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Data-Driven Demand Quantification and AI-Assisted Design of Community Low-Carbon Recycling Terminals

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Abstract—Insufficient user demand quantification and weak integration of intelligent functions remain common problems in the design of community recycling terminals. To address these issues, this paper presents a data-driven and AI-assisted design framework for community low-carbon recycling terminals. Field surveys and questionnaires were used to collect user demand data, and a coupled K-means and Kano-AHP model was adopted to support user segmentation, requirement classification, and design priority ranking. On this basis, a low-carbon recycling terminal and a multi-terminal service platform were developed, including edge-side visual recognition, servo-driven compaction, photovoltaic-assisted power supply, fill-level alerts, intelligent collection scheduling, and carbon-footprint visualization. The proposed framework forms a closed service loop covering disposal, recognition, collection, operation management, and carbon accounting. Methodologically, the integrated K-means clustering and Kano-AHP analysis process provides a standardized, replicable quantitative workflow for user-centric public facility design, eliminating the subjectivity of traditional experience-based design decision-making. This study also provides an application-oriented design case for intelligent public facilities and offers a practical reference for the low-carbon transformation of community recycling services.

1. INTRODUCTION

Under the dual pressures of global climate change and resource constraints, green and low-carbon circular development has become an important direction for urban governance and industrial transformation [1]. China has proposed the dual-carbon goals of carbon peaking and carbon neutrality, making the recycling and reuse of renewable resources an important measure for reducing carbon emissions and resource waste [2]. The recovery of waste materials is a basic component of the circular economy. However, community-level recycling systems still face problems such as fragmented front-end collection, insufficient sorting guidance, and weak process management. These problems reduce residents' willingness to participate and limit the operational efficiency of recycling services [3]. Therefore, community recycling terminals need not only hardware improvement, but also systematic design methods that connect user demand, intelligent functions, and service operation.

With the development of computer vision, edge computing, and the Internet of Things, intelligent technologies provide feasible tools for improving community recycling services [4]. However, in many existing products, these technologies are often embedded as isolated functions, while demand analysis, function prioritization, and service operation remain weakly connected. Taking the community intelligent recycling terminal as the research object, this paper proposes a data-driven design process that links user demand quantification, product function planning, and service platform design. The purpose is not to develop a new algorithm, but to provide a practical and reproducible application framework for low-carbon recycling terminal design.

2. RESEARCH STATUS AND THEORETICAL BASIS

International research on the recycling of waste materials began early and has established a mature theoretical framework and practical systems. The research primarily focuses on four areas: factors influencing household recycling behavior, recycling models and institutional design, low-carbon recycling network optimization, and service design with smart terminals.

Regarding behavioral and citizen-oriented studies, subjective well-being, community participation, incentive mechanisms, and service interfaces are important factors affecting residents' willingness to participate in sustainable recycling behavior [5], [6]. In terms of models and institutions, Singapore has developed a coordinated legal-economic-technological system [7]. EU member states have formed differentiated financial balance mechanisms under the Extended Producer Responsibility (EPR) framework [8], while the United States employs AI-driven prediction models to support policy-making and implements deposit systems [9]. For network optimization and terminal design, route optimization models and IoT-

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based collection bins can reduce unnecessary collection, provide online fill-level data, and support recycling service management [10], [11].

However, existing foreign products exhibit notable shortcomings, including poor local adaptability and a lack of age-friendly design for communities in other cultural contexts. Moreover, smart technologies are mostly applied to isolated operational points, and a full-chain intelligent design logic - from user demand analysis to service implementation-has not yet been formed.

In recent years, the industrial application and academic research of intelligent recycling terminals in China have developed rapidly, and a series of achievements have been made in local scenario adaptation, hardware integration, and technology implementation. On the industrial side, brands including Lianyun Environment, Xiaohuanggou and Aihuisou have realized the large-scale implementation of basic functions such as code-scanning delivery, automatic weighing, and full overflow monitoring [12]. However, these mainstream commercial solutions generally adopt a standardized one-size-fits-all functional configuration, lacking data-driven user stratification and targeted demand quantification for community-specific scenarios, resulting in a mismatch between stacked functions and actual user needs. Meanwhile, their intelligent and low-carbon designs are mostly limited to isolated hardware functions, without forming a full-chain intelligent logic that runs through user demand analysis, product function planning, operation management and carbon accounting. On the academic side, existing studies have carried out multidimensional exploration around AI visual recognition, NBIoT communication, low-carbon structure optimization and other directions, providing theoretical and practical support for local terminal design [13]. Nevertheless, the existing research and industrial practices still share two core common shortcomings: first, demand analysis and design decision-making rely heavily on qualitative experience, and lack of large-sample data-driven user stratification and demand quantification methods, which easily leads to systematic mismatch between product functions and user demands; second, AI technologies are mostly embedded in fragmented single points, not running through the whole process of demand analysis, product design and O&M service. Low-carbon design is only limited to hardware energy saving, and a full-link low-carbon management and control closed loop has not been constructed.

To address the above gaps, this paper proposes a data-driven and AI-assisted design method for community low-carbon recycling terminals. At the methodological level, K-means clustering is used to segment users, and the Kano-AHP model is used to classify and rank user requirements. At the design level, the study translates the quantitative results into an integrated scheme of low-carbon hardware, intelligent interaction, and systematic service. Compared with experience-based design, this framework provides clearer evidence for function selection and priority setting, which is suitable for application-oriented design research.

3. AI-ASSISTED QUANTITATIVE ANALYSIS OF USER NEEDS

3.1. Analytical Framework and Survey Data Foundation

This study conducted a questionnaire survey through online and offline channels, covering different types of communities. A total of 321 questionnaires were collected, and 309 valid responses were retained after screening, with an effective response rate of 96.3%. Based on field observations and preliminary interviews, user needs for intelligent recycling bins were summarized into five dimensions: user interaction, usage experience, equipment operation, service management, and incentive mechanisms. Twenty core requirements were then extracted to cover the process from disposal operation to software service. Reliability and validity tests showed that Cronbach's alpha for the questionnaire was 0.975, higher than the commonly accepted threshold of 0.7. The Kaiser-Meyer-Olkin (KMO) value was 0.985, and Bartlett's test of sphericity was significant ($p < 0.001$), indicating that the data were suitable for subsequent clustering and demand analysis.

3.2. User Intelligent Segmentation Based on K-means Clustering

To reduce the subjectivity of traditional user classification, K-means clustering was used to segment community recycling users. The five demand dimensions were selected as clustering features, and the data were standardized before clustering to eliminate dimensional effects. The optimal number of clusters was determined as $k = 3$ by combining the elbow method and silhouette coefficient. Euclidean distance was used as the similarity measure, and the maximum number of iterations was set to 100. The 309 valid samples were finally divided into three user groups with different demand characteristics.

Based on the clustering results, the three user groups were interpreted as high-frequency convenience-oriented users, family batch-oriented users, and environmental concern-oriented users. High-frequency convenience-oriented users showed stronger demand for interaction efficiency and equipment operation. Family batch-oriented users paid more attention to transfer convenience, odor control, and storage capacity. Environmental concern-oriented users were more sensitive to incentive mechanisms and low-carbon value feedback. These differentiated results provide a user segmentation basis for the following Kano-AHP requirement classification and priority ranking. (as shown in Figure 1)

ANOVA results showed significant differences among the three user groups across the five demand dimensions ($p < 0.01$), indicating that the clustering results were statistically distinguishable. Therefore, the subsequent design strategy avoids treating all residents as a homogeneous group and instead translates different user priorities into layered product and service functions. The summarized segmentation result is shown in Table 1.

Table 1. User segmentation results based on K-means clustering

User Group	Sample count	Sample proportion	User interaction	Usage experience	Equipment operation	Service management	Incentive mechanisms
High-frequency convenience-oriented users	118	38.2%	4.62	4.18	4.55	3.96	3.72
Family batch-oriented users	107	34.6%	4.05	4.56	4.38	4.42	3.81
Environmental concern-oriented users	84	27.2%	3.86	4.02	3.91	4.21	4.68

Note: Demand scores are mean values on a five-point Likert scale; sample proportions are based on 309 valid questionnaires.

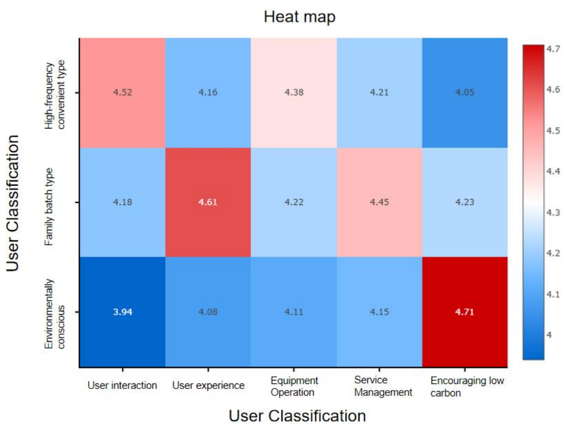

Fig. 1. Heatmap of user group segmentation based on K-means clustering and mean demand values across dimensions.
Note: The horizontal axis represents three user groups, and the vertical axis represents core demand dimensions. Color intensity represents mean demand values.

3.3. Demand Priority Ranking Based on Kano-AHP Coupling Model

After user segmentation, a standardized Kano two-way questionnaire was designed according to the 20 core requirements. A total of 232 valid samples were collected. The reliability and validity tests showed that Cronbach's alpha was 0.841, the KMO value was 0.793, and Bartlett's test of sphericity was significant ($p < 0.001$), meeting the basic requirements for requirement classification and weight analysis.

According to the Kano classification rules and Better-Worse coefficient analysis, the 20 requirements were classified into four categories: seven must-be (M) requirements, six one-dimensional (O) requirements, six attractive (A) requirements, and one indifferent (I) requirement. The indifferent requirement was excluded from the core design decision-making process because it had limited influence on user satisfaction.

Combined with the K-means clustering results, the requirement attributes of the three user groups showed clear differences. For high-frequency convenience-oriented users, contactless delivery and real-time feedback were important basic requirements. For family batch-oriented users, a portable recycling transfer device, odor prevention, and automatic compaction were more critical. For environmental concern-oriented users, carbon-footprint visualization and diversified incentive mechanisms were more attractive and could strengthen continuous participation.

The Analytic Hierarchy Process (AHP) was then used to calculate requirement weights. A three-level AHP model was constructed: the target layer was the intelligent design of a low-carbon community recycling terminal, the criterion layer consisted of the main requirement attributes, and the index layer contained the specific requirements. Six experts in industrial design and intelligent recycling were invited to construct pairwise comparison matrices using the 1-9 scale method [14]. The overall consistency ratio (CR) was 0.046, lower than 0.1, indicating acceptable consistency of the judgment matrix.

The criterion-layer weight ranking was must-be requirements (0.7113) > one-dimensional requirements (0.1903) > attractive requirements (0.0984). Therefore, odor prevention, automatic compaction, and portable transfer should be treated as basic functions that must be ensured first. Fill-level warning, delivery-result feedback, and equipment-status monitoring should be used to improve the service experience. Solar-mains dual power supply, carbon-footprint visualization, and visual-recognition-assisted classification can be used as differentiating functions to enhance the low-carbon guidance value of the terminal. The detailed requirement-level classification and weights are shown in Table 2.

Table 2. Kano classification and AHP weight ranking of 20 user requirements

No.	User requirement	Kano category	AHP weight	Criterion-layer weight
R1	Odor prevention of recycling bins	M	0.1320	0.7113
R2	Automatic compaction of recyclable materials	M	0.1185	0.7113
R3	Portable transfer device for bulky recyclables	M	0.1036	0.7113
R4	Contactless delivery operation	M	0.0948	0.7113
R5	Real-time delivery-result feedback	M	0.0967	0.7113
R6	Safe anti-pinch delivery opening	M	0.0862	0.7113
R7	Stable outdoor operation and waterproof protection	M	0.0795	0.7113
R8	Fill-level automatic warning	O	0.0416	0.1903
R9	Real-time equipment-status monitoring	O	0.0368	0.1903

R10	Accurate weighing and income calculation	O	0.0335	0.1903
R11	Convenient nearby-bin search and navigation	O	0.0298	0.1903
R12	Fault feedback and maintenance tracking	O	0.0257	0.1903
R13	Collection route optimization	O	0.0229	0.1903
R14	Solar-mains dual power supply	A	0.0231	0.0984
R15	Carbon-footprint visualization	A	0.0206	0.0984
R16	Visual-recognition-assisted classification	A	0.0172	0.0984
R17	Community recycling leaderboard	A	0.0146	0.0984
R18	Points redemption and diversified incentives	A	0.0129	0.0984
R19	Environmental knowledge popularization	A	0.0100	0.0984
R20	Decorative appearance personalization	I	0.0000	0.0000

In summary, the Kano-AHP coupling model supports the design principle of ensuring must-be requirements first, optimizing one-dimensional requirements, and selectively strengthening attractive requirements. This principle converts qualitative user insights into more explicit design priorities and reduces the risk of function stacking without user demand support.

4. INTELLIGENT COMPUTING-DRIVEN SYSTEM DESIGN OF THE RECYCLING TERMINAL

The proposed design is positioned for urban community scenarios and serves residents, operation and maintenance personnel, and recycling enterprises. The design follows two principles. First, the life-cycle low-carbon principle is used to reduce unnecessary energy consumption and improve operational efficiency. Second, the user-centered service design principle is used to cover residents' recycling experience and the management needs of operators. The system design is therefore organized around the full process of disposal, recognition, collection, operation management, and carbon accounting.

4.1. Hardware Terminal Design

Based on the requirement priority analysis, a modular low-carbon hardware terminal is designed, as shown in Fig. 2. The overall layout adopts a horizontal modular structure consisting of an interaction area and standardized classification bins. The bin categories and volumes can be adjusted according to community recycling demand. Anti-jamming delivery openings with different sizes are arranged on the front, while a maintenance door and tool-storage space are arranged on the side to improve both user convenience and maintenance efficiency.

The hardware design focuses on three function modules that directly correspond to high-priority user requirements:

- Single-cylinder movable compaction mechanism. A single power source is used to support sequential compaction of multiple bins. The design aims to increase effective storage capacity and reduce unnecessary collection frequency. Because the servo electric cylinder only consumes energy during operation, it is expected to reduce standby energy loss compared with hydraulic or continuously pressurized structures [15].
- Photovoltaic-priority and mains-complementary energy system. Monocrystalline silicon photovoltaic modules and lithium iron phosphate batteries are arranged on the top of the terminal to preferentially supply power to the control and sensing units. Mains power is retained as backup. This design provides a feasible low-carbon energy configuration, and its actual energy-saving effect should be verified according to deployment location, sunlight conditions, and terminal usage frequency.
- Unpowered foldable portable transfer device. A diamond-hinge folding structure is adopted to assist residents in transferring bulky recyclable materials. The device reduces the burden of the "last 100 meters" transfer process and responds to the needs of family batch-oriented users [16].

The warehouse adopts a double-layer sealed anti-odor structure, and the detachable inner liner supports 100% recycling. The main frame is made of hot-dip galvanized steel sheet, and non-load-bearing parts are made of high-proportion recycled ABS/PP plastic. The main color adopts low-saturation medium gray and light beige, which takes into account outdoor durability and full-life cycle low-carbon requirements.

In terms of safety protection, the delivery opening is equipped with an infrared grating anti-pinch structure and rounded corners above R10. The box is equipped with an intelligent electromagnetic lock, backup power supply, and lightning protection, waterproof and anti-leakage modules, which meets the requirements of long-term stable and safe outdoor operation.

Fig. 2. Design drawing of the intelligent recycling terminal.

4.2. Hardware System Design

At the hardware system level, the terminal uses STM32F103VET6 as the main control chip, is equipped with a Quectel BC28 NB-IoT module, and reserves a 4G/WiFi dual-backup communication link. Five types of sensing units are deployed inside the terminal to support AI-assisted recognition, fill-level monitoring, interaction guidance, and operation scheduling [17]. The core purpose of the hardware system is to provide real-time data for front-end interaction and back-end operation management.

- Edge-side visual identification module. A camera and lightweight image-inference module are integrated at the delivery opening to identify disposal categories and provide error-correction guidance. A mini-program photo-assisted identification function is also provided to reduce the classification burden for residents [18].
- Bin perception and low-carbon scheduling module. Ultrasonic sensors are installed at the top of each bin to collect real-time fill-level data. When the fill level reaches the preset threshold, the system pushes a collection alert to the operation and maintenance terminal. This supports on-demand collection and helps reduce ineffective transportation.
- All-age friendly interaction module. An infrared human-body sensor wakes the device and auxiliary lighting when a user approaches. Operation guidance is provided through screens and voice prompts, and the interface uses large fonts and high contrast to improve accessibility. After disposal, the system displays estimated carbon-emission reduction to form positive feedback for low-carbon behavior.

4.3. Software and Service Platform Design

The service platform is designed as a four-terminal collaborative system based on a unified IoT cloud platform. It includes the resident WeChat mini-program, the collection and maintenance mobile terminal, the enterprise management web terminal, and the intelligent recycling terminal. The four terminals share real-time data and cover three links: residents' recycling experience, collection and maintenance management, and enterprise-level digital operation. Through this structure, the system forms a closed loop of front-end low-carbon behavior guidance, middle-end collection efficiency improvement, and back-end low-carbon operation management. (as shown in Figures 3 and 4)

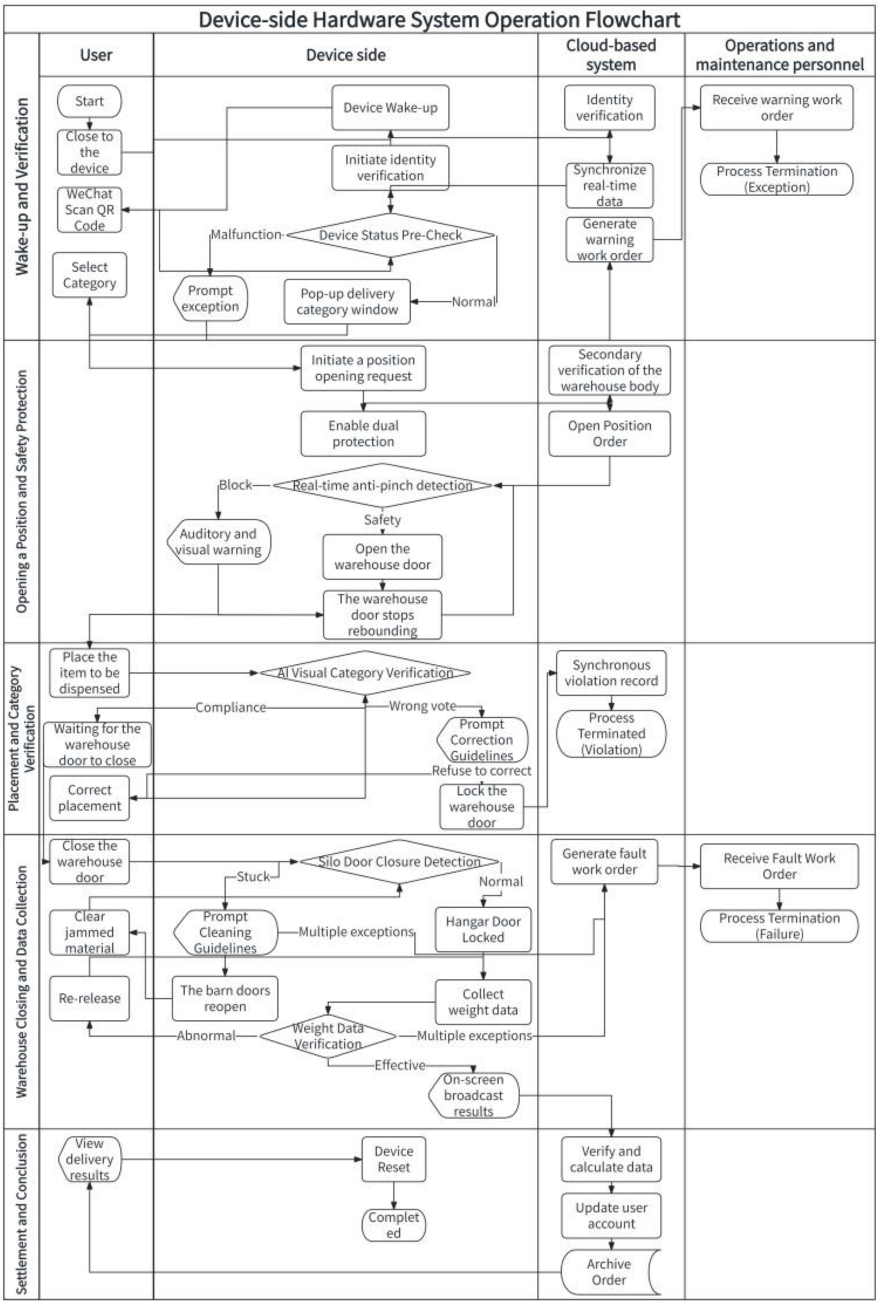

Fig. 3. Flow chart of hardware system operation.

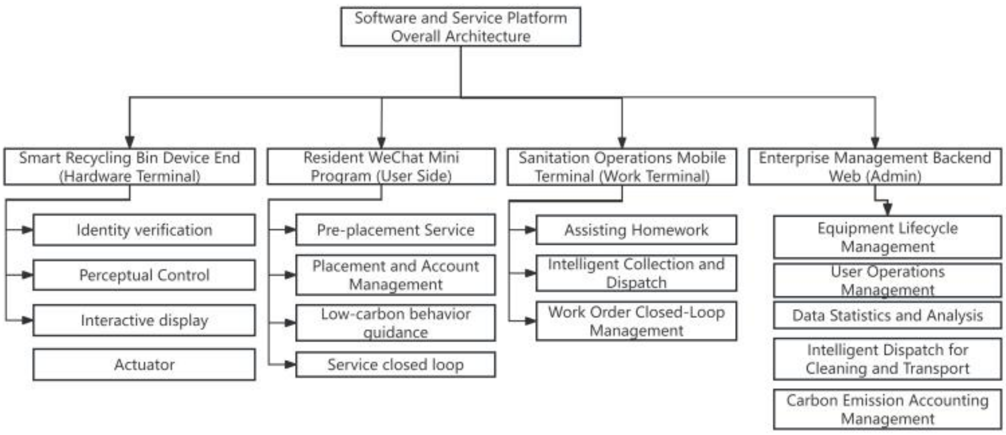

Fig. 4. Architecture diagram of the software and service platform.

The resident-oriented mini-program serves users of all age groups within the community, covering the entire journey of pre-drop-off, during drop-off, and post-drop-off needs. The pre-drop-off module provides functions such as locating nearby recycling bins with navigation, AI-powered waste recognition via image capture, and bulky item recycling reservation, addressing issues of fruitless trips and sorting difficulties. The drop-off and account module synchronizes in real time with terminal devices, instantly displaying information on waste category, weight, earnings, and carbon reduction data, while supporting one-click withdrawal. The core innovation lies in the low-carbon behavior guidance module, which establishes a dedicated low-carbon account, enables carbon footprint visualization and monthly reporting, and integrates community leaderboards and diverse point redemption options, thereby forming a behavioral loop of drop-off, incentive, and re-drop-off. Additionally, the system incorporates fault feedback and environmental science popularization portals, achieving service loop closure and long-term guidance.

The mobile application for waste collection and maintenance is developed for dedicated collection workers and community property maintenance personnel, with role-based access control. Its core component is the intelligent collection scheduling module: driven by real-time fill-level data from terminals, it automatically generates collection tasks, pushes targeted notifications of location, waste category, and fill level according to user permissions, and dynamically plans optimal routes. This replaces fixed-schedule collection with on-demand collection, helping reduce carbon emissions caused by unnecessary commuting. The work order closed-loop management module covers both collection and maintenance tasks, supporting job confirmation, on-site fault photo reporting, and full-process tracking, thereby achieving closed-loop management from initiation to verification. The auxiliary operation module integrates device QR code scanning and verification, data upload, order management, and route navigation, substantially improving frontline operational efficiency.

The enterprise management background serves as the global digital control hub, providing hierarchical access permissions for recycling operators and community administrative departments, and realizes four major management functions. The equipment full-life cycle management module comprehensively displays the real-time operating status, online rate and fault information of recycling terminals, and supports remote configuration of equipment parameters as well as full-process management of operation and maintenance work orders.

The user and operation management module enables the viewing of full-scale user portraits, flexible configuration of recycling revenue and point rules, and establishes a closed-loop processing channel for user feedback.

The data statistics and intelligent scheduling module conducts multi-dimensional statistical analysis on core indicators including total recycling volume, category distribution, user activity and cleaning timeliness. It supports multi-condition screening and generates visual decision charts, providing data support for site layout, transportation capacity allocation and operational strategy optimization, while realizing intelligent scheduling of cleaning resources.

As a distinctive function, the platform includes a full-link carbon-emission-reduction accounting module. The module records recycling behavior, category, weight, estimated carbon reduction, collection status, and regional statistics. Although the carbon accounting model still needs calibration in actual deployment, it provides a clear data basis for community low-carbon governance and later operation evaluation.

5. CONCLUSION

This paper proposed a data-driven and AI-assisted design framework for community low-carbon recycling terminals. In the demand analysis stage, K-means clustering and the Kano-AHP model were combined to segment users, classify requirements, and rank design priorities. In the design stage, the quantified requirements were translated into a modular hardware terminal and a four-terminal collaborative service platform. The resulting scheme covers disposal guidance, visual recognition, fill-level perception, intelligent scheduling, user incentives, and carbon accounting.

The main contribution of this study lies in its application-oriented integration of user demand quantification and intelligent terminal design. Instead of relying only on qualitative experience, the proposed process provides a more explicit basis for selecting terminal functions and service modules. This makes the study suitable as a practical design case for community-level recycling facilities.

This study also has limitations. The survey samples are regionally concentrated, and the proposed terminal has not yet been validated through long-term field deployment. In addition, the visual recognition module and carbon accounting model require further testing under real community conditions. Future work should expand the sample range, conduct pilot deployment, and compare collection efficiency, user participation, and energy consumption before and after system implementation. A small-scale pilot validation is planned in selected communities to record user participation frequency, average disposal time, fill-level change, collection response time, recognition accuracy, and estimated energy consumption. These indicators will support comparison with conventional terminals and further calibration of the carbon-accounting model.

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