speculated on what they would do if they were Amber. This speculative exercise proved effective, as evidenced by the fact that only three institutional and government-related stakeholders were identified. Participants demonstrated greater familiarity with institutional partners and stakeholders than with stakeholders from retail, industry, commerce, and the fitness and creative sectors. Nevertheless, they identified more stakeholders from the latter sectors than the former.

A replicable pattern emerges from the findings: to identify and map stakeholders creatively, the research team should invite people to actively consider the interests and needs of a vast array of speculative characters. This finding finds a vast echo in established literature in organizational behavior and management studies, which has emphasized for nearly a century the need to understand and consider other people's interests.[47,48] This research builds upon and extends those conclusions by suggesting that the interests of fictitious characters within speculative scenarios should be considered to identify and map an organization's stakeholders effectively. Thought exercises are useful for creating a framework that supports creative and empathetic thinking, while what-ifs help participants to broaden and refine their ideas. In this sense, thought exercises and what-ifs complement each other, and both are effective in stimulating creative and critical reflections.

Some limitations of the research must be acknowledged. Regarding the workshop in Phase 4, in particular, the limited number of participants (seven people), their exclusive affiliation with the organization, and the absence of external validation represent key constraints. Such limitations were mainly due to the limited time and resources available for the project, as well as the organization's decision – not to involve external partners at that stage – to validate the methodology and its outcomes. The overall timeframe (10 weeks, including the Christmas break, effectively reduced to 8 weeks) also prevented any long-term validation. As such, a further limitation is that the method's practical impact over time has not been assessed. Nevertheless, there are plans to replicate the method with other organizations to evaluate its long-term effects and impacts.

6. Discussion

The research project addressed several challenges associated with stakeholder identification using a design approach based on participation and speculation. This section focuses on three aspects of the research: first, it reflects on the research question in light of the findings; second, it explores the role of the designer within the project; and finally, it offers a commentary on the application and implications of the speculative design approach adopted.

6.1. Using participatory and speculative design for stakeholder identification

The research reveals that participatory design and speculative design (thinking) are suitable methods to design a methodology and process to identify stakeholders. By the end of the project, it became evident that the organization was capable of creatively and critically identifying its stakeholders using the proposed approach. This finding was validated by the final workshop, during which participants applied the proposed methodology and provided positive feedback about the experiment.

In particular, the organization managed to identify stakeholders that can create value for the organization, stakeholders, and the broader IP ecosystem. In addition, the findings suggest that the design-driven approach overcomes the limitations of the organizational management perspective. In this case study, stakeholder identification emerged as a naturally evolving and iterative process. Users of the Stakeholder Mapping Cone can add, delete, or move stakeholders at any moment.

Participants' feedback revealed that they appreciated the ample discussion time in all participatory workshops, and the clear clarification of the aims of the identification exercise, that is, establishing the concrete questions, issues, or activities relating to which individuals' and organizations' stakes are examined.[27] This research contributes to the understanding that when participants are involved in defining the aims of the stakeholder identification process, conditions are more conducive to productive discussions and richer outcomes.[46] The findings further suggest that stakeholder identification produces more creative results when participants not only determine the overarching aims of the project but also help establish the values underpinning the identification process.

Finally, a future-looking approach added significant value to the project. Speculative design thinking encouraged the organization to explore new stakeholder possibilities, moving beyond a limited and familiar list of pre-identified stakeholders. The speculative and value-based approach, rooted in projections into the future and combined with active participation, is the most outstanding aspect of the research project. This finding contributes to the literature on stakeholder identification with a design-oriented approach that shows not only the desirability but also the feasibility of identifying stakeholders in a participatory, dynamic, and iterative way.

6.2. The role of the designer: An active facilitator

As a research team, the first task was to create conditions for interaction[43] among the organization's members involved in the project. This was initiated through preliminary individual interviews with key staff members to ensure a clear understanding of the project's objectives and to foster engagement. These individuals were subsequently encouraged to interact with the research team and, more importantly, to collaborate with their colleagues during the workshops.

While recognizing that the practices of design facilitation have not been extensively examined in the

literature,[49] the present approach aligns with Manzini's[34] perspective on the designer's role in participatory sessions. He critiques what is often termed "post-it design," wherein the designer's role in co-design processes is narrowly confined to administrative tasks. In such scenarios, creative ideas and design culture tend to fade, reducing the designer to a mere process facilitator. Although digital post-its were used extensively throughout the process, this study rejected such a reductionist view of the designer's role, instead emphasizing the importance of their critical, creative, and dialogic input within the participatory sessions. According to this perspective, designers are expected to contribute to discussions by sharing visions and ideas grounded in their skills and cultural expertise. They should also actively listen to feedback from both their interlocutors and the broader environment in which they operate. Based on this feedback, designers are expected to refine and introduce new, more developed proposals into the conversation.

Designers cannot be passive listeners; experience from this project demonstrates that concrete results would not have been achieved without an active design role. Furthermore, design facilitators need to maintain a clear focus on the core and creative dimensions of facilitation before an event takes place, as this greatly enhances their ability to orchestrate design events effectively.[49]

Participatory design relies on shared responsibility among participants to achieve meaningful outcomes; however, the designer carries the primary responsibility. Designers not only create the conditions for interactions but also ensure the positive outcomes of the project. The present research shows that participatory design methods are highly effective in fostering engagement and creativity, even in management and operational projects, such as stakeholder identification, which are typically performed independently by research teams.

6.3. From speculative design to speculative design thinking

The role of speculative design in our research project is sensitive and challenging. Tools and methods originating from speculative design research were used; however, the radical understanding of speculative design that emerged in the literature review was rejected.

The investigation suggests it is time to reflect on how speculative design can become a more mainstream design practice. Dunne and Raby[37] claim that large-scale speculative thinking in speculative design differs both from design thinking (which is about problem-solving) and social design (which, despite distancing itself from purely commercial pre-occupations in favor of human issues, remains too concerned with fixing things). From a more general perspective, the present research contributes to establishing that designers should break the rigid ties between design, solution, and needs, which are commonly recognized as the starting points of the design process by scholars.[50-53] As noted in the introduction, wicked problems may have different solutions, and often the problem and needs are ill-defined. However, design should bring a change, as suggested by Herbert A. Simon, in his seminal definition of design, "Everyone designs who devises courses of action aimed at changing existing situations into preferred ones."[54(p.111)] The outcome of the stakeholder identification process leads to a change in how the organization understands, approaches, and works with its stakeholders.

Apart from theoretical debates on whether speculative design qualifies as a legitimate design practice – an idea generally opposed here – there is a risk that speculative design, along with other critical practices, may become overly self-referential and inward-looking, confined to a closed community of practitioners.[55] Drawing from participatory design and related practices, such as socially responsive design and co-design, may provide a pathway for speculative design to gain broader acceptance in mainstream design practice or at least contribute meaningfully to everyday design challenges. Participatory design, for example, emphasizes the relationship between design and the communities it serves, whether designed for or with them. This approach is often considered progressive within the design discourse and has been fully integrated into the established norms of the discipline.

The present research indicates that speculative methods and tools have significant potential to address various contexts, including stakeholder management within organizations. While acknowledging that the present paradigm of speculative design cannot be entirely transformed, emphasis is placed on its potential application across different domains. This research lays the groundwork for what is proposed as an emerging speculative design thinking framework. This framework builds on speculative and critical mindsets, as well as conceptual tools and methods, to drive change through design in both micro and macro contexts. It operates independently of technology but places a strong emphasis on imagining and preparing for the future through speculation.

7. Conclusion

The research sets the stage for establishing a connection between stakeholder management and design. It shows that stakeholder identification is a design issue and can be tackled through design. Engagement through participatory design

methods and future-oriented speculations is the pillar of the project methodology. They are the first milestones of this research. However, limitations exist due to the use of just one case study, and further research on the implementation of the methodology is needed. Additional test cases with more scenarios in each (in private and government organizations and in different geographical and cultural contexts) are planned to validate the milestones presented in this paper.

The research also identifies another area requiring further investigation. Speculative design provides interesting methodologies and tools that can be used in several projects and scenarios. However, the present practice of speculative design makes it unfit to truly play a role in promoting change within organizations, both due to its exclusive focus on the relationship between technology and society and its radical, almost sectarian, approach to design. The design need not uphold existing power structures, but its primary function should not be to dismantle them either. Taking a pragmatic, designer approach to speculative design can enhance its value and make it a more relevant tool for driving change.

Finally, future investigations will explore a particular area related to participatory stakeholder identification. Research in the field of biases and noise in predictions suggests that, once stakeholders are identified, forecasting their impact in terms of value can be better done individually by different team members rather than together, for example, in a workshop. When people make predictions together, there is a real risk that one (or some) member of the team strongly influence the other, potentially leading to inaccurate predictions and conformism-driven consensus.[56] In other words, when a team has to make predictions and the stakes are high, participatory design methods show serious limitations. However, the Stakeholder Mapping Cone is designed to be used speculatively both in groups and individually, thus potentially overcoming the limitations of collective predictions.

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Conflict of interest

The authors declare they have no competing interests.

Author contributions

Conceptualization: Davide M. Parrilli
Formal analysis: Davide M. Parrilli
Investigation: Davide M. Parrilli
Methodology: Davide M. Parrilli
Project administration: Davide M. Parrilli
Writing – original draft: Davide M. Parrilli
Writing – review & editing: All authors

Ethics approval and consent to participate

Consent to participate is not required because the research uses data that have been fully anonymized.

Consent for publication

Consent for publication is not required because the research uses data that have been fully anonymized.

Availability of data

Data used in the research can be made available to readers on request, subject to privacy restrictions.

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ARTICLE

Enhancing chatbot usability and UX through activity theory: A case of the road sign chatbot

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Abstract

Many chatbots fail to meet user expectations and are often perceived as not useful due to design, technical, and usability shortcomings. Usability is a critical factor in the design of effective chatbots because it ensures that users can achieve their goals efficiently, effectively, and satisfactorily. A chatbot with high usability enhances the user experience (UX), builds trust, and promotes engagement. UX also plays a pivotal role in the design of effective chatbots, as it directly influences user satisfaction, engagement, and the overall success of interactions. Both usability and UX are critical factors in the design of effective chatbots, as they influence how easily and satisfactorily users can interact with the system. Activity theory provides a robust framework for understanding and designing usability for effective chatbots by focusing on human activities, the tools mediating these activities, and the context in which they occur. It also provides a structured approach for designing UXs by focusing on the interaction between users, tools (*e.g.*, chatbots), and their environment. This paper describes how activity theory has been used to design a road sign chatbot that offers information on road signs in Malaysia to road users. The Road Sign Chatbot was evaluated through a User Acceptance Test and the results revealed that users found the system is user-friendly, satisfactory, and enjoyable to use.

Keywords: Activity theory; Chatbot; Road sign chatbot; Driving license; User experience

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1. Introduction

Road signs are standardized visual signals that convey essential information to road users, including drivers, cyclists, and pedestrians. They play a crucial role in regulating traffic flow, ensuring safety, and providing navigational guidance. Familiarity with these signs and their meanings is essential for all road users to navigate the transportation network safely and efficiently. Chatbots have emerged as effective tools for enhancing road safety education by providing interactive platforms for users to learn about road signs and traffic regulations. Their ability to deliver personalized, on-demand assistance makes chatbots valuable resources for both new and experienced drivers.

The integration of chatbots into road sign education has the potential to revolutionize how learners interact with traffic regulations. These AI-driven systems can offer

personalized, on-demand instruction, making learning more engaging and accessible. However, the success of such systems hinges on their usability. User experience (UX) issues can also impede learning outcomes and user satisfaction.

Manawadu and Wijenayake[1] developed a voice-activated chatbot that utilizes convolutional neural networks for real-time traffic sign recognition. While the system offers auditory feedback, users have reported issues with environmental factors such as poor lighting and adverse weather conditions, which can affect the accuracy of sign recognition. In addition, the chatbot's natural language processing (NLP) capabilities sometimes struggle with complex or ambiguous sign descriptions, leading to misinterpretations.

The European Union's Erasmus + funded project "Smart Learning for Road Safety" employs a chatbot integrated with an e-learning platform to educate users about road signs and traffic rules. Despite its interactive approach, users have encountered difficulties with the platform's accessibility features.

Many chatbots fail to meet user expectations due to shortcomings in usability and UX. There are many common usability problems in chatbot road signs in use. These include:

(i) Inaccurate or irrelevant responses. Users often report that chatbots provide generic or irrelevant information, leading to frustration and diminished trust in the system. This issue is particularly pronounced when chatbots fail to understand context or user intent, resulting in responses that do not address the user's specific query.[1]

(ii) Accessibility barriers. Users with disabilities, particularly those with visual impairments, often face challenges when interacting with chatbots. Issues such as focus jumping, where the screen reader's focus shifts unexpectedly, and inadequate announcements of new messages can impede the user's ability to engage effectively with the chatbot.[2]

(iii) Lack of natural conversational flow. Many educational chatbots struggle to emulate natural human conversation, leading to interactions that feel mechanical or disjointed. This lack of conversational fluidity can disengage users and reduce the effectiveness of the learning experience.

(iv) Repetitive interactions. Some chatbots exhibit repetitive behavior, asking the same questions or providing identical responses without progressing the conversation. Such loops can waste users' time and hinder the learning process, especially when the chatbot does not adapt to previous inputs.

These limitations can result in a lack of trust, low engagement, and reduced effectiveness in achieving the intended goals.

Both usability and UX influence how easily and satisfactorily users can interact with the system because they are crucial for the design of effective chatbots to ensure that chatbots meet user needs, foster engagement, and achieve their intended purpose. Usability is a critical factor in the design of effective chatbots because it ensures that users can achieve their goals efficiently, effectively, and satisfactorily. Good usability enables users to accomplish their tasks quickly, with minimal stress and errors, and ultimately feel satisfied when interacting with a product's user interface. Besides usability, UX is also important for chatbots because it helps to create a positive interaction between a user and a chatbot. It directly influences user satisfaction, engagement, and the overall success of interactions. A chatbot with a well-designed UX not only meets user needs but also fosters trust and long-term usage. A well-designed chatbot provides a seamless interaction experience, minimizes user frustration, and enhances task completion rates. By adopting proven usability and UX design principles, chatbots can better meet user needs and expectations.

Theoretical frameworks provide a structured foundation for designing usability and UX. They help designers understand human behavior, predict user interactions, and create systems that meet user needs efficiently. In his paper, Norman[2] states that applying theories to design ensures a scientific, repeatable approach to design, improving the likelihood of creating effective, user-friendly chatbots.

There are several theories and models for designing usability and UX for chatbots. These include Norman's Design Principles,[2] Nielsen's Usability Heuristics,[3] User-Centered Design,[4] The Eight Golden Rules of Interface Design,[4] Emotional Design,[5] Persuasion Technology,[6] and Conversational UX Design Framework.[7] Despite the fact that each of these theories provides useful principles for chatbots design, they lack the ability to model complex systems[8] because they often focus on specific aspects of usability or interface design.

Activity theory, with its holistic, systemic approach, is better suited for designing chatbots that operate in dynamic, real-world contexts. It ensures that chatbots not only provide usable interfaces but also align with the social, cultural, and organizational factors that influence user interactions. It is our belief that activity theory offers a structured approach to understanding and designing usability and UXs for effective chatbot. This study shows how activity theory principles can be effectively used to design usability and UX in a chatbot for road sign users.

Evaluations from the users show that the road sign chatbot was not only usable, but it also brought satisfaction to the users. This research contributes to the design of effective chatbots by applying activity theory that provides usability and UX to the users.

The remainder of this paper is organized as follows. Section 2 reviews related work on chatbot usability, UX, and activity theory, and the role of feedback in chatbots. Section 3 describes a case study of the road sign chatbot, coupled with the methodology for designing it. The evaluation of the road sign chatbot from the User Acceptance Test is discussed in section 4. Section 5 discusses the implications of these findings. Section 6 concludes the paper and highlights directions for future research.

2. Related areas

Road signs are used to guide and warn drivers as well as to help control traffic flow among vehicles, bicycles, motorcycles, pedestrians, and others who use the streets. They play a significant role in traffic, providing helpful information for drivers and pedestrians to reduce accidents. Therefore, understanding of the road signs should be a prerequisite in mitigating and avoiding the occurrence of traffic accidents. The Global Positioning System (GPS) is a satellite-based navigation technology that provides real-time location, velocity, and time data. Despite the use of GPS for navigation, there are problems with its uses. Drivers may rely excessively on GPS, neglecting road signs and their surroundings, leading to unsafe behavior. GPS systems occasionally provide incorrect or outdated information, causing confusion, such as a route is closed due to construction, but the GPS device does not show the closure.[8] The GPS devices can divert a driver's attention from the road, causing accidents when the driver glances at the screen to read instructions instead of focusing on the road.[9] GPS may not account for local conditions, cultural norms, or temporary restrictions when GPS directs a driver onto a restricted-access road during a festival. Poorly designed user interfaces can confuse drivers, especially when multiple commands or features are displayed simultaneously.[10]

Chatbots have emerged as effective tools for enhancing road safety education by providing interactive platforms for users to learn about road signs and traffic regulations. They can be used in educational institutions and driving schools to provide students with an engaging and interactive method of learning road signs. By interacting with the chatbot, users can input images of road signs and receive accurate classifications and explanations, enhancing their knowledge and compliance with traffic laws. Chatbots powered by AI provide numerous benefits across various industries, enhancing efficiency, UX, and operational cost management. By automating repetitive tasks, chatbots reduce the workload on human agents, allowing them to focus on more complex problems, which improves overall service quality and customer satisfaction.[11-13] In educational settings, chatbots help students by answering queries, offering learning recommendations, and facilitating administrative processes. According to literature,[14] a NLP-based chatbot designed for universities successfully handled over 90% of student inquiries accurately, saving time and improving UX.

Data collected by chatbots on customer preferences and behaviors provide insights that can help in personalizing services and improving customer experience. For example, in e-commerce, chatbots recommend products based on user preferences, driving sales, and improving customer retention.[15]

Although chatbots offer many benefits for many applications in life, there are many failures. Many chatbots fail because they cannot accurately interpret user intent, especially when users phrase their queries in unexpected ways. This leads to frustration and abandonment. For instance, chatbots in customer service settings often struggle with complex or ambiguous queries, which results in users being redirected to human agents or receiving unhelpful responses.[16]

In their analysis chatbots failures, Huang and Dootson[17] have identified several important reasons why chatbots failed. First, chatbot failed because it ignores user requirements and poor conversation design. The authors argue that a chatbot interaction is considered successful when the intended task is completed appropriately by the chatbot, indicating that the chatbot is useful. According to Rodríguez Cardona *et al.*,[18] a chatbot from the user perspective is successful when it can efficiently and satisfactorily perform longer conversations with a user, and the users rate the experiences as enjoyable. This is concerned with UX. The authors argue that companies often focus too much on technology but neglect the point of view of the users. Secondly, the chatbots are not useful. The chatbots were not able to cover what the users expected.

Usability ensures that users can achieve their goals efficiently, effectively, and satisfactorily. Users ought to perceive the chatbot as an easy-to-use and a smooth-functioning system.[17-19] The interface must be intuitive. A chatbot with high usability enhances the UX, builds trust, and promotes engagement.[20]

The UX also plays a pivotal role in the design of effective chatbots, because it directly influences user satisfaction,

engagement, and the overall success of interactions. A chatbot with a well-designed UX not only meets user needs but also fosters trust and long-term usage. A chatbot with a strong UX improves user satisfaction,[2] enhances engagement,[4] builds trust and credibility,[2] fosters emotional connection,[7] and aligns business and user goals.[4] Thus, UX must be considered when designing effective chatbots, and principles of UX from models and theories must be applied.

Theoretical frameworks are important for designing effective chatbots that will support usability and UX because they provide a structured foundation for designing usability and UX. They help designers understand human behavior, predict user interactions, and create systems that meet user needs efficiently. According to Norman,[2] applying theories ensures a scientific, repeatable approach to design, improving the likelihood of creating effective, user-friendly chatbots.[2] Theories are important because they help to identify key use needs and preferences, enabling the design to align with user expectations. Nielsen usability heuristics[3] emphasize visibility of system status, user control, and error prevention, which are critical for chatbots. Another function of theories is to provide benchmarks for evaluating a system's usability. Theories help identify design flaws and areas for improvement, making iterative design processes more effective.[7] According to Shneiderman,[5] a theoretical approach enables designers to predict user behavior, improving the chatbot's ability to deliver intuitive and seamless interactions.

Some examples of the use of theoretical applications in chatbot design are Duolingo's conversational chatbot. It uses cognitive load theory to keep interaction concise by offering hints only when necessary, thus reducing user effort and enhancing learning.[7] Google assistant uses Norman's principles[5] by providing clear feedback and visibility, such as progress indicators for long-running tasks.

Don Norman's *The Design of Everyday Things*[2] introduced a set of design principles focused on creating intuitive and user-centered interfaces. These principles are foundational for interface design and can be applied to a variety of domains, including the design of chatbots. This work[1] primarily addresses interface-level issues and lacks a focus on broader social and cultural contexts. Activity theory, by contrast, goes beyond the interface to address the system-level dynamics that influence usability and UX.

Jakob Nielsen's *Usability Heuristics for User Interface Design*[3] outlines ten general principles to guide designers in creating interfaces that are intuitive, effective, and user-centered. These heuristics focus on improving usability, ensuring interfaces are functional, and minimizing user frustration. Nielsen's Usability Heuristics[3] provide a strong foundation for designing intuitive and error-free interfaces, including chatbots. However, they focus primarily on static, GUI-based designs and may fall short in addressing the dynamic, context-dependent nature of chatbot interactions. Nielsen's Usability Heuristics[3] do not account for how social, cultural, and historical factors influence user interaction, limiting their scope in designing chatbot applications. Activity theory offers a more holistic framework, emphasizing user goals, cultural factors, and adaptability, making it particularly suitable for complex chatbot applications. Combining both approaches can result in more effective and user-centered chatbot designs.

User-Centered System Design[21] provides a robust framework for designing user-friendly systems, emphasizing usability, user involvement, and iterative refinement. Although effective, there are several limitations. User-Centered System Design emphasizes usability over understanding the systemic context of user interactions, which may limit its applicability for goal-oriented, multi-user systems. User-Centered System Design also primarily focuses on individual users' tasks and preferences, potentially neglecting the broader socio-cultural context of chatbot interactions. Activity theory offers a complementary approach, addressing broader socio-cultural contexts, systemic integration, and evolving user goals, making it better suited for complex chatbot design.

Emotional Design, developed by Donald Norman,[6] emphasizes the role of emotions in shaping UX with products and systems. While Emotional Design[6] emphasizes creating products that evoke positive emotions through visceral, behavioral, and reflective design levels, it has significant limitations when applied to chatbot design. The design of chatbots requires a balance of emotional engagement, functional efficiency, and adaptability to diverse user needs and contexts. Norman's Emotional Design[6] focuses on how users emotionally interact with a system at three levels: visceral (esthetic appeal), behavioral (usability), and reflective (personal meaning). While these are valuable for engaging users, the framework tends to neglect the broader socio-cultural and systemic contexts in which chatbots operate.[5] Chatbot interactions often involve evolving user goals that require dynamic adaptability, which Emotional Design does not inherently address. Activity theory,[22] with its focus on user goals, socio-cultural dimensions, and systemic integration, provides a more robust framework for designing adaptive and context-aware chatbots.

The Conversational UX Design Framework primarily focuses on individual conversations without deeply considering the broader socio-cultural and systemic

contexts. Conversational UX Design relies heavily on predefined conversation flows, which may not adapt well to dynamic or evolving user goals.[8] The framework focuses on chatbot design as an isolated system, which may hinder its integration into larger workflows or activities. Conversational UX Design often reacts to user input without actively shaping user behavior or workflows. Its focus on efficiency and engagement might overlook cultural nuances and diverse user needs. Activity theory,[22] with its focus on the interrelation of tools, goals, and social contexts, offers a more comprehensive approach to designing adaptive and inclusive chatbot systems.

Understanding human activity and work practices is the focus of activity theory. The principles and components of activity theory have been used as analytical tools for many different subjects. These include human–computer interaction,[23] information systems,[24] interface design,[25] communities of practice,[26] and education.[22] There are many advantages for using activity theory for designing usable and UX chatbots. It is our belief that the theory from AT offers us an effective way to design chatbots. Principles from activity theory have important implications for effective chatbot design.

An activity is a precursor to learning in activity theory. To know something, we must understand the context of doing.[27] Individual actions are always situated in a meaningful context and are impossible to understand in isolation without the meaningful context as the unit of analysis.[23] Various artifacts, such as procedures, signs, instruments, methods, laws, *etc.*, are always involved in an activity through which actions on objects are mediated. During the development of the activity, artifacts are created, manipulated, and translated, and carry the historical aspect of the development and the outcomes of previous actions on objects.[28]

All activities are mediated by culturally defined tools in activity theory. Because activity is mediated, the implications for road signs learning is crucial. The mediation redefines the nature of learning. Learning based on the activity theory is now re-conceptualized as learning to participate in a cultural practice.[29] Instead of viewing it as the rational abstraction of mental representation from one's own experience, from an activity theory perspective, instead of designing learning based on teacher-centered or student-centered approaches, students move through the activities and progress from being partial participants, who are heavily dependent on the material mediation of tools, to full participants, who are able to more flexibly use the cultural tools of the narrative practice.[29]

The interface design of the road sign chatbot is also benefited from applying activity theory. This is because the interface of the chatbot is in constant development, changing the appearance as the user and use context develop. The interface and the computer artifact, in the chatbots are mediators of learning because activity theory assumes an asymmetric relation between people and things, in contrast to traditional symmetric relations offered by cognitive science or other computer science approaches, where computer programs and human behaviors are modeled using the same language and methods. From the activity theory perspective, computer applications, *i.e.*, our chatbot, act as a mediator of human activity.[30]

Applying activity theory for chatbot design enables us to make important features of human endeavor stand out through the hierarchical structure of activity instead of designing chatbot applications in isolation. It enables us to focus on the context of use. According to activity theory, Computer artifacts can only be understood in their context of use, as embedded in meaningful activity.

An activity comprises a variety of disparate elements, voices, and viewpoints.[30] It is not a homogeneous entity. The multiplicity can only be understood in terms of historical layers. Activities are constantly evolving and are not static or rigid. It is important to know how it is developed into its existing form to understand a phenomenon.[31] This applies to all the elements of an activity. To understand the current relationship between subject and object requires us to have a condensation of the historical development of that relationship.[23]

History plays an important role in activity theory. It is not simply an event in the past, but also is alive in the present, that may shape the future. The structures and behavior of today's learning reflect the culture and circumstance-specific historical development.[32] Historical analysis enables us to examine existing and emerging organizational structures, the result of their evolutionary development, sometimes intentional and others not. It is therefore important to describe and analyze the development and tensions within the activity system. It is the authors' belief that by exploiting information relating to users, devices, and environments through the notion of awareness, using activity theory can bring about effective chatbot design. Activity theory offers an ideal framework for the design of context-aware systems by providing guidance on what elements of context to consider to support the implementation process during the design of the chatbot.

Our approach allows us to interpret the context of user behavior in the application. This allows the minimization of explicit input and becomes personalized for the individual user. Minimizing explicit input helps improve usability for mobile learners. Applying activity theory to the design of

chatbot enables the covering of key elements of context that can influence user activity, and the explanation of how elements influence the user's ability in the actual situation.

2.1. Materials

According to literature,[33] no-code chatbot development systems have been playing an important role in changing the quotidian landscape of business and technology by translating requirements at a quicker pace, realizing more creative ideas, and contributing to demands from both small businesses and large corporations across multiple fields such as customer service, social media marketing, health, entertainment, educational, instructional amongst others. Another research[34] further elaborates on the advantages of no-code chatbot development platforms such as the reduced development and implementation time in the creation of chatbots, the reduced costs in terms of the technologies involved and the technical skillsets gathering as well as the exquisite attribute provided by customizable pre-built templates which allow non-coders to expand their creativity and create more quality chatbots.

The Engati platform (Figure 1) is a no-code chatbot development platform that enables users to make use of their easily navigational and customizable templates to create chatbots in an efficient and effective manner with the goals of "acquiring, retaining, and engaging" their customers.[35] In another research paper,[36] Engati is considered one of the robust chatbot development platforms, which enables users to develop a chatbot that can be embedded across other channels and platforms such as Facebook, Twitter, WhatsApp, Instagram, Messenger, amongst others, within 10 min.

Engati provides a panel of features to its users, such as the following:

(i) Contextual conversations: The ability of the chatbots to understand the conversation flow and provide meaningful conversations.
(ii) Multi-platform support: The developed chatbot can be integrated across multiple platforms such as Slack, Line, and Telegram both on Android and IOS SDKS.
(iii) Human takeover and live chat: The chatbots can attend to conversations and can be overtaken by a real agent at all times, hence providing seamless chat resolution and response flows.
(iv) Conversational modeler: The platform provides users with multiple nodes for drag and drop implementation, testing and maintenance purposes.
(v) Multi-lingual support: Engati chatbots support more than 50 international languages.
(vi) FAQ Builder: This feature enables the training of the chatbots more easily through CSV and the upload of documents in the.doc and.html file formats, hence making it easier for users to train their chatbots in responding to queries.

2.1.1. Case study

In Malaysia, the education of road signs is usually taught in the driving lessons before an individual driver's license is approved and issued. Apart from the driving lessons, the drivers in Malaysia are not obligated to revise their knowledge of traffic road signs unless their driving license is suspended and disqualified. Some road signs are less common and will only appear in certain areas. Thus, this may confuse certain road users due to a lack of education on the road signs. With the increasing complexity of road

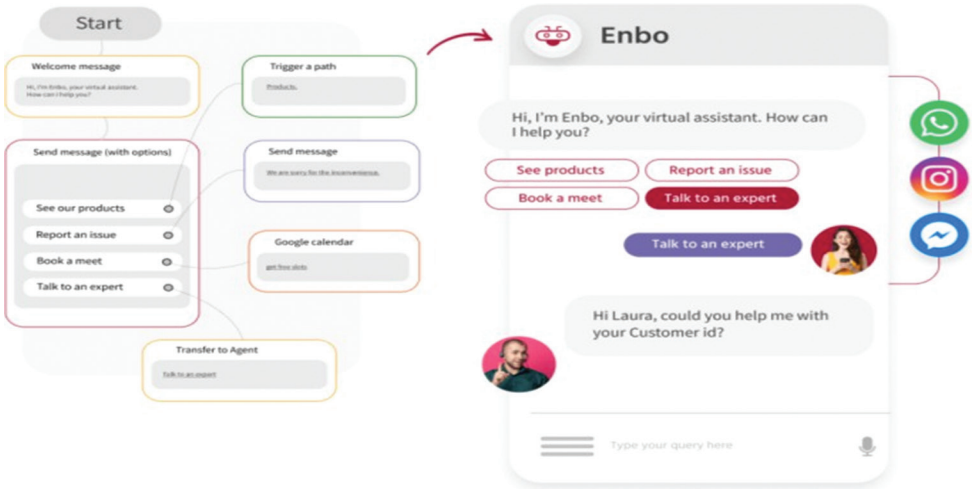

Figure 1. Engati chatbot development platform
Source: Engati.com.

traffic in Malaysia, traffic road signs guarantee a smooth and safe driving experience for all drivers.

Despite advancements in GPS navigation, studies have shown that drivers' over-reliance on GPS can lead to reduced awareness of their surroundings, increasing the risk of traffic accidents due to unexpected situations or navigation system failures. The over-reliance on GPS has induced the degeneration of memory and poor reconstruction of the environment among the GPS users. The distraction brought by the GPS could also cause traffic accidents to happen. In addition, most signs utilize pictures rather than words, so it may lead to misunderstanding. One avenue to explore in assisting the users to interpret traffic road signs was to develop the Expert Systems prior to upgrading the system to generative artificial intelligence. An Expert System is a computer program that simulates the judgment and behavior of a human with expert knowledge and expertise in a particular field. It is very popular across different domains, such as in diagnostic medicine (*e.g.*, arthritis, disorders, agriculture, and information libraries).[14]

This case study presents the implementation of an Expert System enhanced with NLP capabilities, enabling users to interact with the system conversationally through a chatbot. The chatbot delivers real-time traffic and route information via an interactive interface, aiming to educate users about road signs while ensuring a user-friendly and engaging experience.

2.2. Key concepts of activity theory applied to chatbot design

2.2.1. Subject-tool-object framework

Activity theory views tools (chatbots) as mediators between the subject (user) and the object (goal). For chatbots, usability issues often arise when the tool fails to mediate effectively due to poor interface design, lack of intuitive interactions, or insufficient context-awareness. Designing chatbots that dynamically adapt to user goals and contexts can bridge this gap. For instance, a chatbot in education could offer context-specific prompts based on the learner's progress.[8]

2.2.2. Hierarchy of activity

Activities are structured in three levels: Activities (high-level goals), actions (intermediate steps), and operations (automatic processes). Chatbot usability can be improved by mapping user interactions to this hierarchy. For example:

(i) Activity: A user wants to learn about road signs.
(ii) Actions: Searching for particular road sign to learn.
(iii) Operations: Auto-filling personal details.

By optimizing operations and streamlining actions, chatbots can enhance the UX.

2.2.3. Contradictions and breakdowns

Activity theory recognizes that contradictions (conflicts within the system) can lead to breakdowns. For chatbots, these breakdowns might occur when the chatbot fails to understand user inputs or when the interface is not culturally appropriate. Identifying and resolving these contradictions–such as integrating multilingual support or localizing chatbot interfaces–can significantly improve usability.[8]

2.2.4. Cultural-historical context

Usability challenges can also stem from the chatbot's lack of alignment with users' cultural norms and expectations. Activity theory emphasizes designing tools that are culturally relevant and historically informed. For instance, a cultural heritage chatbot could incorporate stories and terminologies familiar to its target audience to create a more meaningful UX.[36]

2.3. Design of road signal chatbot using activity theory

There are two methods that we can use to design chatbot. First, it is possible to select suitable concepts from AT that are deemed relevant for usability and UX design for the road sign chatbot. The crucial consideration is that the selected concepts should be able to guide both the data gathering and analysis process and transfer results into a design representation with structure and continuity. The second is to use the expanded triangle model of activity systems of Engstrom to capture concepts from activity theory that are relevant to the analysis of work practices and chatbot design, whilst giving a structured approach to the analysis.

Activity theory considers the road signal chatbot as a special kind of tool mediating human interaction with the world. Users use the road signal chatbot not because they want to interact with it, but because they want to reach their goals beyond the situation of the "dialogue" with the chatbot. Bødker and Grønbæk[29] called this, "users acting through the interface."[36] The road signal chatbot must be usable and enjoyable for the users. This is concerned with usability and UX.

2.3.1. Clarify the purpose of the activity

The first step in the design is to clarify the purpose of the activity. It is important to clarify the motives and goals of the activity system. The reasons are to understand the context within which activities occurred to reach a thorough understanding of the motivation for the activity

being modeled and any interpretations of perceived contradictions. Techniques that can be used include observations, interviews, and document analysis, *etc.* The information obtained will guide the construction of the problem space (deal with learning).

The following guidelines can be used to clarify the purpose of the activity:

(i) Generate a list of problems that road sign users typically deal with.

In this study, the problems identified are:

- Users find it hard to remember road signs after they passed the driving tests.
- Users who must learn the road signs for the driving test.
- Users find it hard to read the manual and remember the road signs.
- Road signs change due to new regulations by governments.

(ii) Who are the participants involved in the activity?

- The road drivers, learners to drive, pedestrians.

(iii) When and where do these problems normally occur?

- When driving or sitting for driving tests, or using the roads.

(iv) Generate a concise list of subjects, motives, and goals for each of the groups involved in the activity.

- The subjects are road drivers, learners taking up driving, driving school instructors, driving examiners, and anyone who wants to learn about road signs (road users).
- The motive is to be able to understand and use road signs.
- The goal is to apply knowledge learned from the road signs chatbot to use road signs effectively.

(v) What will contribute to the dynamics of the situation under review?

- Knowing the road signs will enable the users, whether they are student drivers, users of the road, or anyone who wants to learn and understand road signs and use road signs.

The information collected in this step will guide the construction of the problem space. The goals will define the objects of the problem.

2.3.2. Analyze the context for learning and use

There are different types of contexts. Context can be both internal to people (involving specific objects or goals) and external (involving artifacts, other people, and settings). There is also the environmental context, such as location and technical aspects concerning the chatbot. Important questions that should be considered are:

- How do things carry out in this context?
- Why you do it?
- Who is doing it, what he or she is doing, and why?

In the design, it is important to understand how things get done in a context, and why. The reason is that different contexts impose different practices. To analyze context, we must know the beliefs, assumptions, models, and methods commonly held by the group members, how individuals refer to their experiences in other groups, what tools they found helpful in completing their problem, *etc.* In addition, there are also external or community-driven contexts. These include issues such as:

How are tasks arranged among the members of the group working toward the object?

- What is the organization of the social interaction surrounding this activity?
- Which activities are critical?
- Is the division of labor flexible? How do we evaluate these roles and their contributions?
- What formal or informal rules, laws, or assignments guide the activities in which people engage?

2.3.3. Analyze the activity system using Engstrom's activity diagram

(vi) Define the subject by answering the following questions.

- Who is participating in the activity system?
  - The group of driving school learners and drivers who want to refresh their learning.
  - What are their roles?
  - The driving school students' roles as learners and the drivers as users.

(vii) Define the object by answering the following questions.

- What are the learning targets?
  - The road sign chatbot.
  - What is the expected outcome of the activity?
  - The outcome is to be able to use the road signs effectively.

(viii) Define the tools used by answering the following questions.

- What tools are used in this activity?
  - Tools include both physical and psychological learning environments.
  - What physical tools are used to perform this activity?
  - The physical tools used are iPad, the Internet, mobile device, books, manuals, videos, pens, *etc.*
  - What are the psychological tools used?

- These include procedures, techniques, instructions, government regulations, GPS, *etc.*

(ix) Define the community. The community includes the learners, driving school students, drivers, government agencies, driving instructors, driving examiners, parents, educational ministry, faculty members, administrative personnel, technicians, *etc.*

(x) Define the rules. The rules can be formal rules such as the instructions book on road signs, driving schools' regulations, government road safety laws, driving tests, highway code, *etc.* The rules for charging fees for each lesson for learners are determined by individual driving instructor as well as the procedure of the lesson.

(xi) Define the division of labor. The roles involved include learner drivers, instructors, driving test examiners, the Driver and Vehicle Licensing Authority, the Transport Department, driving schools, GPS providers, teachers, technicians, and others.

Figure 2 shows the roles played by different components of the activity system, such as the subject, tools, rules, community, object, outcome, and division of labor.

2.3.4. Analyze the activity structure

This step involves analyzing the activity structure (all of the activities that engage the subject), which defines the people of the activity system. The outcomes of this step will consist of a description of the activities, actions, and operations that are required to solve the problem. For each activity, it is decomposed into actions and operations.

Question: How is work being done in practice?

Answer: The chatbot guides learner drivers or drivers to find the road signs and use the road signs correctly.

Question: For each activity, what actions can be performed and by whom?

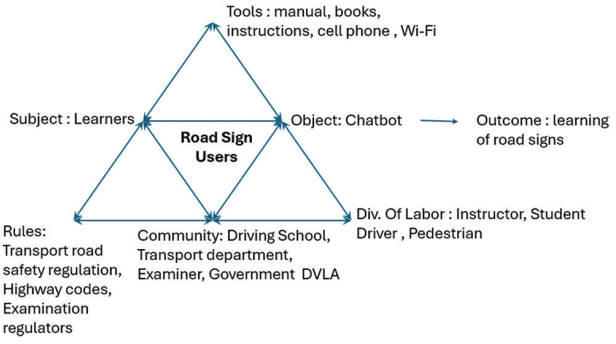

Figure 2. The chatbot activity system. Image created by the authors. Abbreviations: Div: Division; DVLA: Driver and vehicle licensing agency.

Answer: The drivers are guided to learn more about each of the road signs and their meaning and uses.

2.3.5. Analyze the development of the activity and its constituent components and actions

Since activities undergo permanent developmental transformations, it is important to analyze the history of target activities because it can help reveal the main factors influencing the development.[37,38] Analysis of potential changes in the environment can help to anticipate their effect on the structure of target activities.

(xii) What are the results of implementing the target technology on target actions? Did the expected benefits happen? (yes)

(xiii) Did the system show improvement over the process of its use? (yes)

(xiv) Are there benefits or disadvantages associated with the use of the system? (yes)

(xv) Did the tools support the transformations of existing activities into future activities? The users became more and more confident in the use of the chatbot and enjoyed using it.

(xvi) What is the history of the implementation of new technologies to support target actions? As time went by, the users found the system indeed supported the target actions they were doing.

(xvii) What are the predicted changes in target actions after new technology is implemented? The users became more proficient in using the chatbot and found it very useful.

The context modeling in literature[39] is shown in Figure 3. It is used to model the time or historical aspect of the activity we have adopted.

Although time is a crucial part of context, the current diagram is not reflective of the time aspect. But it is important not only to include current time, but also past time (a historical element of context) and future time. (This allows for the prediction of user's action from the current context.) To do this, we adopted the context modeling,[38] as shown in Figure 3.

The context model considers the elements that influence users' intentions. It will then be used as a framework in developing the context aware system. Time is an important element of context as it allows the system to keep records of the context of each activity in the past. This past context has a strong influence on users' intentions in doing their next activity as the user may take past experience into account in determining what they are going to do in the future. Time is added as another dimension to the activity theory model to represent context, as shown in Figure 3.

Time is information, such as date and time of day, when a particular activity is completed.

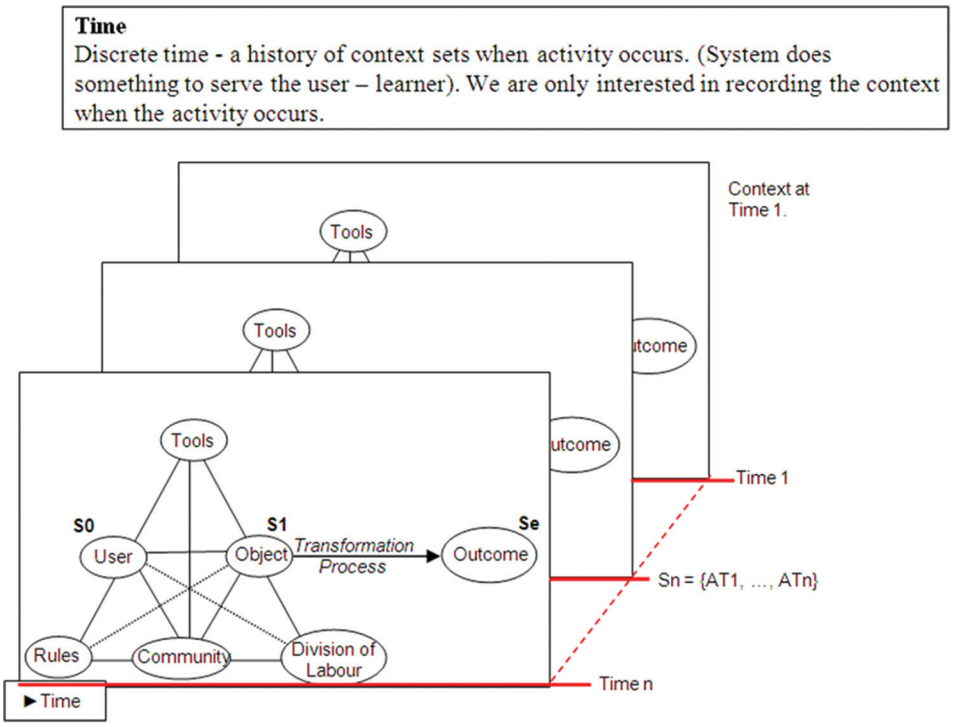

Figure 3. A depiction of the history of activity theory (after Kaenampornpan and O'Neil, 2004)[39]

The elements in the context model can be described as follows:

- User: Information about the user that the system is interested in and her physical environment that has influence on her activity, including user's current location, action, device, and timetable.
- Tools: Tools that are available and their availability, including device characteristics, public services, and computing environment such as network liability.
- Rules: Norms, social rules, and legislation within which the user relates to others in her community.
- Community: Information about people around the user (in both physical and virtual environments) that may have an influence on their activity.
- Division of labor: Roles of user in that situation including who can perform which tasks to the object.
- Object: User's intention and objective. The system uses all the elements above to decide about user's intention or objective.
- Time: This is a time in a particular situation when an activity occurs. The activity in this case is when the system reacts to context to support the user.

2.3.6. Analyze contradictions within the activity system

By identifying the tensions and interactions between the elements of an activity system, it is possible to reconstruct the system in its concrete diversity and richness, and therefore explain and foresee its development[36]

In this step, it is necessary to answer the following questions:

- Question 1: What are the dynamics that exist between the components of the activity system?
- Question 2: Are there contradictions or inconsistencies within the needs of these various components of the activity system?
- Question 3: What are the interrelationships that exist within the components of the system?
- Question 4: How have these relationships changed over time?

Several types of contradictions are identified in our mobile learning design, as shown in Figure 4.

(A) Potential primary contradictions in using the chatbot
  - At the object node, there is tension between the types of learning. It can be used in traditional instructions using the manual instructional book or road sign chatbot.
  - At the tool node, there is the issue of using chatbot compared to traditional manual.

(B) Potential secondary contradictions within the mobile learning environment
  - There is tension between the rules (use of chatbot) because it has an effect on the division of labor.

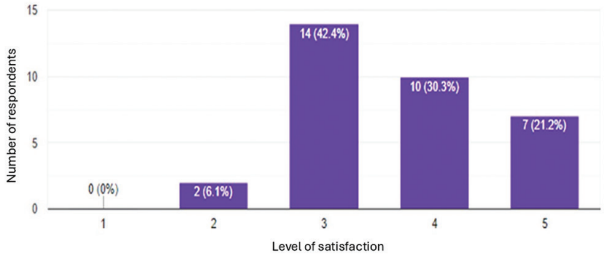

Figure 4. Satisfactory level of road sign chatbot

This tension exists because it is not clear what rules or regulations determine who should be involved in determining the use of signs.

- There are different perceptions of the activity object, which reflects the heterogeneous nature of the subject group and their object (*e.g.*, learning as knowledge construction or information gathering). This causes secondary contradiction.
- There is also tension between community (society) and the object node (learning road signs). Society needs to have students' drivers understand the road signs and use them effectively whereas student drivers are generally interested in passing examinations. This creates secondary contribution.

(C) Potential quaternary contradictions between the use of chatbot and traditional ways of learning the road signs

- There is also tension between the availability of technology and the use of chatbot.

2.3.7. Contributions of the use of activity theory to chatbot design

This study offers a novel contribution by operationalizing activity theory not merely as an analytical tool but as a practical design framework for developing a usable and engaging road sign learning chatbot. Unlike previous research that applies activity theory conceptually, this work systematically incorporates activity theory principles–such as the hierarchy of activities, contradictions, cultural-historical context, and tool mediation–into the end-to-end chatbot design process. It extends prior chatbot usability research by addressing the socio-cultural, historical, and context-dependent factors that influence user interaction, which are often overlooked by traditional usability models such as Nielsen's heuristics or Norman's design principles. Furthermore, this study proposes specific strategies for handling contradictions in chatbot interactions to improve UX and validates the approach through an empirical User Acceptance Test (UAT). By doing so, the paper provides new insights into designing context-aware, goal-directed, and culturally sensitive chatbots, thus advancing both the theoretical and practical understanding of chatbot usability and UX design.

3. Results

Engati also provides a chatbot template that comes with well-defined conversation flows, including display constructs such as messages, carousel cards, and more. Figure 5 shows part of the design of the conversational flow in the road sign chatbot using Engati. The chatbot answers user queries with regards to Malaysian road signs.

The road sign chatbot is based on textual exchanges between the bot and the user. Figure 6 shows the starting conversation with the road sign chatbot. Note that the chatbot offers three options to users: information on road sign definitions, fun facts, and quizzes.

For quizzes regarding road sign definition, users choose the definition, and the chatbot will ask the color of road sign that the user selects.

Figure 7 (left) shows the fun fact functions that the road sign chatbot offers. Figure 7 (right) shows the quiz functions.

3.1. Evaluation

The road sign chatbot was evaluated through a User Acceptance Test involving 33 participants, all of whom were undergraduate students from Asia Pacific University (APU) in Malaysia. The participants were aged between 18 and 25 years and represented a variety of academic disciplines, including information technology, engineering, and business. Before the evaluation, participants were provided with a brief demonstration and a user guide explaining how to interact with the chatbot. Each participant was then instructed to use the chatbot freely for a minimum of 15 min to explore its features, including road sign information, quizzes, and fun facts. Following their interaction, participants completed an online survey through Google Forms, which included questions assessing satisfaction, user-friendliness, engagement, and interface design. The evaluation focused on collecting initial user feedback to validate the usability and UX based on the activity theory-driven design. No control group was utilized in this study, as the primary objective was exploratory–to assess baseline perceptions of usability and satisfaction. Future work will consider the inclusion of comparative control groups to further substantiate the findings.

The respondents were asked:

- Question 1: Are you satisfied with the road sign chatbot?
- Question 2: Do you feel road sign chatbot is user-friendly for you?

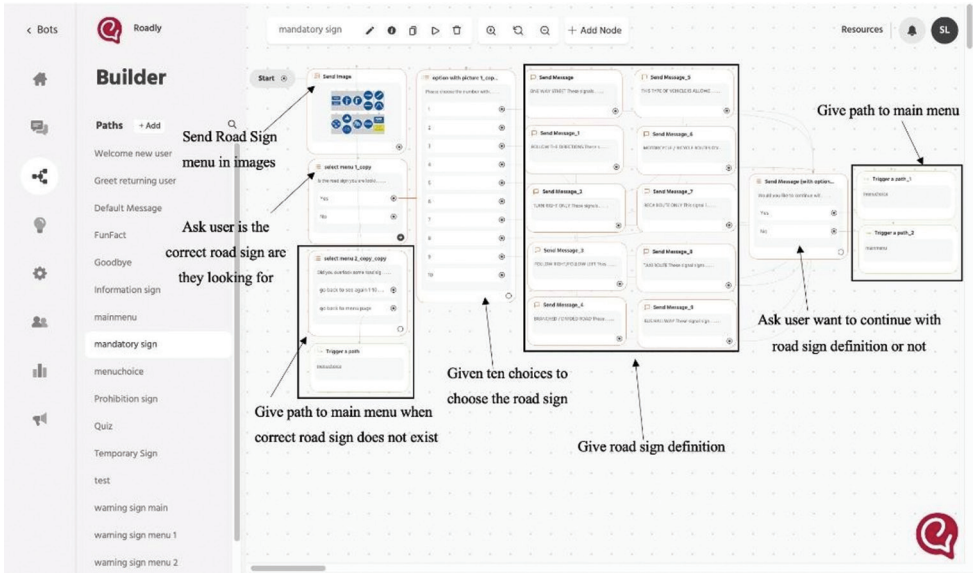

Figure 5. Conversational flow of road sign chatbot
Source: Engati.com.

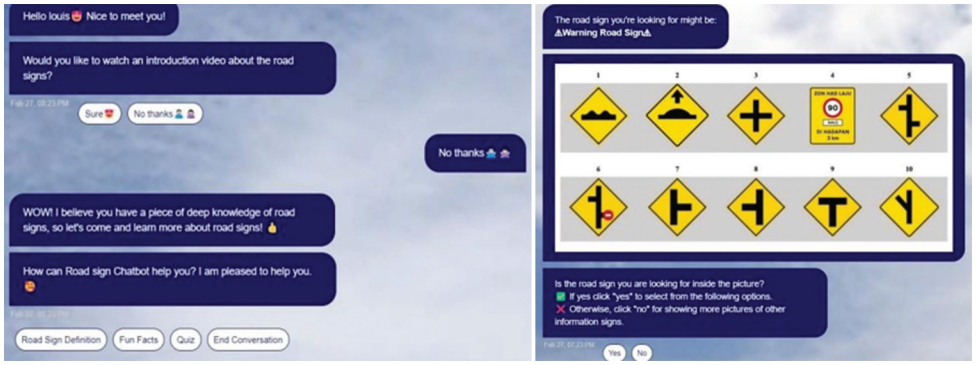

Figure 6. Introduction to the interface of the road sign chatbot

- Question 3: Do you think the interaction of the road sign chatbot is interesting?
- Question 4: Are you satisfied with the user interface of road sign chatbot?
- Question 5: Would you recommend road sign chatbot to be used?

The following sections show the summary of responses to these questions and the statistics. Figure 4 shows the summary of responses for Question 1 with regard to the usage satisfaction from the scale of very dissatisfied to most satisfied. The highest percentage response to this question is satisfactory, which is 42.4%.

Figure 8 shows the summary of responses for Question 2 with regard to user-friendliness from the scale of least friendly to most friendly. The highest percentage response to this question is very friendly, which is 51.5%. Similarly, the responses for Question 3 with regards to interactivity from the scale of least interactive to most interactive also achieved the same percentage, which is 51.5%, as shown in Figure 9.

Figure 10 shows the summary of responses for Question 4 with regard to user satisfaction with user interface from the scale of very dissatisfied to most satisfied. The highest percentage response to this question is neutral, which is 36.4%. Finally, Figure 11 shows the summary of responses for Question 5 with regard to potential recommendations from the scale of very dissatisfied to most satisfied. The highest percentage response of this question is neutral, which is 36.4%.

4. Discussion

Activity theory can be effectively used to design chatbot. The design of context is crucial for successful chatbot application. Designers can use activity theory to help them to better understand the social and material relations that

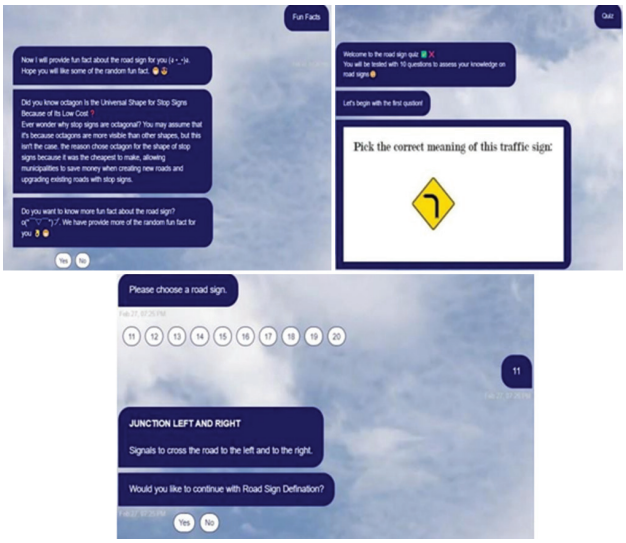

Figure 7. Fun facts (left) and quizzes (right) told and asked by the road sign chatbot

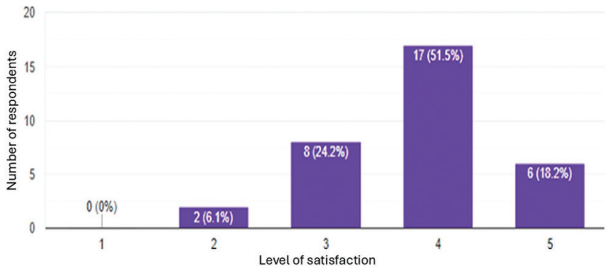

Figure 8. User-friendliness of the road sign chatbot

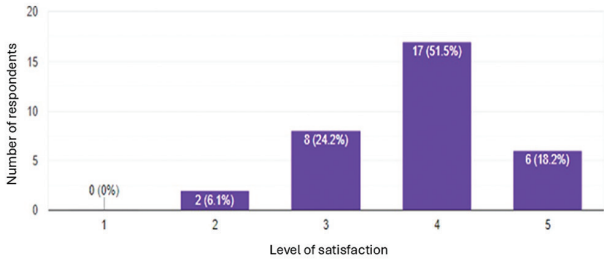

Figure 9. Perception of the interactiveness of road sign chatbot

affect complex human learning and learners' interaction with others as mediated by tools. Activity theory provides a philosophical framework for designers to understand collective human work activities as embedded within a social practice (*e.g.*, an institution), and mediated by artifacts, such as chatbots.

Although activity theory offers many benefits for designing usable chatbot, but it also has limitations. First, the designer using it must have a complete understanding of the activity system under observation, including the

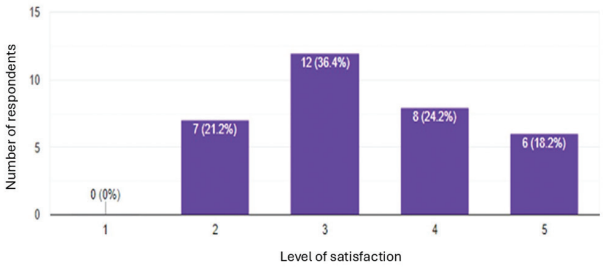

Figure 10. Satisfaction with the user interface of the road sign chatbot

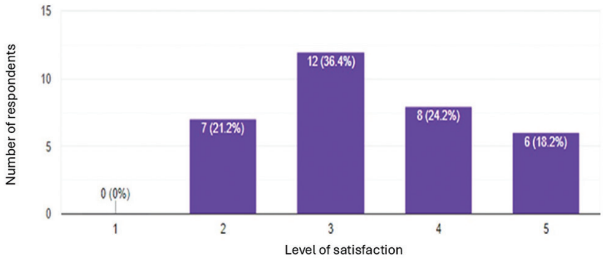

Figure 11. Recommendability rating of road sign chatbot

dynamic interplay of all the units of the activity system.[32] Second, the designer must be able to unravel the activity systems. Third, the designer must be able to distinguish between the levels of activity, actions, and operations.

This study offers a novel contribution by operationalizing activity theory not merely as an analytical tool but as a practical design framework for developing a usable and engaging road sign learning chatbot. Unlike previous research that applies activity theory conceptually, this work systematically incorporates activity theory principles–such as the hierarchy of activities, contradictions, cultural-historical context, and tool mediation–into the end-to-end chatbot design process. It extends prior chatbot usability research by addressing the socio-cultural, historical, and context-dependent factors that influence user interaction, which are often overlooked by traditional usability models such as Nielsen's heuristics or Norman's design principles. Furthermore, this study proposes specific strategies for handling contradictions in chatbot interactions to improve UX and validates the approach through an empirical User Acceptance Test. By doing so, the paper provides new insights into designing context-aware, goal-directed, and culturally sensitive chatbots, thus advancing both the theoretical and practical understanding of chatbot usability and UX design.

Although this shows a novel contribution to the design of usable chatbot with optimal UX for users, there are several limitations in this study.

4.1. Potential biases in user feedback

There are several potential biases in user feedback. First, sampling basis may occur when the group of users providing feedback is not representative of the broader target user population.[19] Second, in chatbot development, users might hesitate to criticize a chatbot directly, especially if they perceive that negative feedback could harm the development team's efforts. This is known as social desirability bias. This can lead to over-optimistic evaluations and under-reporting of usability issues.[39] Third, there is confirmation bias when users unconsciously seek information that supports their existing beliefs or expectations about the chatbot, rather than providing objective feedback.[40] Fourth, the emotional state of users during interaction or testing can influence their feedback.[41] A frustrated or tired user might evaluate the chatbot more negatively than one who is relaxed and engaged. Fifth, some users might experience expectation bias when they expect too much from the chatbot, interpreting any minor failure as a major flaw. Others might have low expectations and accept mediocre performance without critique.[12] Sixth, users may experience recency bias when evaluating a chatbot, disproportionately focusing on either early struggles or final improvements, thus providing unbalanced feedback.[8]

The user evaluation was conducted exclusively among undergraduate students aged 18 – 25 years from APU. As digital natives, participants were likely feeling more comfortable interacting with chatbot interfaces compared to the general population. This introduces potential bias toward positive usability and UX ratings. Furthermore, since participation was voluntary, there may have been a self-selection bias, where students interested in technology were more inclined to participate, skewing results toward more favorable impressions.

4.2. Limitations of using Engati as a chatbot platform

Chatbots have become integral to modern customer service strategies, providing 24/7 support and streamlining interactions. Engati has emerged as a notable platform in this domain, offering features such as omnichannel deployment and a no-code interface. Engati, while offering a user-friendly interface and multi-channel deployment capabilities, presents several limitations that may hinder its effectiveness in complex or large-scale applications. These include:

- Limited customization and flexibility. Engati's no-code approach, while accessible, restricts the depth of customization available to developers. Users have reported challenges in tailoring chatbot behaviors beyond predefined templates, limiting the platform's adaptability to unique business processes.[42]
- Performance and reliability issues. User reviews indicate concerns regarding Engati's performance, including system lags and occasional downtime.[42]
- Integration constraints. Although Engati offers integrations with tools like Salesforce and Google Sheets; however, users have noted difficulties in establishing and maintaining these connections, citing limited integration options and complexity.[43]

Besides the above, the platform primarily supports rule-based conversation flows, which restrict the chatbot's ability to handle highly dynamic, unpredictable user inputs. Advanced AI integration, including deep contextual understanding or adaptive learning capabilities, is limited unless supplemented by external services. Additionally, customization options for complex backend functionalities are constrained, posing challenges for expanding the chatbot into more sophisticated intelligent systems.

4.3. Scalability of the chatbot to other contexts

Activity theory not only can guide the development of road sign chatbots but also can facilitate their scalability across multiple domains. Activity theory's systemic view of user goals, tools, community, and context offers a framework to generalize chatbot usability and UX design. Activity theory provides a robust framework for modeling socio-technical systems by understanding how users engage with tools to achieve their goals within specific cultural and contextual settings.[18,22,31,37] It posits that all human activities can be analyzed through common structural elements: subject, object, tools, rules, community, and division of labor.[44] These elements are transferable across domains.[28] Tool mediation in activity theory allows the chatbot to evolve in form and function as new domains demand different representations of knowledge and interaction styles.[45] This adaptability is critical for cross-domain scalability.

The road sign chatbot, although designed for Malaysian road signs, demonstrates potential for scalability to other educational and informational domains. However, successful adaptation would require careful customization, including language localization, content reconfiguration for different regulatory environments (*e.g.*, different countries' road rules), and interface adjustments to meet diverse user expectations. Moreover, the current platform's dependency on predefined conversation structures may necessitate additional development effort to support broader scalability across multiple contexts or user groups.

5. Conclusion

Both usability and UX must be considered in the design of effective chatbots, as they influence how easily and

satisfactorily users can interact with the system. It is our belief that activity theory provides a robust framework for understanding and designing usability for effective chatbots by focusing on human activities, the tools mediating these activities, and the context in which they occur. It also provides a structured approach for designing UX by focusing on the interaction between users, tools (*e.g.*, chatbots), and their environment. This paper describes the use of activity theory to design a road sign chatbot that offers information on road signs in Malaysia to the road users. The road sign chatbot was evaluated through a User Acceptance Test, and the evaluation showed that users found the system easy to use, satisfactory and enjoyable to use.

Traditional approaches to chatbot design often emphasize usability heuristics, cognitive modeling, or behaviorist paradigms. This paper argues that activity theory provides a novel and more holistic framework for chatbot design, capturing complex user motivations, contextual factors, and socio-cultural mediations. Unlike other models that focus narrowly on interactional patterns or user satisfaction, activity theory enables designers to embed chatbots into broader human activities, enhancing both usability and UX. It offers a powerful lens to view interactions not merely as input–output exchanges but as culturally situated, goal-directed activities mediated by tools. This paper highlights the novelty and value of applying activity theory to chatbot design, showing how it transcends conventional paradigms and enhances both usability and UX.

The novelty of activity theory lies in its capacity to design not just for momentary interaction quality but for sustainable, context-sensitive, and evolving UXs. By embedding design within activity systems, activity theory allows chatbot developers to understand how contradictions and breakdowns reveal deeper usability issues, tailor interfaces to evolving user goals and environments, and anticipate socio-technical implications in deployment contexts. Designing with activity theory ensures that chatbots do not merely serve functions but become meaningful, adaptive parts of human activity.

This study demonstrated the application of activity theory to design a usable and engaging road sign chatbot for improving road sign education. User acceptance testing confirmed positive perceptions of usability, satisfaction, and interaction quality, supporting the effectiveness of the activity theory-driven design.

Practically, the road sign chatbot can be used as a supplementary learning tool in driving schools, public road safety campaigns, and educational digital platforms. Future work will focus on expanding the chatbot to support multiple languages, improving dynamic conversation capabilities, and adapting the system for broader educational domains. Additionally, we aim to formalize a scalable activity theory-based framework to guide the development of context-aware chatbots across diverse learning contexts.

Given the small sample size for evaluation, more empirical studies are warranted. The current study provides a foundation to develop a framework to guide users to design effective, usable and enjoyable chatbot applications. Further empirical studies are needed to verify this method. It is also important to allocate more time to understand and study the objects of activity, the changes of those objects over time, and their relations to objects in other settings. In addition, designing usable and user-friendly chatbots necessitates a commitment to understanding satisfaction level and experiences from the users' point of view.

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Conflict of interest

The authors declare that they have no competing interests.

Author contributions

Conceptualization: Lorna Uden
Formal analysis: Vinothini Kasinathan
Investigation: Vinothini Kasinathan
Methodology: All authors
Visualization: All authors
Writing – original draft: All authors
Writing – review & editing: Lorna Uden

Ethics approval and consent to participate

This study was conducted in accordance with the ethical standards of APU. Although formal approval from an Institutional Review Board was not obtained, the research

adhered to institutional guidelines for educational research involving human participants.

Participation was entirely voluntary, and all participants were clearly informed about the purpose and procedures of the study. Written informed consent was obtained from each participant prior to their involvement. No personally identifiable information was collected, and responses were kept strictly anonymous and confidential.

Consent for publication

Verbal informed consent was obtained from all participants prior to their involvement in the study. Participants were clearly informed that their responses would remain anonymous and that no personal identifying information or images would be collected or published. All data were collected and analyzed in a manner that ensured participant confidentiality. No identifiable information appears in the manuscript or accompanying materials.

Availability of data

The datasets generated and analyzed during the current study are not publicly available due to participant confidentiality and institutional data protection policies. However, anonymized data may be made available from the corresponding author upon reasonable request, subject to approval from the authors and compliance with data protection regulations.

Further disclosure

The research described in this manuscript has been conducted solely for the purpose of this publication. The findings have not been previously presented at any conference, academic meeting, or congress, and the manuscript has not been deposited in any preprint server. All data were collected specifically for this study using a structured questionnaire administered via Google Forms.

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ARTICLE

Beyond carbon credits and green certificates: Designing a climate-change awareness club for new automobile buyers

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Abstract

Initiatives like carbon credits are not sufficient for addressing climate change, particularly if reliance is placed solely on corporations. This study proposes a grassroots initiative in which new automobile buyers join a club that fosters conscious environmental responsibilities through a symbolic declaration of their commitment, and also creating a personal identity. The suggested approach will not only create new sustainable values but also enhance the quality of life by supporting integration into emerging environmental ecosystems of consumption and production. By embedding persuasion using behavioral economics, these changes can be achieved by nudging fossil fuel car buyers using creative marketing strategies and well-designed, recognizable products.

Keywords: Climate change; Carbon footprint; Internal combustion engine cars; Sustainable choices; Grassroots initiatives

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1. Introduction

The world is experiencing unprecedented environmental changes. Climate change is no longer dismissed as a hoax or conspiracy theory perpetuated by nihilists seeking to elicit public panic. According to a report by the World Resources Institute, forest fires are worsening.[1] Fire plays a crucial role in natural regenerative and terrestrial ecosystems,[2] and many plant species rely on forest fire for regeneration and seed dispersal. However, contemporary shifts in climate are affecting wildfire activity, signaling a pyrogeographical shift in wildfires due to changing weather conditions.[3] Additionally, the intensity and impact of hurricanes are increasing as a result of rising sea surface temperatures—a direct result of climate change.[4] An article by the Environmental Defense Fund notes that the most damaging United States hurricanes now occur three times more frequently than a century ago, and the proportion of major hurricanes (Category 3 or above) in the Atlantic Ocean has doubled since 1980.[5] The 2024 hurricane, Helene, directly impacted one of the authors of this paper. The visual evidence of its devastation far surpassed what statistics alone can convey.

In response to climate change, businesses and governments have been exploring different strategies. One of the most prevalent and popular strategies is buying carbon

credits as part of the cap-and-trade program, which contributed to a significant reduction in acid rain at one point. However, these programs have, for some, devolved into what is perceived as a superficial effort rather than a genuine solution. To many, carbon credits now represent a "pay-to-pollute" mechanism and are insufficient on their own to address the climate crisis. This paper proposes nudging the new fossil fuel car buyers into joining an environmental club upon purchasing a new vehicle. The aim is to foster awareness and to promote a higher quality of life through collective action linked with their purchase.

2. The philosophical foundation of the club

The club will build upon the concept of pay-to-pollute by introducing green certificates for the purchase of new automobiles. This concept was introduced by Lai *et al.* in 2023[6] in the article "Walk and Chew Gum: A demand and supply illustration of macro and micro net-zero initiatives for the automobile industry." It proposes an individualized, decentralized approach (rather than a government regulatory approach) to carbon credit trading without relying on specific cap-and-trade programs. Green certificates represent a carbon capture-based solution, objectively calculated based on a new car's projected lifetime carbon emissions. These emissions are then translated into the number of acres of trees needed to absorb the vehicle's total carbon emissions over its lifespan. Essentially, this approach replicates the effect of a Pigouvian tax on pollution without requiring any intervention from a central government authority or an organized carbon-credit trading platform.[17] In addition, open market carbon-credit prices in various regions worldwide are unreliable.[6] The proposed club aims to create a platform for authentic information and discussions about forest fires, alongside educational and recreational activities such as forest field trips and ocean study cruises. Substantive discussions will be conducted via appropriate social media platforms, combining education and entertainment.

Broadly, carbon credits function as macro measures[6] that are often used as international agreements for deciding a country's climate change responsibilities. However, they can risk being superficial tools of carbon offsetting through redemption, without necessarily achieving the intended behavioral change. In contrast, micro measures such as green certificates[7] tend to have a longer-lasting impact on human psychology because they engage individuals on a personal level, thereby fostering stronger environmental responsibility. Thus, to achieve the requisite goal against climate change, a strategy combining both macro and micro solutions is essential. The proposed club will also closely examine the dynamics of carbon credits and green certificates, understand the motivations, psychological drivers, and any ethical dilemmas involved.

Demand for carbon credits is driven by three key factors: compliance requirements, moral self-licensing, or reputational gain. First, companies purchase carbon credits to comply with greenhouse gas regulations. Compliance can also be driven by an organization's need for redemption, motivated by underlying environmental concerns. The original intent of the cap-and-trade program[6] was to incentivize innovation and investment in cleaner technologies. In many ways, this concept ties into the theory of moral licensing, where organizations view purchasing carbon credits as atonement for their environmental impacts.[7] However, acquiring a moral license should exceed mere self-satisfaction. The proposed club seeks to transform inspirations into aspirations, creating a sense of belonging for its members and cultivating a forward-looking, action-oriented ecosystem for the future. Finally, reputational gain is significant for both corporations and individuals. The proposed club addresses how individual reputational gain can be enhanced by purchasing carbon credits linked to new car purchases. Designing a symbol to represent this mission is crucial for uniting members in this cause.

2.1. A grassroots "think big-do big" initiative for enhancing the quality of life

The concern over hypocritical corporate practices is well-founded. Historical developments of sustainability from corporate social responsibility to more recent controversion, ESG movements had shown that society cannot entirely rely on corporate reforms to solve climate change problems. While corporate activism is still important, as described by Henderson,[8] with deep-rooted histrorical skeptocism noted on the role of corporations in a society,[9] numerous studies can be cited from the positive, negative, and internal inconsistencies of corporate intentions.[10] Yet, without overlat stressing the rights and/or wrongs of corporations,[11] we wish to get at the heart of our problem in this paper (how to build a personal identity for a product that will have an impact on a narrowly focused industry). For that, we believed a grassroots movement starting with individuals is important. The club proposed in this paper consciously rejects performative disingenuousness by arguing that combating climate change requires a lifestyle change at the individual level. It will be built on authentic personal commitment, prioritizing genuine environmental pledges over performative pledges.

[1] See the method of calculating the price of green certificate, the foundation in marketing literature, and behavioral and psychological theories-led marketing blurb suggestions in Lorne and Purmehdi, 2025.

A symbol of commitment at a personal level can be enhanced by meticulous designs, as shown in Figure 1.[2] Few symbols are as visible and enduring as a driver of a fossil fuel car displaying the proposed license plate for 10–15 years as part of a one-time lifetime club membership that goes with the serial number of the car. Public figures like Taylor Swift could play a powerful role in promoting sustainability by publicly embracing this initiative. A simple gesture, such as affixing the license plate to the personal vehicle, could serve as a strong gesture of personal commitment to addressing climate change and also a personal identity. In 2023, Taylor Swift generated USD2 billion in revenue, surpassing the earnings of most corporations.[3] With 284 million followers on Instagram, she ranks among the world's most influential celebrities. Although she currently uses carbon credits to offset her travel-related emissions, her direct involvement in a club dedicated to sustainability would be a far more effective contribution. Despite topping charts as the celebrity with the highest carbon emissions, her representative stated that she purchased twice the number of carbon credits required to offset her footprint. However, acquiring carbon credits without a proactive involvement in climate change solutions risks being viewed as hypocritical. In contrast, joining the club would enable her to take visible, meaningful steps toward reducing emissions, thereby reinforcing a genuine commitment to sustainability.[4]

2.2. Design work

Yitai Crystal Craftwork, Dongguan, China, specializes in making crystals of similar quality to Swarovski, Austria. Aside from households and commercial decorative and functional items, the company operates a specialized division for the automobile industry. Yitai, China, and the International Regional Development (IRD), United States, collaborated in designing various items associated with the identity of the proposed new quality of life club linked to the purchase of new cars. Joining the club provides members with a distinct personal identity, symbolizing an individual's commitment to a new quality of life as reflected through their new vehicle. Figure 2 shows the detailed work of how crystals are designed and arranged around a license plate would look like.

Figure 1. The green crystal frame for Michigan's car license plate, manufactured and licensed by the club to Yitai Crystal Craftwork, Dongguan, China

Figure 2. Uniform quality of design

Note that in Figure 2, each piece can also be etched with the signature of a person making the frame completely personalized, adding to the personal identity to the design Needless to say, this design is for a celebrity class of car buyers, e.g., Taylor Swift, as qualified in footnote 2. In this sense, the proposed club will target supports of celebrities as a better use of funds as an alternative to whatever climate-change initiatives they are currently contributing to.

The concept of moral-self licensing, where buying carbon credits leads individuals to feel they have fulfilled their environmental commitment without making genuine behavioral changes, warrants renewed discussion. This is completely different from other carbon credit programs that enabled organizations to masquerade as environmentally conscious entities while maintaining their usual operations. The proposed club will be unique by comprising new vehicle buyers who

[2] Crystal frames are provided for exclusive clients only, typically celebrities. As celebrities, they usually park their cars in private garages. If damaged, the license plate must be completely remade, which can be included in the original license contract with a particular celebrity.

[3] https://www.billboard.com/business/business-news/taylor-swift-earned-2-billion-music-movie-touring-1235555994/

[4] https://carbonmarketwatch.org/2024/02/13/taylor-swift-and-the-top-polluters-department/

commit themselves as catalysts for change. To foster zealous participation, the automobile buyers' club will offer different membership categories based on the level of engagement each member desires. Those intending to contribute more significantly will pay higher fees, embodying a model of participatory licensing at the club's core. Incentives for participation will be closely tied to the issues and activities promoted within the club, generally crafted and discussed on social media and the club's website for public transparency. Additionally, a localized membership platform will facilitate grassroots localized events and activities shared exclusively among members within their specific jurisdiction.

The proposed club allows member to select their membership categories based on the level of participation they wish to commit to the "think big-do big" endeavors. This system uses color-coded crystals to denote different scales of involvement; green represents grassroots, local-level initiatives, orange signifies participation in country-level efforts, and purple indicates engagement in global or world-level activities. Figure 3 shows how single crystal can be attached to a license plate. Figure 4 shows the license plate of the grassroot local level of membership.

The fundamentals of establishing a club have long been recognized by economists.[12,13] The proposed automobile buyers/high-quality lifestyle club represents an application of the various theoretical concepts featured by economists. The constitution of this club will begin with drafting a legal document locally, and will gradually be revised over time to realize a global vision.

3. Other carbon-credit suppliers

In this context, it is essential to understand the motivation of carbon credit suppliers. While much of the discourse focuses on the demand side, the existence of the market fundamentally depends on the suppliers, whose motivation and commitment warrant closer examination. Are they driven solely by profit, or do they embody genuine green visionary principles?

Many carbon offset projects, such as those involving forestry, cookstoves, and renewable energy, often originate with the intent to protect local ecosystems. However, these efforts have frequently been compromised by profit-driven actors. Creating and supplying carbon credits can be a way for an organization to demonstrate its commitment to the environment and thus enhance its brand.

Similarly, cognitive dissonance may influence supplier behavior; by supplying carbon credits, organizations ease their internal conflict between their environmentally conscious values and their emission-intensive activities.

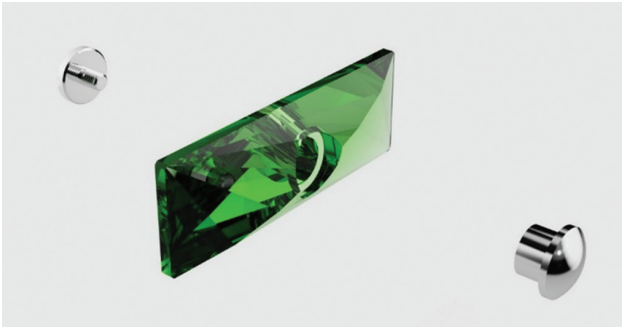

Figure 3. Attachment mechanism of a crystal to a plate

Figure 4. The appearance of the crystal on a license plate (denoted by the red arrow)

For example, the pulp and paper company APP Sinarmas allegedly generated and supplied carbon credits through reforestation and avoided deforestation (REDD+) projects while simultaneously being accused of ongoing deforestation activities and peatland development activities.[14]

Additionally, for companies like Tesla, supplying carbon credits provides a competitive advantage. This strategy not only serves as social signaling to sustainability-focused investors and customers but also provides investors with a stable return through revenue generated from carbon credit sales.[15] Although Tesla's tactics may verge on performative, its strategic positioning as a green company has effectively reinforced its brand and positioned it at the forefront of the carbon offset market. Tesla enjoys a quasi-monopoly in this domain by maximizing its carbon credit allocation as a "pure play" zero-emission company. Despite these dynamics, it is important to acknowledge altruistically driven suppliers of carbon credits. Social enterprises often operate by a genuine desire to effect positive environmental change. However, these efforts are often marred by financial viability and ecological ineffectiveness of these projects. Additionally, suppliers sometimes overestimate the impact of their carbon offset projects. As an example, South Pole, a leading carbon developer, was accused of overstating the climate benefit of the carbon credits generated by its REDD+ projects in Kariba.[16]

Can carbon credits and green certificates fully solve the climate change crisis? The answer is no. Critics argue that carbon credits serve as a band-aid solution, influenced by the psychological tendencies of both buyers and suppliers. In contrast, micro measures, such as joining an environmental club, entail small, actionable steps with small measurable changes leading to large, sustained behavioral changes.[6] There is a need for micro solutions such as green certificates, which offer a nuanced, customer-focused approach to environmental responsibility that embodies the principle of Pigouvian taxation. Green certificates function as a non-traditional, voluntary form of carbon tax, representing a one-time fee equivalent to a vehicle's lifetime carbon emissions. The funds collected from green certificates are earmarked and utilized primarily toward nature-based mitigation efforts, such as tree planting, thereby directly linking the cost to tangible environmental benefits. The amount associated with the green certificate is tailored to vehicle emissions and calculated based on factors like fuel type, efficiency, and expected usage. Furthermore, it incorporates additional information that can enhance the overall quality of life, focusing on individual actions. When aggregated, these individual actions can lead to a bigger macro impact.

4. The marketing of green certificates

Green certificates can serve as a marketing tool to promote conscious environmental responsibility. The mechanism involves nudging consumers to be more eco-friendly in various creative ways. For example, integrating green certificates as a default option at the point of car sales, unless actively declined, can enable small changes to accumulate into a significant impact. The concept of nudging in marketing was awarded an Economic Nobel prize for studying behavioral economics.[17] By reviewing different types of nudges,[18] promotion tactics can be tailored to new car purchases for different cultures and regions, considering the demographics of the targeted audience. In doing so, awareness of climate change solutions aimed at enhancing quality of life can be bundled with vehicle sales, just like insurance is commonly included with automobile purchases.

Equally important, green certificates incorporate an element of conspicuous consumption that allows consumers to publicly signal their environmental commitment to friends and the wider public. Driving a car as a "member of a club", consumers can gain social recognition while reinforcing their sustainable behaviors. This can satisfy the need of buyers (demanders) of carbon credits and may ultimately compete with other brand-name green products that are already successfully accepted in the market,[19] as exemplified by many sustainable fashion products that have successfully adopted this strategy.

This marketing approach makes auto dealerships the ideal venue to promote green certificates, given their pivotal role as the interface between customers and their point of purchase. By showcasing the green certificate program as an integral part of responsible auto ownership, dealers can nudge consumers toward becoming environmentally conscious buyers, igniting a localized impact.

Additionally, due to their direct interaction with consumers, dealerships can facilitate faster adoption by educating consumers about the positive aspects of green certificates, offering customized products, and promptly addressing customer concerns interactively. This personalized approach benefits the dealership in creating a long-term relationship within the community and customers committed to sustainability. A suggested method of marketing is shown in Figure 5.

The marketing of green certificates can be extensive, even within North America alone. According to the National Automobile Dealer Association,[20] there were 16,835 franchised light-vehicle dealers in the United States, collectively selling 15.5 million light-duty vehicles in 2023. Total light-vehicle dealership sales exceeded USD1.2 trillion. In Canada, there were 4,561 new car dealers in 2024,[21] and these figures are expected to grow. Even if only 10% of the dealers choose to adopt green initiatives, the club's membership base could become substantial. As illustrated in Figure 6, "going green" at dealerships often remains limited to superficial gestures such as exterior decorations, rather than aiming for substantive changes in lifestyle proposed by the environmental club. Advocating for Leadership in Energy and Environmental Design certification or implementing its processes in car dealership operations is not the only way to "go green". The automobile industry's contribution to combating climate change needs to be far more comprehensive and systemic.

Figure 5. Auto showroom accessories
Source: https://juniordavis.com/news/automotive-promotional-products.

Figure 6. Decoration of a green dealership
Source: https://canadianautodealer.ca/2013 / 11/going-green.

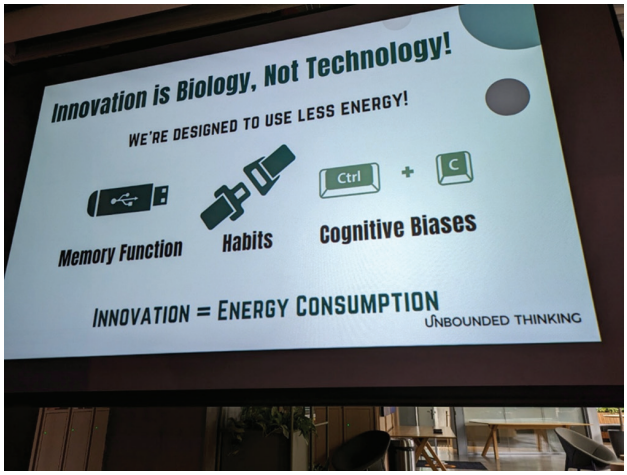

Figure 7. Template displayed by Unbounded Thinking
Source: Photograph by the authors.

5. Conclusion

The current measures to tackle climate change using carbon credits are well-intentioned but partially, if at all, effective, as they fail to tackle the root cause of climate change: human behavioral change, particularly the widespread insensitivity to the true private and social costs of energy consumption. Building on the preceding discussions of carbon credit and green certificates, we have explained the motivation behind the design of an environment club grounded in personal commitments and the creation of personal identity. The proposition illustrated in Figure 7, which captures a slide from a public forum, can be suggestive to those who are willing to make personal commitments within the climate change movement in designing their local/regional club activities.

Figure 7 is suggestive in the sense that for lifestyle changes of various kinds, all could be aiming for a reduction in energy consumption. Climate-change consciousness ultimately has to tie with smart energy usages, not only on industrial production but also at a personal level calling for a change in lifestyle. A personal commitment to lifestyle changes in establishing a new self-identity in that sense could arise from a biological need. It can certainly be used as a food for thought for any grassroot attempt in the building of the club going forward.

Whether one accepts the premise in Figure 7 or not, there is a pressing need to start a zero-emission movement at the individual level for changing habitual, energy-wasteful activities. This effort must extend beyond corporate Environmental, Social, and Governance practices. As reviewed in this study, organizations that advertise their green commitment through the purchase of carbon credits are often hampered by a lack of genuine commitment, transparency, or regulatory control. Companies like Shell, Cadbury, Mars, and Asia Pulp and Paper exemplify the use of carbon credits as a form of atonement or a pay-to-pollute mentality. Green certificates, on the other hand, present an alternative solution by privatizing a Pigouvian tax.[6] When combined with macro-level policies, green certificates can influence human behavior and promote a sustainable and responsible society by utilizing marketing tactics that resonate with customer values.

To drive genuine environmental change, we must integrate macro-level country policies with micro-level behavioral nudging of green certificate purchases. Marketing via car dealerships has been suggested in this article as a pragmatic method to promote membership for a club of new automobile buyers, with a participatory license that can generate real climate-change actions. Club members must ensure transparency in their collective decisions by buying appropriate carbon credits from responsible suppliers. Simultaneously, carbon markets and businesses each have their institutional features that need to align with practices compatible with their commitments. We focus on a design using high-quality crystals to raise awareness. Consumers must be empowered to make informed, sustainable, voluntary choices, especially given the significance of purchasing a new car for most individuals. This paper helps to promote an international endeavor in these possible frontiers. Ultimately, the goal is to create sustainable values[7,22] while recognizing that good governance is equally important,[23] as member loyalty requires absolute confidence in financial stewardship. This effort aspires to mark the beginning of a widespread movement, choosing new automobile buying as a fertile ground for cultivating a climate-change awareness lifestyle among new car buyers.

Theoretically, a crucial difference separates the proposed automobile buyers' club from other carbon credit trading platforms: Beyond being voluntary and individual-based—unlike most government-mandated or, in some cases, privately exploited cap-and-trade platforms—the club concept is demand-pulled, driven by consumer choice rather than supply-pushed mandates. Ultimately, credibility for any climate initiative requires the effective alignment and cooperation of both the demand and supply sides.

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Conflict of interest

The authors declare that they have no competing interests.

Author contributions

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Further disclosure

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ARTICLE

Evaluation of recreational suitability of urban waterfront green spaces: A case study of Calligraphy Square in Linyi, Shandong, China

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Abstract

Urban waterfront green spaces are key elements in the urban framework, enhancing city livability. Centered around water bodies, they often form the most vibrant open spaces in cities. They offer people leisure, entertainment, fitness, and other diversified activities, enriching the cultural life of citizens. In addition, developing waterfront green spaces helps enhance a city's image and foster residents' sense of belonging and pride. At present, there is limited research on evaluating the recreational suitability of urban waterfront green spaces. This study aims to establish an evaluation system for recreational suitability tailored for Linyi's waterfront green spaces. The Delphi method and analytic hierarchy process were employed to screen evaluation indicators and determine their weights, constructing the evaluation system. The evaluation standards were clarified, and Linyi Calligraphy Square was evaluated as an example. Data were gathered through questionnaires, on-site surveys, and reviews. The fuzzy comprehensive evaluation method showed that the recreational suitability score of Linyi Calligraphy Square is 4.004, indicating a high level of recreational suitability. Among these, the evaluation results rated the facility (0.42), recreational experience (0.484), and location and transportation (0.375) as "very good," the environment (0.503) and landscape (0.391) as "good," and the resources (0.439) as "average." Based on these results, suggestions were made for Linyi Calligraphy Square, including increasing children's activity facilities and venues, strengthening safety measures for water-related recreation, and providing reasonable and effective references for future development and construction.

Keywords: Analytic hierarchy process; Fuzzy comprehensive evaluation; Linyi Calligraphy Square; Recreational suitability; Urban waterfront green spaces

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1. Introduction

With the continuous innovation of urban development concepts, the construction of green and ecological cities has gradually become mainstream.[1,2] The structure and function of urban waterfront green spaces, as the driving force of the economy and industry, have become increasingly complex.[3] Meanwhile, these spaces also play an important role in enhancing residents' well-being and meeting their spiritual needs.[4,5] Therefore, the construction of urban waterfront green spaces and the improvement of these existing spaces have received extensive attention.

Foreign scholars have researched the recreational suitability of urban waterfront green spaces from various perspectives. Japanese scholars selected five rivers in Japan as research samples for four dimensions: landscape shaping, recreational function, environmental protection effectiveness, and public participation level. They conducted a comprehensive analysis and evaluation of urban riverside greenways, concluding that the development of these greenways should integrate their natural resource endowments with local characteristics.[6] Similarly, Steinwender *et al.*[7] conducted a comparative study by investigating tourists' satisfaction with the water environment quality of urban waterfront spaces, selecting six static and six dynamic water bodies in Vienna. They concluded that differences in participants' impressions of the water spaces were also decisive factors affecting the final results. Sairinen and Kumpulainen[8] conducted research on the enhancement and transformation of urban waterfront green spaces in Helsinki, evaluating and analyzing them from the perspectives of resources and status, development experience, and recreation. Meanwhile, Kong-Jian and Di-Hua[9] studied the planning and construction of riverside areas from the perspectives of ecology and aesthetics, emphasizing the concept of ecological design in landscape creation. Liaoji and Huiqing[10] offered new insights into the recreational management model for urban waterfront spaces, proposing an ecological benefits-based recreational management model for these spaces and conducting relevant feasibility studies.

At present, domestic research primarily focuses on explorations from various perspectives, such as the ecological environment,[11] visual environment,[12] security pattern,[13] and tourist perception,[14,15] combined with case studies to analyze a specific park,[16] riverfront tourism corridor,[17] or greenway. The perspectives are diverse and varied, but there is a lack of comprehensive research on evaluating the recreational suitability of waterfront green spaces within a region.

Different scholars have employed various methods to conduct an overall evaluation of certain areas. For example, Zhan[18] summarized the characteristics of recreational spaces and the methods for constructing a recreational system in riparian green spaces at the current stage, aiming to address the urgent need for urban recreation. Cao[19] mainly conducted field research on 42 plant species of lakeside, riverfront, and riverfront green spaces in Ma'anshan city and used the analytic hierarchy process (AHP) method to build a naturalness evaluation system for plant species of Ma'anshan waterfront green spaces. Similarly, Xiangxiang *et al.*[20] explored the characteristics of conventional evaluation methods and proposed a set of evaluation index systems and methods for blue and green spaces, suitable for evaluating the degree of urban blue and green integration. Li *et al.*[21] examined 36 representative urban waterfront green spaces, including Xihu Park and Zuohai Park in Fuzhou city, employing a landscape evaluation method that integrates image semantic segmentation and gray-scale statistical analysis. This approach investigated the relationship between urban park waterfront green spaces and public preferences, thereby assessing the esthetic quality of these urban waterfront areas. Meanwhile, Wang and Zhao,[22] using the AHP and incorporating the concept of night sky protection, screened and calculated the weights of evaluation indicators for the quality of nighttime landscapes in urban waterfront green spaces and established a corresponding evaluation system. Li *et al.*[23] combined AHP with an expert scoring method to establish a classification standard of evaluation indicators and conducted a comprehensive evaluation of the urban green space landscape pattern in the study area.

To construct an evaluation system, the focus must be on determining the weights of various evaluation indicators. The methods are primarily divided into three categories: subjective weighting methods, objective weighting methods, and a combination of both. Subjective weighting methods include the Delphi method, AHP, and expert scoring method. These methods are characterized by determining weights based on expert experience and subjective judgment, relying on human cognition and logic. On the other hand, objective weighting methods include the entropy weight method, principal component analysis, coefficient of variation method, and criteria importance through the intercriteria correlation method, calculating weights based on objective information, such as the data's inherent variation and correlation, thereby avoiding human interference.

This study aims to construct a multidimensional, multi-level indicator system that requires professional opinions and experience as references. After reviewing and researching literature on various evaluation system constructions, the AHP was employed to develop a recreational suitability evaluation system from multiple perspectives, and a comprehensive evaluation of the Linyi Calligraphy Square was conducted. This approach aims to propose rational suggestions from a more comprehensive perspective, providing a theoretical basis for future evaluations of the recreational suitability of waterfront green spaces.

2. Research methodology

2.1. Study location

This study used the Linyi Calligraphy Square in Linyi city, China, as a case study to establish a suitability evaluation system for waterfront green spaces and conduct a

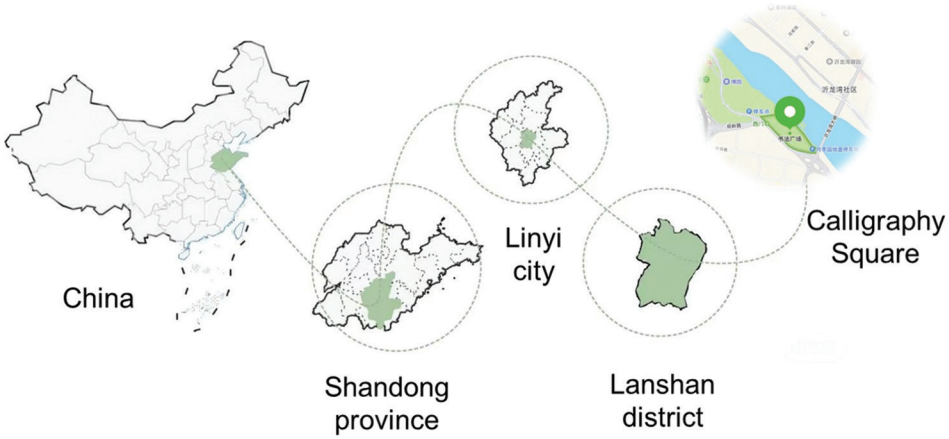

Figure 1. Area map of Linyi Calligraphy Square

Figure 2. Linyi Calligraphy Square. Photograph by the authors.

comprehensive evaluation. Linyi Calligraphy Square is located in the urban area of Linyi city, Shandong province, China (Figures 1 and 2). It is an open, large-scale theme park or square on the bank of the Yi River, serving as a centralized display area for the calligraphy works of famous Chinese calligraphers throughout history. It has been selected as one of the top 10 cultural landmarks in Shandong province, known as the Qilu cultural landmarks. The square is 1,200 meters long from east to west and over 200 m wide from north to south, covering a total area of more than 200,000 square meters. Its design adopts a mixed garden layout, blending classical garden landscaping with modern water culture and calligraphy art.[24,25] It is a highly representative urban waterfront green space in the Lanshan district, Linyi city.

2.2. Research design and method

This study employed the Delphi method to screen data, the AHP to obtain the index weights, and the fuzzy comprehensive evaluation method to evaluate the case sites and draw conclusions. The overall research process is illustrated in Figure 3.

The Delphi method is a technique developed based on individual expert judgment and expert meetings to consult expert opinions. At present, this method is widely used in various fields, including social surveys, opinion consultation, and data analysis. Its core is to refer experts as consultation subjects, leveraging their knowledge and insights to make scientific and reasonable judgments and analyses of the survey subjects, ultimately aiming to draw predictive conclusions. In a previous study, Zheng *et al.*[26] designed a Delphi expert method questionnaire, inviting 25 experts to conduct three rounds of surveys to evaluate and rate potential influencing factors. Likewise, Pei *et al.*,[27] using the Delphi method and cloud model, developed a theory and method for evaluating urban safety resilience in China, providing important guidance for enhancing resilience levels in urban safety.

The AHP is a subjective evaluation method proposed by the American operations researcher Saaty in the early 1970s. The AHP breaks down decision-related elements into multiple levels, such as goals, criteria, and alternatives, allowing for both qualitative and quantitative analysis. It is a systematic, simple, flexible, and effective decision-making method. This algorithm is a multi-criteria comprehensive evaluation tool. Due to its simplicity and practicality, it is widely used in real life, primarily for two purposes: determining indicator weights and quantifying alternative selections. For example, Zuo and Wang[28] used AHP to establish a comprehensive product evaluation system that is both reliable and valid. Similarly, Li *et al.*[29] proposed an improved AHP—a fuzzy comprehensive evaluation algorithm, which shows broad application prospects in evaluations.

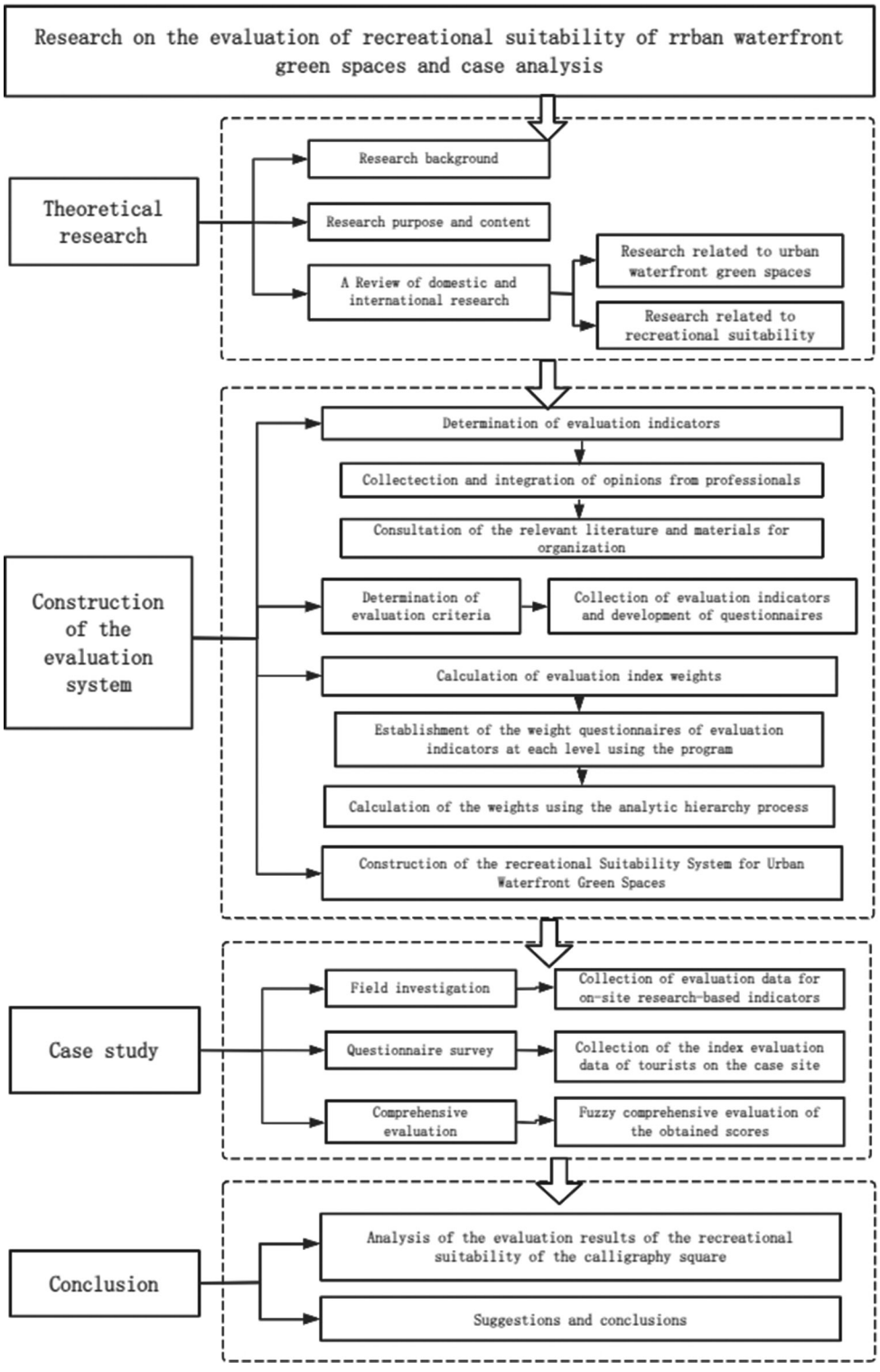

Figure 3. Technical flowchart

2.2.1. Construction of the preliminary evaluation system

The primary objective of this study was to establish a system for evaluating the recreational suitability of Linyi's waterfront green spaces. The principles of scientific rigor, comprehensiveness, leadership, practicality, and guidance were adhered to when selecting evaluation indicators.

Factors affecting the recreational suitability of urban waterfront green spaces are diverse and multifaceted. For example, Xia *et al.*[30] noted in their research that visual environmental elements, such as vegetation and water bodies, can enhance the recreational experience. Mingde and Jiayi[31] analysis of the factors influencing the vitality of waterfront spaces identified location and accessibility as the primary driving factors. Based on the literature review, the factors influencing the recreational suitability of urban waterfront green spaces were discussed from various perspectives, including space, environment, facility, activity, and image.

By referencing the recreational suitability evaluation systems for urban wetlands, comprehensive parks, and urban green open spaces constructed by Yang,[32] Zhang and Chen,[33] Sun,[34] Liu *et al.*,[35] and others, and incorporating Lang's[36] research on the evaluation index systems for waterfront space characteristics, along with expert consultations, a total of 52 indicators were predominantly selected from six categories:

(i) Environmental elements: Ultraviolet rays, temperature, air humidity, air quality, rainfall, wind speed, water quality, noise, and environmental sanitation.
(ii) Landscape elements: Plant landscape, landform landscape, revetment landscape, water body landscape, rock landscape, skyline landscape, garden path landscape, small architecture, historical and cultural relics, and facility landscape.
(iii) Resource elements: Plant diversity, greening coverage, topography and landforms, water resources, cultural monuments, local customs, festival activities, and science education.
(iv) Facility elements: Signage completeness, category comprehensiveness, usage status, maintenance status, comfort level, distribution status, diversity of recreational facilities, interest level of recreational facilities, management status of recreational facilities, safety of recreational facilities, safety of water-friendly facilities, interest level of water-friendly facilities, and rationality of water-friendly facilities.
(v) Recreational experience elements: Diversity of recreational spaces, comfort of recreational spaces, safety of recreational spaces, water-friendliness of recreational spaces, diversity of recreational activities, participation in recreational activities, attractiveness of recreational activities, and entertainment value of water-friendly experiences.
(vi) Location and transportation elements: Geographical location, visitor arrival distance, internal transportation conditions, and external transportation conditions.

The primary election indicators were screened using the Delphi method. Thirty professional teachers and relevant practitioners were invited to score and evaluate, and the indicators were revised and sorted out based on their opinions. The requirements for expert selection were as follows: first, having engaged in the study or research of this field for 5 years or more and second, having rich practical experience and a certain understanding of related research. The Likert scale method was used to evaluate the primary election indicators according to five evaluation levels of "important, relatively important, generally important, less important, and not important," and their values were assigned as "5, 4, 3, 2, and 1 point," respectively (Appendix 1). The experts proposed corresponding rectification suggestions according to their opinions.[37] After integration and modification, a recreation suitability evaluation system for urban waterfront green spaces comprising six target layers, 12 primary indexes, and 43 secondary indexes was established.[36]

2.2.2. Determination of indicator weights

After the preliminary construction of the evaluation system for the recreation suitability of urban waterfront green spaces, it is necessary to calculate the weight values of the sub-indicators at each level. The AHP[38-41] and the nine-level scale scoring standard were used to construct the importance judgment matrix of indicators at each level. The weight questionnaires for the factor level, first-level indicator, and second-level indicator were designed respectively. In this study, the weight calculation of evaluation indicators was directly obtained using the AHP calculation in the "Wen Juan Xing" website (https://www.wjx.cn/). By constructing questionnaires with the AHP model in Wen Juan Xing, the system was broken down into different levels, and the importance of indicators was compared pairwise to build a judgment matrix. Then, through operations such as solving for the maximum eigenvalue and performing weighted summation, the final weight of each indicator was determined. The relevant calculation formula is presented in Equations I and II:

$$\lambda_{max} = \frac{1}{n}\sum_{i=1}^{n}\frac{(AW)_i}{W_i} \quad \text{(I)}$$

$$C.I. = \frac{\lambda_{max} - n}{n-1} \quad \text{(II)}$$

where λ_{max} is the maximum eigenvalue, n is the number of dimensions, and AW is the product of the judgment matrix and the normalized weights.

Data from 30 experts and relevant practitioners were collected to calculate the indicator weights and perform a consistency check for each level. The principal model is illustrated in Figure 4.

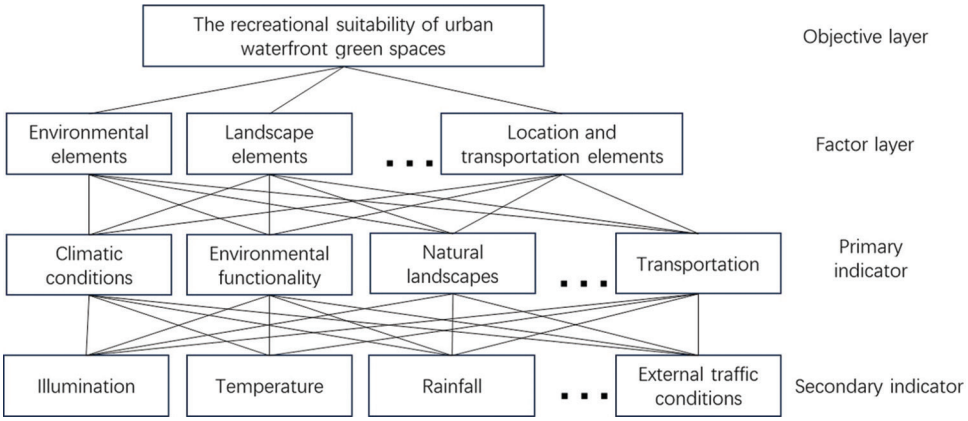

Figure 4. Schematic diagram of the hierarchical analysis model of the "Wen Juan Xing"
Source: https://www.wjx.cn/.

2.2.3. Determination of evaluation criteria

According to the current state of Linyi's waterfront green spaces, the evaluation indices were divided into five levels, and the acquisition of evaluation index data was classified into three types: questionnaire survey, field investigation, and data collection. Among these, the questionnaire survey focused on collecting data from tourists and staff; the field investigation involved on-site observation of the research site; and data collection referred to the compilation of relevant literature and official statistics. After referring to relevant research literature and standards,[42-44] considering the actual situation, and consulting with relevant experts, the evaluation criteria for the recreation suitability of urban waterfront green spaces were finally established (Table 1).

2.2.4. Fuzzy comprehensive evaluation

Due to the numerous factors influencing the recreational suitability evaluation results of urban waterfront green spaces, alongside the differences in evaluators' assessments and cognitive standards regarding various elements, the evaluation results can be affected to a certain extent. Therefore, the fuzzy comprehensive evaluation method was adopted to establish a multi-level model, ultimately obtaining the fuzzy comprehensive evaluation results and the final assessment value of the recreational suitability of urban waterfront green spaces. This method is based on the principles of fuzzy mathematics and fuzzy relation synthesis, providing a comprehensive evaluation approach that quantifies factors with unclear boundaries and difficult quantification.[45-48] A key aspect of the fuzzy comprehensive evaluation method is determining membership degrees, which involves dividing the indicators in the urban waterfront green spaces' recreation suitability evaluation system into soft and hard indicators. Soft indicators refer to those that cannot be classified into standard grades with clear numerical values and can have their membership degrees determined through social statistical methods. In this study, the soft indicators were evaluation indicators derived from questionnaire surveys. Hard indicators can be determined according to evaluation standards; if the evaluation indicator results are the same or fall within the corresponding standard value range, the data are recorded as 1; otherwise, it is recorded as 0. The results are summarized to form the membership degree of the evaluation matrix, and then, the degree is multiplied by the weight to calculate the membership degree of the primary indicators. Through this calculation, the fuzzy comprehensive evaluation score for Linyi Calligraphy Square was finally obtained.

This study employed the weighted average type fuzzy operator in the fuzzy comprehensive evaluation method for calculation. The core idea is to perform a weighted calculation on the weight vector and the evaluation matrix, obtaining the comprehensive evaluation result. Its calculation formula is as follows in Equation III:

$$M_K = Min\{1, \Sigma (a_j \times b_{jk})\} \quad \text{(III)}$$

where a_j represents the weight of the j^{th} factor in the weight vector, b_{jk} represents the value of the j^{th} row and the k^{th} column in the evaluation matrix, and M_k represents the k^{th} evaluation value in the comprehensive evaluation result.

2.3. Data collection and processing

Using Linyi Calligraphy Square as a case study, this research collected data for evaluation indicators based on relevant research standards and official documents. Field investigations at Linyi Calligraphy Square were carried out to obtain index data related to the evaluation indicators, such as recreational facilities, recreational space types, and plant diversity. A questionnaire was designed to collect data for the survey-based evaluation indicators. The questionnaire covered three aspects: demographic and sociological characteristics (e.g., gender and age), recreational

Table 1. Evaluation criteria for recreational suitability indicators of Linyi's waterfront green spaces

Evaluation indicator	Data source	Evaluation criteria				
		Excellent (5)	Good (4)	Average (3)	Poor (2)	Very poor (1)
Sunshine hours (annual, hours)	Data collection	>2,600	2,400–2,600	2,200–2,400	2,000–2,200	<2,000
Temperature (annual average, °C)	Data collection	18–22	14–18	12–14; 18–20	X–12; 20–25	<X; >25
Air quality index	Data collection	≤35	35–75	75–115	115–150	>150
Rainfall (annual, mm)	Data collection	750–950	650–750; 950–1,050	550–650; 1,050–1,150	450–550; 1,150–1,350	<450; >1,350
Wind speed (km/h)	Data collection	<11	11–19	20–28	29–49	>50
Water quality[a]	Data collection	Better than Class III	Class III	Class IV	Class V	Worse than Class V
Noise levels	Questionnaire	Excellent	Good	Average	Poor	Very poor
Sanitation	Questionnaire	Excellent	Good	Average	Poor	Very poor
Vegetation landscape	Questionnaire	Excellent	Good	Average	Poor	Very poor
Geomorphic landscape	Questionnaire	Excellent	Good	Average	Poor	Very poor
Water landscape	Questionnaire	Excellent	Good	Average	Poor	Very poor
Rock landscape	Questionnaire	Excellent	Good	Average	Poor	Very poor
Pathway landscape	Questionnaire	Excellent	Good	Average	Poor	Very poor
Architectural sculptures	Questionnaire	Excellent	Good	Average	Poor	Very poor
Historical sites	Data collection	National level	Provincial level	Municipal level	Unlisted	Negligible
Plant diversity	Field survey	Excellent	Good	Average	Poor	Very poor
Greening coverage rate (%)	Data collection	>90	80–90	70–80	60–70	<60
Topography	Data collection	Excellent	Good	Average	Poor	Very poor
Water resources	Data collection	National level	Provincial level	Municipal level	County level	Below the county level
Cultural relics	Data collection	National level	Provincial level	Municipal level	Unlisted	Negligible
Folk customs	Questionnaire	Excellent	Good	Average	Poor	Very poor
Educational facilities	Questionnaire	Excellent	Good	Average	Poor	Very poor
Signage completeness	Questionnaire	Excellent	Good	Average	Poor	Very poor
Facility diversity (types)	Field survey	5	4	3	2	1
Maintenance status	Questionnaire	Excellent	Good	Average	Poor	Very poor
Comfort level	Questionnaire	Excellent	Good	Average	Poor	Very poor
Distribution	Questionnaire	Excellent	Good	Average	Poor	Very poor
Recreational facility diversity (types)	Field survey	6	5	4	3	2
Recreational facility fun	Questionnaire	Excellent	Good	Average	Poor	Very poor
Facility management	Questionnaire	Excellent	Good	Average	Poor	Very poor
Facility safety	Questionnaire	Excellent	Good	Average	Poor	Very poor
Waterfront facility rationality	Questionnaire	Excellent	Good	Average	Poor	Very poor
Recreational space diversity (types)	Field survey	5	4	3	2	1
Space comfort	Questionnaire	Excellent	Good	Average	Poor	Very poor
Space safety	Questionnaire	Excellent	Good	Average	Poor	Very poor
Waterfront accessibility	Questionnaire	Excellent	Good	Average	Poor	Very poor
Activity diversity (types)	Field survey	6	5	4	3	2
Participation level	Questionnaire	Excellent	Good	Average	Poor	Very poor
Waterfront entertainment	Questionnaire	Excellent	Good	Average	Poor	Very poor
Geographic location (km from downtown)	Data collection	<5	5–10	10–15	15–20	>20
Visitor proximity	Questionnaire	Excellent	Good	Average	Poor	Very poor
Internal transportation	Questionnaire	Excellent	Good	Average	Poor	Very poor
External transportation	Questionnaire	Excellent	Good	Average	Poor	Very poor

Note: [a]Classification of water quality based on environmental quality standards for surface water in China (GB 3838-2002).

frequency, and a recreational suitability evaluation form (Appendix 2). Through on-site distribution and online questionnaire survey, 320 questionnaires were distributed, and a total of 300 valid questionnaires were recovered, an effective rate of 93.75%. These data were imported into Microsoft Excel (version 2003), and the comprehensive score of recreational suitability was calculated using the fuzzy comprehensive evaluation method.

The Wen Juan Xing application is a professional online platform for surveys, examinations, assessments, and voting. It provides users with a range of services, including powerful and user-friendly online questionnaire design, data collection, custom reports, and survey result analysis. Compared to traditional survey methods and other survey websites or systems, the Wen Juan Xing application offers advantages such as speed, ease of use, and low cost. It has been widely used by both businesses and individuals.

To reflect the actual evaluation situation, the survey area encompassed the entire Linyi Calligraphy Square, and a random sampling method was adopted. The calculation formula is presented in Equation IV:

$$n = \frac{Z^2 \times P \times (1-P)}{E^2} \quad \text{(IV)}$$

Where n is the overall size, which is the total number of individuals in the target population; Z is the confidence level, which is usually set at 95% with a corresponding Z-value of 1.96, indicating the level of confidence in the results; E is the margin of error, which is the allowable range of sampling error (e.g., ±5%); P is the population variability, which is typically estimated using a proportion (e.g., support rate p=0.5), and if unknown, the default is 0.5 (the most conservative estimation).

This study employed a random sampling method and collected a total of 300 valid questionnaires. Based on statistical formulas, the margin of error is ±5.7% at a 95% confidence level, indicating that the results can reliably represent the overall population of Lanshan Road (n = 160,000). Although the margin of error is slightly higher than the general standard of ±5%, the sample size still meets the scientific and feasibility requirements in resource-constrained scenarios. Future research can improve accuracy by increasing sample sizes. The survey subjects included tourists of all age groups. To ensure the objectivity and scientific validity of the survey results, questionnaires and interviews were also conducted with park management personnel.

The reliability of each questionnaire was verified using Cronbach's alpha coefficient. The coefficients of each scale were all above 0.7, meeting the standard of the reliability test. The results are presented in Tables 2-4.

3. Results and discussion

3.1. Index weight results

Scoring data from 30 experts and related practitioners were collected through the Wen Juan Xing application and questionnaires to calculate the weight and consistency test of indicators at each level. All matrices in this study passed the consistency tests (consistency ratio <0.1), and the recreational suitability evaluation system of Linyi's waterfront green spaces was finally constructed after normalization (Table 5). It can be seen from Figure 5 that the order of weights at the elemental

Table 2. Reliability analysis of the index screening questionnaire

Dimension	Project	Cronbach's alpha coefficient
Environmental elements	9	0.790
Landscape element	10	0.819
Resource elements	8	0.853
Facility elements	13	0.876
Recreational experience elements	8	0.872
Location and transportation elements	4	0.761

Table 3. Reliability analysis of the index weight questionnaire

Dimension	Project	Cronbach's alpha coefficient
Environmental elements	28	0.782
Landscape element	20	0.799
Resource elements	21	0.966
Facility elements	45	0.946
Recreational experience elements	21	0.936
Location and transportation elements	6	0.935

Table 4. Reliability analysis of the tourist evaluation questionnaire

Dimension	Project	Cronbach's alpha coefficient
Tourist evaluation	25	0.964

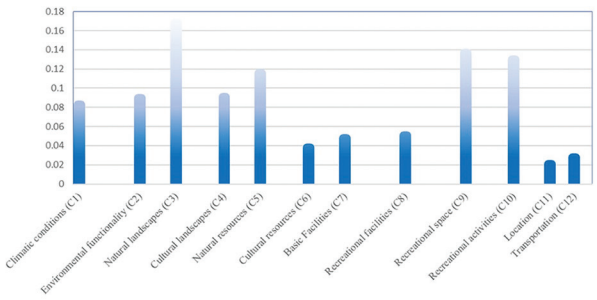

Figure 5. Weight chart of primary indicators

Table 5. Weights of the recreational suitability evaluation indicators of Linyi's waterfront green spaces

Objective layer	Factor layer	Weight	Primary indicator	Weight	Secondary indicator	Composite weight	Rank
Urban waterfront green spaces' recreational suitability (A)	Environment (B1)	0.172	Climatic conditions (C1)	0.083	Sunshine hours	0.023	22
					Temperature	0.024	19
					Air quality	0.029	15
					Rainfall	0.020	24
					Wind speed	0.014	28
			Environmental functionality (C2)	0.090	Water quality	0.019	25
					Noise levels	0.014	30
					Sanitation	0.029	14
	Landscape (B2)	0.259	Natural landscapes (C3)	0.168	Vegetation landscape	0.044	3
					Geomorphic landscape	0.038	6
					Water landscape	0.040	4
					Rock landscape	0.032	10
			Cultural landscapes (C4)	0.091	Pathway landscape	0.039	5
					Architectural sculptures	0.029	13
					Historical sites	0.037	7
	Resource (B3)	0.154	Natural resources (C5)	0.116	Plant diversity	0.026	18
					Greening coverage rate	0.027	16
					Topography	0.024	20
					Water resources	0.021	23
			Cultural resources (C6)	0.038	Cultural relics	0.023	21
					Folk customs	0.019	26
					Educational facilities	0.014	29
	Facility (B4)	0.099	Basic facilities (C7)	0.048	Signage completeness	0.009	38
					Facility diversity	0.008	42
					Maintenance status	0.010	36
					Comfort level	0.011	34
					Distribution	0.010	37
			Recreational facilities (C8)	0.051	Recreational facility diversity	0.009	40
					Recreational facility fun	0.007	43
					Facility management	0.008	41
					Facility safety	0.017	27
					Waterfront facility rationality	0.010	35
	Recreational experience (B5)	0.267	Recreational space (C9)	0.137	Space diversity	0.031	11
					Space comfort	0.061	1
					Space safety	0.051	2
					Waterfront accessibility	0.034	8
			Recreational activities (C10)	0.130	Activity diversity	0.030	12
					Participation level	0.032	9
					Waterfront entertainment	0.027	17
	Location/ Transportation (B6)	0.049	Location (C11)	0.021	Geographic location	0.009	39
					Visitor proximity	0.013	33
			Transportation (C12)	0.028	Internal transportation	0.013	32
					External transportation	0.013	31

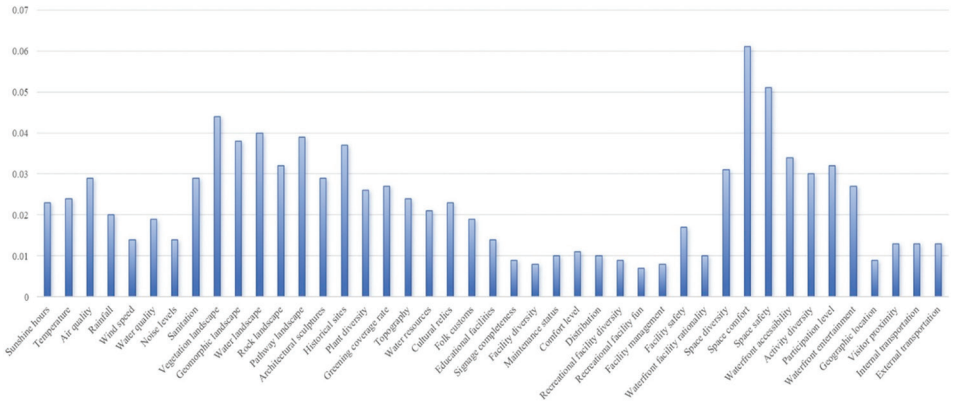

Figure 6. Weight chart of secondary indicators

level is recreational experience elements > landscape elements > environmental elements > resource elements > facility elements > location and transportation elements. This indicates that when evaluating the recreational suitability of Linyi's waterfront green spaces, greater emphasis was placed on whether the recreational experience met people's needs. Second, the construction of landscapes and the environment was also considered an important factor. The aspects of facilities and location/transportation had relatively less impact on the evaluation results. Among the first-level indicators, natural landscape, recreational space, recreational activities, and natural resources recorded high weights. These factors are often limited in urban environments, resulting in increased demand from tourists, which is reflected in their high weight proportions. It can be concluded from Figure 6 that among the secondary indexes, the comfort and safety of recreational spaces ranked highest. This indicates that the introduction of safe and comfortable recreational spaces in urban waterfront green spaces has a significant impact on the evaluation of recreational suitability.

In Yang's[32] evaluation of urban wetland park recreational suitability based on multivariate data, a rating system with 28 factors was developed, with the recreational landscape recorded the highest weight, highlighting its importance. Similarly, in the evaluation system constructed by Guo *et al.*[49], 25 indicator layers were selected, with the recreational environment criteria exhibiting the highest weight. In contrast, the current study established an evaluation system with 43 secondary indicators, providing a more comprehensive selection of evaluation indicators. Among these, recreational experience and landscape elements received higher weights, aligning with previous studies.

3.2. Visitor demographics

As can be seen from Table 6, the majority of tourists visiting Linyi Calligraphy Square are between 26 and 50 years old, accounting for approximately 65% of the total sample. This indicates that the square primarily attracts predominantly adulthood and middle-aged tourists between 26 and 50 years old. Owing to the superior geographical location and convenient transportation access of Linyi Calligraphy Square, visitors frequently visit this place for recreation, with most traveling by bicycle or on foot. In addition, some visitors visit by private car.

Table 6. Visitor demographic statistics

Category	Subcategory	Count	Proportion (%)
Gender	Male	101	34
	Female	199	66
Age	<18	9	3
	18–25	45	15
	26–30	62	21
	31–40	71	24
	41–50	61	20
	51–60	23	8
	>60	29	10
Transportation mode	Walking	94	31
	Cycling	94	31
	Driving	86	29
	Public transit	26	9
Visit frequency	Rarely	43	14
	Occasionally	128	43
	Frequently	129	43

3.3. Recreational suitability evaluation of Linyi Calligraphy Square

After collating the tourists' evaluations of Linyi Calligraphy Square, the survey results of the soft indicators are summarized in Table 7.

According to the result of the evaluation indicators, a fuzzy comprehensive evaluation matrix of 12 first-

Table 7. Results for the evaluation indicators of Linyi Calligraphy Square

Evaluation indicator	Evaluation criterion (%)				
	Excellent (5)	Good (4)	Average (3)	Poor (2)	Very poor (1)
Noise-limited condition	21.3	45.7	20.0	9.7	3.3
Environmental health	28.3	41.3	23.7	5.0	1.7
Vegetation landscape	35.0	40.7	18.0	4.0	2.3
Geomorphologic landscape	29.7	45.3	19.0	4.7	1.3
Water landscape	25.7	49.7	16.0	5.7	3.0
Rock landscape	29.7	41.0	22.7	4.0	2.7
Pathway landscape	26.3	48.7	20.7	3.0	1.3
Architectural sculptures	27.3	42.7	22.3	6.0	1.7
Folk customs	30.7	39.3	20.0	8.3	1.7
Educational facilities	29.3	41.0	26.0	2.7	1.0
Signage completeness	29.3	42.0	20.7	6.0	2.0
Maintenance status	33.7	40.7	20.0	4.0	1.7
Comfort level	33.0	44.0	16.3	5.0	1.7
Distribution	25.7	47.3	20.3	5.3	1.3
Recreational facility fun	31.7	37.7	22.0	6.7	2.0
Facility management	29.3	43.7	20.3	4.7	2.0
Facility safety	29.0	39.7	25.3	3.7	2.3
Waterfront facility safety	29.3	40.0	23.0	5.0	2.7
Space comfort	30.3	45.7	16.3	5.3	2.3
Space safety	32.0	44.3	19.3	1.7	2.7
Waterfront accessibility	29.7	40.3	23.0	5.0	2.0
Participation level	30.7	41.0	21.3	5.7	1.3
Waterfront entertainment	30.3	39.7	23.3	5.0	1.7
Visitor proximity	15.3	29.3	35.0	10.0	10.3
Internal transportation	26.3	46.3	22.3	2.7	2.3
External transportation	29.7	42.0	22.3	3.7	2.3

level evaluation indicators was established as follows in Equations V-XVI:

$$R_{C1}=\begin{pmatrix}0&0&1&0&0\\0&0&1&0&0\\0&1&0&0&0\\0&0&1&0&0\\0&1&0&0&0\end{pmatrix} \quad (V)$$

$$R_{C2}=\begin{pmatrix}0&1&0&0&0\\0.213&0.457&0.2&0.097&0.033\\0.283&0.413&0.237&0.05&0.017\end{pmatrix} \quad (VI)$$

$$R_{C3}=\begin{pmatrix}0.35&0.407&0.18&0.04&0.023\\0.297&0.453&0.19&0.047&0.013\\0.257&0.497&0.16&0.057&0.03\\0.297&0.41&0.227&0.04&0.027\end{pmatrix} \quad (VII)$$

$$R_{C4}=\begin{pmatrix}0.263&0.487&0.207&0.03&0.013\\0.273&0.427&0.223&0.06&0.017\\1&0&0&0&0\end{pmatrix} \quad (VIII)$$

$$R_{C5}=\begin{pmatrix}0&0&1&0&0\\0&0&1&0&0\\0&1&0&0&0\\1&0&0&0&0\end{pmatrix} \quad (IX)$$

$$R_{C6}=\begin{pmatrix}1&0&0&0&0\\0.307&0.393&0.2&0.083&0.017\\0.293&0.41&0.26&0.027&0.01\end{pmatrix} \quad (X)$$

$$R_{C7}=\begin{pmatrix}0.293&0.42&0.207&0.06&0.02\\1&0&0&0&0\\0.337&0.407&0.2&0.04&0.017\\0.33&0.44&0.163&0.05&0.017\\0.257&0.473&0.203&0.053&0.013\end{pmatrix} \quad (XI)$$

$$R_{C8}=\begin{pmatrix}1&0&0&0&0\\0.317&0.377&0.22&0.067&0.02\\0.293&0.437&0.203&0.047&0.02\\0.29&0.397&0.253&0.037&0.023\\0.293&0.4&0.23&0.05&0.027\end{pmatrix} \quad (XII)$$

$$R_{C9}=\begin{pmatrix}1&0&0&0&0\\0.303&0.457&0.163&0.053&0.023\\0.32&0.443&0.193&0.017&0.027\\0.297&0.403&0.23&0.05&0.02\end{pmatrix} \quad (XIII)$$

$$R_{C10}=\begin{pmatrix}1&0&0&0&0\\0.307&0.41&0.213&0.057&0.013\\0.303&0.397&0.233&0.05&0.017\end{pmatrix} \quad (XIV)$$

$$R_{C11}=\begin{pmatrix}1&0&0&0&0\\0.153&0.293&0.35&0.1&0.103\end{pmatrix} \quad (XV)$$

$$R_{C12}=\begin{pmatrix}0.263&0.463&0.223&0.027&0.023\\0.297&0.42&0.223&0.037&0.023\end{pmatrix} \quad (XVI)$$

Using the multiplication bounded operator to comprehensively calculate the fuzzy vector, after normalization processing, the membership degree evaluation results of the first-level indicators were obtained. Similarly, the comprehensive evaluation results of the element layer and the target layer were calculated. As a result, the membership degree of Linyi Calligraphy Square was determined to be 0.352, 0.36, 0.244, 0.031, and 0.014. According to the principle of maximum membership degree, it can be concluded that the overall comprehensive evaluation of the recreational suitability of Linyi Calligraphy Square is "excellent," and its membership degree is 0.36. To obtain the final score, the evaluation level V = (V1, V2, V3, V4, V5) was assigned a value from 5 to 1, respectively. Finally, the score for the recreational suitability of Linyi Calligraphy Square is 4.004. According to the evaluation score and grade description for the recreational suitability of urban waterfront green spaces (Table 8), the recreational suitability degree of Linyi Calligraphy Square is high and belongs to the excellent level.

Based on the above analysis, the overall score for the recreational suitability of Linyi Calligraphy Square was obtained, providing a more quantifiable evolution result. The fuzzy comprehensive evaluation method played a key role in this analysis, offering significant advantages for the comprehensive analysis of both qualitative and quantitative indicators. This method was primarily informed by the evaluation system construction and case analysis conducted by Li *et al.*[50] and Wang *et al.*[51] The evaluation of the case area also verified the feasibility of the proposed recreational suitability evaluation system, offering valuable reference for future evaluations of recreational suitability in Linyi's waterfront green spaces.

3.4. Overall evaluation of Linyi Calligraphy Square

After data consolidation, the results of the fuzzy comprehensive evaluation of the recreational suitability of Linyi Calligraphy Square are presented in Table 9. Based on the results, several secondary indicators, such as sunshine hours, temperature, rainfall, plant diversity, greening coverage rate, and visitor proximity, were rated as "average." Among these, sunshine hours, temperature, and rainfall are influenced by Linyi's climate, which is characterized by a temperate monsoon climate with distinct seasons and concurrent rainy and hot periods, as well as low temperatures in winter. These factors, to some extent, affect the recreational experiences of visitors and are considered objective influences.

Table 8. Recreational suitability evaluation levels

Level	Score range	Description	Final score
Excellent	>4.0	Very high recreational suitability	4.004
Good	3.0–4.0	High recreational suitability	
Average	2.0–3.0	Moderate recreational suitability	
Poor	1.0–2.0	Low recreational suitability	
Very poor	<1.0	Very low recreational suitability	

Similarly, plant diversity and greening coverage rate were rated as "average." The current vegetation in Linyi Calligraphy Square is primarily composed of native species, leading to a relatively homogeneous species composition and a noticeable landscape uniformity. It is recommended that the park moderately introduce ornamental horticultural varieties that have been domesticated and selected to adapt to local climatic conditions, thereby enriching the plant community layers through scientific planning. This approach not only helps to build a more ecologically resilient vegetation system and optimize the park's visual landscape effects, but also expands the tangible resources for public ecological education, creating a composite plant landscape system with both aesthetic value and educational function. According to the goals proposed by the government of Linyi city, the green land rate of built-up areas should not be <38%, and the greening coverage rate should not be <45% by 2025. The plant richness of Linyi Calligraphy Square can be improved to align with these goals, and the evaluation of recreational suitability in this aspect will also be enhanced.

Based on the analysis of survey questionnaires, visitors gave a generally high overall evaluation of Linyi Calligraphy Square. However, a significant number of visitors suggested adding a children's play area and adult fitness equipment. This is because the park is located near residential areas, where the primary purposes of visitation include exercise and leisure activities for children. According to the actual situation, it is recommended that the park expand its functional zoning by increasing the provision of children's activity areas, enriching recreational facilities for children, adding resting places, and enhancing the types of fitness equipment to better accommodate the needs of surrounding residents. At the same time, field investigations found that ongoing renovation and construction at Linyi Calligraphy Square have resulted in a lack of safety measures along the riverside walkways, posing potential risks to visitors. It is suggested that relevant management authorities implement appropriate safety protection measures, install warning signs or safety slogans, and improve safety infrastructure for water-related activities.[52-54]

Table 9. Fuzzy comprehensive evaluation results of Linyi Calligraphy Square

Objective layer	Result	Factor layer	Result	Primary indicator	Result	Secondary indicator	Result
Urban waterfront green spaces' recreational suitability (A)	Excellent	Environment (B1)	Good	Climatic conditions (C1)	Average	Sunshine hours	Average
						Temperature	Average
						Air quality	Good
						Rainfall	Average
						Wind speed	Good
				Environmental functionality (C2)	Good	Water quality	Good
						Noise levels	Good
						Sanitation	Good
		Landscape (B2)	Good	Natural landscapes (C3)	Good	Vegetation landscape	Good
						Geomorphic landscape	Good
						Water landscape	Good
						Rock landscape	Good
				Cultural landscapes (C4)	Excellent	Pathway landscape	Good
						Architectural sculptures	Good
						Historical sites	Excellent
		Resource (B3)	Average	Natural resources (C5)	Average	Plant diversity	Average
						Greening coverage rate	Average
						Topography	Good
						Water resources	Excellent
				Cultural resources (C6)	Excellent	Cultural relics	Excellent
						Folk customs	Good
						Educational facilities	Good
		Facility (B4)	Excellent	Basic facilities (C7)	Excellent	Signage completeness	Good
						Facility diversity	Excellent
						Maintenance status	Good
						Comfort level	Good
						Distribution	Good
				Recreational facilities (C8)	Excellent	Recreational facility diversity	Excellent
						Recreational facility fun	Good
						Facility management	Good
						Facility safety	Good
						Waterfront facility rationality	Good

(Cont'd...)

Table 9. ***(Continued)***

Objective layer	Result	Factor layer	Result	Primary indicator	Result	Secondary indicator	Result
		Recreational experience (B5)	Excellent	Recreational space (C9)	Excellent	Space diversity	Excellent
						Space comfort	Good
						Space safety	Good
						Waterfront accessibility	Good
				Recreational activities (C10)	Excellent	Activity diversity	Excellent
						Participation level	Good
						Waterfront entertainment	Good
		Location/ transportation (B6)	Excellent	Location (C11)	Excellent	Geographic location	Excellent
						Visitor proximity	Average
				Transportation (C12)	Good	Internal transportation	Good
						External transportation	Good

4. Conclusion

This article reviewed research on the evaluation of recreational suitability for waterfront green spaces in both domestic and international cities, highlighting the need to establish a system tailored for assessing the recreational suitability of Linyi's waterfront green spaces. This aimed to provide reasonable recommendations for enhancing the recreational suitability of existing waterfront green spaces in Linyi. By employing AHP, the Delphi method, and the fuzzy comprehensive evaluation method, a recreational suitability evaluation system for Linyi's waterfront green spaces was developed, comprising six element layers, 12 primary indicators, and 43 secondary indicators. The evaluation of the recreational suitability of Linyi Calligraphy Square was conducted using questionnaire surveys and relevant data calculations, resulting in a recreational suitability evaluation score of 4.004 for Linyi Calligraphy Square. Based on the feedback from the questionnaires and survey results, the following suggestions for improvement are proposed for Linyi Calligraphy Square:

(i) Increase the diversity of plant species in Linyi Calligraphy Square by introducing species suitable for the local climate, diversifying plant arrangements, and increasing both interest and aesthetic appeal.
(ii) Install children's play areas and fitness equipment to cater to the recreational needs of nearby residents and tourists.
(iii) Enhance safety measures by improving warning signs and notices to ensure visitor safety and improve the safety levels of water-related activities.
(iv) Plan parking spaces effectively, with separate areas for motor vehicles and non-motor vehicles, to accommodate more people.

In conclusion, this study conducted a systematic evaluation of the recreational suitability of urban waterfront green spaces, summarizing the primary factors influencing this evaluation. It established an evaluation system tailored to the recreational suitability of Linyi's waterfront green spaces, clarifying the standards for various indicators. With the continuous development of the economy, people are increasingly pursuing spiritual fulfillment. In the context of fast-paced urban life, there is a growing desire for access to natural landscapes. Urban waterfront green spaces combine both natural and cultural landscapes, with the presence of water bodies and greenery highlighting their uniqueness and importance. They not only enrich the comprehensive utilization of the city but also promote diversified urban development. The reasonable planning and construction of waterfront green spaces contribute to shaping the unique character and enhancing the overall image of the city. In addition, waterfront green spaces can effectively integrate with other functional areas of the city, forming an urban spatial pattern of complementary functions and coordinated development. Therefore, it is crucial to grasp the current level of recreational suitability of waterfront green spaces. In-depth research

and comprehensive evaluations of recreational suitability play a positive and promoting role in the construction and development of urban waterfront green spaces.

Due to limited time and energy, this study has several limitations. The evaluation indicators were compiled from existing literature and refined based on expert opinions. However, their comprehensiveness may still be limited, and certain dimensions warrant further exploration. In addition, the evaluation process may have been influenced by subjective factors, which should be addressed through improved methods in future research applications. Moreover, the field validation focused solely on Linyi Calligraphy Square as a single case study, resulting in a somewhat limited and context-specific analysis. An important future research direction is to incorporate more perspectives and increase the number of expert participants. In terms of case study analysis, more urban waterfront green spaces should be selected for comprehensive research to further explore the generalizability of the recreational suitability evaluation system.

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Conflict of interest

The authors declare that they have no competing interests.

Author contributions

Conceptualization: All authors
Data curation: All authors
Formal analysis: All authors
Investigation: Haixia Chen
Methodology: Qianda Zhuang
Visualization: Haixia Chen
Writing–original draft: Haixia Chen
Writing–review & editing: Qianda Zhuang

Ethics approval and consent to participate

Informed consent was obtained from the participants before participation.

Consent for publication

Participants consented to the publication of their data.

Availability of data

The data presented in this study are available on request from the corresponding author.

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Appendices

Appendix 1. Questionnaire for screening evaluation indicators of recreational suitability in urban waterfront green spaces

Dear expert,

Hello! I am a professional student from the College of Agriculture and Forestry Science Garden, currently conducting research on the urban waterfront green space recreation suitability evaluation index system. Given your in-depth research in this field, I am seeking your professional knowledge and insights to determine the evaluation index. Hope you can, despite being very busy, take a glance and precious time to fill in this form! Dear experts, based on your professional judgment, please make important judgments and reasonable screenings for the indicators of this research, and score them according to their importance at the end: "Unimportant 1 point, relatively unimportant 2 points, moderately important 3 points, relatively important 4 points, important 5 points." Thank you very much for your help and guidance!

Table A1. Scoring table for recreational suitability indicators of urban waterfront green spaces

Objective layer	Factor layer	Primary indicator	Classify and code	Secondary indicator	Score
Urban waterfront green spaces' recreational suitability	Environmental elements	Climatic conditions	1	Ultraviolet radiation	
			2	Temperature	
			3	Air quality	
			4	Air humidity	
			5	Rainfall	
			6	Wind speed	
		Environmental functionality	7	Water quality	
			8	Noise levels	
			9	Sanitation	
	Landscape elements	Natural landscapes	10	Vegetation landscape	
			11	Geomorphic landscape	
			12	Revetment landscape	
			13	Water landscape	
			14	Rock landscape	
			15	Skyline view	
		Cultural landscapes	16	Pathway landscape	
			17	Architectural sculptures	
			18	Historical sites	
			19	Hard landscape	
	Resource elements	Natural resources	20	Plant diversity	
			21	Greening coverage rate	
			22	Topography	
			23	Water resources	
		Cultural resources	24	Cultural relics	
			25	Folk customs	
			26	Festival activities	
			27	Educational facilities	
	Facility elements	Basic facilities	28	Signage completeness	
			29	Facility diversity	
			30	Service condition	
			31	Maintenance status	

(Cont'd...)

Table A1. ***(Continued)***

Objective layer	Factor layer	Primary indicator	Classify and code	Secondary indicator	Score
			32	Comfort level	
			33	Distribution	
		Recreational facilities	34	Recreational facility diversity	
			35	Recreational facility fun	
			36	Facility management	
			37	Facility safety	
			38	Safety of water-friendly facilities	
			39	The fun of water-friendly facilities	
			40	Waterfront facility rationality	
	Recreational experience	Recreational space	41	Space diversity	
			42	Space comfort	
			43	Space safety	
			44	Waterfront accessibility	
		Recreational activities	45	Activity diversity	
			46	Participation level	
			47	The appeal of recreational activities	
			48	Waterfront entertainment	
	Location/transportation	Location	49	Geographic location	
			50	Visitor proximity	
		Transportation	51	Internal transportation	
			52	External transportation	

1. Do you think the above indicators are reasonable?
   A. Very reasonable
   B. Reasonable
   C. Basically reasonable
   D. Unreasonable
   E. Very unreasonable
2. In your opinion, the indicators that need to be added are:
   A. The indicators that need to be deleted are:
   B. The indicators that need to be modified are:

This concludes the questionnaire. To prevent any omissions, please check each question again to see if you have missed any. Thank you! I wish you a smooth work and good health!

Appendix 2. Questionnaire for the evaluation of the recreational suitability of Linyi Calligraphy Square

Dear visitors:

Hello! I am a student majoring in landscape architecture at Linyi University. My supervisor is Dr. Zhuang. I am currently conducting research on the recreational suitability of the Calligraphy Square in Linyi to better understand everyone's attitudes and thoughts toward the Calligraphy Square in Linyi and to propose feasible construction and countermeasures for the recreational suitability of the Calligraphy Square. We hereby raise the following questions to you. We hope you can cooperate actively. Thank you for your cooperation! If you have any questions, please contact: 1786449XXXX.

I. Basic information of tourists

1. Your gender:
   A. Man
   B. Woman
2. Your age:
   A. Under the age of 18
   B. 18–30
   C. 31–50
   D. 51–60
   E. Over 60
3. The main mode of transportation for you to come to the park:
   A. Walk
   B. Bicycle
   C. Driving a car
   D. Public transport
4. Your frequency of visiting the park for recreation:
   A. Seldom
   B. Occasionally
   C. Frequently
5. The purpose of your visit to the park**:** (Multiple choices available)
   A. Appreciate a beautiful scene
   B. Be close to nature
   C. Relax and live
   D. Do physical exercise
   E. Widen horizons
   F. Communication and friends
   G. Others
6. The distance from you to the park:
   A. 500–1,000 m
   B. 1,000–3,000 m
   C. 3,000–5,000 m
   D. over 5,000 m

II. Survey form on tourists' evaluation of the recreational suitability of Linyi Calligraphy Square

Evaluation indicator	**Evaluation criterion (percentage)**				
	Excellent	**Good**	**Average**	**Poor**	**Very poor**
	5 point	**4 point**	**3 point**	**2 point**	**1 point**
Noise-limited condition					
Environmental health					
Vegetation landscape					
Geomorphologic landscape					
Water landscape					
Rock landscape					
Pathway landscape					
Architectural sculptures					
Folk customs					
Educational facilities					
Signage completeness					
Maintenance status					

Comfort level
Distribution
Recreational facility fun
Facility management
Facility safety
Waterfront facility safety
Space comfort
Space safety
Waterfront accessibility
Participation level
Waterfront entertainment
Visitor proximity
Internal transportation
External transportation

Your overall evaluation of this park is:

A. Excellent
B. Good
C. Average
D. Poor
E. Very poor

Your opinions and suggestions on Linyi Square:

The questionnaire is over. Thank you for your cooperation. I wish you good health and smooth work. Thank you!

ACCSCIENCE PUBLISHING

Design+

ARTICLE

Evaluating the benefits of using the Building Code Calculator app for design educators and industry professionals

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Abstract

Technology has transformed the field of interior design, improving efficiency through the use of digital tools. However, calculating building codes remains a complex, time-consuming, and error-prone task. Mobile apps have demonstrated their ability to facilitate complex tasks such as calculating clinical scoring systems and medication dosage in the medical field. Despite this potential, user-friendly solutions for building code compliance remain limited. Therefore, this study aims to explore the experiences and challenges faced by design professionals when working with building codes and to assess their willingness to adopt a new mobile app designed to help with building code calculations. Using a mixed-methods approach, 31 participants from the Midwest and South Central regions, including industry professionals and instructors, were interviewed about their experience with building codes. Participants were then introduced to the Building Code Calculator (BCC) app and surveyed using the innovation diffusion theory framework. The interviews revealed that professionals and students experience challenges with the current available resources and traditional calculation methods. Professionals also recognize the potential of the BCC app in improving efficiency and enhancing students' learning. Survey results indicated strong agreement among instructors regarding the app's relative advantage, image, ease of use, result demonstrability, visibility, and trialability, indicating a high willingness to adopt the tool. In addition, statistical analysis using the one-sample Wilcoxon test suggested a significant difference between the observed median and the hypothesized median for all survey questions. These findings suggest that the BCC app can potentially enhance efficiency in professional practice and serve as a teaching aid in classroom settings.

Keywords: Building code; Interior design; Cognitive load; Mobile app; Design tool; Digital tool

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1. Introduction

1.1. The role of building codes

Interior design aims to create spaces that protect the health, safety, and well-being of the occupants while meeting their needs. Designers are responsible for various tasks, including space planning, egress, fire safety, lighting, material and finishes selection,

and accessibility. In addition, they are required to possess a diverse range of knowledge and skills to work on various types of buildings, as each building has its own set of requirements.[1]

To ensure safety and compliance, interior designers must follow building codes and regulations. Codes are a set of laws and acts established by local, state, or national authorities to protect the public, such as the Americans with Disabilities Act, occupancy load, and egress.[1] The International Code Council developed building codes that are widely used throughout the United States to ensure safety and fire prevention in residential and commercial buildings.[2] These codes are often found in text documents (i.e., textbooks) and written in natural language for human interpretation. However, they can be ambiguous, causing confusion in understanding what the code requires.[3]

The design process begins with programming, where designers identify the client's needs. In the schematic stage, preliminary designs are produced before the development stage. Subsequently, construction drawings are provided to contractors during the construction phase.[4] These documents must follow building and fire codes, municipal codes, and other jurisdictional regulations to obtain a building permit. Throughout this process, architects and designers collaborate with consultants and engineers to ensure that the design is both compliant and practical.[1,4]

Similar to architects and engineers, interior designers share the same responsibility of protecting society's well-being. Therefore, their work is regulated to ensure safety, requiring professionals to have knowledge about building rules and regulations.[1] The National Council for Interior Design Qualification certifies individuals as professional interior designers through experience and examination. This examination assesses designers' knowledge of codes and regulations essential to occupant safety. Designers are also responsible for selecting fabrics that comply with fire codes and furnishings that meet Occupational Safety and Health Administration standards.[1]

1.2. Challenges with building codes

Conventionally, checking for code compliance is done manually and after the design is completed. This method creates challenges since it heavily requires human intervention and interpretation, making it costly, time-consuming, and prone to errors. If the design is non-compliant, corrections could create challenges, as it may involve various modifications and would require rechecking for compliance.[2,3] There have been various efforts to create automated building code checking systems, especially for Building Information Modeling. For instance, CORENET was the first automated building code checking system that was used by the Architecture, Engineering, and Construction industries. DesignCheck was developed to automatically check against accessibility, while SMARTcodes aimed to convert text-based building code documents into computer-readable formats for automated checking.[5] Altıntaş and İlal[5] developed an automated code compliance checking system for zoning codes to improve the manual process. However, these tools, such as Solibri Model Checker, CORENET ePlanCheck, and DesignCheck, contain a fixed set of rules that require programming experience to create new or modify existing rules, making it difficult for non-programmers to understand and edit. Therefore, Sydora and Stroulia[3] argued that computer-readable rules and guidelines could improve the evaluation process by automatically checking for code compliance and placing items according to design codes and guidelines.

1.3. Technology in interior design

Technology has vastly evolved in the field of interior design, transitioning from hand drafting and rendering to the use of design software that saves time, effort, and labor, such as AutoCAD, Virtual Reality, Sketchup, Revit, and Photoshop.[6] Digital technology can also enhance cognitive skills and abilities, such as creativity and design thinking.[4,6] Therefore, designers should stay updated with current trends and explore emerging technologies that can accomplish design tasks more quickly and more efficiently by reducing effort, time, and labor costs.[6] For instance, Almaz *et al.*[4] argued that architects must adapt and learn how to use new technologies, such as artificial intelligence (AI), in both professional practice and architectural education to prepare students for the increasingly digitized industry.

1.4. Usage of smartphones and apps for work

Smartphones are widely used for both personal and professional purposes, offering numerous benefits in the workplace. Studies have found that smartphones promote autonomy, improve relationships among colleagues, and enhance knowledge-sharing, which increases job satisfaction and promotes work efficiency. Smartphones with internet access allow individuals to perform various tasks on their devices.[7] This tool also helps facilitate flexible, on-the-go learning.[8] Apps are software programs designed to perform specific tasks on computers and mobile devices.[9] For instance, the use of smartphones in the medical field has increased due to their ability to run applications such as medical calculating apps. These apps can help calculate complex clinical scoring systems that assess the severity or risk of diseases.[10] Similar to building codes, these clinical scores involve complex formulas and

are manually calculated, making them time-consuming and error-prone. Other medical apps assist in calculating proper drug dosages.[9] These apps provide instant results and are often used multiple times a day by doctors.[10] Based on these findings, similar technology could be used in interior design for building code calculations to provide professionals with instant and accurate results.

1.5. Interior design apps

In interior design, most apps mainly focus on augmented reality (AR) to help visualize furniture in a physical space. For instance, Pranav *et al.*[11] developed an app that used AR to overlay virtual objects onto the real world, allowing users to see how the object would look in the physical world. Similarly, Dsouza *et al.*[12] developed an AR application for visualizing interior decor to improve decision-making. Sandu and Scarlat[13] developed an AR app that scanned the room and allowed the removal of existing objects and the placement of virtual objects to help both clients and interior designers communicate their designs.

Miri[14] developed an app to help lighting designers, professionals, and students conduct lighting analysis, allowing a quick and easy analysis compared to other methods that are time-consuming and prone to errors. In addition, Atwal *et al.*[15] explored occupational therapists' perspectives on the use of virtual reality interior design applications to collaborate with patients in designing safe predischarge homes that met their needs.

1.6. Current building code-related apps

The Apple App Store and Google Play feature a few apps related to building codes. For instance, the International Code Council developed a digital code app designed to eliminate navigating through multiple code books, offering a faster way to search codes, organize notes, and collaborate more seamlessly (Figure 1).

Building Tools is another example; this app displays the Australian National Construction Codes through interactive diagrams, as shown in Figure 2, to reduce costly mistakes and increase efficiency. This app covers most of the codes used by designers, except for the occupancy load. It includes a critical icon feature that explains code requirements, along with references from the National Construction Codebook. In addition, the app allows users to share code information with others and is available on both platforms.

Another example is OneClick Code-Roofing Codes, an app that provides quick access to roofing building codes across the United States. It helps roofing contractors, insurance adjusters, and estimators save time and reduce

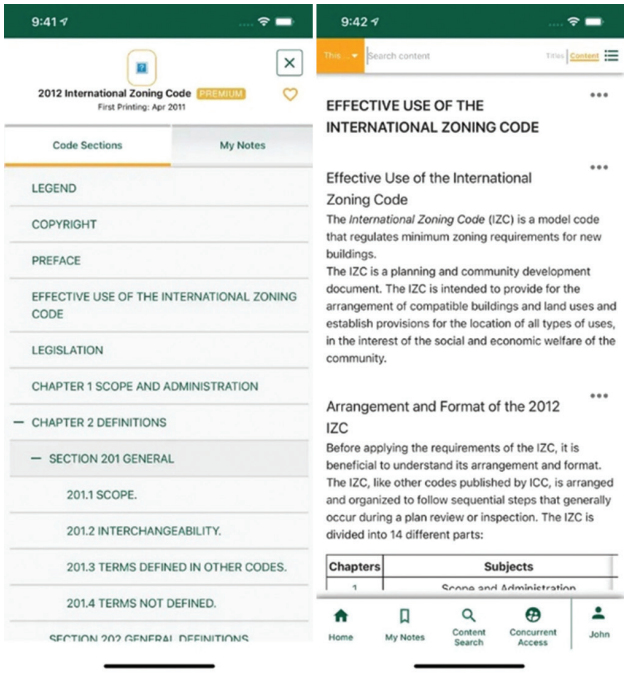

Figure 1. The International Code Council digital code application

costly errors. The app can calculate ice and water shield, waste, and ventilation requirements, and allows users to create and share detailed reports (Figure 3).

The Heights and Areas Calculator is an app that calculates the maximum allowable heights and areas for buildings based on different occupancies and fire protection requirements from the International Building Code. Figure 4 shows the basic and advanced forms of the calculator.

Trax Codes is an app that digitizes the Ontario Building Codes and the National Building Codes of Canada, offering the Architect, Engineer, and Construction professionals easier, on-demand access to up-to-date regulations, with the use of AI technology. Similarly, Building Codes Made Easier (Figure 5) is an app for property and liability claims, restorations, and legal professionals. This app helps legal professionals find and understand codes by providing them with simple answers, responses to frequently asked questions, and the ability to consult with code experts.

Despite advancements in automated compliance tools, there remains a gap in developing accessible building code solutions for interior designers. Although there are various attempts to create automated compliance checking systems—such as the system by Nguyen and Kim,[2] which utilized Autodesk Revit for collaborative compliance tracking—there are no apps designed to assist designers with building code calculations.[16]

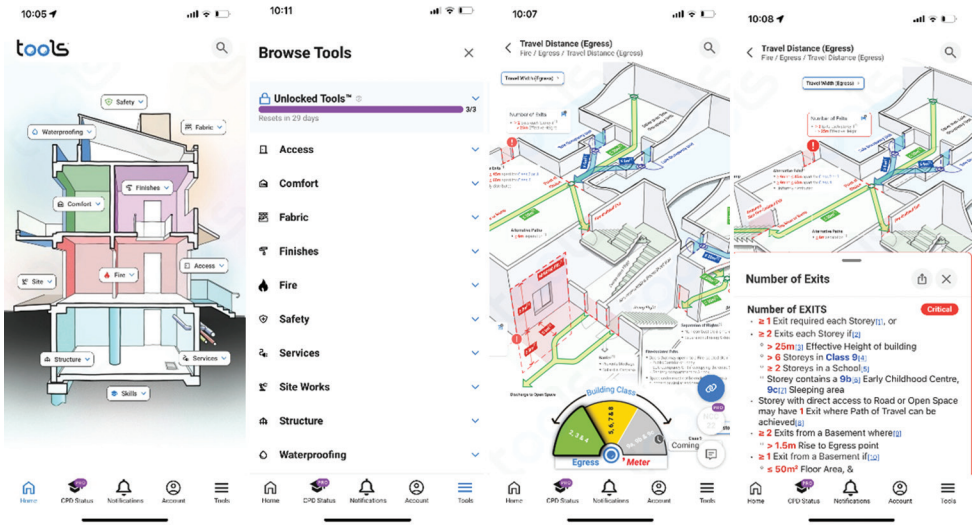

Figure 2. The Australian National Codes Building Tools application

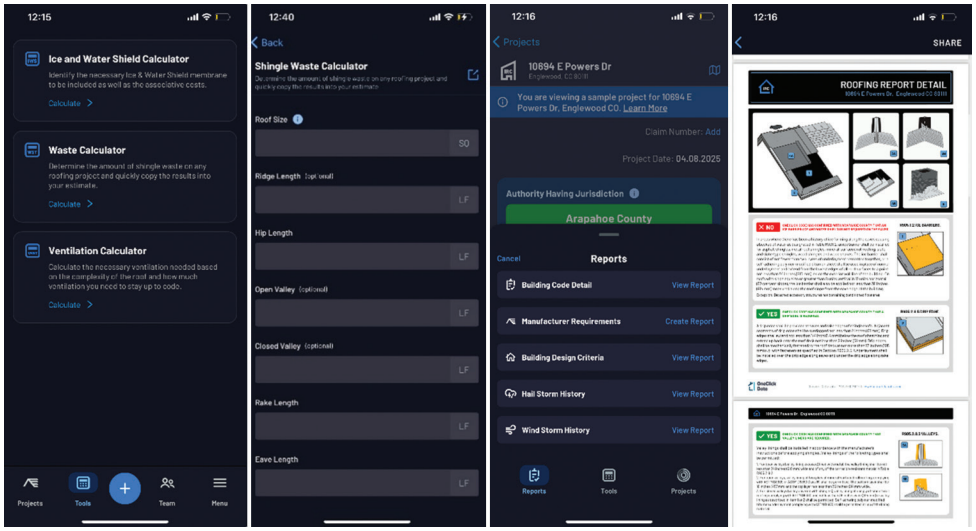

Figure 3. The OneClick Code-Roofing Codes application

1.7. Unique advantages of the Building Code Calculator (BCC) app

1.7.1. Support for creativity in the early design stage

One of the key differentiators of the BCC app is its emphasis on providing quick, real-time answers during the schematic design phase. Designers can use the app to check code compliance during initial sketches, allowing them to explore creative possibilities without worrying about overlooking code requirements. This capability is particularly useful during client meetings or when working on the fly, especially when the designer is away from a desktop computer.

1.7.2. Aid for student learning

In addition to aiding professionals, the BCC app is designed to support educational goals. Its visually appealing structure, with step-by-step guidance and interactive visuals, makes it an ideal tool for students learning about building codes. Unlike other tools that present building code data in complex, text-heavy formats, the BCC app uses visuals and simplified workflows, making the learning process more intuitive and accessible.

1.7.3. On-the-go use for designers

Another key feature that differentiates the BCC app from other compliance-checking tools is its mobility. Designers can use the app on mobile devices while on-site, allowing them to check code compliance in real time without needing their computers. Whether answering a client's question during a site visit or making quick adjustments to a design based on client feedback, the app facilitates fast, real-time decision-making.

1.7.4. Ease of communication between entities

The BCC app enhances communication between design teams, clients, and contractors by generating detailed PDF reports that include both input data and the results of compliance calculations. This feature ensures transparency and simplifies discussions, as all stakeholders can easily review the calculations and their underlying assumptions. By providing a clear, professional report, the app streamlines project management and ensures that everyone is on the same page, reducing the potential for miscommunication or misunderstandings.

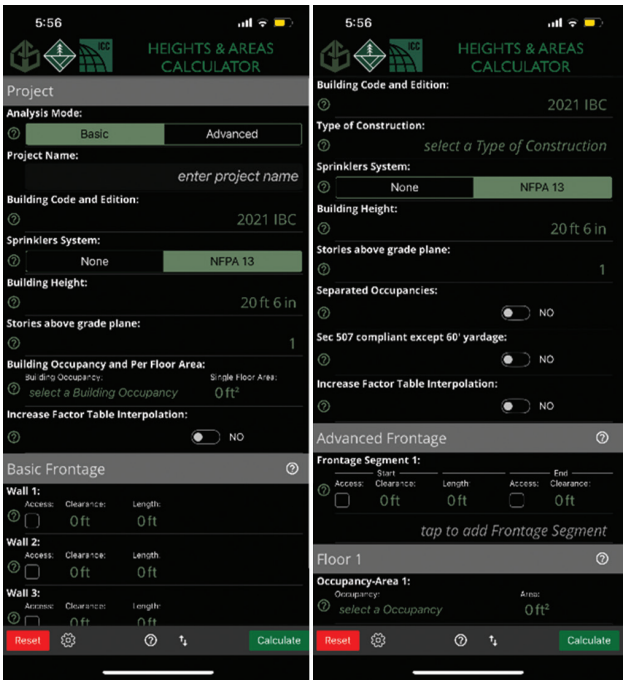

Figure 4. The Heights and Areas calculator application

1.8. Theory of technology adoption

The technology acceptance model explains users' motivations, attitudes, and responses toward the acceptance and usage of technology. When individuals are presented with a new technology, their intention to use and their actual use are influenced by perceived usefulness and perceived ease of use. Perceived usefulness is how individuals believe the new technology will help them complete a task. Perceived ease of use is the belief that using a new technology will require minimal effort.[15] The innovation diffusion theory identifies five attributes that influence the acceptance of a new technology:

1.8.1. Relative advantage

The perspective that new innovations are better than previous ones.

1.8.2. Compatibility

The perception that innovation aligns with the potential adopters' values, needs, and past experiences.

1.8.3. Complexity

The perceived difficulty of using innovation.

1.8.4. Observability

The visibility of the benefits of using innovation.

1.8.5. Trialability

The ability to experiment with an innovation before adoption.[17]

2. Methodology

The BCC app was developed to help calculate complex building codes. At present, the BCC app addresses the

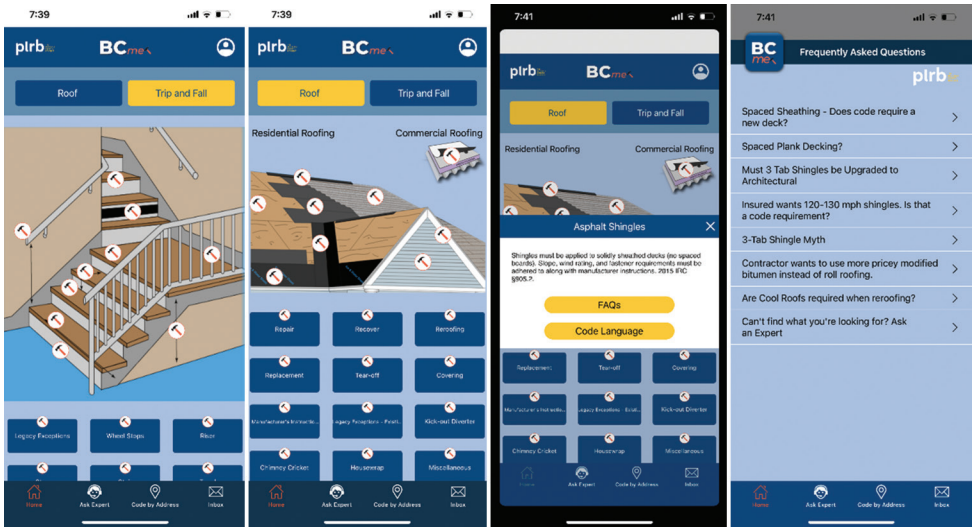

Figure 5. The Building Codes Made Easier application

occupant load calculation—a common challenge for design professionals, as it requires consideration of variables such as floor area, egress routes, and occupancy classification. The BCC app automates this process, allowing professionals to quickly determine the maximum occupancy for a space, ensuring compliance with safety regulations. In a typical scenario, the app could be used to calculate the occupant load for a dining space. For instance, the app will allow the designer to input dimensions and occupancy type, such as a dining area, and then automatically calculate the maximum number of people allowed in that room based on fire safety codes. This functionality saves time and reduces the risk of errors compared to manual calculation methods, which require interpreting complex tables and formulas from the building code. To explore how interior design educators and industry professionals perceive the benefits and usability of the BCC app, this study employed a mixed-methods approach, combining qualitative interviews and quantitative surveys.

2.1. Participant recruitment

The mixed-methods study recruited 31 participants, including instructors from universities in the Midwestern and South Central regions, as well as industry professionals from different sectors, such as interior designers, architects, fire marshals, code officials, sales representatives, and individuals working in finance. These participants were recruited through snowball methods, personal interceptions, personal contacts, and emails.

2.2. Study location and platform

The study took place in a south-central university. The interviews were conducted in person and virtually. In-person interviews took place in different settings, such as at networking events, conferences, and at institutions, while virtual interviews took place through Zoom. These sessions were recorded for transcription and analysis.

2.3. Data collection

Data were collected through interviews and surveys. Interviews were conducted with instructors and industry professionals to understand their perspectives, challenges, frequency of use, available resources, and implementation of building codes in their companies or classroom settings. The interview questions are outlined in Tables 1 and 2. The interviews were recorded, and field notes were taken when transcription was not feasible within the study's timeframe. Toward the end of the interview, participants were shown a tutorial demonstrating how the app functions and were given the opportunity to trial the prototype. Subsequently, surveys were conducted to understand instructors' perceptions of the app, including its relative advantage, compatibility, complexity, observability, and trialability.

Table 1. Instructors' interview questions

No.	Interview questions
1	Which institution are you affiliated with?
2	What is your current position?
3	Do you teach/do research, or both?
4	What classes/levels do you teach?
5	Do you teach building code?
6	Can you tell me more about the building code components that you teach?
7	Can you walk me through a building code exercise that your students work on?
8	What did you like about the teaching experience related to building code?
9	What did your students like about their building code learning experience?
10	What is frustrating about building code teaching experience for you?
11	What is frustrating about the building code learning experience for your students?
12	Have you ever thought of looking up existing building code apps?
13	Have you ever had students mess up their building code calculations at a late stage in the design process? If yes, can you describe that experience to me?
14	How much would you/or your students pay to make this problem go away?
15	What other features would you like to see incorporated into the BCC app?

2.4. Interview procedure and app demonstration

After providing consent for recording and participation, participants were interviewed about their use of and challenges with building codes. They were then shown a video demonstrating how the BCC app functions. Following the demonstration, the participants were allowed to try the app on their personal devices by scanning a QR code. Finally, instructors were asked to complete a survey assessing their perceptions of the app, with items derived from the innovation diffusion theory. The interviews took approximately 20–30 min.

2.5. Data analysis

Both qualitative and quantitative data were collected in this study. Transcriptions of the interview recordings were obtained through Otter (version 3.57), an AI transcription tool. All transcriptions were carefully reviewed to correct errors and to understand the overall meaning of the responses. These transcripts were then analyzed in NVivo

Table 2. Industry professionals' interview questions

No.	Interview questions
1	Which company do you work for?
2	What is your current position?
3	What is your role in your company?
4	What type of projects do you work on?
5	Do you refer to the building code in your current job?
6	Can you tell me more about the building code components that you use?
7	Can you walk me through a building code scenario that you encounter?
8	What do you like about work experience related to building code?
9	What did your employer like about the building code work experience?
10	What is frustrating about building code work experience for you?
11	What is frustrating about building code work experience for your employer?
12	Have you ever thought of looking up existing building code apps?
13	Have you ever messed up building code calculations at a late stage in the design process? If yes, can you describe that experience to me?
14	How much would you/or your employer pay to make this problem go away?
15	What other features would you like to see incorporated into the BCC app?

(version NVivo 15.1.0) to generate codes. Afterward, these codes were analyzed to identify themes. These themes were organized into Tables 3 and 4. The quantitative data gathered from the instructor's survey responses were analyzed using descriptive analysis and a one-sample Wilcoxon test in the Statistical Package for the Social Sciences (SPSS Statistics 29), with a hypothesis median value set at 3 and a significance level (*p*-value) of 0.05.

3. Results

The interview questions for the industry professionals explored the frequency of code usage, project type, design stage, and types of code used. Findings indicated that the project type largely determined which codes professionals needed to consult. Many participants reported using international code standards such as the International Building Codes, the International Fire Codes, and the International Residential Codes, as well as national and local codes. In addition, the interviews revealed the workflow of collaborations among design team members and their responsibilities. Participants were unaware of mobile apps that could help them with codes, relying on online web resources, creating Excel sheets, and using the physical code book as available resources. However, many expressed frustrations with existing resources, such as difficulties in finding information and understanding the language of the physical code book. Designers also experienced code miscalculations due to misinterpretations, leading to time-consuming revisions. When asked about how much they were willing to pay to resolve these issues, participants considered the app's value and suggested pricing models such as group licenses, subscriptions, free versus premium versions, and discounted prices for organization members. Other feedback included requests to incorporate additional resources and features into the app, expand code content, add a region selection feature, and implement marketing strategies.

Architects, architectural engineers, and interior design academic instructors, along with department heads and program directors, were also interviewed to understand how building codes are introduced and taught in academic programs. Students are introduced to building codes in their 2nd year and continue to apply them throughout subsequent lectures and studio courses. The codes taught include fire safety, occupancy load, plumbing, structural, and energy conservation codes. Based on their learning experience, students can embrace the rules, gain confidence, and develop reference resources. However, feelings of inexperience, intimidation by code complexity, and difficulty in memorizing and relating them to real-world experiences lead to frustration. The organization of the textbook further contributes to their frustration. Students also tend to miscalculate egress, corridors, floor openings, and compliance with the Americans with Disabilities Act guidelines. While these mistakes are part of the learning process, fixing them is time-consuming, and students are often reluctant to make changes.

Instructors reported appreciating the presence of concrete rules that challenge creativity. They enjoy teaching code through hands-on activities, helping students understand their relevance, and seeing them apply this knowledge in design projects. However, instructors also experience frustration due to the complexity and intimidation of codes, students' lack of interest or feelings of being overwhelmed, and the cost of the required codebook. Instructors are aware of online resources, plugins for Building Information Modeling software, physical code books, and instructional videos. One participant mentioned a Steel Code app, but no instructor was aware of the existence of BCC apps. Regarding the cost of the app, instructors suggested making the app free, offering a student discount, possibly through a subscription, or paid for by the department. Additional feedback includes adding other helpful app features and including more code content.

Table 3. Themes emerging from the industry professionals' responses to the interview

Parameters/ questions	Themes	Codes	Example
Positions	Design	Architect	"Architect."
		Interior design	"My title is interior designer."
	Human resources		"Hiring and retaining talent"
	Business development		"Technology commercialization."
	Public safety		"University fire marshal."
	Sales and financing		"Materials sales rep."
Project type	Commercial design	Healthcare	"But my current role is within the healthcare market."
		Multifamily	"We did a lot of homes and a lot of multifamilies that were contracted out through firms throughout the United States."
		Hospitality	"We did a lot of hotels."
	Residential design	Single family	"Custom homes in the Park City area, where there's a lot of money in the ski resort."
Reference building code	Frequency		"I would probably say multiple times a week."
	Stage		"During the design development phase."
Building code components	International code standards	IBC	"Local codes, IBC, and IRC."
		IRC	"Local codes, IBC, and IRC."
		IFC	"The state of...is an I code state we use, IBC, IFC, IEBC."
		IEBC	"The state of...is an I code state we use, IBC, IFC, IEBC."
		ISO	"ISO is the international body for a global standard."
		IMC	"Then we would move on to, and then it was sent to mechanical and plumbing, and electrical, we would go through those codes."
		IPC	"Then we would move on to, and then it was sent to mechanical and plumbing, and electrical, we would go through those codes."
	National and local standards	NFPA	"I also reference NFPA."
		ADA	"They'll come back with things to fix so it has occupancy load, ADA access, and things like that."
		Local codes	"Local codes, IBC, and IRC."
	Furniture	BIFMA	"BIFMA standards are voluntary and are for commercial furniture."
Building code scenarios	Design stages	Client meeting	"Usually, we would meet with the client, and they would let us know what we wanted."
		Preliminary design	"Then we would go back and give them a preliminary design."
		Approval	"They would okay it."
	Design team roles	Architects	"We would work with the architects for plumbing like count to make sure that everything was right."
		Interior design	"We did all the public areas, so the lobbies, the gyms, the swimming areas, so, like, if there was a swimming pool, indoor or outdoor, we would do the courtyards, we would do any of the like the club rooms, and then we would also design the units."
		Mechanical, plumbing, and electrical	"Then we would move on to, and then it was sent to mechanical, plumbing, and electrical."
	New projects		"So, when we get a new project, . that's when I would bring out the codebook and look that up."
	Renovations		"So, we usually see the drawings before we even, you know, approve the renovation or change that's going on."
	Frequency		"So, I reference code very frequently to make sure I'm complying with what's required."

(Cont'd...)

Table 3. ***(Continued)***

Parameters/ questions	Themes	Codes	Example
	Swimming pools		"A couple of our projects had rooftop swimming pools, so we had to do codes concerning the three-foot depth and the construction."
	Ada restrooms		"I would go to the ADA guidelines and double check a restroom, for example, what are the requirements for grab bars in a shower? How many? What's the height, for placement, what are the length requirements? And go through those types of details."
	Universities	Review and permits	"So, any project on campus, when it comes to us for building review and stuff like that, we're the one that issues the actual building permit."
		Jurisdiction	"Yeah, the way the university works is the university has its own authority having jurisdiction."
	Permits		"When they submit the permit, they have to submit drawings with it."
	Occupancy load		"A lot of times they like to play with the numbers, because if they can get the occupant load down, for some reason, that changes the bathroom count."
Work experience related to building code	Satisfaction	Enjoyment	"I enjoy finding answers right away when I can."
		Accomplishment	"From the moment you start building and then you go through and check it, and your codes are correct, it was just like, there was that sense of, like, I did it right."
Employer building code experience	Physical code book	Tangibility	"My employer likes to physically touch the code book."
		Efficiency	"Just because sometimes it's easier to find things in a physical capacity, as opposed to endlessly searching and scrolling online."
	Frustration about building codes		
	Book edition		"The city team, I think they just switched to 28th...there's been some issues with that."
	Finding information		"Try to find something and you're not able to find it right away."
	Misleading language		"Sometimes the language of the code is misleading, or it can be interpreted multiple ways, and sometimes that can lead to frustration, too."
	Dissatisfaction with resources		"Designers do not want to carry books or check websites."
	Fix issues		"The frustration also kicked in when there was something that came up, and you're like, oh, like, I have to fix that in one of the projects."
Looking up building code apps	Apps	Unaware	"Honestly have not, but I wasn't necessarily familiar that something like that would be out there, so I guess I didn't know to search for it."
		Opportunities	"But if there was an opportunity to use one, it's not something I would turn away from."
		Advantages	"I think I would look into it and see what the advantages of using it would be."
	Existing resources	Physical code book	"I didn't access anything other than the physical book."
		Online	"Maybe references from online that kind of clarified what needed to be exact in these codes."
		Excel sheets	"Some designers created Excel sheets that are not currently updated."
	Manual calculations		"Most of our occupancy determinations, especially for classrooms and renovations like that, you're probably somewhere 15–20 min of going through the book, verifying the number, and then doing all the calculations."
Miscalculated building codes	Misinterpretation of codes		"The way that the city interpreted it was different than how my boss was interpreting, and it could, honestly, it could have gone either way."
	Occupancy load		"He also called again a couple times about the group rooms, where, again, the occupancy load was just too high, so we had to rearrange the design to make sure that they met those codes."
	Modifications	Adjustments	"It was about 600 plus units... and it was three buildings... but yeah, so we had to rearrange all three buildings to match that same height."

(Cont'd...)

Table 3. ***(Continued)***

Parameters/ questions	Themes	Codes	Example
		Timeframe	"Even though we were working with the architects, it took about three weeks to really re-alter the size of this multifamily."
How much would you pay for the problem to go away?	Employer versus employee		"I might spend less than maybe what an employer might invest if he could get more than one."
	Employer investment	Employer subscription	"I think definitely my employers, the four architects who are the presidents, they would have definitely used it and offered it to the employees."
		Group license	"Group license about $500"
	Value of the app	Help beginners	"She didn't know codes, and I think something like this could have been very helpful in those beginning stages."
		Save money and time	"Feels that a firm would be willing to pay for this app if it could save time and money in the long run."
		NCIDQ prep	"Certain firms require NCIDQ certification."
	Subscriptions	Monthly	"So, I guess if you are paying for your Adobe prescription personally, and you just tacked on another, say, $10, then I could see where monthly would be a benefit, because then you can just kind of keep track of all those expenses at the same time."
		Yearly	"If I can just pay one time for the year, then and not have to think about it again for another year, I think that would be preferred, as opposed to having to keep up with it monthly."
		Trial	"I'd want to test out the app and understand the frequency of use and, like, its accuracy and whatnot, before I would pay a lot of money for it up front, like basically test it out, see if it's worth it before investing."
		Free version	"Have a free downloadable version with limited capabilities."
		Premium version	"Charge for popular features."
	Organization discounts		"Can be offered through ASID with a discount for members."
	Code book price		"Refer to the code book for pricing."
Other features	Graphics		"Add more clarification to the buttons."
	App features	Search bar	"If there was, like, a better way to find the keywords or really direct you to what you're looking for, I definitely think people would resort to whatever saves them the most amount of time."
		Links	"Link to BIFMA or level as additional things to consider."
		Tutorials	"Add a tutorial page."
		Help menu	"Add a help menu."
		Chat box	"Maybe add a chat box to the building permit counselor."
		Output files	"Suggested an output file to share with the code official."
		Plugins	
	Content	Fire rating	"I remember there were a lot of codes concerning fire ratings on textiles, and that can help interior designers within architecture firms."
		Acoustics	"Acoustical concerns for materials."
	Regions		"There needs to be a version for each municipality to account for different ordinances."
	Marketing	Platforms	"YouTube for marketing and advertisement."
		Audience	"Consider different age ranges when providing resources."
		Updates	"Collect data to learn who is using the app to help make decisions related to updates."

Abbreviations: ADA: Americans with Disabilities Act; ASID: American Society of Interior Designers; BIFMA: Business and Institutional Furniture Manufacturers Association; IBC: International Building Codes; IEBC: International Existing Building Code; IFC: International Fire Code; IMC: International Mechanical Code; IPC: International Plumbing Code; IRC: International Residential Code; ISO: International Organization for Standards; NCIDQ: National Council for Interior Design Qualification; NFPA: National Fire Protection Association.

Table 4. Themes emerging from the instructors' responses to the interview questions

Parameters/questions	Themes	Codes	Example
Positions	Professors	Architecture	"Professor at the School of Architecture."
		Architectural engineer	"I'm an Assistant Professor of architectural engineering."
		Interior design	"Interior design professor."
	Administration	Department head	"I know you are the department head."
		Program director	"Program director, yeah."
Teach or conduct research	Teach		"I just teach. I teach two different classes."
	Both		"Mostly teach, but I do both."
Classes and levels	Classes	Architecture studio	"I teach fourth-year studio, which is a studio that prepares students for the comprehensive design, which encompasses all phases of architecture."
		History & theory in architecture	"I also teach history and theory of East Asia and architecture specifically."
		Environmental control	"I teach the environmental control courses."
		Sustainable design	"One elective on sustainable design."
		Comprehensive design	"I teach in the comprehensive design studio, which is like the capstone studio."
		Study abroad	"I also teach study abroad in Asia."
		Capstone studio	"I teach the senior capstone studios."
		Graphics I	"I teach graphics."
		Graphics II	"I have taught graphics II, which is the first year."
		Heritage of interior design	"Then I also teach heritage, which is a lecture class."
		Lighting	"Lighting class for juniors."
		Facility management	"I teach Facility management and design, and diversity and facility management and design."
		Great plains	"I teach two great plains idea courses."
		Thesis	"I teach our graduate thesis"
	Levels	First/Freshman year	"One which is a freshman-level class, so it's their first interior design class."
		Second year	"Second year interior design studio."
		Third year	"I primarily teach third year."
		Fourth/Senior year	"I teach senior level."
		Graduate	"I teach graduate-level courses."
Teaching codes	Yes		"So, in the past, I've taught building codes."
	No		"No, I do not."
Building code component	Year introduced to the codes	Second	"In the second part of the second year, they take a course where they go deeper into that."
		Third	"Building codes are mainly covered in the third-year class."
		Fourth	"Then, in the fourth year, we actually start making it more evident that the code has a lot of guidance on their shapes, on their forms."
	Courses	Methods & materials	"I used to, a very long time ago, teach the methods and materials course, where we introduced building codes."
		Studio/Capstone	"So, with the senior capstone project, you know, codes of course are an integral part of the project that the students are working on."
	Projects	Commercial	"But in undergrad, we went over a lot of different types of building codes for mostly commercial."

(Cont'd...)

Table 4. ***(Continued)***

Parameters/questions	Themes	Codes	Example
	Design process	Design phase	"Big focus in that class, related to codes, is doing a building code analysis... where the students have already developed their design program and are, you know, getting ready to sort of transition into the design phase of the project."
		Design development	"Basic code research that will affect the conceptual forms, and then later on in design development, when we ask them to do a wall section."
	Content	ADA guidelines	"I cover ADA so students can apply the ADA requirement in their project."
		Concrete codes	"I use ACI 318, which is the concrete design code."
		Fire codes	"In studio five, we talk about egress fire stairs."
		Occupancy codes	"We talk about occupancy loads very generally."
		Plumbing codes	"It's so much in the beginning plan is more planning concepts about plumbing fixtures."
		Structural codes	"I use AISC 360 15th Edition, which is the steel design code."
		Steel design codes	"I use ASCE 7, and that is the Structural Building Code for loads on buildings."
		Energy conservation codes	"So, we typically use the IECC, the International Energy Conservation Code."
		Wall sections	"We also look into a little bit on how that wall section, how the code is going to affect the wall section."
Building code exercise	Introduction to codes	Lectures	"I just give a lecture of about 30 min."
		Breakdown	"So, I have kind of a markup to kind of pop out the equations that are used from the code, and really. What is the intent of the code?"
		Resources guidance	"Walk them through where to find this information in the concepts...the section in the IRC for this particular project, and I'll show them where to find that information."
		Terminology	"We start with just kind of translating some of the terminology, because they might read it, but they might not understand what they're reading."
		Overview	"We usually give them a brief because the code could be very daunting. There's a lot of information."
	Calculations	Occupancy	"Initially, it's to get them used to identifying occupancies, occupancy loads, and how that's calculated."
		Plumbing fixtures	"I'll ask them to calculate the plumbing fixtures needed for the size of this facility."
		Snowdrift	"Then they'll have a homework assignment that also calculates the snow drift on our roof."
	Real-world applications	Exercise	"We actually ask them to look at an exit like egress, and just like walk through the building in our own building and understand what the egress components are, and then go back and read on the code."
		Private client	"But if you were working for a client and it's a private then you really, really need to have a secondary entry and you need to follow so, you know, you need to follow the code."
		Government facility	"We're the government, so sometimes we don't follow the code to the letter."
	Design projects	Elderly care	"Program for all-inclusive care for the elderly, which is a program for older adults that includes social services, a medical clinic, physical therapy, and occupational therapy."
		Institutional kitchens	"Kitchen appliances and the kinds of things that would be put in, institutional kitchen that would be required by the fire Marshall, as well as the kind of doors that can open and close in case of a fire in the kitchen."
		Hospitality	"Third year. they do a full-scale hospitality, restaurant hotel project in which they apply a lot of these codes, life safety and access issues, or access codes."

(Cont'd...)

Table 4. ***(Continued)***

Parameters/questions	Themes	Codes	Example
		Museum	"Student last spring was designing a museum... and she wanted to, she wanted to know whether her exits were far enough apart."
		Row houses	"One project that we commonly start looking at code is a row house."
	Applying codes to design	Fire codes	"Taking things into consideration like evacuation and fire safety plans."
		ADA	"Wheelchair accessibility, making sure that doors are wide enough, there's enough room, and around furniture to maneuver around it safely and sit comfortably."
		Egress	"One project where we start to look at this type of egress component for the code."
		Lighting allowance	"So make sure that after they design the electric lighting system, they don't exceed the allowance for the load and do the same thing in a comprehensive way."
	Comprehension		"Come back with some sketches that show they understand corridor dimensions, for example, and basic egress components."
	Code checklist		"The students go through all those checklists and complete all the checklists as they pertain to the project."
	Design critiques		"Every week when we're doing design critiques, looking at how their design is meeting different building codes."
	Documenting		"Go out and actually document and build sort of a little library of all of the backup code documents that pertain to the information that they're pulling out in the code checklist."
	Progress		"So, we started them off fairly small scale, little problems in their second year, just to get their brain around, determining occupancy."
Code teaching experience	Rules		"I really love having rules that guide the design."
	Challenging creativity		"Okay, these are the parameters, and now how can I be creative and inventive within those parameters?"
	Research driven		"Very research driven, that the students have to really, you know, understand their project, and they really have to research the codes that are applicable to their project type."
	Subjective versus objective		"So, it's much more concrete, and, you know, definitive, and not as subjective as a lot of other things that the students are considering when developing their design projects."
	Understanding codes	Hands-on teaching	"I asked students to go to the bathroom and... ask them to check the accessible one, and I asked students to bring a tape measure, and ask them to measure the actual dimensions, because they cannot visualize."
		Connections with real-world applications	"Kind of connecting that idea of social behavior to practical applications through what the code outlines."
		Assistance	"Helping them understand feels kind of rewarding to me because then they can take that and kind of grow with that."
		Relevance	"I think it's nice when they realize that the point is to make people safe, and you feel good when they finally realize that that's something worth doing."
		Applying knowledge	"Enjoy making them learn about it and see them apply what they know."
Students learning experience	Embrace rules		"Then they start getting more responsible and really embracing the rules, because they become liable, but that liability is not apparent to them at the beginning."
	Reference Resources		"They spend a lot of time and gather a lot of information, and then they have that information to reference."
	Confidence	Code competence	"I think that sense of knowing and competence is the reward for them."
		Future career	"I hope they find some usefulness in it, and they gain confidence in their ability to design structures and understand what their job in the future is going to be."

(Cont'd...)

Table 4. ***(Continued)***

Parameters/questions	Themes	Codes	Example
	Functional Spaces		"There's not necessarily specific codes, but there are sort of strategies and space planning operations that work better, and they function better."
	User-centered design		"How do people use them on a day-to-day basis, so sort of like user-centered or human-centered design?"
	Site Visit		"They visit the site, so they walk into the doors of the building that they're going to be doing the renovation on."
	Feedback		"Invite professionals to come and, like, give feedback to the students."
Frustrating teaching experience	Teaching methods	Need for guidance	"We incrementally, sort of spoon feed them, in some ways, the code that they're learning and the code that is applicable to the project types that we set up for them."
		Relatable learning	"When you teach it as a way to keep people safe, and you connect it in ways that they'll remember to what it is you're trying to accomplish, then they see purpose in it."
	Challenges	Complicated	"It is kind of a complicated document, especially since the concrete code is written in a way that it's not easy to navigate... I think it's a very complicated code."
		Cost	"The expense of the codes that you know I require for these classes, and they are expensive documents."
		Intimidating	"The International Building Code is a very intimidating document."
		Lack of interest	"Students think it's kind of boring, they don't know how important it is, and all the clearance and all the numbers, they are not interested. So, I think it's really important to make them, make them interested in these issues."
		Overwhelming	"Helping the students overcome that sense of feeling overwhelmed., something that I found to be frustrating."
Frustrating students' learning experience	Inexperience		"I think that the maturity of the architect comes into play; this is very frustrating for them, because they don't have either the maturity or they don't have the years of practice that help them navigate that gray area."
	Intimidating		"It's intimidating, it's a lot, and to learn how to teach them what's important for them to know without overwhelming them."
	Complexity		"I think that sometimes they don't know exactly where to start, and you have to kind of give them a roadmap to help them break it down into, you know, some incremental categories and pieces to make it more manageable for them."
	Memorization		"So, the frustrating part, I guess, is when they only think of it as rules that they have to memorize, and they don't want to memorize any rules."
	Textbook	Organization	"They have expressed the same frustration with the concrete code that I have and its organization."
	Difficulty relating to real-world situations		"They don't realize how big the space is, how that clearance will work for the wheelchair users, because they don't have that kind of disability, they do not have any experience.
Looked up building code apps	Code app unfamiliarity		"I have not looked up anything. I don't have any familiarity with any sort of apps that might be available, if there are any."
	Online websites		"I always just end up going back to the building code websites."
	Plugins		"I know for BIM, there have been some attempts to do like once you design a building, to have these applications, like these plugins that will tell you when a corridor is too long or a dead-end corridor."
	Videos		"I found a few things on YouTube that I kind of like, so I actually have a little cheat sheet of my favorite YouTube places."
	Code book		"We also had kind of like a code guidebook or a code to reference book."
	Steel code app		"I do have one app on my phone for the steel code."

(Cont'd...)

Table 4. ***(Continued)***

Parameters/questions	Themes	Codes	Example
	Feedback from professionals		"During the studio, we invite the code reviewers... to come and give feedback to the students."
Students miscalculating building codes	Egress		"At least for interior designers, that's always been a challenge to try and get them to understand what a common path to travel means."
	ADA		"You know, there are all sorts of ADA and, you know, access things that they miss because there's so much to know about it."
	Corridors		"The dead-end corridor issue is always a big one."
	Floor openings		"They really do not understand floor-to-floor openings."
	Hand drafting		"Then if you get that far in and have to fix it, then you have to erase your table and your chairs and all the wood grain that you did and all the shading and then redraw it."
	Prevention measures	Early feedback	"So, it would have saved me a lot of time if I were able to double-check that before going through all the rendering stages."
		Grading	"We actually try to grade codes pretty early as a preliminary submission, so that we catch that stuff."
		Design progress updates	"Get set up with the information that they need so that they don't have to keep going back and fixing and changing and changing."
	Errors	Time-consuming	"I mean that can set them back like 10 or 20 h or something, just way, way time-consuming."
		Reluctant to fix	"The hard part is they're reluctant to make the changes they need to make it right."
		Time management	"If they mess it up, it's mostly just because they were in a hurry because they didn't put in the time."
		Learning process	"I was teaching sophomore-level studio when, you know, messing up was really part of the learning process for them."
How much would students pay for the problem to go away?	References	Software	"I think our students pay for other software, like Rhino. And I think there are, there are a few other ones that they pay."
		Code book	"I think it can be, if it's comparable to the price of a book, it might be affordable."
	Free		"I think if it's free, obviously it's better."
	Student discount		"I don't know if students would be willing to, or maybe if they got some sort of student discount."
	Subscription	Monthly versus yearly	"I think if I were going to have to pay for it, being able to choose either monthly or yearly, having both of those would be nice."
		Trial	"Okay, I'll pay $4.99 this month to see if I like it, and then if I like it and use it a lot, then I'll pay the $60.00 for a year."
	University	Tuition	"Maybe paid for by the university. So, it's like a service provided to the students as part of that tuition."
		Department license	"I think if our department purchased a subscription to an app-type service that we can then share with the students. Probably they would be more likely to engage with that."
	One-time payment		"I would think probably a one-time payment would be better for students."
	Reasons for purchase	Cheaper	"If there were an alternative to that that allowed them to access the same information for a cheaper price, they would be interested in that."
		Helpful	"I think this would be something that would be really helpful for faculty. I think the students would be very receptive toward it."
		Class requirement	"Faculty could also, you know, incorporate it into the resource requirements for a class, if it was something the faculty wanted to require the students to all have."

(Cont'd...)

Table 4. ***(Continued)***

Parameters/questions	Themes	Codes	Example
		Books versus apps	"If there were an electronic app version of a textbook that helped them understand these things and by plugging in information, I think they'd be willing to pay for it."
Other features	App features	User animations	"If the app can show how people with disability actually use the space... if some kind of animation shows how the space is used depending on size, then students can realize why they need to provide this much space."
		Project folders	"Save different portions to a folder, maybe almost like Pinterest or something."
		Code book references	"If there's some way that relates back to the actual IBC numbers, so if they get lost or need to go check on something... they can reference back to the code book."
		Highlight extra space	"It would be nice to see how much extra space you have if you want to put like a changing table or a spot to set your bags."
	Materials	Finishes	"What about finishes for interior designers?"
		Construction materials	"So, are there construction materials? You know what kind of structural steel you needed to use or if you could use glulam and those kinds of things."
	Fire codes	Allowable height	"Calculate things like allowable height and area."
		Exit widths	"Is it going to count also the desired width of the exit?"
		Glazing	"What kind of glazing does it have to be, you know, like this kind of stuff?"
	Occupancy classifications		"I think before you get into the occupant load, I think sometimes you need a little bit of a reminder of those occupancy classifications that you might be selecting."
	Focus on specific codes		"Everything covered by code it's going to be too much. Maybe tailored to certain courses."

Abbreviations: ADA: Americans with Disabilities Act; AISC: American Institute of Steel Construction; ASCE: American Society of Civil Engineers; IECC: International Energy Conservation Code; IRC: International Residential Code.

As for the quantitative data, the survey revealed that 85% of the instructors strongly agree/agree that the BCC app would help them accomplish their tasks and teaching goals more quickly, as shown in Figure 6. Figure 7 demonstrates that 92% strongly agreed that the app fits into their working style, with only one participant disagreeing with this statement.

Figure 8 shows that 60% strongly agree/agree that people who used BCC apps had high profiles, while the other 40% responded neutral. Figure 9 reveals that all respondents believe that the app is easy to use.

About 85% of participants strongly agree/agree that the results of using the app were apparent to them. Meanwhile, one participant indicated that the results were not apparent, as seen in Figure 10. Figure 11 demonstrates that 73% strongly agree/agree that there is no visibility for the BCC app in the interior design field.

Figure 12 shows that 92% strongly agree/agree that they had enough time to try the app and see its abilities. In addition, 83% strongly agree/agree that they will use the app in the future, as shown in Figure 13.

The results of the one-sample Wilcoxon test, presented in Tables 5 and 6, revealed that Questions 1–8 had a p-value less than 0.05, indicating that the observed median significantly differs from the hypothesized median value of 3.

4. Discussion

Based on the interviews conducted, both industry professionals and instructors rely on traditional methods for calculating building codes. However, these methods often cause confusion and frustration among industry professionals, instructors, and students. The misinterpretation of codes also leads to miscalculations, requiring revisions that are time-consuming. Overall, participants are dissatisfied with the current available resources but are unaware of mobile apps that could help them with code calculations. Both professions and educators recognize the value the app could bring to the industry and student education. They believe the app would help save time and money, help prepare for the National Council for Interior Design Qualification examination, and enhance student learning. Furthermore, interviewees expressed satisfaction when they could find answers rapidly and when their calculations were correct. Therefore, this app would help them calculate building codes more efficiently and accurately.

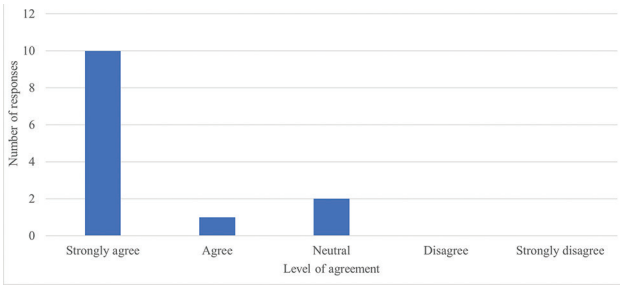

Figure 6. Participants' responses indicating agreement that the Building Code Calculator app would help them accomplish tasks or teaching goals more efficiently

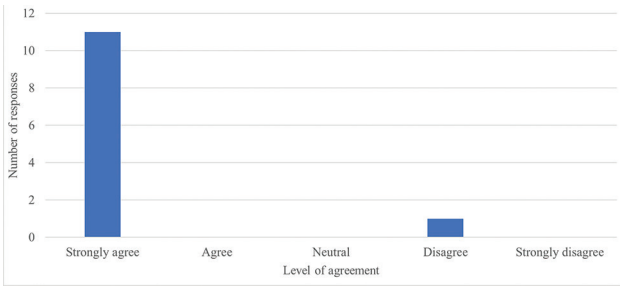

Figure 7. Participants' responses indicating agreement that the Building Code Calculator app aligns with their work or teaching style

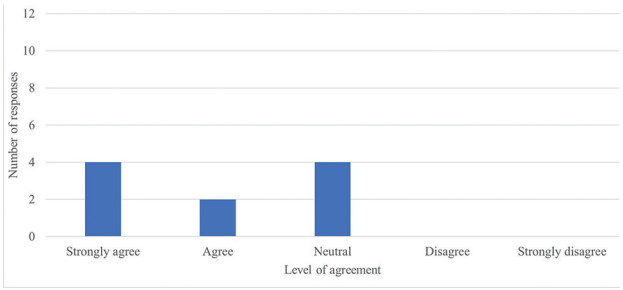

Figure 8. Participants' agreement reflecting perceptions of the professional image associated with using the Building Code Calculator app in their field

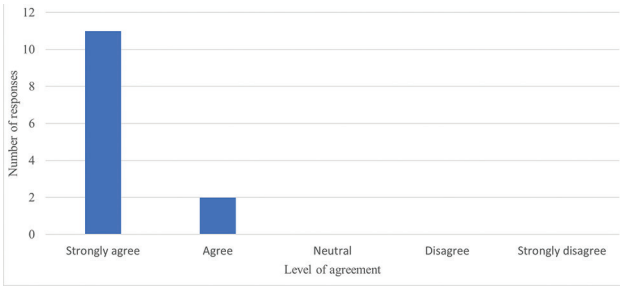

Figure 9. Participants' agreement regarding the perceived ease of use of the Building Code Calculator app

Factors such as relative advantage, compatibility, image, ease of use, result demonstrability, visibility,

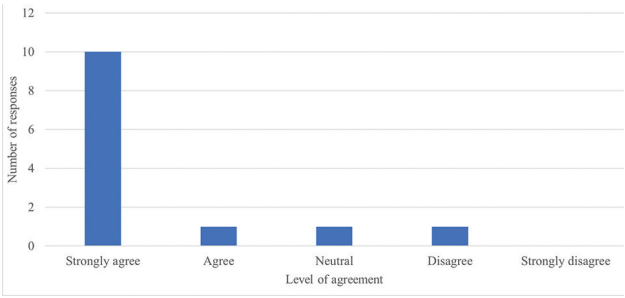

Figure 10. Participants' agreement indicating the extent to which the results of using the Building Code Calculator app were apparent to them

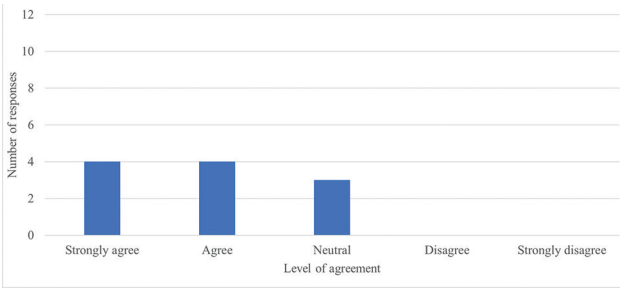

Figure 11. Participants' agreement regarding the perceived visibility of the Building Code Calculator app within their field

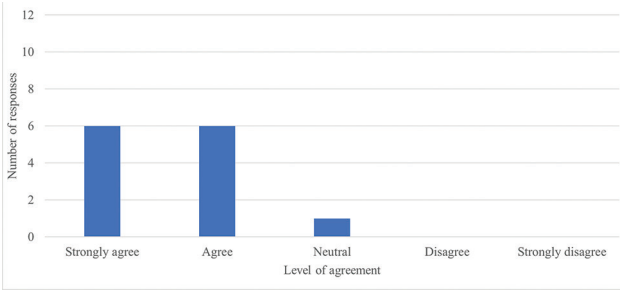

Figure 12. Participants' agreement about having sufficient opportunity to trial the Building Code Calculator app and explore its capabilities

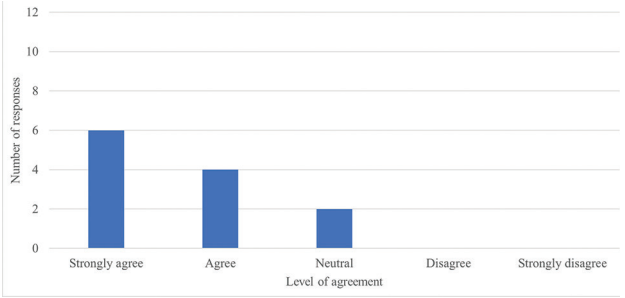

Figure 13. Participants' agreement indicating their intention to use the Building Code Calculator app in the future

and trialability are essential for the adoption of new technology.[17] The majority of participants strongly agreed/agreed that the BCC app would help them accomplish

Table 5. Instructors' survey responses based on the one-sample Wilcoxon rank hypothesis test

Question	Null hypothesis	Significance
1	The median for the statement, "using the Building Code Calculator App enables me to accomplish my tasks more quickly," equals 3	0.001
2	The median for the statement, "Using the Building Code Calculator App fits into my work/teaching," style equals 3	0.001
3	The median for the statement, "People in my field who use the Building Code Calculator App have a high profile," is 3	0.023
4	The median for the statement, "Overall, I believe that the Building Code Calculator App is easy to use," equals 3	<0.001
5	The median for the statement, "The results of using the Building Code Calculator App are apparent to me," equals 3	0.002
6	The median for the statement, "The Building Code Calculator App is not very visible in my field," equals 3	0.010
7	The median for the statement, "I was permitted to use the Building Code Calculator App on a trial basis long enough to see what it can do," equals 3	0.002
8	The median for the statement, "I plan to use the Building Code Calculator App in the future," equals 3	0.004

Note: Significance level at p=0.05.

Table 6. Instructors' survey responses based on the one-sample Wilcoxon signed rank test

Question	Total (N)	Test statistics	Standard error	Standardized test statistic	Asymptotic significance (2-sided test)
1	13	66.000	10.290	3.207	0.001
2	12	77.000	11.619	3.271	0.001
3	10	21.000	4.623	2.271	0.023
4	13	91.000	13.309	3.419	<0.001
5	13	76.500	11.906	3.150	0.002
6	11	36.000	6.964	2.585	0.010
7	13	78.000	12.400	3.145	0.002
8	12	55.000	9.520	2.889	0.004

Note: Significance level at p=0.05.

their tasks or teaching goals faster. This finding suggests that professionals perceived the app as having a relative advantage over the manual calculation method, likely due to its efficiency. Furthermore, the majority of respondents indicated that the app was compatible with their working/teaching style. Question number 3 assessed the app's image and its potential to enhance one's status. More than half of the respondents strongly agreed/agreed, while the others remained neutral. A total of 40% of participants who responded neutral may not have encountered apps like BCC in their field, which explains their neutrality.

All participants strongly agreed/agreed that the app was user-friendly. Similarly, for Question number 4, the majority strongly agreed/agreed that the app's results were apparent to them. Recognizing the benefits of innovation is important for its adoption.[17] Furthermore, the results for visibility suggest that apps like BCC are not common in the field of interior design. Participants also agreed that they had enough time to test the app and understand its functions. Based on respondents' agreement with each adoption attribute, almost all participants agreed that they would use and adopt the app in the future.

There are no studies using the innovation diffusion model for interior design apps. However, Gharaibeh *et al.*[18] and Emani *et al.*[19] also used the theory and both found that relative advantages, ease of use, trialability, and observability influenced the adoption of mobile health apps among elderly adults and electronic personal health records. Although the context differs, this study's findings, along with previous research, demonstrate that these adoption attributes influence technology adoption across different fields.

The results of the one-sample Wilcoxon test indicate that there is a significant difference between the observed median and the hypothesized median for all questions, indicating that the participants either agreed or disagreed with the survey questions, deviating from neutrality. The study also highlights some of the practical challenges and support needs for long-term integration of the BCC app.

4.1. Diverse geographic locations and jurisdictional differences

Design professionals and students work across different regions, and each location may have unique building code requirements and local regulations. This geographic diversity presents challenges in ensuring that the BCC app remains relevant and useful across various jurisdictions. These challenges can be addressed through the following strategies:

(i) Localized code variability: Different states, countries, or municipalities may have specific building codes, standards, and zoning laws that must be considered. The app would need to be adaptable to these local variations. One solution could be to provide customizable modules within the app that allow users to input local regulations, creating a more flexible system for various regions.

(ii) Continuous updates for code changes: Building codes are subject to periodic revisions, and the BCC app would require frequent updates to stay in line with evolving codes. This can be addressed through a subscription-based model or regular automatic updates that ensure users always have access to the latest regulations.
(iii) Geographic-specific customer support: Designers in different regions may face unique challenges in using the app due to their local building code structures. Offering region-specific customer support, such as through a help desk or localized online resources, would be essential in ensuring the app's long-term effectiveness.

4.2. Different types of designers with varying needs

The needs of design professionals can vary widely depending on their role, design discipline, and the scale of the projects they work on. The BCC app should be able to address these differing needs in the following ways:

(i) Small firms versus large firms: Smaller design firms, which may have limited resources, will require an app that is easy to integrate and does not require extensive training or support. For these firms, a more streamlined, user-friendly version of the BCC app with simple features may be the most effective approach. In contrast, larger firms may need more advanced capabilities, such as bulk compliance checks for multiple projects or the ability to integrate the app with other project management tools.
(ii) Architects versus engineers: Different types of designers have different requirements. Architects may prioritize creative flexibility and visualization tools, while engineers may require more detailed technical features such as load-bearing calculations or mechanical compliance checks. Customizing the app's features to cater to these needs, as offering different versions for different design professionals, would ensure the BCC app's long-term adoption.

4.3. The need for more features

While the BCC app provides valuable services, additional features would make it even more indispensable in everyday design workflows. Some of the features that would benefit the app and its users include:

(i) Collaboration tools: Designers often work in teams or collaborate with other professionals, such as engineers, contractors, and consultants. Integrating real-time collaboration features (similar to Google Docs or Slack) would allow multiple users to access and edit the same compliance checks, track changes, and leave comments for more efficient teamwork.
(ii) Customizable reporting: While the app generates PDF reports with calculations, a feature to customize report layouts and include or exclude specific data could help designers tailor the reports for different clients or projects. For example, adding client-specific branding or highlighting key compliance issues could make the reports more useful for presentations.

4.4. More testing for the app

To ensure that the app can seamlessly integrate into the workflows of busy professionals, more extensive testing is necessary, particularly in the following areas:

(i) User testing across various regions: Conducting thorough testing in diverse geographic locations to ensure the app performs well with local building codes and regulations is crucial. This will help identify any gaps or issues in the app's ability to meet the specific needs of different regions.
(ii) Feedback from different design disciplines: Testing the app across different design disciplines—such as architecture, civil engineering, and mechanical engineering—will ensure that the app's features meet the specialized needs of each profession. Engaging a variety of users in testing phases can provide critical insights into feature performance and usability.
(iii) Scalability for large projects: The app needs to be tested in larger-scale projects with complex compliance requirements. Ensuring that the app can handle a large number of compliance checks, multiple inputs, and cross-jurisdictional code applications is essential for its adoption by larger design firms.

4.5. Marketing strategy for educators and professionals

To ensure that the BCC app reaches both professionals and educators, a robust marketing strategy needs to be developed. This should focus on:

(i) Outreach to educational institutions: Partnering with universities and design and architecture schools to introduce the app as a teaching tool is critical. Offering free trials for educators and students can encourage adoption in academic settings. Furthermore, creating educational resources, such as webinars, workshops, and tutorials, can help integrate the app into curricula seamlessly.
(ii) Professional associations and networks: Building relationships with professional associations, such as the American Institute of Architects or the American Society of Interior Designers, could help spread awareness of the app to established professionals. Offering special promotions or certifications for professionals who use the app could drive widespread adoption.
(iii) Social media and online presence: Promoting the app through digital channels such as social media, industry blogs, and professional forums would help engage a wider audience. Content marketing that

highlights the app's unique features, case studies, and testimonials from users would be effective in attracting both students and professionals.

5. Conclusion

Building codes ensure the safety of buildings for occupants. Hence, designers are required to understand and calculate them accurately. Conventionally, this process has been performed manually, making it time-consuming, error-prone, and costly. With technological advancements, interior designers are encouraged to stay updated and explore new tools that can accomplish design tasks more efficiently. While attempts have been made to automate building code checking systems, they typically require programming skills that many designers do not possess. Therefore, the BCC app was designed to help calculate codes and improve efficiency. The interviews revealed that professionals and students experience frustration with the current available resources and traditional calculation methods. They also recognize the potential value of the BCC app in improving efficiency, reducing errors, and enhancing students' learning. Moreover, the results for relative advantage, compatibility, image, ease of use, result demonstrability, visibility, and trialability demonstrate that professionals are willing to adopt the app. Overall, the BCC app is an effective tool that can be used in the industry to help interior designers calculate complex codes and can be integrated into design courses to help students learn how to calculate codes. For the BCC app to become a permanent and valuable tool in the long-term workflows of busy design professionals and academic curricula, addressing geographic and jurisdictional diversity, expanding features, conducting more extensive testing, and executing a targeted marketing strategy are essential. With the right support and adaptations, the app can establish itself as an indispensable resource for building code compliance across a wide range of disciplines and locations.

While the study's findings are valuable within the specific regions of the study, it is important to recognize that variations in building codes, regional industry practices, and educational frameworks could lead to different outcomes in other geographic areas. Future studies that include a wider range of regions with differing codes and industry standards will be crucial for confirming whether these findings hold across diverse settings.

In addition, while the instructors provided valuable insights into potential educational applications and challenges, we recognize that industry professionals may have different concerns, such as the app's practicality in real-world projects or its compatibility with existing workflows. For instance, an industry professional might place more weight on the app's ability to streamline daily code compliance tasks, while an instructor might be more concerned with its use as an educational tool in the classroom. These differences highlight the need for further research that directly surveys industry professionals to better understand how they perceive the app's relative advantage, compatibility with current practices, complexity, trialability, and observability, all of which are key attributes of the innovation diffusion theory.

While the study's qualitative component provided valuable insights into the challenges and perceptions regarding building codes and the BCC app, it is important to recognize a limitation in the data collection process. Specifically, nearly half of the qualitative data were captured through field notes, which, while effective for noting overarching themes and key points, may lack the depth and detail found in full interview transcripts. Future research should aim to transcribe all interviews in full to provide a richer and more nuanced understanding of participants' experiences. In addition, incorporating other methods such as member checking or follow-up interviews could further enrich the data and help ensure a more comprehensive analysis. Despite this limitation, the study offers an important foundation for understanding how building codes and the BCC app are perceived by design educators and industry professionals. While the BCC app currently handles samples of complex calculations, we acknowledge that there are additional features that could be developed to enhance its usefulness and applicability across various code systems. For example, we plan to incorporate additional features such as plumbing fixtures calculations and means of egress sizing. These future improvements will help address even more specific code-related challenges. We also plan to enhance the app's ability to support multi-jurisdictional code compliance, which will allow users to automatically adjust for local building codes when designing projects in different geographic regions. This would significantly improve the app's flexibility and value for both educators and professionals working in diverse geographic areas with varying requirements.

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Conflict of interest

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Ethics approval and consent to participate

This study was approved by the Oklahoma State University Institutional Review Board (IRB) under the application number IRB-25-7. The IRB granted approval on January 3, 2025, and processed the application as expedited. Human subjects were involved in this study, and verbal consent was obtained from all participants, ensuring their informed participation.

Consent for publication

Participation in this research study was entirely voluntary, and informed consent was obtained from all human subjects before their involvement. No personally identifiable information was shared, and the findings are presented solely in aggregate form.

Availability of data

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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ARTICLE

Machine learning strategies for predicting Alzheimer's disease progression

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Abstract

Alzheimer's disease (AD) represents a significant global health challenge, affecting millions of individuals worldwide through progressive cognitive decline and behavioral changes. The burden extends beyond patients to caregivers and healthcare systems. While traditional diagnostic methods pose financial obstacles, emerging non-imaging techniques show promise. Machine learning has emerged as a transformative approach for enhancing both diagnosis and management. This study aims to develop a robust multi-class classification model using random forest (RF) and extreme gradient boosting algorithms on non-imaging data from the Australian AD Neuroimaging Initiative, with emphasis on the Australian Imaging, Biomarkers, and Lifestyle Study of Aging. Extensive data analysis was conducted, including feature importance and selection, to improve interpretability and classification accuracy. Synthetic oversampling was applied to address class imbalance. The findings indicate the superiority of the tuned RF model, achieving 90% in accuracy, precision, recall, and F1 scores. In addition, cost-effective diagnostic variables were explored, with neuropsychology assessment variables demonstrating exceptional accuracy (90%). This research contributes to early AD detection, personalized treatment, and optimized resource allocation.

Keywords: Alzheimer's disease; Machine learning; Python classification model; Non-imaging data; Random Forest; Extreme gradient boosting; Australian imaging biomarkers and lifestyle study of aging; Diagnosis

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1. Introduction

Alzheimer's disease (AD) represents a significant global health challenge, affecting millions of individuals worldwide. This condition progressively impairs memory, cognitive function, and behavior, ultimately leading to severe disability and death. AD not only affects those diagnosed but also places considerable strain on caregivers and healthcare systems, escalating the burden of care and resource allocation. Initially, AD may manifest as mild forgetfulness, but it gradually progresses to encompass a wide range of symptoms that deteriorate over time, subjecting both patients and their families to a distressing trajectory of decline and loss. The emotional toll of AD extends beyond cognitive impairment, significantly affecting the well-being of families and caregivers.[1] The continuous demands of caregiving challenge emotional resilience and endurance. However, amidst these challenges, there is a shared commitment to confronting AD with resolve and innovation.

One significant obstacle in addressing AD is the high cost associated with traditional imaging techniques and diagnostic procedures. While these methods are beneficial, they are often highly expensive for patients and healthcare systems. Nevertheless, emerging alternatives, such as genetic markers, neuropsychological assessments, and biomarker analysis, show promise as more accessible and cost-effective diagnostic tools.[2] By prioritizing these non-imaging methods, the financial burden of diagnosis may be alleviated, thereby broadening access to care for individuals with AD.

In this landscape of challenges and opportunities, machine learning (ML) has emerged as a transformative tool. With its ability to process complex datasets and extract valuable insights, ML holds the potential to improve AD diagnosis and management. Through the utilization of novel data and rigorous training, ML algorithms excel at predicting outcomes and providing invaluable guidance for decision-making processes. Moreover, ML enables earlier disease detection and intervention, thereby contributing to improved patient outcomes and enhanced quality of life.[3] The adaptability of ML models further allows for continual refinement and optimization, ensuring ongoing improvements in prediction accuracy and diagnostic efficacy.

The primary objective of this study is to develop a robust multi-class classification model for predicting AD among three distinct groups: Healthy control (HC), individuals with mild cognitive impairment (MCI), and those diagnosed with AD. Leveraging non-imaging data from the Australian AD Neuroimaging Initiative,[4] with a particular emphasis on the Australian Imaging Biomarkers and Lifestyle Study of Aging (AIBL),[5] this study utilizes random forest (RF) and Extreme Gradient Boosting (XGBoost) algorithms, along with their optimized models. Through comparative analysis, the most effective classification model is identified. In addition, this study aims to enhance interpretability through feature importance analysis and the evaluation of various classifiers. These efforts are expected to streamline the predictive process for AD, facilitate early detection, enable personalized treatment strategies, and optimize resource allocation. The ultimate goal is to provide valuable insights to inform the development of improved, cost-effective diagnostic and therapeutic approaches for addressing this debilitating condition.

2. Existing work

Many researchers have conducted studies on classifying AD using various datasets. In alignment with the present study's objectives, Rahman and Prasad[6] addressed the challenge of accurately diagnosing AD—a disease that severely impacts cognitive and behavioral abilities—as a binary classification problem. Utilizing non-imaging data from the AIBL, they built RF models employing different combinations of data and preprocessing steps. An RF is an ML algorithm that uses an ensemble of decision trees to make predictions. It is a supervised learning method, trained on labeled data to classify or predict outcomes. RFs are known for their accuracy and ability to handle complex datasets.

Their approach included using scaled and unscaled data for simple RF classifiers, tuned RF classifiers, and RF classifiers with selected features using DALEX and Boruta packages in R software. Their results showed that the tuned RF classifier, which utilized the original data, achieved an impressive 96% accuracy in classifying AD into HC and non-HC categories, with precision and recall scores exceeding 97%. Model evaluation was primarily focused on accuracy, in line with their research objective of effectively classifying instances of AD. Furthermore, they developed multiple diagnostic classifiers and evaluated them to streamline the prediction process, aiming to create a cost-effective diagnosis method.

Notably, their classifier based on neuropsychological assessment variables demonstrated exceptional performance, achieving an accuracy of 93.68%. This model required only 4 out of 30 test variables, highlighting its potential to increase efficiency in diagnostic processes.

3. Dataset description

The AIBL study commenced in 2006 with the aim of investigating the origins of AD and developing tools for identifying cognitive decline at its early stages.[4,5] The study includes a diverse population comprising healthy individuals, those with MCI, and those diagnosed with AD. With over 1,000 participants, the AIBL dataset represents a comprehensive resource for AD research. It supports investigations into the associations between lifestyle factors and cognitive impairment and facilitates the development and evaluation of algorithms for early AD detection. A summary of the dataset is presented in Table 1.

4. Methodology

The Cross-Industry Process for Data Mining (CRISP-DM), a widely adopted methodology recognized for its effectiveness across industries, was employed in this study. It offers flexibility while maintaining a comprehensive and structured approach compared to other methods.[7] The method comprises distinct phases: business understanding, data understanding, data preparation,

Table 1. Dataset summary

Variable	Description
Demographics	
Age	55–96 years old
Gender	Categorized as "Female" or "Male"
Medical history	
Psychiatric (MH_PSYCH)	Binary features
Neurologic (MH_NEURL)	
Cardiovascular (MH_CARD)	
Hepatic (MH_HEPAT)	
Musculoskeletal (MH_MUSCL)	
Endocrine–metabolic (MH_ENDO)	
Gastrointestinal (MH_GAST)	
Renal–genitourinary (MH_RENA)	
Smoking (MH_SMOK)	
Malignancy (MH_MALI)	
ApoE genotype	
Two-allele genotype	Each individual carries two ApoE alleles, and each allele can be E2, E3, or E4
Neuropsychological assessments	
Clinical dementia rating (CDGLOBAL)	Total number of story units recalled immediately; scores ranged from 0 to 25
Mini-mental state exam (MMSCORE)	Total number of story units recalled after a delay; scores ranged from 0 to 25
Logical memory immediate recall (LIMMTOTAL)	-
Logical memory delayed recall (LDELTOTAL)	
Blood analysis	
Thyroid stimulating hormone (AXT117)	
Vitamin B12 (BAT126)	
Red blood cell count (HMT3)	
White blood cell count (HMT7)	
Platelet count (HMT13)	
Hemoglobin (HMT40)	
Mean corpuscular hemoglobin (HMT100)	
Mean corpuscular hemoglobin concentration (HMT102)	
Urea nitrogen (RCT6)	
Serum glucose (RCT11)	
Cholesterol (high performance; RCT120)	
Creatinine (rate blanked; RCT329)	
Diagnosis	
Diagnostic results	Categorized into healthy control, mild cognitive impairment, and Alzheimer's disease

Abbreviation: ApoE: Apolipoprotein E.

modeling, evaluation, and deployment. Figure 1 illustrates a graphic representation of these CRISP-DM phases.

4.1. Business understanding

The business understanding phase involves defining business objectives, assessing the current context, establishing data mining goals, and formulating a project plan. As outlined in the introduction, a background study was conducted, and the research objectives were clearly defined. The success criteria for this study involved benchmarking classifier performance against the AD classification model presented by Rahman and Prasad[6] and comparing the best diagnosis classifier with the one identified in their study.

This comparison focused on four key metrics critical for evaluating classifier performance: (i) Accuracy, indicating the proportion of correctly predicted instances relative to the total number of instances in the dataset; (ii) precision, a measure of prediction reliability, reflecting the ratio of true positive predictions to all positive predictions; (iii) recall, also referred to as sensitivity, measuring the classifier's ability to identify actual positive cases; and (iv) F1-score, the harmonic mean of recall and precision, which balances the trade-off between these two metrics.[8]

A comprehensive project plan was formulated based on available resources, requirements, and risk assessments. The plan encompassed tasks across each CRISP-DM phase, including the selection of appropriate tools, methodologies, and risk mitigation strategies. The primary tools utilized were Google Colab and Python, with tasks involving data preparation, cleaning, and analysis. Python libraries, particularly functionalities

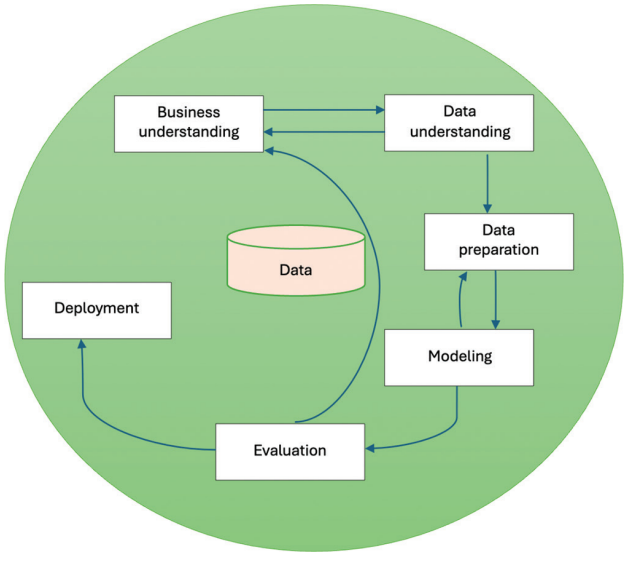

Figure 1. Phases of the cross-industry process for data mining

from Scikit-learn,[9] were employed for modeling and evaluation purposes.

4.2. Data understanding

In the second phase of the methodology, we began by familiarizing ourselves with the collected data using a comprehensive data dictionary, which outlined feature descriptions and properties. The dataset comprised eight distinct CSV files, imported into Google Colab via file synchronization from Google Drive using the PyDrive library in Python.[10] Subsequently, these CSV files were merged to construct a master dataframe, facilitated by shared key columns such as RID, SITEID, and VISCODE, resulting in a unified dataframe containing 1,688 rows and 36 columns.

Given our focus on baseline data, we filtered the dataset for baseline entries using the VISCODE column, yielding 862 observations. To prepare for pre-analysis, we systematically transformed several features into categorical formats based on predefined values. Medical history variables—including MHPSYCH, MH2NEURL, MH4CARD, MH6HEPAT, MH8MUSCL, MH9ENDO, MH10GAST, MH12RENA, MH16SMOK, and MH17MALI—were categorized as "No" or "Yes" based on their respective binary values. Apolipoprotein E (ApoE) genotypes (e.g., APGEN1, APGEN2) were labeled as "E2," "E3," or "E4," corresponding to their genetic variants. MMSCORE was segmented into severity levels (e.g., "Severe," "Moderate," "Mild," "Normal") based on predefined score ranges. PTGENDER was categorized as "Male" or "Female" according to gender data. CDGLOBAL was classified into health status categories (e.g., "Healthy," "Very Mild," "Mild," "Moderate," "Severe") based on clinical assessment scores. DXCURREN was mapped to clinical stages (e.g., "HC," "MCI," "AD") using a predefined mapping dictionary. These transformations enhance the interpretability of the dataset by aligning feature values with clinically relevant categories for subsequent analysis. During this preparatory phase, it was observed that 2.28% of the data were missing; however, no duplicates were detected.

Before the exploratory data analysis, a few data cleaning procedures were performed to enhance the interpretability of the findings. This step was essential to ensure the accuracy and reliability of the analyses by removing any inconsistencies and inaccuracies within the dataset. Initially, the age of patients was calculated by comparing examination dates with their respective birthdates. This process involved cleansing the date of birth column to remove unnecessary characters, followed by the creation of the EXAMYEAR column to compute the age as a distinct feature. Furthermore, noisy values of "–4"—recurrent across multiple columns—were identified and replaced with NaN. Concurrently, redundant columns such as RID, SITEID, VISCODE, EXAMDATE, EXAMYEAR, APTESTDT, and PTDOB, among others, were eliminated to streamline the dataset for analysis.

In the exploratory data analysis, the distribution of output classes was visualized, revealing a significant class imbalance among HC, MCI, and AD. Specifically, HC emerged as the predominant class with 609 instances, followed by MCI with 144 instances and AD with 105 instances. A subsequent review of summary statistics for numerical features revealed slight discrepancies in feature counts, suggesting the presence of missing values. Moreover, notable differences in scales and variances were observed across many features.

Upon delving further into the distributions of numerical features, distinctive patterns were observed. Variables such as AXT117, BAT126, and HMT7, alongside RCT6 and RCT11, displayed a notable tendency toward higher values, suggesting a right-skewed distribution. Similarly, RCT392 exhibited a comparable pattern, indicating a concentration of data at the lower end with potential outliers extending toward higher values.

In contrast, the distributions of HMT13, HMT40, HMT100, HMT102, RCT20, RCT392, and AGE showed a unimodal pattern, indicative of relatively normal distributions with a pronounced peak at the center. This characteristic suggests the presence of a central value around which the data clusters. Furthermore, LIMMTOTAL displayed a unimodal distribution with an additional smaller peak, while LDELTOTAL exhibited a similar pattern with a slightly less distinct secondary peak.

The analysis was extended using box plots to assess the spread of numerical variables. Except for LIMMTOTAL, LDELTOTAL, and AGE, potential outliers were observed in the remaining variables at both ends of the distribution.

To assess multicollinearity,[11] a correlation matrix was constructed and visualized using a heatmap (Figure 2). LIMMTOTAL and LDELTOTAL exhibited a strong positive correlation, indicating a close relationship between these variables. Additionally, HMT3 and HMT40, HMT100 and HMT102, as well as RCT6 and RCT392, demonstrated strong positive correlations, further highlighting interdependencies within the dataset. Conversely, strong negative correlations were observed between HMT100 and HMT3, HMT40 and HMT3, as well as HMT13 and HMT3, suggesting inverse relationships between these variables.

Finally, the association between categorical variables and the target variables was evaluated. As shown in Figure 3,

CDGLOBAL and MMSCORE displayed significant Chi-square statistics[12] with extremely low *p*-values, indicating a robust association with the target variable. This suggests that these variables hold substantial predictive power with respect to the target outcome. In addition, MH2NEURL, APGEN1, and APGEN2 exhibited moderate chi-square statistics accompanied by small *p*-values, indicating a noticeable association with the target variable, although not as strong as that of CDGLOBAL and MMSCORE. However, MH8MUSCL and PTGENDER demonstrated relatively smaller Chi-square statistics along with higher *p*-values, suggesting a weaker association with the target variable.

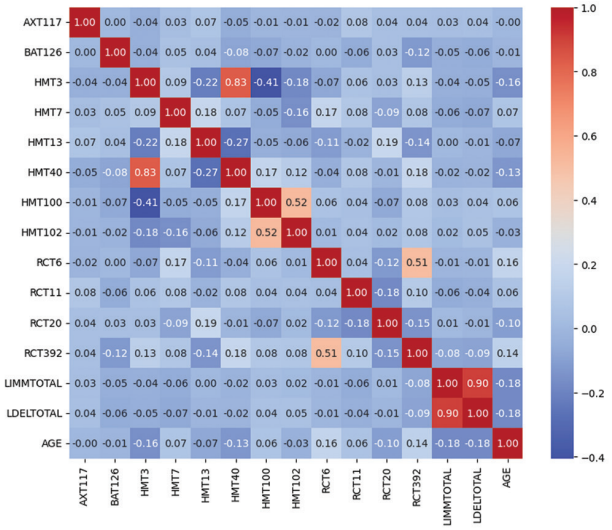

Figure 2. Correlation matrix heatmap of numerical features

Overall, the exploratory data analysis identified several areas for improvement, including class imbalance, missing values, outliers, multicollinearity, and skewed distributions.

4.3. Data preparation

Data preparation, the third phase of the CRISP-DM methodology, began by following the basic data cleaning steps conducted during the data understanding phase. The initial step involved converting categorical data into a numerical format to facilitate model development. However, it was noted that the "pd.factorize"[13] function assigned "−1" in place of missing values, necessitating further replacement with NaN values to enable imputation at a later stage.

To prevent data leakage and assess the model's efficacy in generalizing to previously unseen data, a critical first step was to split the data before implementing any preprocessing techniques.[14] The data was split in an 80:20 ratio, allocating 80% for training and the remaining 20% for testing. Subsequently, we focused on handling missing values within the training dataset, acknowledging the potential impact on predictive accuracy due to data loss if inadequately addressed. To address this, the MissForest imputation technique,[15] an algorithmic approach that initially uses mean and mode values to replace missing data, was applied. This was followed by the implementation of an RF methodology to iteratively predict missing values, prioritizing data accuracy over processing speed.

Given the high dimensionality of the dataset, an analysis of feature importance was conducted to determine the most

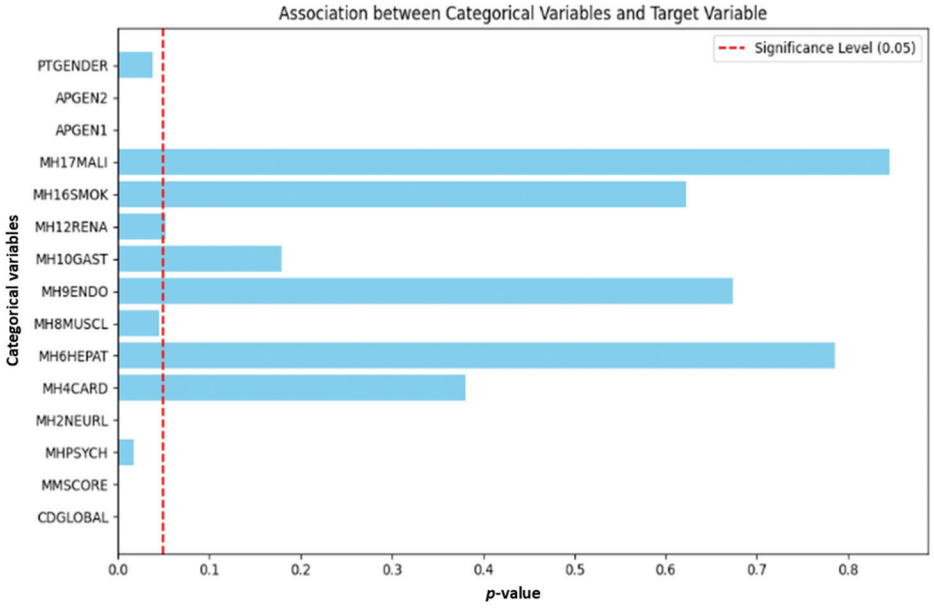

Figure 3. Visualization of the results from the Chi-square test

influential features for accurate predictions. By combining the permutation feature importance technique[16] with an RF classifier over 150 iterations, this analysis revealed the significance of specific features in influencing predictive accuracy, thereby guiding further modeling decisions. The importance of each feature was systematically assessed to ensure a comprehensive understanding of its contribution to the overall predictive capability of the model.

Subsequently, feature selection was performed to streamline computational resources and optimize model performance. Using an RF feature selection technique[17] with 100 estimators and a maximum depth of 5, the algorithm evaluated each feature's contribution to impurity reduction (Gini impurity) before decision tree construction, thereby identifying the most significant features for predictive modeling. By selecting the most informative, non-redundant features, data utilization was optimized, resulting in improved computational efficiency and enhanced model performance.

Addressing class imbalance, a common challenge in ML, was essential to ensuring model robustness across all classes. The Synthetic Minority Over-Sampling Technique (SMOTE)[18] was applied to oversample minority classes (e.g., MCI and AD) by generating synthetic samples, yielding a balanced representation across all classes. Following resampling, further adjustments were made to facilitate model training and evaluation, resulting in the creation of two distinct dataframes for analysis.

4.4. Modeling

In selecting ML models during the data preparation phase, non-parametric models were prioritized due to their flexibility in handling complex datasets.[19] Outliers, multicollinearity, and skewness were identified as key challenges that were unaddressed in the previous phase. Therefore, tree-based models were considered suitable due to their adaptability to such issues. For multiclass classification, the RF and XGBoost algorithms were selected.[20,21]

RF[21] is an ensemble learning algorithm that combines multiple decision trees to yield more accurate and reliable predictions. By training each decision tree on randomly selected subsets of the training data, RF reduces overfitting and enhances model generalizability.

XGBoost, commonly known as XGBoost,[22] is another powerful algorithm in the gradient boosting family. XGBoost is a widely used open-source software library that implements a gradient boosting algorithm. It is commonly applied to ML tasks such as classification, regression, and ranking, particularly when dealing with tabular or structured data. XGBoost is known for its speed, efficiency, and ability to handle large datasets. It sequentially builds a strong predictive model by aggregating the predictions of multiple weak decision trees. Through advanced feature selection and regularization techniques, XGBoost minimizes overfitting and improves model performance.

Two models were developed for the prepared data: baseline models and their fine-tuned equivalents. For fine-tuning, the "RandomizedSearchCV" function was used.[23] This method selects random combinations of hyperparameter values from a grid, trains the model on a subset of the training data, and evaluates its performance on a different subset using cross-validation. The combination that yields the best performance metric represents the optimized set of hyperparameters for the model.

In addition, three distinct diagnosis classifiers were developed to identify the most reliable method for reducing the number of tests required for disease detection, thereby lowering diagnostic costs. These classifiers utilize medical history variables, blood analysis, ApoE genotype variables, and neuropsychological assessment variables individually. To model these classifiers, we employed the fine-tuned version of the best-performing algorithm, ensuring optimal predictive performance. This approach aims to streamline the diagnostic process while maintaining diagnostic accuracy.

4.5. Model evaluation

In this phase, a comprehensive evaluation of the models was conducted to guide future actions. Predictions from all models were compared against actual values using the "classification_report" function.[24] The evaluation included accuracy, as well as weighted-average precision, recall, and F1-score, offering a detailed overview of overall model performance. This approach accounts for class imbalances, ensuring robustness across all classes.[25] In addition, macro-average and class-wise performance metrics were emphasized when further insights were required. Given the research focus of this study, the deployment phase was omitted. A detailed analysis of the models is presented in the Results and Discussion section.

5. Results

5.1. Feature importance

The Chi-square test results revealed a significant association between the target variable and two key features, CDGLOBAL and MMSCORE, as indicated by their strong chi-square statistics and extremely low p-values. This finding was further confirmed by the permutation feature importance test. Figure 4 shows the feature importance ranking, highlighting CDGLOBAL as the most influential feature, followed by LDELTOTAL, MMSCORE, and

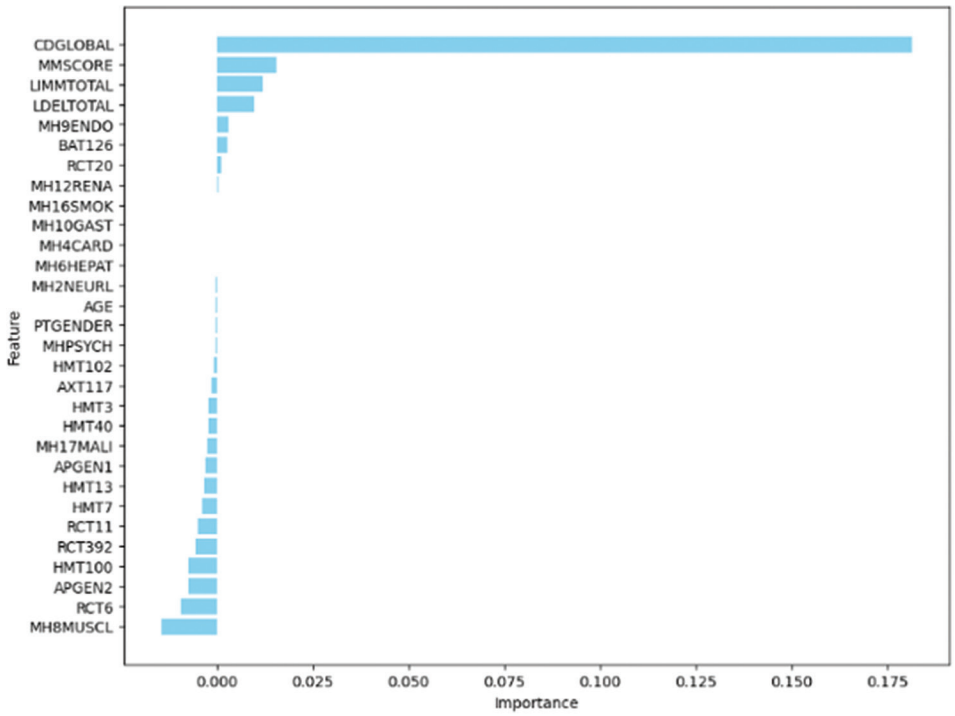

Figure 4. Feature importance using permutation method

LIMMTOTAL. While MH9ENDO ranked next in importance, its contribution during the imputation process was relatively less significant compared to the other features. This comprehensive analysis underscores the pivotal role of these features in predicting the target outcome, thereby guiding subsequent steps in the analysis.

5.2. Feature selection

The RF-based feature selection process identified four key features as crucial for predicting the output class, DXCURREN: CDGLOBAL, MMSCORE, LIMMTOTAL, and LDELTOTAL. These features demonstrated significant importance in accurately predicting the target outcome. Additionally, the feature importance analysis revealed MH9ENDO as an additional feature, though its contribution was relatively minor compared to the others. Implementing this feature selection approach supported decision-making by excluding MH9ENDO from the final feature set.

5.3. Class balancing

In the dataset exhibiting class imbalance, the sample distribution was skewed, with 609 samples for HC, 144 for MCI, and 105 for AD. By generating additional synthetic samples using SMOTE, each class was balanced to contain 490 samples.

5.4. Performance evaluation

As shown in Table 2, the performance evaluation metrics indicate that the tuned RF model with selected features outperformed the other models. The best hyperparameters included "n_estimators" = 100, "min_samples_split" = 15, "min_samples_leaf" = 1, and "max_depth" = 50—identified through randomized search with five-fold cross-validation over 100 iterations. Furthermore, the tuned RF model with selected features demonstrated exceptional performance across multiple evaluation metrics.

In Class 0 (HC), the model exhibited high precision (97%) and recall (93%), ensuring accurate identification of HCs. For Class 1 (MCI), while precision was moderate (69%), the model displayed commendable recall (89%), which is crucial for identifying MCI instances. Class 2 (AD) demonstrated balanced precision (95%) and recall (78%), essential for accurately identifying AD cases.

The overall accuracy of 90% underscores the model's efficiency, with both macro-average (precision: 0.87; recall: 0.87; F1-score: 0.86) and weighted-average metrics (precision: 0.91; recall: 0.90; F1-score: 0.90) confirming its consistency and superior performance across all classes. This comprehensive evaluation highlights the effectiveness of the tuned RF model in accurately distinguishing between different diagnostic categories. The Appendix

Table 2. Performance metrics of the machine learning models

Machine learning model	Complete features					Selected features				
	Accuracy	Weighted average				Accuracy	Weighted average			
		Precision	Recall	F1-score	Support		Precision	Recall	F1-score	Support
Simple RF	0.88	0.90	0.88	0.88	74	0.86	0.86	0.86	0.86	134
Tuned RF	0.88	0.90	0.88	0.88	74	0.90[a]	0.91[a]	0.90[a]	0.90[a]	134[a]
Simple XGBoost	0.86	0.87	0.86	0.87	74	0.85	0.85	0.85	0.85	134
Tuned XGBoost	0.85	0.86	0.85	0.85	74	0.89	0.90	0.89	0.89	134

Notes: This table presents the performance of machine learning models evaluated on two datasets—one with complete features and one with selected features. "Tuned" models refer to those that were optimized via hyperparameter tuning using "RandomizedSearchCV" function. Metrics include accuracy, precision, recall, and F1-score. The "weighted average" accounts for class imbalance, while "support" indicates the number of test samples.
[a]Indicates the tuned RF model with selected features outperformed the other models.
Abbreviations: RF: Random forest; XGBoost: Extreme gradient boosting.

outlines the macro-average metrics and provides a detailed classification report.

The evaluation of the diagnostic classifiers highlighted the superior performance of the "neuropsychological assessment" classifier compared to the other two. Leveraging the variables CDGLOBAL (clinical dementia rating [CDR]), MMSCORE (mini-mental state examination [MMSE]), LIMMTOTAL (logical memory immediate recall), and LDELTOTAL (logical memory delayed recall), this classifier achieved a remarkable 90% accuracy in classifying AD cases. These variables were modeled using optimal hyperparameters—"n_estimators" = 100, "min_samples_split" = 15, "min_samples_leaf" = 1, and "max_depth" = 50—identified through randomized search with five-fold cross-validation and 100 iterations. Performance metrics of the diagnosis classifiers are presented in Table 3.

In terms of macro-average metrics, precision, recall, and F1 scores were all approximately 0.86, indicating consistent and balanced performance across all classes. Furthermore, the weighted-average precision, recall, and F1 scores exceeded 0.90, demonstrating excellent overall performance, with precision slightly surpassing recall. This detailed evaluation supports the effectiveness of the "neuropsychological assessment" classifier in accurately classifying AD cases. The Tables A1 and A2 outline the macro-average metrics and provide a detailed classification report.

6. Discussion

This study focused on developing robust multi-class classification models to predict AD across three distinct groups—HC, individuals with MCI, and diagnosed AD patients—and selecting the best-performing model based on its evaluation metrics. The results obtained from the optimal model could contribute to the early diagnosis of disease progression and provide valuable insights for advancing diagnostic methods and treatment strategies.

Table 3. Performance metrics of the diagnosis classifiers

Diagnostic classifier	Accuracy	Weighted average			
		Precision	Recall	F1-score	Support
Medical history variables	0.52	0.43	0.52	0.46	111
Neuropsychological assessment variables	0.90[a]	0.91	0.90	0.90	134
Blood analysis and ApoE genotype variables	0.65	0.85	0.68	0.66	148

Notes: This table presents the performance of three classifiers, each constructed using a single feature group—medical history variables, blood analysis and ApoE genotype data, and neuropsychological/clinical test results. The "neuropsychological assessment" classifier is further broken down into four individual cognitive tests: CDGLOBAL (clinical dementia rating), MMSCORE (mini-mental state examination), LIMMTOTAL (logical memory immediate recall), and LDELTOTAL (logical memory delayed recall). All classifiers were developed using the tuned Random Forest algorithm.
Abbreviation: ApoE: Apolipoprotein E.

Several data mining techniques used in this research, particularly feature importance and feature selection, yielded information that may inform further studies on this debilitating condition.

The comparative analysis between RF and XGBoost models, using the complete dataset, revealed detailed differences in their performance metrics, offering valuable insights into their predictive capabilities. Initially, both the simple RF and tuned RF models demonstrated a commendable overall accuracy of 88%, reflecting their ability to generate accurate predictions. This finding underscores the robustness of the RF algorithm in identifying complex patterns within the dataset. Furthermore, their high precision scores (90%) highlight the model's effectiveness in minimizing false positives—a critical factor in healthcare applications and resource optimization decision-making.

Additionally, the notable recall scores (88%) confirm the model's ability to correctly identify relevant cases in the dataset. The consistent F1-scores of 88% across both RF models further validate their balance between precision and recall, indicating their resilience to class imbalances and capacity to maintain predictive integrity. In contrast, the simple and tuned XGBoost models, while showing competitive performance, exhibited slightly lower accuracy scores of 86% and 85%, respectively. This indicates a slight reduction in overall predictive capability compared to the RF models. Nevertheless, the XGBoost models maintained comparable precision and recall scores—approximately 87% and 86%, respectively—demonstrating a consistent ability to minimize false positives and accurately detect relevant cases. Despite this slight decrement in accuracy, the F1-scores of 87% (simple XGBoost) and 85% (tuned XGBoost) indicate a well-maintained balance between precision and recall, affirming their reliability to sustain predictive accuracy across multiple evaluation metrics.

Both the simple RF and simple XGBoost models, utilizing selected variables, exhibited comparable accuracies of 86% and 85%, respectively, suggesting similar predictive performance. However, upon tuning, the RF model demonstrated a notable improvement, achieving an impressive accuracy of 90% and outperforming the tuned XGBoost model, which attained a respectable score of 89%. This enhancement underscores the effectiveness of fine-tuning in optimizing the RF algorithm's predictive capabilities, potentially making it a preferred choice in scenarios where maximizing prediction accuracy is crucial.

Additionally, evaluating precision, recall, and F1-score metrics provided a more comprehensive understanding of model performance beyond overall accuracy. Both the simple and tuned RF models consistently achieved higher precision, recall, and F1 scores compared to their XGBoost counterparts. Specifically, the tuned RF model yielded the highest scores across all three metrics, indicating superior ability to minimize false positives while effectively capturing relevant instances from the dataset. While the XGBoost models also demonstrated good precision, recall, and F1 scores, they slightly underperformed relative to the RF models, suggesting a moderate reduction in their effectiveness at minimizing misclassifications and accurately detecting relevant cases.

The predictive simple RF model from a previous study achieved an impressive accuracy of 96.05% for a binary classification task using all features of the AIBL non-imaging dataset.[3] In comparison, our best model—the tuned RF model using selected features—achieved a slightly lower accuracy of 90%. When comparing equivalent models from both studies, our simple RF model using all features yielded an accuracy of 88%. However, it is important to note that the prior study addressed a binary classification problem, whereas our study considered all three AD-related classes. This difference in classification scope likely accounts for the observed decrease in accuracy. The added complexity of distinguishing among three classes inherently increases the challenge and may reduce model performance relative to a binary setting.

Therefore, while our model's accuracy may appear slightly lower, its ability to classify across multiple classes provides valuable insight into the severity of AD. Furthermore, in our study, the train–test split was performed prior to preprocessing, supporting the model's ability to generalize to unseen data. In contrast, the previous study preprocessed the entire dataset, except for SMOTE, which may have contributed to their enhanced performance. Nonetheless, both studies consistently identified CDGLOBAL (CDR), MMSCORE (MMSE score), LIMMTOTAL (logical memory immediate recall), and LDELTOTAL (logical memory delayed recall) as the most informative predictors.

The comparison across classifiers based on medical history, neuropsychological assessment, and blood analysis with ApoE genotype variables offered valuable insights for medical diagnostics and predictive modeling. Initially, the classifier utilizing neuropsychological assessment variables emerged as the top performer, displaying impressive accuracy, precision, recall, and F1-score metrics, all exceeding 90%. This underscores the robust predictive capability of neuropsychological assessment data, highlighting its potential as a crucial diagnostic tool for AD. However, the classifier relying on medical history variables exhibited substantially lower performance metrics, with accuracy, precision, recall, and F1 scores hovering around 52%. This indicates its limited predictive accuracy when used in isolation. Despite its relatively lower accuracy, the classifier based on blood analysis and ApoE genotype variables demonstrated notable improvement. With precision at 85% and recall at 68%, resulting in an F1-score of 66%, the classifier shows promise in enhancing predictive accuracy and diagnostic capabilities by incorporating blood analysis and genetic data.

Both the existing and the present study identified that the classifier based on neuropsychological assessment variables as the most effective, consistently demonstrating exceptional performance metrics. Palmqvist[26] underscored the significance of the MMSE score in predicting the transition from MCI to AD. Similarly, Bloch and Friedrich[27] concluded that cognitive test results, including MMSE and CDR values, were the most informative features for effectively classifying AD. These findings highlight the

critical role of cognitive assessments in the early detection and diagnosis of AD.

7. Conclusion and future work

In this study, non-imaging data from the AIBL were analyzed to classify AD into three classes: HC, individuals with MCI, and those diagnosed with AD. Extensive data cleaning and exploration were conducted to reveal underlying patterns and extract information using various data mining techniques and statistical methods, including correlation analysis, feature association analysis, feature importance analysis, and feature selection.

To address the challenge of class imbalance, synthetic oversampling methods were employed to generate artificial samples to balance the target classes. Subsequently, the data were modeled and evaluated using advanced non-parametric ML algorithms, such as RF and XGBoost, first with complete feature set and then with selected features obtained through the feature selection process. Fine-tuning techniques were applied to enhance predictive accuracy. The results from these models underwent thorough evaluation to determine the most effective algorithm. The tuned RF model emerged as the top performer, achieving an accuracy of 90%, with precision, recall, and F1 scores also reaching 90%.

Furthermore, to reduce the diagnosis cost of AD and provide valuable insights toward developing a more reliable and affordable diagnostic tool, the data were segmented into three main variable groups: medical history, neuropsychological assessment, and blood analysis with ApoE genotype variables. Corresponding ML models were then developed using the fine-tuned model of the best-performing algorithm. The "neuropsychological assessment" classifier emerged as the most effective, exhibiting an exceptional accuracy of 90%.

Beyond its strong classification performance, this study presents a replicable and cost-effective methodology that may benefit other research groups, clinical practitioners, and public health systems aiming to improve early detection of AD. By leveraging non-imaging data—including widely available neuropsychological assessments—our approach avoids the high costs and limited accessibility associated with imaging-based diagnostics. The use of interpretable ML models, combined with robust feature selection and data preprocessing techniques, facilitates deployment in diverse clinical or research settings without the need for extensive computational infrastructure. Moreover, the proposed methodology can be adapted to other populations or datasets, supporting generalizability studies and cross-cohort validation efforts. This makes it particularly relevant for low-resource settings or large-scale screening efforts where rapid, accurate, and affordable tools are essential. Ultimately, this framework serves as a foundation for developing intelligent, personalized diagnostic support systems that prioritize early intervention and optimized resource allocation.

Given the time constraints of this research, explicit handling of outliers, multicollinearity, or distribution abnormalities was not performed. However, the selected models possess built-in capabilities to address these issues. Involving domain experts to directly address these factors could further enhance model performance. Moreover, the models were fine-tuned using the "RandomizedSearchCV" function; however, a more exhaustive approach, such as "GridSearchCV,"[28] could potentially yield better parameters by exploring a wider range of combinations. Although this study focused solely on direct multi-class classification, alternative approaches such as one-versus-one and one-versus-the-rest[29] may offer additional insights. Acknowledging these limitations provides a pathway for future research and further exploration of the problem.

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Conflict of interest

The authors declare that they have no competing interests.

Author contributions

Conceptualization: All authors
Formal analysis: Adhinrag Kalarikkal Induchudan
Investigation: All authors
Methodology: All authors
Writing–original draft: Adhinrag Kalarikkal Induchudan
Writing–review & editing: All authors

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data

Data is available from the corresponding author upon reasonable request.

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Appendices

Table A1. Classification performance of machine learning models using complete and selected features

Dataset type		Classification report								
Complete features		Simple RF					Tuned RF			
		Precision	Recall	F1-score	Support		Precision	Recall	F1-score	Support
	HC	0.95	0.93	0.94	40	HC	0.95	0.93	0.94	40
	MCI	0.70	0.89	0.78	18	MCI	0.70	0.89	0.78	18
	AD	1.00	0.75	0.86	16	AD	1.00	0.75	0.86	16
	Macro-average	0.88	0.85	0.86	74	Macro-average	0.88	0.85	0.86	74
		Confusion matrix					Confusion matrix			
		37	3	0			37	3	0	
		2	16	0			2	16	0	
		0	4	12			0	4	12	
		Simple XGBoost					Tuned XGBoost			
		Precision	Recall	F1-score	Support		Precision	Recall	F1-score	Support
	HC	0.93	0.93	0.93	40	HC	0.90	0.93	0.91	40
	MCI	0.71	0.83	0.77	18	MCI	0.70	0.78	0.74	18
	AD	0.92	0.75	0.83	16	AD	0.92	0.75	0.83	16
	Macro-average	0.85	0.84	0.84	74	Macro-average	0.84	0.82	0.83	74
		Confusion matrix					Confusion matrix			
		37	3	0			37	3	0	
		2	15	1			3	14	1	
		1	3	12			1	3	12	
Selected features		Simple RF					Tuned RF			
		Precision	Recall	F1-score	Support		Precision	Recall	F1-score	Support
	HC	0.93	0.94	0.93	84	HC	0.97	0.93	0.95	84
	MCI	0.63	0.70	0.67	27	MCI	0.69	0.89	0.77	27
	AD	0.89	0.74	0.81	23	AD	0.95	0.78	0.86	23
	Macro-average	0.82	0.79	0.80	134	Macro-average	0.87	0.87	0.86	134
		Confusion matrix					Confusion matrix			
		79	5	0			78	6	0	
		6	19	2			2	24	1	
		0	6	17			0	5	18	
		Simple XGBoost					Tuned XGBoost			
		Precision	Recall	F1-score	Support		Precision	Recall	F1-score	Support
	HC	0.91	0.95	0.93	84	HC	0.97	0.93	0.95	84
	MCI	0.63	0.63	0.63	27	MCI	0.68	0.85	0.75	27
	AD	0.89	0.74	0.81	23	AD	0.90	0.78	0.84	23
	Macro-average	0.81	0.77	0.79	134	Macro-average	0.85	0.85	0.85	134
		Confusion matrix					Confusion matrix			
		80	4	0			78	6	0	
		8	17	2			2	23	2	
		0	6	17			0	5	18	

Abbreviations: AD: Alzheimer's disease; HC: Healthy control; MCI: Mild cognitive impairment; RF: Random forest.

Table A2. Classification report of diagnosis classifiers

Diagnosis classifier		Classification report			
Medical history variables		Precision	Recall	F1-score	Support
	HC	0.60	0.80	0.68	69
	MCI	0.09	0.04	0.06	24
	AD	0.25	0.11	0.15	18
	Macro-average	0.31	0.32	0.30	111
		Confusion matrix			
		55	10	4	
		21	1	2	
		16	0	2	
Neuropsychological assessment variables		Precision	Recall	F1-score	Support
	HC	0.97	0.93	0.95	84
	MCI	0.69	0.89	0.77	27
	AD	0.95	0.78	0.86	23
	Macro-average	0.87	0.87	0.86	134
		Confusion matrix			
		78	6	0	
		2	24	1	
		0	5	18	
Blood analysis and ApoE genotype variables		Precision	Recall	F1-score	Support
	HC	0.78	0.85	0.81	107
	MCI	0.19	0.14	0.16	22
	AD	0.47	0.37	0.41	19
	Macro-average	0.48	0.45	0.46	148
		Confusion matrix			
		91	11	5	
		16	3	3	
		10	2	7	

Abbreviations: AD: Alzheimer's disease; ApoE: Apolipoprotein E; HC: Healthy control; MCI: Mild cognitive impairment.

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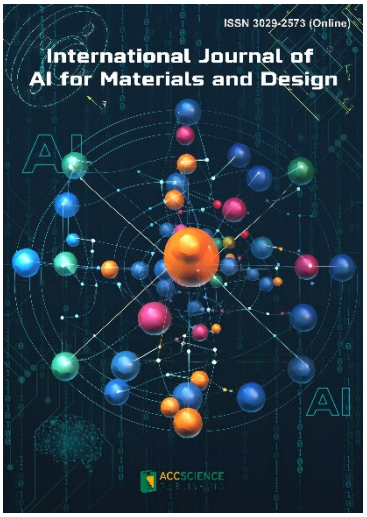

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