# Life Cycle Analysis for Reconstituted Decorative Lumber from an Ecological Perspective: A Review

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In response to global Sustainable Development Goals (SDGs), the Chinese government has pledged to curtail increased carbon dioxide emissions beyond 2030 and to achieve carbon neutrality by 2060, thus achieving a status of an ecological civilization. Reconstituted decorative lumber, with rotary-cut (or planed) veneer from plantation or common species timber as the main raw material, has beneficial development opportunities for forestry from the perspective of an ecological civilization. This paper first discusses China's current state of ecological civilization, then researches the various life cycles of reconstituted decorative lumber using the life cycle theory and provides a reference for the Chinese reconstituted decorative lumber industry's development by analyzing progress in related fields. The eco-friendliness of reconstituted decorative lumber is explained *via* systematic combing, and proposals for the use and promotion of reconstituted decorative lumber in the new period are presented. Research and analysis findings show that it is necessary to comprehensively regulate the production chain of reconstituted decorative lumber based on life cycle. Research on the development and utilization of reconstituted decorative lumber needs to be strengthened. The promotion and marketing of reconstituted decorative lumber can be promoted by emphasizing its ecological significance.

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## INTRODUCTION

In 2016, the global Sustainable Development Goals (SDGs) were established, thus providing a comprehensive and multidimensional guide to countries' sustainable development paths until 2030 (Allen *et al.* 2018). Initiatives of different scales and forms have been proposed under the SDGs (Ningrum *et al.* 2022). To express its concern for global climate change, the Chinese government promises to strive to reach a peak in carbon dioxide emissions by 2030 and to reach carbon neutrality by 2060; the Japanese government has adopted the SDGs Implementation Guiding Principles as its main strategic program for the implementation of the SDGs; Sweden's private institutions, civil society, scientific research organizations, and municipalities have established a range of platforms and cooperation mechanisms related to the theme of the Agenda 2030, and the Swedish government has also established a seven-member SDGS National Delegation to encourage and support the exchange of experience and knowledge among international or domestic stakeholders (Guan and Xue 2019). The world's ecological concerns have made it necessary to reassess current production and construction from the perspective of ecological civilization. Forestry, as an important link in the construction of ecological civilization, has realized the transformation from economic priority to ecological priority in policy in China (Tu and Liu 2020), but it is more necessary to start with specific issues to address the dependence on natural timber resources.

Reconstituted decorative lumber (RDL) can be defined as a type of wood decorative material that has the texture, pattern, tone, and other characteristics of natural precious tree species or other artistic patterns, and is made from rotary cutting (or planing) veneer of artificial fast-growing or common species (*i.e.* basswood, obeche, poplar) as the main raw material, with veneer color matching, lamination, molding, and gluing technologies (Zhuang 2004; Wang and Huang 2007). RDL is a type of wood reconstituted material that possesses geometric qualities, identity, consistency, and surface formability that the original wood lacks (Wang *et al.* 2009). As a result, the development of RDL might be considered a type of wood alteration. Low-value plantation fast-growing wood can achieve high-value use through reconstituted technology processing, allowing it to better substitute for hardwood lumber and meet the needs of consumers. Reconstituted decorative veneer (RDV) is one of the most extensively utilized types. RDV can be used as a finishing material on a variety of substrates to protect the substrate, cover faults, and beautify the appearance. This method of transforming low-quality, small-diameter logs into laminated timber and artificial-grain man-made wood veneers can be used to replace precious solid wood veneers with natural grain and color, and has become one of the most practical methods to complement natural decorative veneers (Li *et al.* 2018), with production costs 50% to 70% lower than natural wood veneers (Hu *et al.* 2012). It also provides superior human tactile comfort (Wang *et al.* 2020) compared to other decorative materials (decorative paper, PVC, aluminum foil, *etc*.). Up to this point, research on RDL has focused on the production phase and has been mainly divided into two types. One is the improvement of the dyeing process. Recently, some scholars have improved the veneer dyeing process and standardized the best dyeing process conditions (Li and Guo 2018; Yang *et al.* 2019). The other type involves the performance improvement of RDL, broadening the scope of its applications. Recent studies focus on developing more environmentally friendly flexible decorative veneer through modification (Fang *et al.* 2021; Zhi *et al.* 2022). Specifically, Gao *et al.* (2022) reviewed the progress of research on reconstituted wood manufacturing technology and proposed that in the future, the fine thinning technology of wood bundle units should be optimized, the level of automation of processing equipment should be improved, the types of adhesives should be expanded, and the application of reconstituted wood in transportation tools such as automobiles, trains and airplanes, and high-rise wooden buildings should be expanded.

The concept of life cycle analysis or LCA (also known as life cycle assessment) is widely used, especially in the political, economic, environmental, and social spheres. LCA is the quantitative computation and evaluation of a product's actual and potential resource and energy consumption, as well as its discharged environmental load, over its entire life cycle, from raw material acquisition to design, production, usage, recycling, and ultimate treatment (Consoli *et al.* 1993). In life cycle research, the boundaries of the life cycle need to be defined according to the actual situation, with each boundary having a different focus. There are four main variants in the current study. One is the process from cradle to grave (Gursel *et al.* 2021), which focuses on products from raw material mining, processing, manufacturing, use, maintenance, *etc*., to final waste disposal. The second is the process from cradle to gate (Nadeem et al. 2022), which only considers the manufacturing stage and does not consider the use and waste stage of products. The third is the process from cradle to cradle (Gomes *et al.* 2020), which involves paying attention to the process of recycling discarded products. The final variant considers gate to gate, a partial LCA technique that examines only one value-added process across the whole production chain (Cao 2017). Gate-to-gate modules can also be linked in their individual manufacturing chains to provide a cradle-to-gate assessment (Jiménez-González *et al.* 2000). Recent research on RDL has only focused on the production phase and has lacked a life-cycle perspective. As manufacturers need to be in charge of the environmental performance of their products throughout the products' life cycle (Alting 1995), it is essential to analyze the life cycle of RDL.

The research of RDL in China began in the mid to late 20$^{th}$ century, during which time the cold and wet gluing and pressing process developed by the Wood Industry Research Institute of the Chinese Academy of Forestry Sciences effectively promoted the development of RDL (Xu 1998). In December 2012, China's national standard for RDL came into force (GB/T 28998-2012 2012). Although it has a certain development history, the acceptance of RDL in China is not high, so more research is needed to promote the development of this field. Based on the background of global ecological civilization construction, especially China's ecological background, this paper comprehensively provides an analysis of the life cycle of RDL. By comparing and learning from the practices in similar fields, this paper provides a direction for the follow-up ecological research of RDL, in order to advance the development of the RDL sector in China.

## ECOLOGICAL CIVILIZATION

The ecological civilization desired in this new era requires a change in the human-centered mindset towards a harmonious coexistence between man and nature. The continuous promotion of ecological civilization in contemporary China and the creation of a beautiful China underlies the scientific insight and aspiration of this historical law and the conscious manifestation of adherence to the path of historical necessity. The construction of ecological civilization in China has also provided theoretical guidance and practical support for global ecological protection. But this is a long-term process that will require constant advancement and effort.

### Forestry Development in the Context of Ecological Civilization

As an important part of the natural ecosystem and an ecological safeguard for human survival, the status of forests in the construction of ecological civilization is becoming increasingly prominent. The context of ecological civilization provides positive opportunities for forestry reform and development of the environment.

The wood industry is a low-carbon industry that consumes less energy and creates less environmental pollution than others, especially when compared to traditional building materials such as steel, glass, and cement. According to a US economic database, the $CO_2$ intensity of timber manufacture is roughly 20% lower than that of fabricated metal goods, under 50% for iron and steel, and under 25% for cement. (Winchester and Reilly 2020). Carbon stocks in wood forest products, mainly wood and wood products, are significant for evaluating the potential of greenhouse gas emission reduction and compiling the national greenhouse gas emission inventory (Hu and Zhang 2021; Wu *et al.* 2021a; Wu *et al.* 2021b; Lao 2022). However, China's current wood resources are severely depleted.

China is a country with few forests, and its per capita forest stock is below the world average. China's annual timber consumption is more than 300 million cubic meters, and it is expected that by 2025 China's timber demand will reach 800 million m³, with a shortfall of more than 200 million m³ (Shen *et al.* 2020). China's existing wood forests account for only 13% of the harvestable area and 23% of the harvestable reserves, with few available wood resources, even fewer large-diameter trees and precious timber species, and a large proportion of medium and young forests. The lack of domestic timber supply capacity in China has necessitated the importation of timber to alleviate the contradiction between supply and demand, but this has also led to a gradual increase in China's external dependence on wood (as shown in Fig. 1). In 2000, external wood dependency remained at 27.9%, but by 2019 it had reached 58.8%, which means that the situation in the Chinese wood market is serious (Zhao *et al.* 2021).

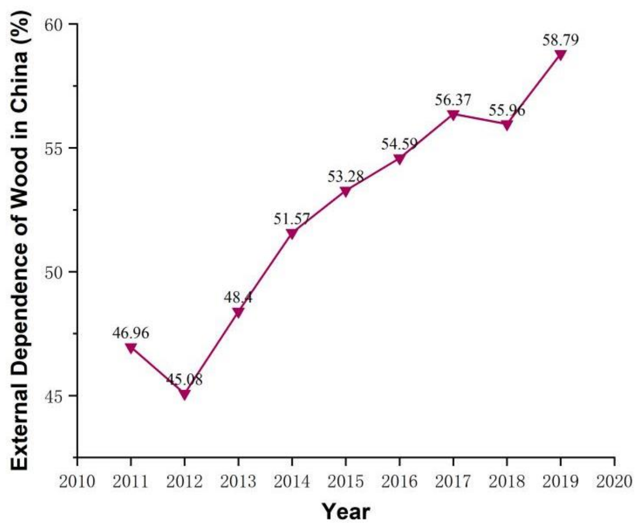


**Fig. 1.** Line chart of China's external dependence of wood in recent ten years

In other words, although the total amount of China's planted forest resources has continued to grow, it still relies too much on imported timber, and the condition of China's forests remains disappointing in terms of changes in indicators such as timber volume, growth rate, age structure, and diversity (Chen *et al.* 2021; Yin 2021). This also shows that China still needs further optimization in terms of promoting the greening of the country, optimizing the structure of resources, and strengthening management and supervision (Du *et al.* 2020). However, China's forestry policy has shifted from an 'economic priority' to an 'ecological priority'. Tu and Liu (2020) used the multiple streams theory to explain the reasons for this shift. First of all, in terms of problematic streams, it was triggered by the global ecological crisis and economic losses in state-owned forest areas. Secondly, in terms of political streams, it is the result of a shift in the country's top-level design thinking. Moreover, in terms of policy streams, it is driven by theoretical trends such as sustainable development and multi-functionalism in forestry from home and abroad, as well as policy experiments by local governments. For example, part 11 of "Outline of the 14$^{th}$ Five-Year Plan (2021-2025) for National Economic and Social Development and Vision 2035 of the People's Republic of China" shows China's concern for coexistence between humans and nature and green development. It mentions the need to accelerate the green transformation of development methods, which reflects a higher level of social development philosophy and helps promote new development formats; Article 32 of the Forest Law of the People's

Republic of China 2020 specifically mentions the natural forests protection system, in which the state improves the ecological functions of natural forests by limiting the logging of natural forests and strengthening the management and construction of natural forests; the National Reserve Forest Construction Plan (2018-2035) specifies that by 2035, 20 million hectares of national reserve forests will be built. After completion, the annual net increase in reserves will be about 200 million cubic meters, realizing basic self-sufficiency in general timber.

### Eco-forestry Development and Reconstituted Decorative Lumber

As the raw material for RDL is artificial fast-growing timber or common species timber, it helps to reduce the over-dependence of China's wood processing industry on natural timber resources, realize the comprehensive and reasonable development of natural and planted forests, and plays a positive and healthy role in promoting the use of China's overall timber resources. Based on current environmental challenges, it is vital to improving the availability of wood (Xiong *et al.* 2020a). Strengthening the research, development, and use of RDL is an important means of protecting valuable natural species (by reducing reliance on them), making efficient use of artificial fast-growing species, and resolving the structural imbalance between timber supply and demand. It is also a useful development direction for forestry in the context of ecological civilization. In addition, with the improvement of technology in recent years, more and more aldehyde-free RDL have been introduced to the market, greatly improving the environmental friendliness of RDL and echoing the green and sustainable development strategy proposed by the state.

## LIFE CYCLE OF RECONSTITUTED DECORATIVE LUMBER

### Raw Material Acquisition Phase

Reconstituted decorative lumber (RDL) achieves value-added utilization of natural lumber by retaining 92%-95% of the natural lumber content while maintaining natural qualities such as heat insulation, insulation, moisture regulation, and temperature regulation (Zhuang 2004). Therefore, for RDL, the main raw material is natural lumber. Compared with other materials, wood is of great significance to reduce carbon emissions (Winchester and Reilly 2020). Oliver *et al.* (2014) claimed that when compared to product and wood energy contributions, utilizing wood instead of steel and concrete saves the greatest carbon dioxide ($CO_2$) and fossil fuel (FF). Linkosalmi *et al.* (2016) stated that wood-based materials have an impact on total greenhouse gas emissions of 8% to 54%, which is relatively modest. And wood-based products with biogenic carbon storage can cut greenhouse gas emissions by 6.5% to 105%. Suter *et al.* (2017) calculated a net benefit of 0.5 tonnes $CO_2$ equivalent per cubic meter of wood utilized in terms of climate change. All of these scholarly studies confirm the use of wood as a remedy for global warming and imply the eco-friendliness of the raw material phase of RDL, whose main material is wood.

Fast-growing lumber from plantation forests can be used as the primary raw material for RDL, which is critical given the current scarcity of forest resources (Chai *et al.* 2022). If RDL is produced instead of hardwood lumber, the amount of land required for hardwood lumber would be reduced. However, to maintain sustainable management of plantation forests, the raw material for RDL must be obtained in accordance with the plantation harvesting system. This includes thinning activities (tending), which not only can create better growth environmental conditions for the reserved trees but also can yield some timber, which is a more effective sustainable management measure of the plantation. By analyzing the management system of foreign plantation logging, Ugis *et al.* (2019) made suggestions for the management system of plantation logging in China. They believed that it is necessary to publicize forest harvesting and strengthen forest certification, which can promote the sound development of China's plantation system. Song *et al.* (2020) showed that tending-thinning (*i.e.* regularly and repeatedly cutting of some trees in immature forests) can effectively regulate the growth function of the plantation. He also emphasized that tending-thinning can promote the diversity of plantation ecosystem, which is a better way to meet the requirements of sustainable development than the traditional plantation cutting methods. Similarly, Han (2021) discussed effective paths for forestry ecological construction and the development of the forest economy, and also mentioned the need to strengthen the management of nurturing intervals in forest areas.

## Design Phase

*Low carbon design optimization*

Carbon emissions as an indicator can be used to quantify the potential greenhouse impact of product design, and low-carbon design optimization is presently a popular topic of research (Peng *et al.* 2018). According to recent studies, developing appropriate design solutions to reduce product life cycle carbon emissions is critical. The current research on the topic of architecture is relatively mature. Yang and Yu (2021) developed a parametric design optimization approach and tool for the early phases of building design that may achieve the lowest life cycle environmental impact and cost with a variety of options, supporting architects in their design selections. Similarly, Wang (2022) presented a method for forecasting building carbon emissions during the early design stage, allowing for quick input on design options' carbon performance. The products of RDL are already eco-friendly in terms of material, and through low-carbon design optimization, they can mainly reduce the impact on the environment in the later production process and in the recycling process, which has practical value and can be used as a reference for RDL enterprises.

*Color healing*

Eco-sustainability is not just about quantifiable efficiency or visible hardware. No matter how precise the technical specifications are, if the user is not empathetic towards it, then it should not be regarded as eco-sustainable. Therefore, during the design phase, the focus also can be on the subjective ecological perceptions of the user. A study has shown that human beings recognize things first from their color and then from their shape. During the first 20 seconds of exposure to an object, the color accounts for 80% of the impression (Wang 2007). So, while many material characteristics can influence the user's experience (Hu *et al.* 2020), color is a key consideration in the design of RDL. Moreover, color also has certain well-being effects. The human brain has different levels of stimulation to different colors, and the use of color changes can bring balance to the body's environment. If the color of RDL can play a color healing role while satisfying the ecological perception, it can relieve the anxiety caused by social situations in the post-trauma (*i.e.* epidemic/ pandemic eras) to a certain extent (Zhang 2021; Wang *et al.* 2022). It also responds to the need for softer tones in the ageing trend (older person environments) (Ran and Li 2017; Xia 2021).

Other areas of design have demonstrated the healing value of color. Kometiani (2017) conducted a community art therapy experiment, and the results showed that art therapy facilitates the formation of a sense of community identity. In addition, participants were also better at dealing with stress in work and life. Based on the healthy color matching, proposed by Professor Axel Venn, Liu *et al.* (2020) analyzed and commented on the corresponding color matching in the case of medical space. The results show that color schemes for healthcare spaces are consistent with the color combination with Professor Venn's color schemes for health with positive imagery, and good color schemes can help patients improve their healing power. Zhou *et al.* (2021), intelligently generated the color composition of healing colors of the four seasons by using *Processing* programming and practiced the color matching for the exterior decoration of the bus. According to the verification experiment, the color scheme showed a certain healing effect. The practice of these scholars is a testament to the positive effects of color healing. Whether for spaces or products, color has become an element that can no longer be ignored when designing. It is therefore justifiably viable to apply it to the field of RDL.

*Constructing the correlation between textural style and ecological landscape*

When designing the texture and color characteristics of the RDL, the correlation with the ecological landscape can be sought to make the textural style of RDL more tangible. This, in line with the background of ecological civilization, makes the subjective experience of the user enhanced at a later stage and is also more conducive to marketing. The two types of veneers of *Ipir* correspond to the ecological landscape of the Badain Jaran Desert in China (as shown in Fig. 2), thus making the abstract texture style of the reconstituted decorative veneer (RDV) product itself concrete and giving it a certain ecological connotation, thus enhancing its eco-aesthetic value.

(a) (b) (c) (d)

**Fig. 2.** Examples of the correlation between textural style and ecological landscape **: (a)** one kind of veneer patterns from *Ipir* (BX300-ST422); **(b)** a picture of pink lake in Badain Jaran Desert; (c) another kind of veneer patterns from *Ipir* (AX13-ST-763B); (d) An aerial view of Badain Jaran Desert

## Processing and Production Phase

Current research in the literature on RDL has largely focused on process improvements. Process improvements can reduce the negative environmental impact during the processing and production phase and increase the value of RDL by improving their performance. Wu *et al.* (2016), studied the preparation of the flame-retardant RDL, mainly by adding flame retardants to the dyeing process of RDV and using the conventional cold-press gluing process to prepare flame-retardant RDV. The physical and chemical properties and flame retardant properties of the products were also tested and analyzed to explore the reasonable process and operating parameters for large-scale industrial production to further improve the application effect of the engineered wood veneer and the fire safety performance of the laminated products. Furthermore, in order to solve the problem of poor levels of the toughness of conventional urea-formaldehyde (UF) used in the production of RDL, Shi *et al.* (2017) prepared a modified adhesive for the production of RDL by mixing modified corn-starch emulsions with urea-formaldehyde resin (UF) and adding modifiers such as polyvinyl acetate emulsions (PVAc), polyvinyl alcohol (PVOH), anionic polyacrylamide (APAM), and polymethylene polyphenyl isocyanate (PAPI). Zhan *et al.* (2018) summarized their innovations in the production technology and product development of RDL, including the end sealing technology of logs and wood squares, the automatic pH adjustment system of bleaching tank, horizontal dyeing tank equipment, the application of non-formaldehyde glue, and high frequency gluing process. They also mentioned the development of new engineered wood products relating to high light fastness, flame retardant, being paint-free, and having a focus on adhesives for RDL. Cheng *et al.* (2019) used polyvinyl acetate emulsion to manufacture RDL/veneer and investigated the adhesive sizing process and application properties. The results showed that the use of polyvinyl acetate emulsion could produce environmentally friendly RDV with formaldehyde emission of less than 0.3 mg/L. When the dosage of the crosslinking agent was 5% and the gluing amount was 160 g/m$^2$, the adhesive was found to be operable and to have suitable gluing quality in the production application. The quality of the RDL produced still met the production requirements within 20 days of storage. In other respects, Li and Guo (2018) elaborated the significance of the research on the dyeing modification of RDV, emphasizing that the manufacturing technology can fully display and give complete excellent decorative performance of the dyed veneer by coloring the wood veneer as a whole and reproducing various colors on the wood veneer. They verified that the color difference between the dyed veneer and the target color was hard to recognize by the naked eye. Similarly, Yang *et al.* (2019) optimized the dyeing process for RDL by improving the veneer dyeing process, using the dyeing rate, light fastness, dye dissolution time, and dyeing time as evaluation indicators. The results showed that the optimum dyeing conditions were: dye molecular weight of 500; dyeing temperature of 96 °C; and penetrant dosage of 0.05%. With the improvement of production technology, the advantages of RDL will be more prominent, and more environmentally friendly and beautiful RDL will further promote the replacement of wood materials.

Additionally, another group of scholars has focused on broadening the range of applications for RDL. Wang *et al.* (2020) conducted impregnation trials on the industrialized production line of impregnated paper with rolled RDV (artificial veneer) as the material and melamine formaldehyde resin (MF) as the impregnating liquid. The study showed that it was entirely feasible to achieve industrial and continuous impregnation of large-format decorative veneer directly using conventional impregnated paper production equipment, which provided a reference for promoting the large-scale production and application of impregnated decorative veneer. Some scholars have also considered the limitations of flame-retardant panels and carried out the practice of optimizing the performance of flame-retardant panels with the goal of adapting to humid environments. For example, Zhang *et al.* (2021) aimed to produce a flame-retardant man-made panel that could be insulated from moisture in humid air, based on flame-retardant plywood base material with oxygen index ⩾38%, with thermoplastic PE film as the adhesive and RDV as the panel. The produced panels exhibited stable moisture content, and there was no problem with flame retardant leakage. Moreover, to obtain flexible decorative veneers to broaden their application range, Fang *et al.* (2021) focused on the use of plastic films and evaluated the overlay performance of decorative veneers. After that, Zhi *et al.* (2022) provided a vacuum impregnation process of castor oil-based waterborne polyurethane (PUDs). This process eliminated the hot-pressing and pretreatment process, thus simplifying the production of flexible decorative wood veneer.

*Green manufacturing*

In addition to the concern for the improvement of the production process, in the processing and production phase, enterprises must pay attention to the construction of a green manufacturing system. Under the background of ecological civilization construction, the traditional manufacturing method can no longer meet the green requirements of products throughout their life cycle. To maximize resource utilization and minimize waste in the manufacturing process, a resource flow model for the green manufacturing system should be constructed, taking into account all factors in the manufacturing system (as shown in Fig. 3). Green manufacturing is a comprehensive pollution prevention strategy for products and production processes. Based on the reality of the manufacturing system, it minimizes the generation of pollutants through continuous control. Enterprises should not only care about the initial investment but should think about the longer term. Although the initial investment in green manufacturing is large, it can make the company's products more competitive.

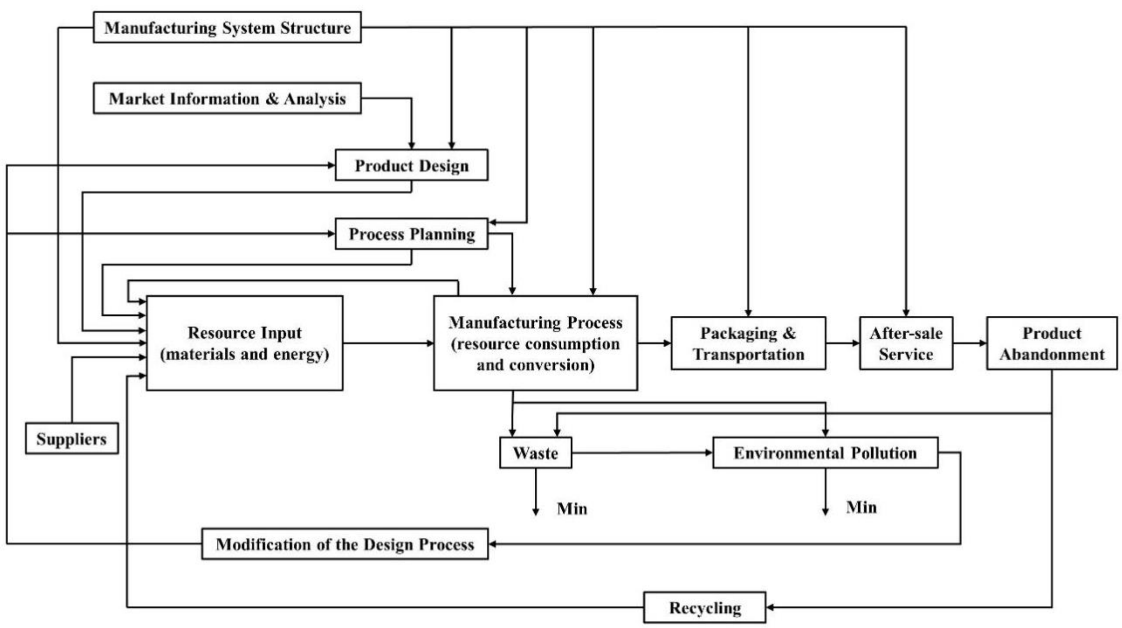


**Fig. 3.** The resource flow model for green manufacturing

## Packaging and Transportation Phase

The environmental effects of locally sourced timber are far superior to those of imported timber. It has been calculated that the greenhouse gas emissions from the use of domestically sourced timber are 74% lower than those from imported timber and that the emissions of other greenhouse gases (including $SO_2$, $NO_2$, $CH_4$, and $N_2O$) are also significantly reduced (Chu *et al.* 2014). Therefore, domestic RDL companies can use as much domestic timber as possible for their production, thus reducing the logistical burden. Moreover, the packaging and transportation phase of RDL requires green logistics, which means reducing damage to the natural environment in a greenway in the operational aspects and management activities of logistics, as well as the full use and recycling of logistics resources. Liu *et al.* (2018), believed that solving the dilemma of green logistics development and strengthening the endogenous impetus of the logistics industry to the construction of ecological civilization is a real problem that needs to be solved urgently at present. They proposed that green logistics development should formulate green logistics industry planning and evaluation system. Green development also can be used as a guide to strengthening the technical transformation of infrastructure. More specifically, Jiang (2021) proposed the development direction of green transportation from two aspects: One is through the use of green transport such as new energy vehicles, and the other is through reasonable planning of logistics routes to improve transportation efficiency. Additionally, from the perspective of the supply chain, Yang and Xu (2021) explored the logistics costs of wood processing enterprises and combined with the concept of sustainable development, to apply green logistics to the supply chain of the wood processing industry, such as using big data and artificial intelligence as carriers to calculate the optimal delivery path or adopting economic order quantity algorithms to reasonably plan the order quantity and reduce storage pressure. More visually, De Souza *et al.* (2022) directly created a tool that can effectively evaluate the green logistics performance of a company. They have applied the tool in practice to assess the green logistics performance of a plastics company. The results of their research are important for improving the environmental performance of enterprises and for the standardization of green logistics. Based on these existing studies, the RDL enterprises need to apply green logistics to the supply chain, to enable compliance with the green development orientation.

## Waste Disposal Phase

*Production waste disposal*

Recycling the waste from the production of RDL will not only increase economic efficiency but also reduce the environmental impact. Firstly, the leftover trimmings from the production of RDL can be used as the substrate for particleboard and fibreboard plants (Hu *et al.* 2012), truly making the most of fast-growing timber. In addition, the manufacture of wood products generates a huge amount of biomass residues. These wastes can be recycled and converted into biofuel, which reduces carbon emissions as compared to fossil fuels (Sathre and Gustavsson 2009). One academic study pointed out that a wood processing company with an annual processing capacity of 100,000m3, for example, is able to generate an additional income of 1.1 to 1.5 million yuan per year from wood waste recycling alone (Li 2019). Secondly, how the wastewater from the production of RDL is treated is also a key issue. Wang *et al.* (2006) proposed that the combination of multi-processes and in-depth treatment is an ideal solution for the treatment of industrial wastewater from RDL enterprises. Among them, it mainly involves tertiary biochemical treatment or tertiary electrochemical treatment. However, there is still relatively little research on the subject. RDL enterprises can actually learn from the solution of printing and dyeing enterprises for industrial wastewater treatment optimization because the industrial wastewater of printing and dyeing enterprises is relatively similar to the industrial wastewater from RDL enterprises. For example, Xue (2021) pointed out that the treatment of printing and dyeing wastewater should first consider biological or intensification methods due to cost considerations. As for the future trend of printing and dyeing wastewater treatment, he proposed that a large amount of sludge will be generated from wastewater treatment, and how to recycle it will be a contentious issue. In another study, the authors looked at the problem of sludge treatment in terms of cost reduction. They evaluated the sludge reduction efficiency and nitrogen removal rate of different bioreactors for printing and dyeing wastewater treatment, and the results showed that the reactor with basalt fibers as a biological carrier had a better effect (Ni *et al.* 2021). Moreover, Zampeta *et al.* (2021) combined hydrodynamic cavitation with green oxidants as an alternative method for the treatment of printing and dyeing wastewater, which proved to have positive results in the production of real factories. Furthermore, the treatment of waste heat from the production of RDL is also a priority in the waste disposal phase. *TABU*, one of the top Italian veneer brands, implemented a cogeneration plant in 2020, which allows the combined production on-site of electric and thermal energy. The installed cogeneration plant, which covers 64% of the plant's annual electric energy needs and 14% of its annual thermal energy needs, effectively helps *TABU* avoid the $CO_2$ equivalent emissions of about 800 t/year. The emphasis on waste heat treatment illustrates *TABU*'s commitment to sustainability and demonstrates the sense of responsibility of a top brand.

*Recycling of waste products*

The durability of wood and wood products is generally good, but improving the quality and service life of wood and wood products can further extend the carbon storage cycle of wood and wood products and fully exploit the contribution of wood and wood products to carbon storage in the fight against global climate change (Lao *et al.* 2022), so increasing the durability of wood products has always been a major research topic (Wu 2021; Peng *et al.* 2021; Chen *et al.* 2022). Many scholars have been able to improve the durability of RDL through process improvements (Zhan *et al.* 2018; Zhang *et al.* 2021). However, the life span of a product is always limited, so the question of how to increase the efficiency of recycling discarded RDL products is a matter of concern.

Recombination of wood chips to produce engineered wood products such as plywood and particleboard is the most prevalent use of waste wood products. Azambuja *et al.* (2018) used urea-formaldehyde resin to make particleboard after reducing wood product leftovers to pellets. There are also some studies that indicate promising findings and promise for using waste wood materials in the form of wood flour and wood fibers for wood-cement composites and as a more ecologically friendly alternative to conventional treatment methods (Berger *et al.* 2020; Ince *et al.* 2021). However, because wood waste contains additives and contaminants (resins, paints, preservatives, heavy metals, *etc*.), using it as a raw material for new panels is a relatively complex procedure. Gibier *et al.* (2022) investigated the hydrolysis of wood waste under various regulated circumstances (temperature/pressure, steam ratio), obtaining a nitrogen removal rate of 33% to 70%. Without the use of chemicals, this decontamination procedure could provide a formula for future wood waste repurposing. In addition, Mayer *et al.* (2022) looked at the availability of natural wood and ash from waste wood burning as a fertilizer, estimating that the treated ash might replace part of the fertilizer based on nutrient recovery potential. The Delignification of wood chips produces lignin, which can be used as an ingredient in natural rubber, synthetic resins, bioplastics, and other products, according to Spreafico and Landi (2022). All of these methods of treatment provide an example of how to recycle RDL waste products.

## Marketing Phase

From the perspective of ecological civilization, the competitiveness of RDL can be enhanced by providing easy-to-understand sustainability messages in the marketing phase.

Alting (1995) mentioned early on that life cycle assessment (LCA) is the measure that visualizes the environmental performance of products in all life cycle phases. Additionally, LCA is the only standardized and internationally certified environmental assessment method (Kloepffer 2008). Therefore, displaying LCA as a form of product information is a way to improve the competitiveness of green products. For example, on the *ONA lighting* website, product information has a section for LCA information, right next to the product description (as shown in Fig. 4). This helps consumers to understand the life cycle index of the product. The LCA information on the *ONA lighting* website is calculated based on the Eco-indicator99 method, which divides the data from the product inventory analysis into individual environmental issue categories and then normalizes them, ultimately dividing the environmental impacts into three components for assessment: human health, ecosystems, and resources.

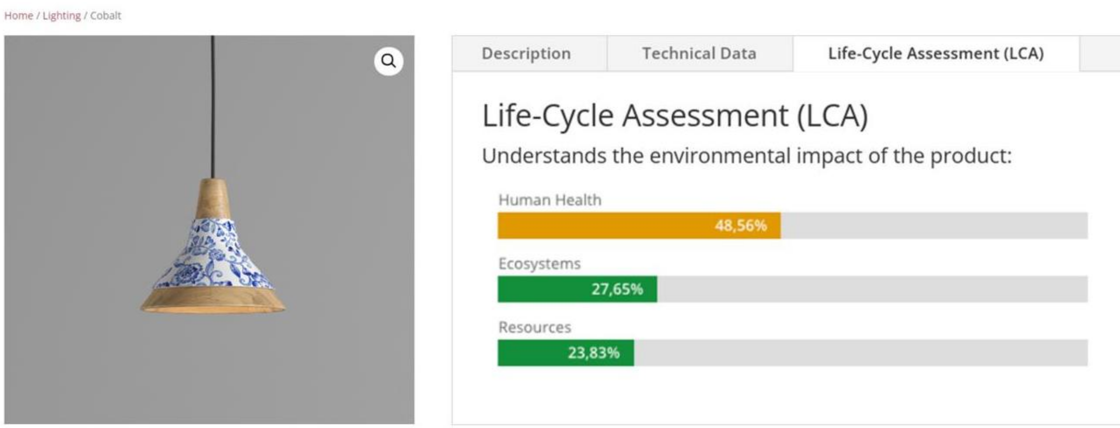


**Fig. 4.** LCA visualization information of the Cobalt lamp displayed on the ONA official website

Therefore, it is necessary to introduce LCA into the marketing phase of RDL. In fact, as early as 2018, China issued the first standard for ecological design evaluation technology of RDL (T/CAB 0039-2018 2018), which also classified the life cycle list factors of RDL (as shown in Table 1). To evaluate the environmental performance of the life cycle of RDL, it is necessary to clarify the input and output data list of the life cycle process of RDL. When the environmental performance evaluation results of the life cycle of RDL lumber are multi-dimensional indicators, due to the different units of each indicator, the evaluation results need to be normalized when comparing the environmental performance of different products. In addition, it should be noted that the consistency of the accounting boundary is the premise of the comparability of the environmental performance quantification and evaluation results of RDL, and any change in the boundary will lead to the fluctuation of the results. In addition to LCA information, eco-labeling also deserves the attention of green furniture manufacturers (Cai *et al.* 2017).

**Table 1.** Factor Classification of Life Cycle Inventory of Reconstituted Decorative Lumber

| Impact Type | Chemical Factors |
|---|---|
| Climate Change | $CO_2$, $CH_4$ |
| Eutrophication | NH4-N, TN, TP, $PO_4^{3-}$ |
| Acidification | $SO_2$, $SO_3$, $H_2S$ |

Furthermore, it is necessary to focus on the construction of a green brand communication strategy. Brands with characteristic value propositions will be more attractive to consumers, especially young consumers. In the context of today's ecological civilization construction, the emphasis on product sustainability has become inevitable (Yang and Zhu 2021). Green brand marketing has also become one of the strategies for brand development in recent years. Yin (2020) believed that the EBM model, a consumer decision model named after the initials of the three revisers Engel, Blackwell, and Miniard (Engel *et al.* 1995), has great potential for development and will be widely used by furniture companies in the future. The EBM model enables effective management of all uncertainties in the chain and facilitates the use of modern classifier architecture. Based on the EBM model, companies are able to combine online brand building with offline resources. This is one of the flexible ways of green brand marketing. In the same year, Vilasanti da Luz *et al.* (2020) proposed that the credibility of matching the brand positioning with the green message and the brand evaluation showed a positive correlation. The green features of products can change consumers' attitudes toward brands and mitigate the negative effects of overconsumption. This further shows that green products deserve more attention.

## TRENDS IN FUTURE RESEARCH

Firstly, a review of current research on RDL reveals that research has focused on the production phase of RDL and little research has been related to the other life cycle phases of RDL. Process improvements in RDL can indeed help produce more environmentally friendly and durable products, but products are not supported by the production phase alone (Hu *et al.* 2021). With the promotion of sustainable design and the development of ecological civilization, it is predicted that more scholars will focus on the pre-production and post-production phases of RDL to further enhance their utilization and value. In subsequent research, the methods used in similar fields can be adapted to the production of RDL. For example, the treatment of wastewater from RDL can be considered in the same way as wastewater from printing and dyeing plants, being similar to wastewater from printing and dyeing companies (Wang *et al.* 2006; He *et al.* 2020).

Secondly, RDL has been developed for a long time, and there are many companies and industry chains involved. However, in China, the acceptance is still not very high. In the current context of ecological development, in particular, the advantages of RDL are becoming increasingly evident. People have progressively learned to accept green consumerism (Xiong *et al.* 2020b), and emphasizing the green significance of RDL, it will help to promote the spread of RDL and the replacement of new materials. In the future, the marketing of RDL may be considered as a way to increase the competitiveness of RDL by adding a visual environmental message or by creating a green brand image (Vilasanti da Luz *et al.* 2020; Yao *et al.* 2022). As RDLs are adapted to individual aesthetic expressions (Hu *et al.* 2012), it is envisaged that in the future they will also be widely used in exhibitions, museums, and retail shops, in line with the call for green development.

Thirdly, when studying the product life cycle, the design phase is often overlooked. But the design phase has a significant impact on the overall ecology of a product. Ecology is not only achieved through technological advances. Rather, it is also about the sensory experience of the material. If the technical specifications are precise, then it still cannot be regarded as ecological if people do not perceive it as such. The overall visual effect is determined by the color and texture of the RDL, so the design phase can be used to convey an ecological aesthetic by changing the color and texture of the RDL. Under the development of ecological civilization, ecological aesthetics has also received attention (Lv 2020; Mi 2022). Especially in interior design, spiritual ecological reconstruction has become one of the new trends (Wang 2021). On this basis, the design of RDL will also break through traditional parameters and develop output solutions that have desirable contemporary characteristics, making RDL not only economically significant but also aesthetically significant.

Finally, to increase the global evolution of RDL China should encourage more RDL production enterprises including upstream and downstream supply chains to refer to the development experience of RDL in regions that influence furniture design and other possible uses of RDL, such as Europe and the US (Zhao *et al.* 2018). In addition, life cycle research and implementation of RDL, focusing on large, medium, and representative enterprises to concentrate resources on the implementation of demonstration projects should be supported to regulate the RDL industry both in China and further afield (Liu *et al.* 2019).

## CONCLUDING STATEMENTS

1. Strengthening the research, development and utilization of reconstituted decorative lumber (RDL) is an important means to protect precious natural tree species, make efficient use of artificial fast-growing tree species, and solve the structural contradiction between timber supply and demand. It should also a beneficial development aim for forestry from the perspective of ecological civilization.
2. Although RDL has been developed for a long time and there are many relevant companies and product chains, the public acceptance in China is still not very high. How to promote the application and dissemination of RDL in the new era is a priority.
3. Further research is required on process improvements, as currently used processes cannot meet the development needs of the RDL production. To ensure the needs of achieving an ecological civilization, it is essential to investigate the whole life cycle of the RDL process.
4. In terms of raw material acquisition, packaging and transportation, and waste disposal, RDL enterprises can learn from the practices of other similar fields to achieve green production and comply with the sustainable development strategy. In addition, the RDL enterprises can skillfully use ecological aesthetics in the design phase to keep with the background of ecological civilization construction thus reflecting the advantages of the material itself.
5. The application of RDL has not only economic and aesthetic significance but also ecological significance. In the new era, by emphasizing the environmental characteristics of RDL, the promotion of RDL can be achieved. Furthermore, the competitiveness of related products can be enhanced, which helps to enhance a green brand reputation for RDL.

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