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Research on the Recyclable Design of Wooden Furniture Based on the Recyclability Evaluation

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Abstract: With the rapid development of the economy and the change in people's aesthetic concepts, the renewal of furniture has become more and more frequent. Among the huge amount of used furniture, solid wood and wood-based panel furniture account for the vast majority, but the imperfective recycling system and insufficient recycling efforts result in serious waste, which is contrary to the low-carbon transition and sustainable development means. Based on the whole life-cycle theory of products, the recyclable designability of wooden furniture at all stages of design, manufacturing, sales, use, and recycling was researched and analyzed, and feasible suggestions to the government, enterprises, and consumers were proposed respectively. In particular, an evaluation index system and evaluation model for the recyclability of wooden furniture were established with an aim of quantitatively analyzing the recycling of wooden furniture, which will provide certain references not only to achieve reasonable recycling and disposal of used furniture but also to solve the furniture recycling issues from various levels.

Keywords: wooden furniture; product life cycle; recyclable design; recyclable evaluation; evaluation index system

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1. Introduction

With the development of the economy accompanied by the upgrading of people's consumption level and concept, the consumption mode of furniture has undergone profound changes. The frequent replacement or accelerating upgrade of furniture can create so much discarded furniture, among which the discarded wooden furniture accounts for a large proportion. According to relevant statistics, China alone produces about 60 million tons (85 million cubic meters) of discarded wood products, mainly used furniture, every year [1]. As an important part of the global manufacturing industry and also one of the leading producers, consumers, and exporters of furniture in the world, the cumulative revenue of China's furniture industry reached nearly $124.08 billion in 2021 according to the report by the China National Furniture Association (CNFA). With the further expansion of the furniture market, the environmental impact is increasing, and the consumption of natural resources is also growing.

Under the increasing awareness of environmental protection and sustainability, various types of waste wooden furniture recycling institutions have been gradually established all over China. In addition, relevant rules and regulations have been formulated to guide the reuse of waste wooden furniture. Although it is likely to spot successful cases and policy support, in general, furniture recycling has always been a kind of difficult problem [2]. First of all, the conventional appearance-oriented or performance-oriented materials selection of furniture products will inevitably result in unrecyclable furniture parts. Secondly, the low standardization level of furniture parts will lead to the difficulty of reusing after disassembly. Third, various degrees of the properties' losses will usually happen to furniture after

use, making it difficult to reuse. Finally, the unreachable cost of dismantling, sorting, and recycling waste furniture when recycling wooden furniture will bring negligible economic benefit. As a result, public recycling of waste wooden furniture has several options in general: refurbish it when sold at flea markets, use it as fuel, or send it to landfill for burning. These practices not only affect the price mechanism of furniture but also cause certain pollution to the environment [3].

On the one hand, industrialization has brought convenience to people's lives; on the other hand, industrial production has caused damage to the ecological environment to a certain extent and brought excessive energy consumption. Therefore, ecological design, green design, and sustainable design have become important issues that we should consider. The furniture industry should combine the concept of sustainable design with green ecological design to reduce waste of resources to a certain extent and achieve harmonious coexistence between man and nature [4]. China's "Manufacturing 2025 Report" pointed out that it is necessary to fully implement green manufacturing, improve the efficient recycling of resources, and increase the recycling rate of waste products. Strengthening the recycling of waste wooden furniture can reduce the environmental pollution caused by waste wood resources, expand the source of raw materials for the wood-based panel industry, and ease the tight supply and demand of wood resources [5]. This paper aims to explore the design scheme of recyclable wooden furniture and improve the recycling system of wooden furniture through the analysis of the whole life cycle of wooden furniture products, so as to provide certain reference for promoting the green development of recyclable wooden furniture.

2. Theoretical Background and Research Significance

2.1. Recycling and Utilization of Waste Furniture

In the 1990s, developed countries built and formed a recycling system for wood waste. Developed countries such as the United States, Germany, and the United Kingdom mainly carry out research on the recycling of waste wooden furniture and the manufacture of wood-based panels from waste wood. Japan is a country with limited resources. As early as 1995, resource recycling was listed as an important national policy, achieving an ultra-high recovery rate of 82% of waste wood, which is mainly used for papermaking, wood-based panel production, power, and heat supply [6]. In Australia, recycled wood is used for a variety of purposes, although these markets are fairly limited. The main uses of recovered wood are for mulch, fuel, animal bedding, and recycling into particleboard [7]. Germany has enacted a waste wood recycling ordinance called the Ordinance on the Management of Waste Wood. This decree prohibits the arbitrary disposal of discarded wooden furniture [8] and classifies recycled wood into five categories. Depending on the species, there are different methods of treating and reusing waste wood. Taiwan has been promoting relevant recycling projects to encourage the recycling and reuse of waste furniture and has excellent waste furniture restoration technology. However, its current demand for remanufacturing furniture remains low. And due to the difference in living habits between urban and rural areas in Taiwan, discarded furniture collected from urban and rural areas is in different states [2].

On 1 June 2009, China implemented GB/T 22529-2008 [9] "Management Specification for Recycling and Utilization of Waste Wood Materials" to encourage the reuse, recycling, and energy utilization of waste wood, among which old wooden furniture is the focus of classification and recycling, and encourage waste solid wood household product materials reprocessing into furniture materials. In the practical application of recycling old wooden furniture, the Shanghai Wanxiang Wood Company (Shanghai, China) is the earliest enterprise in China to recycle Shanghai waste wood to make artificial boards, and old wooden furniture is its main recycling object [10]. In 2011, when Changsha City was creating a hygienic and civilized city, residents disassembled and assembled some old wooden furniture with relatively good quality and transformed them into rest furniture in public places [11]. In 2018, at the request of the government, Beijing piloted the whole process

of waste furniture delivery, recycling, transportation, and processing in Haidian District and granted subsidies to enterprises to use the recycled waste wood and sponge as fuel for power generation. In July 2021, Shenzhen drafted the local standard "Specifications for Recycling and Comprehensive Utilization of Waste Furniture", which stipulates the definition, collection, temporary storage, transportation, and comprehensive utilization requirements of waste furniture and improves the recovery rate of domestic waste in Shenzhen [12].

Mao et al. [13] divided the recycling methods of old wooden furniture into five aspects, namely reuse, recycling, regeneration, energy utilization, and special utilization (as shown in Figure 1).

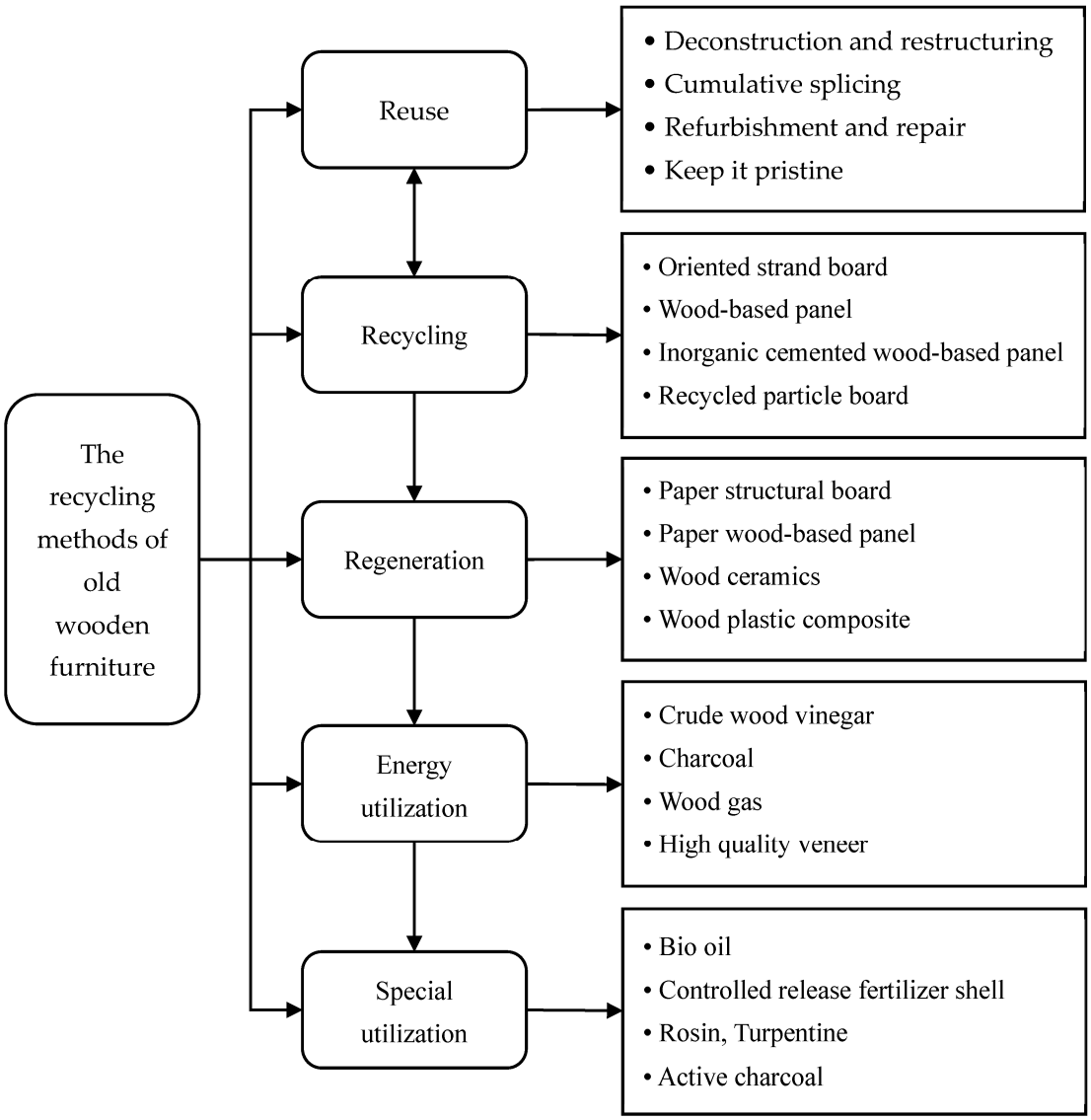

Figure 1. The recycling methods of old wooden furniture.

Reuse refers to the restoration, renovation, or use of a part of recycled old wooden furniture, which belongs to direct utilization and does not change the original attributes. Wang and Li [14] also made a detailed discussion on the reasons for the waste of rural furniture and the methods of recycling: one is directly used for combustion, the second is the renovation of furniture, and the third is the recycling of furniture, disassembly, and recombination.

Recycling refers to the classification, separation, and crushing of old wooden furniture, chipping into sawdust, wood granulates, wood fiber, etc., and then further processing and

utilization [15]. In 2000, in the project (FPS) supported by the Fifth European Commission, countries such as Germany, Greece, France, and Portugal mixed the discarded wood materials into wood-based panels with high added value in a certain proportion and developed the process technology with reference significance for this purpose [16]. The Mauro Saviola Group in Italy has carried out the actual production of waste wooden furniture and achieved good results; the recycled waste wooden furniture is processed into various particleboards through a series of classification processes [17]. Wang [18] studied the method of hot water treatment of waste wood materials and found out the best process parameters for the hydrothermal treatment of waste wood materials to recycle and regenerate particleboard, the best ratio, and the most ideal process conditions in the whole recycling process.

Regeneration refers to making products that are completely different from old wooden furniture by changing the material properties. For example, wood ceramics can be made of old furniture wood as raw materials, by resin impregnation, high-temperature carbonization formation of new carbon material, a porous structure with high strength, high wear resistance [19]. Li et al. [20] mentioned a series of methods for recycling waste wood-based panels and the resulting new products in the article, such as wood–plastic composite materials, regenerated particleboard, and chemicals. Researchers at the Mining Research Institute in New Mexico, USA, used waste wood materials and plastics to effectively combine a certain proportion and then made wood–plastic composite materials through heating and pressure processing. Wood chips are often considered waste in the wood industry, and these materials can be converted into value-added thermoplastics through benzylation. The chemical properties of lignocellulosic materials make them suitable for a large number of products, and the use of lignocellulosic materials in the production of plastics and composites is becoming more and more attractive [21].

Energy utilization refers to the processing of old wood for furniture into fuel. Oh and Okabe [22] mentioned in the article the research on pyrolysis and gasification of wood materials by using waste wood materials as raw materials. He and Mu [23] used a mechanical furnace and other equipment for high-temperature pyrolysis to produce wood gas, charcoal, and crude wood vinegar with higher usable value, thereby realizing the recycling and reuse of waste wood-based panel resources. Cao and Wang [24] also mentioned in the article that crude wood vinegar is a liquid produced by condensation and separation of the gas mixture in the dry distillation process of carbon materials such as wood or wood waste.

Special utilization refers to the use of breeding, planting, sideline, and so on. Wiltcher et al. [25] believe that mixing recycled plywood with chicken manure, cow manure, and inorganic fertilizers can effectively reduce the toxicity of fertilizers and can be used as soil conditioners. Fu et al. [26] proposed the use of wood residues to make slow/controlled-release fertilizer shells. The shell has the advantages of low cost, simple manufacture, easy degradation, and no pollution, which made a certain contribution to the recovery of wood residues.

2.2. Recyclable Design of Wooden Furniture

It is now widely believed that design can play a key role in society's transition to sustainability. In the process of wooden furniture recycling, design can act as a catalyst to trigger and support innovation, and proper recyclable design can help us recycle discarded furniture better on different levels. Building on this, Ceschin and Gaziulusoy [27] present design as the foremost approach to sustainability challenges, proposing an innovative framework that coherently integrates multiple Design for Sustainability (DfS) elements developed to date and is of great help in the recyclable design of furniture. Hebrok [28] proposed to carry out Design for Sustainable Behavior (DfSB) from a practical point of view, which can help prolong the life of furniture and make furniture a more durable commodity. Wang [29] conducted research on sustainability in furniture design and manufacturing, and points out sustainable strategies in wooden furniture manufacturing, namely reducing ma-

terial usage, reducing scrap, reducing packaging, reducing energy consumption, reducing the choice of toxic resources, using renewable resources, extending the life cycle, etc., to provide design direction for sustainable design. Yang and Sun [30] explored the combination of "new materials" and innovative design methods with practical examples and proposed the methods of sustainable design using new materials, such as the combination innovation method, the alternative creation method, and the transplantation creation method.

In the research of systematic design, Zhu [31] briefly mentioned in his article that he designed more than 80 standard panels, which can be combined flexibly and can be used as a way to replace a certain part of the damaged panel in furniture recycling, which is an excellent case of having strong reference value. Wang and Wang [32] analyzed the design of furniture from the aspects of modular design and group technology design, which provided a good reference for reorganization and replacement of parts in furniture recycling. For IKEA, an internationally renowned furniture manufacturer, most of their products are typical products of modular design and detachable design, which is a good combination of design concept and product design for a model to facilitate recycling household products [33].

In order to improve the recycling efficiency, in addition to the design of the furniture itself, people have also carried out corresponding explorations on the design of the furniture recycling system. Fujii et al. [34] discussed the demand for recycled products, economic conditions, weight reduction, product reuse, the number and types of recycled products that are competitive, and developed a social system for the convenience of customers. From the perspective of design, relying on the modern e-commerce business model and based on the concept of "customer-centric", Li et al. [35] focused on the basic methods and applications of the furniture recycling design system, described the design process of furniture recycling based on the network platform, analyzed and summarized the strengthening service content, and provided theoretical guidance for the system innovation construction. Lin, Chen, Tseng, Chiu, and Ali [2] established a cradle-to-cradle production planning model for recycled furniture, remanufacturing the furniture through recycling centers, including cleaning teams responsible for removing and transporting the waste furniture, and the processing center for recycling and remanufacturing the waste furniture.

A series of specific recyclable furniture designs have also been carried out by domestic and foreign design teams: Armchair of the Architecture Department is the work of the team of Boțoroga Ion et al., using cardboard cylinders and 100% recyclable OSB boards, this design work is preserved in the museum as an example of green furniture; Loom chair is the work of the Alexandrov Artem team, made from wood and twine reused in the building, this furniture has a special shape and a comfortable sitting feeling, inspired by the looms in the homes of Romanian farmers; Zig zag chair is inspired by the concept designed by Gerrit Rietveld in 1934, it adopts the sustainable method of plywood reuse and presents a stripe pattern decoration with storage performance and an elegant shape [36]. Taiwan designer Zeng [37] designed an assembled furniture called PLAYER. With the characteristics of assembled furniture and circular design, when some components are damaged, a single component can be simply replaced to reduce the generation of waste, and the recycled parts can be returned to the cycle more accurately and quickly, so that the recycling can be optimized. While developing new products, Zeng considered the subsequent treatment methods of the whole product life cycle (manufacturing, using, waste disposal, etc.), so that the raw materials can be recycled continuously and resources can not be exhausted.

2.3. Evaluation Study on Recyclability of Wooden Furniture

As governments and enterprises increasingly recognize the importance of recycling, the recycling market is expanding rapidly. Improving the recyclability of furniture is an effective way to promote recycling, and assessing the recyclability of wood furniture can help governments and enterprises make scientific choices. There are fewer sustainability assessment studies on the furniture industry, and most of the existing studies focus on Europe and the timber industry [38]. Measuring the environmental performance of closet

manufacturing in the furniture industry is carried out in Brazil through the use of techniques for assessing the life cycle of products [39]. A company in central Germany uses an indicator-based life cycle management tool to assess sustainability strategies at the local level [40]. In Indonesia, sustainability assessment in the furniture industry is limited to the manufacturing process [41]. Sustainability of the timber industry in West Malaysia was assessed by considering whether its forest management is sustainable or unsustainable in terms of raw material consumption status [42]. Feil et al. [43] used a set of indicators on Medium Density Fiberboard (MDF) furniture manufacturing to assess the sustainability of the furniture industry, and the main findings showed that the construction of sustainability indicators was validated by a statistical methodology, which supported the consistency and quality of the sustainability evaluation of furniture companies. Li et al. [44] proposed a time series prediction method for assessing the recyclability of products at the product design stage. It takes into account various economic and environmental factors at different stages of the product life cycle. In addition, the time series prediction method can be used to predict the cost of recycled materials at the end of product life. All of the above studies provide some reference for conducting recyclability evaluation of wooden furniture.

2.4. Life Cycle of Wooden Furniture Products

According to the product life cycle theory, a new design scheme is proposed for the furniture products entering the life cycle, put forward to reduce the negative impact on the environment as much as possible, minimize the energy consumption, and maximize the utilization rate of resources, so as to realize the sustainable recycling of material, achieve the purpose of reducing expenditure and emission reduction [45,46].

According to the theoretical basis of PLC, considering the characteristics of wooden furniture products, it is divided into five stages: design stage, manufacturing stage, sales stage, use stage, and recycling stage (as shown in Figure 2).

Figure 2. Schematic diagram of the life cycle of a general wood furniture product.

The recyclable design of furniture is a design concept that runs through the whole product life cycle from the beginning of design to the end of life. It includes product packaging material recycling, product raw material recycling, product parts recycling, and other aspects. Therefore, at the beginning of the design, it is necessary to fully consider the possibility of product recycling, treatment methods, the degree of pollution to the environment, and many other factors [47].

With the increasing awareness of environmental protection, recycling institutions for used furniture and wood have been established, and there are many corresponding studies on recovery and recycling means, in addition to the development of relevant regulations to guide the reuse of used furniture and wood. Although there are successful cases and policy support, there is less cooperation between government and enterprises, local recycling varies widely, and recycling of used wooden furniture is not widely promoted. In terms of the recyclable design of wooden furniture, modular design and disassembled design of furniture products have emerged one after another, but their design process needs further improvement. Furniture recycling system design can be realized through multiparty cooperation, and the concept of recyclable furniture can be promoted to the whole life cycle of the product.

2.5. Research Significance

2.5.1. Focusing on Recyclable Design

The overall analysis found that whether it is the research on the recycling of waste furniture or the design research on recyclable furniture, the research mainly focuses on the

three aspects of material modification treatment, redecoration and renovation design after the recycling of waste wooden furniture, and focuses on the end prevention and treatment of furniture recycling; there is less recyclable design work in the front of furniture design. The mode of obtaining new materials through material modification treatment is mainly processed into new products such as various particleboards, fiberboards, wood–plastic composite materials, wood fuel particles, and chemical fertilizers; solid wood furniture is mostly refurbished, and panel furniture directly recycles the intact boards, the seriously damaged boards decompose the wood materials into raw materials for wood-based panels. This series of research methods usually have high technical requirements, high recycling costs, and large recycling limitations. This requires us to avoid ineffective recyclable designs in the recycling process and focus on recyclable designs.

2.5.2. Systematically Analyzing the Recycling of Discarded Furniture

Through the analysis of the current situation of waste furniture recycling at home and abroad, although the existing methods and policies have achieved some results, there are still many problems in the process of furniture recycling. Waste furniture products lack reuse value, it is difficult to evaluate and recycle old furniture, there is almost no profit for secondhand furniture, and it is also difficult to renovate furniture [48]. It is necessary to design the recycling system and solve the problem of waste furniture recycling from the perspective of recycling methods, information management and control, and processing methods.

2.5.3. Strengthening the Evaluation Criteria on Recyclability

Although laws related to product recycling have been introduced, there are many deficiencies in the evaluation of furniture recycling performance. The structure of furniture products is complex, the composition of materials is diverse, and the recycling methods for different parts are also different. The existing research only considers the recycling performance of furniture from the perspective of economy or environment and lacks the comprehensive measurement of recyclability. In addition, there is a lack of models for furniture recycling, and their technical indicators are not analyzed from the perspective of product life cycle. Strengthening the evaluation criteria on recyclability and providing effective feedback to furniture-related enterprises help enterprises to reasonably choose recycling methods [49].

One of the fields of research and improvement in recent years is waste, which can solve the whole production and consumption cycle, from waste prevention, recyclable process, and product design to reuse and waste management. Through analyzing the whole life cycle of products, we can update, reconfigure, and customize the previously obsolete products to meet the current market demand, the life cycle of discarded furniture can be extended, and extended beyond the scope of traditional remanufacturing [50,51].

In the article, Gu and Sosale [52] discussed the modularization strategy in the life cycle of furniture products and studied the design method based on the integrated modularization research of the whole life cycle of furniture products, opening up a new method for the design and research of wood furniture that is convenient for recycling. Iritani, Silva, Saavedra, Grael, and Ometto [39] propose two sustainable strategies based on the results of the life cycle assessment of wardrobes: optimization of transportation systems and use of alternative raw materials during the manufacture of MDF. These conclusions can help the furniture and wood-based panel industries to improve their environmental conditions and encourage research into other options to promote cleaner production of wardrobes from a life cycle perspective. Carlisle and Friedlander [53] studied the impact of durability and recycling on the life cycle of window frame components, a systematic approach they emphasized in their end-of-life recycling approach to facilitate material recycling and reduce environmental impact. Kim et al. [54] evaluated the economic and environmental impact of product life cycle design, which can provide us with a corresponding reference.

Integrating sustainable design, ecological design, environmentally conscious manufacturing, and other concepts into the product life cycle can help us solve environmental problems better [55]. Munteanu [36] believes that eco-design is to combine environmental protection standards with the life cycle of products, by maximizing the conservation and recovery of natural resources through an eco-design approach, supporting the entire life cycle of products from a circular economy perspective, using recyclable materials and promoting eco-innovation to reduce the negative impact of materials on the environment, while also taking environmental, social, and economic benefits into account. Zhang et al. [56] discussed the life -cycle cost minimization of furniture material selection with the goal of environmentally conscious manufacturing. In order to improve the environmental protection performance of furniture in the life cycle, so that the life cycle of furniture covers design, manufacture, delivery, use, disposal, and other links, the ecological design of furniture with environmentally conscious manufacturing as the main body combines environmental concept with ecological furniture design.

In conclusion, the research on the recyclable design of wooden furniture by analyzing the whole product life cycle can effectively reduce costs, improve efficiency, increase the recycling rate of discarded furniture, and can effectively solve the difficult problem of furniture recycling. Under the current situation that the environment is further harsh, the amount of discarded wooden furniture is growing, and the labor cost is greatly increased, it is particularly important and urgent to carry out the research on the recyclable design of wooden furniture.

3. Research Methodology

In the process of furniture recycling, it is very important to judge the recyclability of furniture. Modern furniture products have complex and diverse structures, and there are differences in the selection of recycling methods and recycling processes for different parts and furniture. Therefore, according to the characteristics of wooden furniture, the establishment of a wooden furniture recyclability evaluation model can be a comprehensive measure of the ease of recycling options, quantifying the recyclability of furniture under different recycling methods, solving the problem of subjectivity in the process of furniture recycling, and helping enterprises to make better choices.

The construction of the evaluation system is divided into two parts: first, starting from the whole life cycle of furniture, the evaluation indexes affecting recyclability at each stage are sorted out, and the index framework is constructed. In the second step, the evaluation system is quantified according to the adoption of scientific research methods, and mathematical models are used to compare the degree of strengths and weaknesses of each furniture solution, so that the data information can be used to choose the recycling method or to assess the recyclability of furniture products.

3.1. Construction of Evaluation Index System

Consumers should consider not only price, quality, and practicality but also environmental impact, safety, and overall sustainability when choosing furniture. Enterprises in furniture design, manufacturing, and follow-up work also need to consider the economy, technical difficulty, and other issues. In order to avoid subjectivity and one-sidedness, based on the recyclable performance of furniture and the current situation at home and abroad, the evaluation index system of product recycling performance was established by integrating economy, environmental impact, and technology, as shown in Figure 3.

The economy of the recycling process is the main driving force for furniture recycling, so economic benefits is used as one of the metrics. Consider the cost of furniture in the whole life cycle, including enterprise production costs, user costs, and recycling costs. Enterprise production costs mainly include product design, manufacturing, enterprise management costs, and sales costs; user costs include acquisition costs, product use, maintenance, spare parts costs, and disposal costs of end-of-life products; recycling costs mainly include the cost of disassembly and classification of end-of-life products, the cost of recycling recyclable

materials, the cost of remanufacturing parts that can be remanufactured, and the cost of harmless treatment of waste materials that have no value for use.

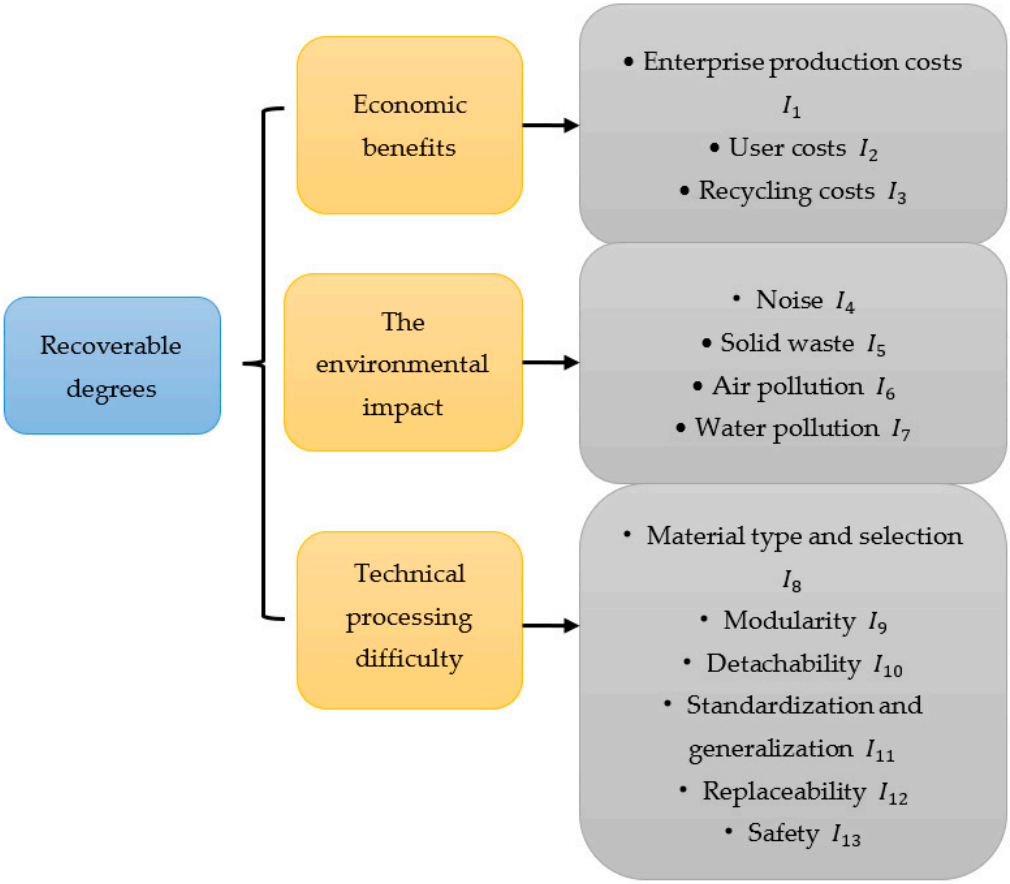

Figure 3. Wooden furniture recyclability evaluation index system.

Secondly, under the influence of concepts such as green environmental protection, more and more attention is paid to the environmental impact of the recycling process. The hazards generated in the furniture manufacturing process, including waste water, toxic organic chemicals, and solid waste, have caused an increasing number of environmental and ecological problems [3]. This includes the consumption of energy and raw materials required for the production and processing of products; solid waste such as shavings and sawdust produced during the cutting and drilling process; and the emission of harmful substances such as waste water and exhaust gas during the production process [57]. Based on the existing national standards for limiting pollutant emissions, combined with the specific data in the actual recycling process of furniture, the environmental pollution generated mainly includes noise, solid waste, air pollution, and water pollution.

Thirdly, based on the theory of the whole life cycle of products, comprehensively consider the impact of product design, manufacturing, distribution and sales, use and maintenance, and recycling stages on the recyclability of furniture in the whole life cycle of wooden furniture. The construction of the index system for the recyclability of wood furniture makes its index frame more comprehensive and scientific [49].

Material type and selection: judge whether to use materials with good use properties and good harmony with the environment. For wood materials, try to consider the use of materials with high wood utilization, prefabricated molding materials, specialized production of components, and wood composites [47]. The appropriate choice of materials can reduce waste in the process of recycling old furniture later on and increase the residual value at the end of the furniture life cycle, and the recycling of raw materials can effectively reduce production costs at the same time.

Modularity: Modularity-oriented structural design. Certain parts of the furniture are combined by standard structural components to form subsystems with specific functions. Large-scale modular production can be more efficient use of materials, reduce waste, accelerate product design, and facilitate product renewal. At the same time, damaged modules can be replaced and renewed in a timely manner, reducing the workload of recycling parts and materials.

Detachability: Detachable performance is an important factor affecting the furniture recycling rate. A reasonable component structure design can help workers remove the target parts more easily and without damage, which can reduce disassembly time and disassembly workload and improve disassembly efficiency [58].

Standardization and generalization: to make the structure as simple and uniform as possible on the basis of ensuring the stability of the structure, and to realize the standardization and generalization of parts. The use of standard parts can eliminate the need for later structural classification processing and simplify the workflow.

Replaceability: Separate the function of each part, so that a part can be reused many times or replaced in time. For some parts with a load-bearing role or fragile parts, these can be disassembled for replacement after deformation; in addition, certain decorative parts are designed to be flexibly disassembled, which not only avoids the stress of decorative parts but also allows these parts to be recycled.

Safety: furniture to satisfy the need to meet the structural safety and stability of the basis for other designs.

3.2. Establishment of Evaluation Model

There are many ways to recycle furniture, such as reuse, remanufacturing, recycling, landfill, and so on, and each recycling method corresponds to different recyclable degrees. The recycling process should consider utilization at three levels: product level, component level, and material level, as well as energy recovery and landfill of waste.

Reuse process: discarded furniture can be reintroduced to the market as a product after proper repair, with a simple surface treatment or structural treatment (replacement of parts, repair of joints, etc.) to cope with dirt, corrosion, and wear, etc. [59]. It is the product-level use of used furniture, which is the highest level of recycling from the point of view of environmental protection and conservation of resources and energy.

Remanufacturing process: adaptive remanufacturing is performed to make the EOL (end-of-life) product a similar but not identical product with functional and use characteristics equivalent to the original new product. Adaptive remanufacturing maintains the functionality of the original product in the same application, but may change its form, configuration [50]. Parts-level recycling is where the parts of the product that can be reused after disassembly and dismantling are refurbished and tested to enter the remanufacturing chain or enter the spare parts market.

Recycling process: the resources recovered from discarded furniture can be re-entered into the market as raw materials, reducing the environmental load by reducing the amount of waste disposed of by incineration or landfill [60]. Parts or products that cannot enter the above levels of recycling after disassembly can be recycled as materials, after material separation and generating recycled materials to supply raw material producers, i.e., material-level furniture recycling.

Landfill: the parts of discarded furniture that cannot be effectively recycled in the above three levels are partly incinerated to obtain energy, and the remaining residue is landfilled and eventually decomposed naturally.

Therefore, the recycling process is divided into four levels, which can be carried out in the order of finished product level–parts level–material level–incineration, and landfill, by ranking the advantages and disadvantages of different types of furniture recycling and processing methods to determine which way the furniture should be processed. The specific steps are shown in Figure 4.

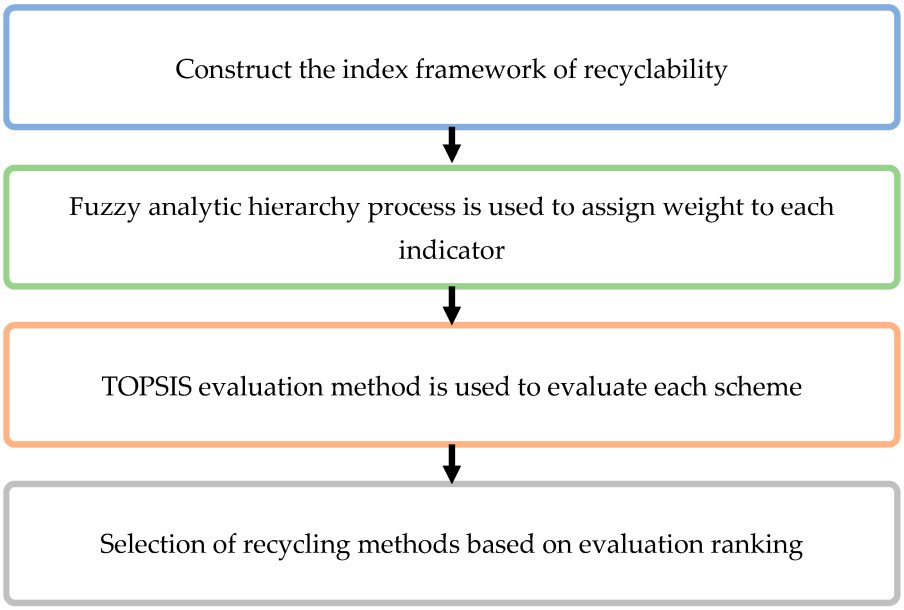

Figure 4. Flowchart of evaluation system.

Step 1: The constructed evaluation indexes are divided into first-level and second-level, and the index set is established according to the evaluation indexes.

Step 2: According to the established evaluation index set, the fuzzy hierarchical analysis method is used to determine the weight coefficient of each index. The specific algorithm is as follows: experts are invited to compare the relative importance of two factors of each index at the same level and with the same affiliation, and the dimension is subdivided into three scales (as shown in Table 1) to construct the priority relationship matrix Q_1, Q_2, Q_3, Q_4. The values in the matrix are transformed into the fuzzy relationship value transformation formula, as shown in Equation (1), and then the corresponding fuzzy relationship matrix is obtained, and the matrix is produced by row to establish the original weight vector corresponding to the fuzzy relationship matrix. The normalized weights of each influencing factor are calculated by normalization process [49].

Table 1. Scale specification.

Scale	Definition	Explanatory Notes
1	Important	while comparing two elements, i is more important than j
0.5	Equally important	while comparing two elements, i and j are equally important
0	Unimportant	while comparing two elements, i is less important than j

In the following formula, t_{ij} is the fuzzy relation value after transformation; q_i is the sum of the elements in the i row of the corresponding priority relationship matrix;q_j is the sum of the elements in the j column of the corresponding priority matrix.

$$t_{ij} = \frac{q_i - q_j}{2n} + 0.5 \quad (1)$$

Step 3: The TOPSIS evaluation method is used to evaluate the economics, environmental impact, and technical processing difficulties of the product recycling process and to determine how far the evaluated object is from the reasonable standard. In order to obtain the optimal preparation solution, the gap with the positive ideal solution is minimized, while the gap with the negative ideal solution is maximized. The specific steps are as follows:

Construct the evaluation matrix X. The elements in the matrix are m preselected programs and n indicators, where the semantic variables of the evaluation indicators and their corresponding triangular fuzzy numbers are shown in Table 2.

(1) Normalize the matrix X according to the following equation:

$$R = \left[r_{ij}\right]_{m\times n} \tag{2}$$

$$r_{ij} = \begin{cases} \left(\frac{a_{ij}}{c_j^+}, \frac{b_{ij}}{c_j^+}, \frac{c_{ij}}{c_j^+}\right), x_{ij} \in I'; i = 1,2,\cdots,m; j = 1,2,\cdots,n \\ \left(\frac{a_j^-}{c_{ij}}, \frac{a_j^-}{b_{ij}}, \frac{a_j^-}{a_{ij}}\right), x_{ij} \in I''; i = 1,2,\cdots,m; j = 1,2,\cdots,n \end{cases} \tag{3}$$

Table 2. Decision Language Terminology.

Judgment Indicator	Triangular Fuzzy Number
Very low (VL)	(0,0,0.1)
Low (L)	(0,0.1,0.3)
Medium low (ML)	(0.1,0.3,0.5)
Medium (M)	(0.3,0.5,0.7)
Medium high (MH)	(0.5,0.7,0.9)
High (H)	(0.7,0.9,1)
Very high (VH)	(0.9,1,1)

In the above equation, for qualitative indicators (a_{ij}, b_{ij}, c_{ij}), $c_j^+ = max\{a_{ij}, b_{ij}, c_{ij}\}$ is the maximum value in a_{ij}, b_{ij}, c_{ij} when it is a gain-based indicator I', and $a_j^- = min\{a_{ij}, b_{ij}, c_{ij}\}$ is the minimum value in a_{ij}, b_{ij}, c_{ij} when it is a cost-based indicator I''.

A weighted fuzzy matrix V is created from the matrix R with the weight coefficients calculated in step 2, as follows:

$$V = \left[v_{ij}\right]_{m\times n} = \left[r_{ij} \times \omega_{ij}\right]_{m\times n} \tag{4}$$

(2) Construct the fuzzy positive ideal solution A^+ and the fuzzy negative ideal solution A^- as follows, respectively:

$$A^+ = \left\{v_1^+, v_2^+, \cdots, v_j^+\right\}, j = 1,2,\cdots,n \tag{5}$$

$$A^- = \left\{v_1^-, v_2^-, \cdots, v_j^-\right\}, j = 1,2,\cdots,n \tag{6}$$

Among them,

$$v_j^+ = \begin{cases} \left(\max a_j, \max b_j, \max c_j\right), v_{ij} \in I'; i = 1,2,\cdots,n \\ \left(\min a_j, \min b_j, \min c_j\right), v_{ij} \in I''; i = 1,2,\cdots,n \end{cases} \tag{7}$$

$$v_j^- = \begin{cases} \left(\min a_j, \min b_j, \min c_j\right), v_{ij} \in I'; i = 1,2,\cdots,n \\ \left(\max a_j, \max b_j, \max c_j\right), v_{ij} \in I''; i = 1,2,\cdots,n \end{cases} \tag{8}$$

(3) Calculate the distance between each alternative and the positive and negative ideal solution:

$$d_i^+ = \sum_{j=1}^{n} d\left(v_{ij}, v_j^+\right), i = 1,2,\cdots,n \tag{9}$$

$$d_i^- = \sum_{j=1}^{n} d\left(v_{ij}, v_j^-\right), i = 1,2,\cdots,n \tag{10}$$

The triangular fuzzy numbers in the positive and negative ideal solutions are $a = (a_1, a_2, a_3)$, $b = (b_1, b_2, b_3)$, and the distances between them are:

$$d(a,b) = \sqrt{\frac{1}{3}\left[(a_1 - b_1)^2 + (a_2 - b_2)^2 + (a_3 - b_3)^2\right]} \tag{11}$$

(4) The evaluation results given to the participants are as follows:

$$C_i = \frac{d_i^-}{d_i^- + d_i^+}, i = 1, 2, \cdots, m \tag{12}$$

Step 4: The alternatives are selected based on the ranking of the evaluation results. the greater the C_i, the closer the alternative is to the ideal value [61,62].

Through the above steps to establish the wooden furniture recyclability evaluation index system and evaluation model, a scientific and reasonable evaluation of wooden furniture recyclability can be carried out, which is simple and easy to operate in practice, and can provide corresponding improvement measures for enterprises in practical application to further improve the recycling efficiency.

4. Results

This Section presents our methodology's application scenarios of recyclability evaluation in the furniture industry. First, we describe the specific implementation steps of a recyclable wooden chair as a case study, and then we explain the typical application scenarios of recyclability evaluation. The study's outcome identified the opportunities for improving the recycling efficiency of furniture.

4.1. Wooden Furniture Recycling Case Study

The evaluation of a recyclable wooden chair is used as an example to illustrate the specific implementation steps of the method. The chair type for a domestic backrest chair, no armrests, take mortise, and tenon structure connection, belong to the solid wooden chair.

(1) Weight distribution. According to the above steps, the factors in the evaluation index set are scored for relative importance, and a priority relationship matrix is constructed. Q_1 compares the economic benefits, environmental impacts, and technical processing difficulties contained in the first tier of indicators, Q_2, Q_3, Q_4 classify and compare those contained in the second tier of indicators, and the priority relationship matrix is as follows:

$$Q_1 = \begin{bmatrix} 0.5 & 1 & 1 \\ 0 & 0.5 & 1 \\ 0 & 0 & 0.5 \end{bmatrix}$$

$$Q_2 = \begin{bmatrix} 0.5 & 1 & 1 \\ 0 & 0.5 & 0 \\ 0 & 1 & 0.5 \end{bmatrix}$$

$$Q_3 = \begin{bmatrix} 0.5 & 0.5 & 0.5 & 0.5 \\ 0.5 & 0.5 & 0.5 & 0.5 \\ 0.5 & 0.5 & 0.5 & 0.5 \\ 0.5 & 0.5 & 0.5 & 0.5 \end{bmatrix}$$

$$Q_4 = \begin{bmatrix} 0.5 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0.5 & 1 & 1 & 1 & 0 \\ 1 & 0 & 0.5 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0.5 & 0 & 0 \\ 1 & 0 & 1 & 1 & 0.5 & 0 \\ 1 & 1 & 1 & 1 & 1 & 0.5 \end{bmatrix}$$

Later, after fuzzification and normalization, the weight values of the normalized weight vector are obtained as follows in Table 3:

Table 3. Weight value of each indicator.

Indicator	Weight Value
weight vector N_1	$(0.652,0.481,0.303)^T$
Normalized weight vector W_1	$(0.454,0.335,0.211)^T$
weight vector N_2	$(0.652,0.302,0.481)^T$
Normalized weight vector W_2	$(0.454,0.211,0.335)^T$
weight vector N_3	$(0.5,0.5,0.5,0.5)^T$
Normalized weight vector W_3	$(0.25,0.25,0.25,0.25)^T$
weight vector N_4	$(0.249,0.608,0.345,0.435,0.522,0.694)^T$
Normalized weight vector W_4	$(0.088,0.213,0.121,0.152,0.183,0.243)^T$

The final total weight W is obtained as:

$$W = (0.206,0.096,0.152,0.084,0.084,0.084,0.084,0.018,0.045,0.025,0.032,0.039,0.051)^T$$

(2) TOPSIS Evaluation

Invite relevant industry practitioners and academics to evaluate. The participating furniture was evaluated according to Table 2, where $I_1 - I_{13}$ represent the evaluation indicators, $P_1 - P_4$ represent the treatment options, in order of reuse, remanufacturing, recycling, and landfill. The evaluation form is shown in Table 4.

Table 4. Evaluation of decision-making programs.

	I_1	I_2	I_3	I_4	I_5	I_6	I_7	I_8	I_9	I_{10}	I_{11}	I_{12}	I_{13}
P_1	MH	H	VL	ML	L	VL	VL	L	H	MH	MH	H	MH
P_2	H	MH	M	MH	H	ML	ML	L	M	H	VH	MH	M
P_3	L	ML	H	ML	M	MH	MH	VH	VL	L	VL	VL	M
P_4	L	L	VH	ML	ML	VH	VH	MH	VL	VL	VL	VL	MH

Based on the above evaluation, a fuzzy matrix is established, and the matrix is normalized to give:

$$R = \begin{bmatrix} (0.556,0.714,1) & (0.700,0.778,1) & (0,0,0) & (0,0,0) \\ (0.700,0.778,1) & (0.556,0.714,1) & (0.200,0.333,1) & (0,0,0) \\ (0,0,0) & (0.429,0.600,1) & (0.700,0.778,1) & (0.900,0.900,1) \\ (0.200,0.333,1) & (0.556,0.714,1) & (0.200,0.333,1) & (0.200,0.333,1) \\ (0,0,0) & (0.700,0.778,1) & (0.429,0.600,1) & (0.200,0.333,1) \\ (0,0,0) & (0.200,0.333,1) & (0.556,0.714,1) & (0.900,0.900,1) \\ (0,0,0) & (0.200,0.333,1) & (0.556,0.714,1) & (0.900,0.900,1) \\ (0,0.333,1) & (0,0.333,1) & (0.900,1,1) & (0.556,0.778,1) \\ (0.700,0.900,1) & (0.429,0.714,1) & (0,0,1) & (0,0,1) \\ (0.556,0.778,1) & (0.700,0.900,1) & (0,0.333,1) & (0,0,1) \\ (0.556,0.778,1) & (0.900,1,1) & (0,0,1) & (0,0,1) \\ (0.700,0.900,1) & (0.556,0.778,1) & (0,0,1) & (0,0,1) \\ (0.556,0.778,1) & (0.429,0.714,1) & (0.429,0.714,1) & (0.556,0.778,1) \end{bmatrix}^T$$

After constructing the weighted fuzzy evaluation fuzzy matrix V according to Equation (4):

$$\begin{bmatrix} (0.115,0.147,0.206) & (0.144,0.160,0.206) & (0,0,0) & (0,0,0) \\ (0.067,0.074,0.096) & (0.053,0.069,0.096) & (0.019,0.032,0.096) & (0,0,0) \\ (0,0,0) & (0.065,0.091,0.152) & (0.106,0.118,0.152) & (0.137,0.137,0.152) \\ (0.017,0.028,0.084) & (0.047,0.060,0.084) & (0.017,0.028,0.084) & (0.017,0.028,0.084) \\ (0,0,0) & (0.059,0.065,0.084) & (0.036,0.050,0.084) & (0.017,0.028,0.084) \\ (0,0,0) & (0.017,0.028,0.084) & (0.047,0.060,0.084) & (0.076,0.076,0.084) \\ (0,0,0) & (0.017,0.028,0.084) & (0.047,0.060,0.084) & (0.076,0.076,0.084) \\ (0,0.006,0.018) & (0,0.006,0.018) & (0.016,0.018,0.018) & (0.010,0.014,0.018) \\ (0.032,0.041,0.045) & (0.019,0.032,0.045) & (0,0,0.045) & (0,0,0.045) \\ (0.014,0.019,0.025) & (0.018,0.023,0.025) & (0,0.008,0.025) & (0,0,0.025) \\ (0.018,0.025,0.032) & (0.029,0.032,0.032) & (0,0,0.032) & (0,0,0.032) \\ (0.027,0.035,0.039) & (0.022,0.030,0.039) & (0,0,0.039) & (0,0,0.039) \\ (0.028,0.040,0.051) & (0.022,0.036,0.051) & (0.022,0.036,0.051) & (0.028,0.040,0.051) \end{bmatrix}^{T}$$

After constructing the positive and negative ideal solutions, the distance between each solution and the positive and negative ideal solutions is calculated according to the formula.

$$d_1^+ = 0.263,\ d_2^+ = 0.584,\ d_3^+ = 0.474,\ d_4^+ = 0.452$$

$$d_1^- = 0.504,\ d_2^- = 0.230,\ d_3^- = 0.325,\ d_4^- = 0.321$$

Finally, the closeness of each solution to the relative ideal solution is calculated and compared.

$$C_1 = 0.658,\ C_2 = 0.282,\ C_3 = 0.406,\ C_4 = 0.416$$

Since $C_1 > C_4 > C_3 > C_2$, Option 1 is the optimal solution for this furniture.

4.2. Application Scenarios of Recyclability Evaluation

4.2.1. Development of Furniture Recovery and Disposal Center

The furniture recovery and disposal center is one of the most important facilities for recycling the discarded furniture. The established evaluation model can help to perform the most elementary information analysis. When consumers have the need to deal with waste wooden furniture, they can call the hotline or register information online, and the furniture will be collected by the enterprise or directly transported to the furniture recovery and disposal center. The center will collect the information (connection type, material used, structure, etc.) in advance, and then quickly integrate and analyze the information of the furniture through the evaluation model to judge the processing method. After judgment, some can be used as raw materials for furniture remanufacturing and reused parts continue to enter the cycle, some can be used as fuel, fertilizer, and the unusable part can be landfilled. The remanufactured furniture goes into the reuse sales center to consumers, thus forming a closed-loop supply chain (as shown in Figure 5).

The establishment of a furniture recovery and disposal center can provide a recycling and processing site for wooden furniture to avoid the waste furniture having nowhere to be stored. At the same time, the recyclable furniture materials, parts, and so on are classified and recycled in batches, which is more efficient and reduces the cost of recycling. The center uses the above evaluation model data information to control the furniture recycling and processing process in an all-around way to further improve recycling efficiency and solve recycling problems.

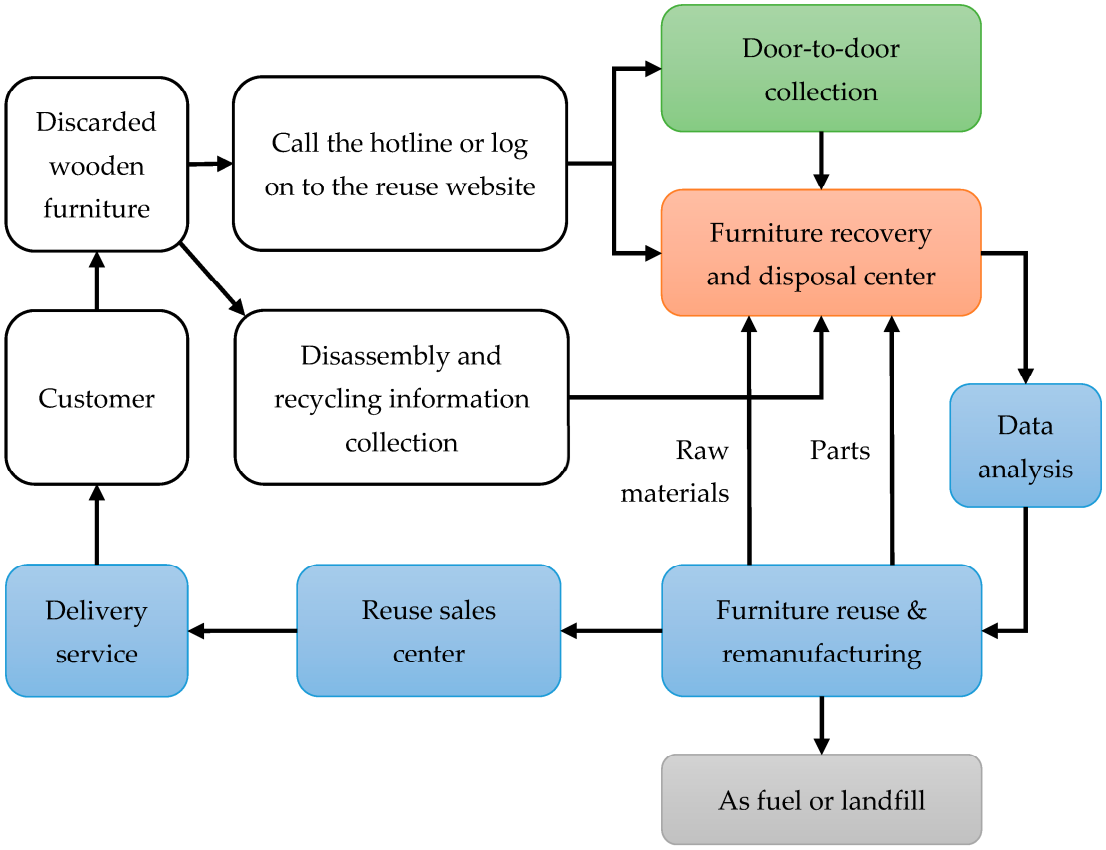

Figure 5. Waste wooden furniture recycling process.

4.2.2. The Establishment of a Strategic Alliance for Recycling Discarded Furniture

As with traditional remanufacturing, recycling discarded furniture remains a critical logistical task [50]. In the process of recovery and disposal of waste wooden furniture, furniture manufacturing enterprises and professional recovery enterprises should always cooperate to form a special strategic alliance organization based on the principles of information disclosure and resource sharing, which is responsible for recovery and disposal. The process is shown in Figure 6. This mode of strategic alliance enterprise makes it less difficult to implement cooperation. Professional third-party recycling companies do not need to store refurbished products, semi-finished products, and parts after recycling, but they directly enter the manufacturing process or sales process of the manufacturing company, which greatly improves the efficiency.

The growing need for modern companies to take responsibility for creating a sustainable society has led to an increased focus on recyclability assessment [44]. In this recycling model, the evaluation model quantifies factors such as economic benefits and environmental impacts, thus helping companies to judge the benefits of recycling. In addition, due to the establishment of information-sharing channels, furniture manufacturers can more quickly understand customer needs and formulate the next market strategy [63].

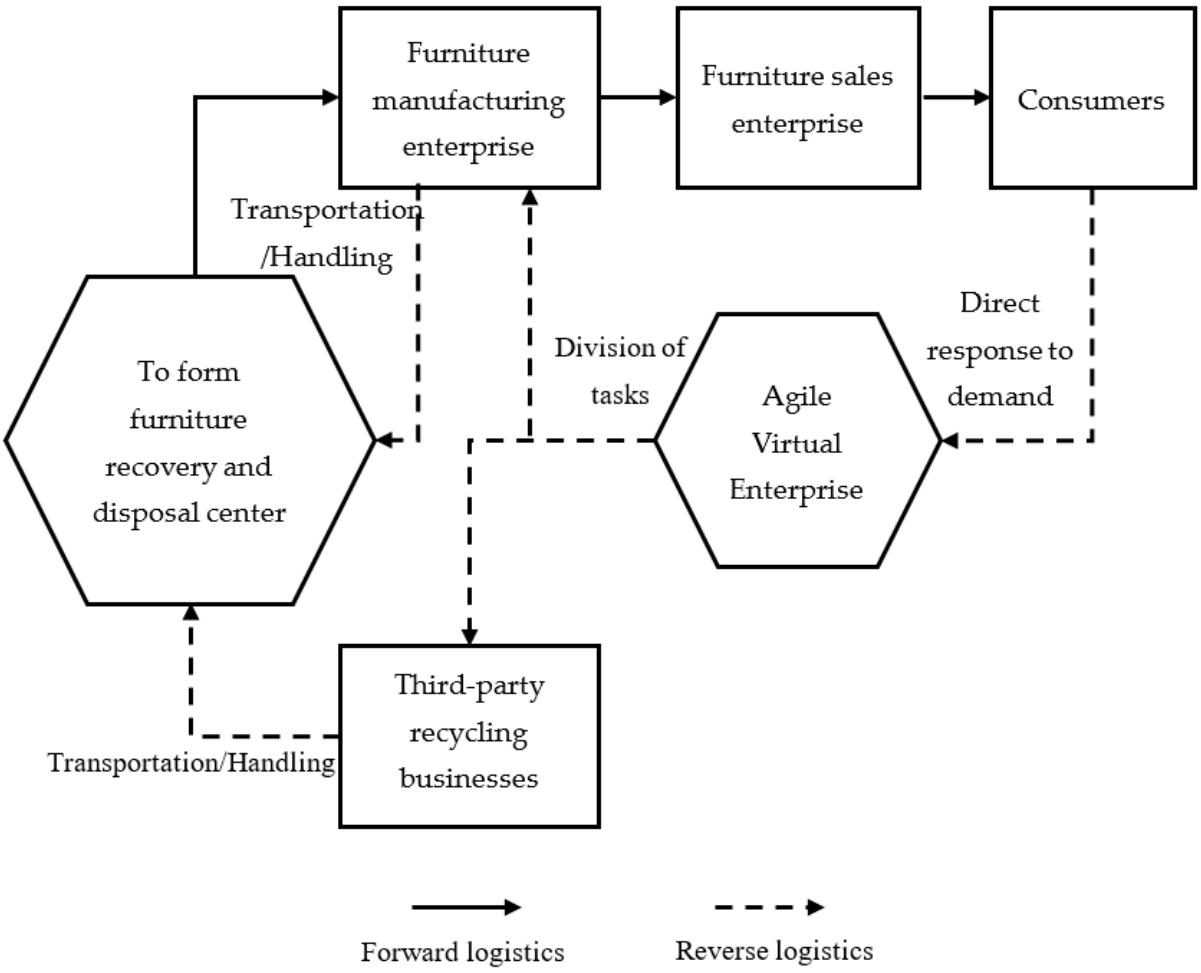

Figure 6. Flowchart of strategic alliance business model.

5. Discussion

Furniture recycling is a systematic process that requires the active participation of consumers, furniture manufacturers, sales companies, and governments at all levels. Faced with the predicament of low profit, difficult sales, and narrow sales scope in the furniture recovery market, it is a good policy to replace old furniture with old furniture. In this regard, in 2013, Beijing, China, implemented the policy of "trade-in" furniture and formulated the "Beijing Municipal Furniture Replacement from Old to New Implementation Measures", which clarified the corporate responsibilities of furniture sales enterprises and used furniture dismantling enterprises. Guangdong Province has raised the recycling and utilization of waste furniture to the policy level in the "13th Five-Year Plan for the Development of Energy Conservation and Environmental Protection Industry in Guangdong Province". However, except for precious mahogany furniture, a large volume of discarded furniture still faces difficulty re-entering the market due to the lack of an established and viable recovery method. Therefore, there is still a long way to go to realize the recovery of wooden furniture in China, but it also provides more research space for the government, enterprises, and scholars [3].

Building a mature wooden furniture recovery system requires the cooperation of the government, enterprises, and society to achieve sound development. The relevant suggestions are as follows:

(a) At the government level, the government needs to issue relevant policies and laws and regulations, formulate relevant process requirements, standardize production processes, guide the concept of green consumption, vigorously encourage the recycling and utilization of discarded furniture from the whole product life cycle, jointly establish

furniture recovery and disposal centers with enterprises, and introduce policies to improve the recyclability evaluation index system, as well as macro-control of recycling efficiency and recycling methods.

(b) At the enterprise level, the enterprises should control the overall process of the product life cycle from the beginning to the end. Carry out the initial wooden furniture design from the aspects of material design and structural design; in the production and manufacturing stage, pay attention to the production energy consumption and the impact on the environment; in the sales stage, pay attention to the packaging method and transportation process, under the condition that the basic use functions are met, adopt the means of green packaging; in the use stage, enterprises should conduct regular inspections on the furniture products that have been sold and replace damaged parts to extend the product life cycle; finally, furniture manufacturing enterprises should cooperate with recycling enterprises to form strategic alliance organizations, realization of data, and information sharing, and on this basis, establish a furniture recovery and disposal center, so as to improve the recycling system and improve the recycling efficiency.

(c) At the consumer level, consumers should actively respond to the national recycling strategy, change the consumption concept to green consumption, pay attention to the information of furniture recycling enterprises, and actively participate in the recycling of discarded furniture products.

6. Conclusions

Based on the various stages of the life cycle of wood furniture, this paper established the evaluation index system and evaluation model of the recyclability of wood furniture by the fuzzy hierarchical analysis method and TOPSIS evaluation method and illustrates the calculation of specific cases of recyclable furniture to verify the feasibility of the evaluation model. The evaluation index system clarifies the criteria and factors to be taken into account in decision-making, and the recyclable evaluation model can be used as the standard for furniture recycling and processing centers to handle waste wooden furniture, while laying the foundation for establishing a strategic alliance for recycling waste furniture. Through the analysis and judgment of data processing means, the furniture recycling method can be quickly selected to achieve rapid response of each process, thus improving the recycling efficiency, solving the recycling problem, and avoiding the waste of resources. At the same time, quantify the data of furniture recovery and disposal to provide the basis for building a furniture recycling database and obtaining the optimal preselection program in advance. In addition, the evaluation index system and evaluation model of recyclability described in this paper still need to be improved, the standardized system close to the actual situation contains many uncertainties, the evaluation system needs to be continuously improved, there are more physicochemical-related branches of recovery methods, and the choice of methods can be further subdivided, which is expected to be improved in the future research work. The evaluation of the recyclable design of waste wooden furniture will become the key field of ecological design and green design of wooden furniture.

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