A Review on Carbon Reduction Analysis during the Design and Manufacture of Solid Wood Furniture

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Reducing carbon emissions is the direction various industries will head in the future. Solid wood furniture products that occupy important market shares have high carbon reduction potential. This article briefly describes the carbon footprint of the solid wood furniture production process. In addition, it analyzes the feasible carbon reduction technologies applicable during the design and manufacturing process through the potential emission reduction-oriented approach, ranging from the upstream raw materials to overall power consumption. The primary carbon reduction potential points entail the high efficiency and reuse of primary materials, the reduction of auxiliary materials, and the optimization of solid wood processing based on spraying and dust removal. In this study, the carbon reduction design of solid wood furniture primarily covers the design methods, material selection, structural design, and packaging design. The carbon reduction manufacturing technology was analyzed from a process, equipment, and management aspect. It is hoped that this study can provide a reference for the future strategic design of solid wood furniture companies, which will promote low-carbon development in the wood furniture industry.

Keywords: Solid wood furniture; Carbon reduction technology; Carbon footprint; Design and manufacturing

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INTRODUCTION

The emission of harmful greenhouse gases (GHG) leads to global warming, with carbon being its primary component (Linkosalmi *et al.* 2016). The limitation of carbon emissions has become one of the leading concerns of international topics, with energy conservation and emission reduction also in the forefront of the future development of industries in various countries (González-García *et al.* 2011). As the largest furniture manufacturer in the world, in 2017 the furniture output of China was 807 million pieces, an increase of 3.64% year-on-year. In 2019, the market size of the home furnishing industry was 750 billion yuan, an increase of 8% year-on-year. The furniture industry report predicts that by 2024 the market size of the Chinese furniture industry will exceed 1 trillion yuan (Yu and Shen 2015). This shows that Chinese furniture consumption capacity has risen. However, it has also led to the continuous increase of energy consumption during the production of furniture. The carbon emissions generated by the furniture supply chain are also increasing year by year, which hinders the green and low-carbon development of the furniture supply chain (Yu *et al.* 2013). However, the solid wood furniture industry is an important pillar of the Chinese furniture industry. Compared with panel furniture, its structure and manufacturing process is more complex, its processing energy consumption is greater, and it has more potential in terms of carbon reduction (Lin and Huang 2016).

Through targeted design and the manufacture of the inherent characteristics of solid wood furniture, it has potential to effectively avoid or reduce carbon loss and carbon emissions, improve corporate, social, and economic benefits, as well as contribute to the global climate change response and improve human living environments (Wu 2020).

The research on carbon emission reduction of furniture companies is very rich and extremely valuable. Wood resources are good carbon-reducing materials. As one of the main materials of furniture, wood, bamboo, straw, and other biomass products absorb a large amount of carbon in the air during the growth of raw materials, and form carbon storage, the amount of carbon storage is generally far greater than the carbon emission of this building material in the production process. Therefore, carbon storage should be taken as a negative value in the life cycle carbon emission of furniture, which can reduce the total carbon emission (Huang 2013). Geng *et al.* (2019a) found that replacing non-wood materials with harvested wood products (HWP) can effectively reduce GHG. This means that the use of wood furniture can also bring some help, although in the construction industry, HWP is more effective in replacing greenhouse gas intensive materials in construction and furniture production. Geng *et al.* (2019b) quantified the substitution benefits of wood furniture in China through a nationwide emission reduction analysis. The importance of material selection in mitigating climate change in the furniture industry was emphasized. There is an urgent need to make effective use of existing wood resources and seek alternative emission reduction schemes to achieve the goal of GHG emission reduction.

Huang (2013) concluded that furniture carbon footprint research should sort out the characteristics of all kinds of furniture materials, define their life cycle from raw material mining, processing and transportation, manufacturing, sales channels, final use to waste reuse, and subdivide them into different stages and process parts, establish product flow chart, so as to determine the analysis boundary. Medeiros *et al.* (2017) used the life cycle assessment (LCA) method to measure the environmental performance of office cabinets. The assessment showed that the reuse, recovery, or energy recovery of waste has brought significant environmental benefits in the main categories. Xue *et al.* (2013) believed that the low-carbon furniture industry is mainly reflected in two aspects: one is to implement lean thinking in the management system, control environmental pollution and carbon emissions by improving building materials manufacturing technology and production process; the other is to improve environmental protection measures, such as using clever structural design and equipment processing as far as possible to reduce the use of glue.

In terms of design, An *et al.* (2020) thought that product design not only can meet the needs of the target population, but it also can reduce carbon emissions and reduce the damage of products to the ecological environment. New materials, new technology, new structure, and new recycling mode provide effective guarantee for low-carbon design, and designers' creativity brings new ideas for low-carbon design. Bumgardner and Nicholls (2020) believed that sustainable design can increase the consideration of resource acquisition and use, as well as the choice of product end-of-life, which has a positive significance for carbon storage and resource utilization. Rinawati *et al.* (2018) evaluated the ratio of ecological cost and ecological efficiency of products and found that the furniture has been profitable and efficient, but it can still improve the performance of the production process by minimizing the use of raw materials, so as to improve the ecological efficiency. Charmondusit *et al.* (2013) used 10 design principles of human ecological economics to optimize the economic dimension of product life cycle, from material to wastewater recycling process. They demonstrated a new furniture model of green kitchen and showed the balance between economic and environmental dimensions by implementing the concept of product ecological design.

In terms of manufacturing, most of the research on carbon emission reduction has focused on energy and waste utilization. González-García *et al.* (2011) studied nine furniture factories with artistic level in Spain. Through inventory analysis and global warming potential (GWP) results, they found that the implementation of design for environment (DFE) strategy in wood-based product development promoted effective communication between environmental technicians and designers, promoted environmental analysis with the help of carbon footprint report, and provided guidance for product improvement programs. One of the biggest benefits is the development and introduction of alternatives in the production process, thereby reducing the impact on the environment. These alternatives focused on the use of renewable energies such as photovoltaic cells, the use of national fibres, or changes in the materials used. All of them showed a better environmental profile in comparison with the current production process with improvements up to 60%. Lun *et al.* (2016) studied and evaluated the carbon flow and carbon footprint of *Larix gmelinii* var. *principis-rupprechtii* plantations from cradle to gate in China and concluded that manufacturing process is the most important carbon emission source in the whole life cycle, accounting for more than 90% of the total carbon footprint; HWP can store part of the carbon sequestered from the atmosphere in a certain period of time, which is conducive to carbon emission reduction. In addition, all the wood fuel and part of the waste HWP can be burned into energy, thus reducing the consumption of fossil fuels, so it is also considered to have a positive impact on reducing carbon emissions. Laemlaksakul and Sangsai (2013) conducted a study on ecological products of Thai furniture industry based on life cycle assessment. They found that the production of input materials such as wood materials and metals, energy demand, and providing input to factories can be regarded as the most important environmental issues. A common aspect under study is that environmental impacts depend on upstream processes, and improvement options should also focus on upstream processes. Kadric *et al.* (2017) analyzed the energy consumption of furniture manufacturing facilities. Installing frequency regulator on the engine of dust removal system and introducing alternative cleaning equipment instead of compressed air can effectively save energy and reduce carbon dioxide emissions.

Massote *et al.* (2013) used clean production method (CP) to audit the raw material and water consumption of solid waste and wastewater and proposed to reduce the production of solid waste and liquid effluents, raw material input, and water inflow. This measure not only reduces the production cost, but it also obtains some additional environmental benefits. Ratnasingam *et al.* (2016) found that the rubber wood furniture industry produced a lot of factory waste. The study shows that factory waste has the potential to be used as bio-energy and to completely replace fossil fuels for power generation to meet the needs of the industry. In fact, the residual energy generated by burning wood waste can also be a potential source of income. Chan *et al.* (2016) found that most companies buy more environmentally friendly materials and collect waste for recycling. However, lack of awareness is the biggest obstacle for purchasing managers to implement green purchasing practice. Purchasing managers seldom consider the impact of purchasing on the environment. This situation will lead to many environmental problems, such as carbon dioxide emissions, climate change, greenhouse effect, pollution, and deforestation. Another study conducted by Chan *et al.* (2018) used the quantitative method and analyzed the data of the questionnaire by using the social science statistical software package 20.0. Descriptive analysis was used to achieve the research objectives. The results showed that the current green procurement practices of furniture manufacturing companies include ensuring that products enter the factory safely, and then ensuring that the supplier's location operates in a safe manner.

This paper takes solid wood furniture as the research object, including solid wood chairs, tables, cabinets, and other types of furniture. It is a kind of wood furniture made of solid wood materials (such as logs, sawn wood, finger jointed wood, and Glulam), whose surface can be veneered with solid wood veneer or thin veneer and painted. Through the analysis of the above research, solid wood furniture has good storage capacity for carbon sequestration, but there is still a lot of room for energy conservation and emission reduction in its production process. Therefore, the content that follows will focus on the carbon footprint of solid wood furniture production and build a carbon reduction technology system in the process of solid wood furniture product design and manufacturing.

EXPERIMENTAL

Methods

This study used a systematic method to collect data from reliable resources. References came from Google Scholar and China National Knowledge Infrastructure (CNKI). The authors used keywords related to carbon emissions and solid wood furniture to search different combinations, *e.g.*, solid wood furniture, manufacturing, life cycle assessment (LCA), green furniture, design method, climate, solid wood furniture manufacturing, energy conservation and emission reduction, and then expanded to searching through the title and abstract, the data identification, the initial screening, as well as qualification determination to ensure the reliability of the article.

Currently, there are few articles detailing the carbon reduction technology of solid wood furniture published by either domestic or foreign journals. This paper is based on refining and analysis of only the literature content. On the basis of this research, combined with the existing design theory and the actual situation of enterprise production, it puts forward the opinions and direction of future research, *i.e.*, the induction and analysis, problem discovery, and solution.

This paper focuses on the manufacturing process of solid wood furniture, from design to processing, and often these two parts are in a low degree of integration. Therefore, the authors paid equal attention to overall carbon reduction, the refinement of the carbon reduction process of furniture design, the standardization of the production and emission reduction scheme, as well as solving the problem with a systematic solution.

RESULTS AND DISCUSSION

Carbon Footprint of Solid Wood Furniture

Carbon footprint

The term “carbon footprint” has many definitions. In order to evaluate the products, it is generally considered as the estimation of the total greenhouse gas emissions (expressed as carbon equivalent CO_2-e) during the entire life cycle of a products, *i.e.*, from raw materials used in the manufacturing process to the treatment of the final products (Liu and Li 2014). The current carbon footprint measurement methods include the life cycle assessment (LCA) method, which is calculated by the energy, fossil fuel emissions calculation (IPCC), the input-output method (IO), and the Kaya carbon emission identity. The IPCC Carbon Emission Law is a greenhouse gas inventory guide prepared by the United Nations Climate Change Commission, which fully considers greenhouse gas emissions in the calculation process. The Kaya carbon emission identity uses a simple mathematical formula to link economic, policy, and demographic factors with the carbon dioxide generated by human activities. The IO method is a top-to-bottom calculation method that uses input and output for calculations, and the calculation results are not accurate. The LCA method is commonly used since it is more accurate and specific than the approaches mentioned above.

The primary steps of the LCA method are to set the carbon footprint assessment objectives, establish the system boundary of the research object, make the flow chart, and then collect the field data. Finally, using evaluation software, the carbon emissions are analyzed and calculated according to Eq. 1,

$$E = \sum Q_i \times C_i \quad (1)$$

where E is the carbon footprint of a product, Q_i is the activity level data of a substance or event, and C_i is the carbon emission factor unit of a substance or event, with i equaling 1 (Wenker *et al.* 2018).

Carbon footprint of solid wood furniture

In recent years, many scholars have performed carbon footprint calculations on solid wood furniture products. These studies have important research value in terms of the carbon reduction of solid wood furniture design and the manufacturing process, but they have not attracted the attention of enterprises due to the lack of knowledge, policies, and practical benefits. The main reason is that China's furniture low-carbon environmental protection certification is disordered, with a lack of relevant policies, and lack of enforcement. These factors lead to furniture enterprises not being able to foresee the benefits of carbon reduction, and therefore not utilizing existing methods to implement carbon reduction measures. However, in the future these studies will certainly be able to play a certain role in the transformation and upgrading of enterprises. Currently, the system boundary established by most solid wood furniture carbon footprint research is from the cradle to the door, *i.e.*, it only includes the two major stages of upstream product production and on-site production. The calculation excludes the construction of fixed assets, maintenance and loss of equipment, materials in non-production sectors, energy consumption, and employee transportation, *etc*. This stage is under the direct control of the manufacturer, making people more confident in the accuracy of the data obtained and facilitating benchmark data analysis. The content of the LCA list primarily covers the consumption of raw materials, *e.g.*, solid wood, laminated timber, adhesives, hardware, coatings, and packaging materials, energy consumption, and waste, *e.g.*, wastewater, exhaust gas, and waste residue (Liu *et al.* 2019).

A study by Lin and Huang (2016) used the LCA method to evaluate the carbon footprint of panel bedside cabinets and solid wood bedside cabinets during the production process. Among the carbon emissions of solid wood bedside cabinets, the raw material emissions accounted for 61% of the total emissions, of which wood materials accounted for 24%. While the auxiliary materials only accounted for 14.8% of the mass, the carbon emission reached 37%. Bai (2013) collected and calculated on-site data from a company and calculated the carbon emissions of a solid wood coffee table *via* the Simapro life cycle assessment software. The total emissions measured were 89.9 $kgCO_2eq \cdot kg_{-1}$, and the direct emissions from electricity were 68.0 $kgCO_2eq \cdot kg_{-1}$. The carbon emission during the spraying process was 52.7 $kgCO_2eq \cdot kg_{-1}$, and carbon emissions during the sanding and dust removal processes were 4.40 $kgCO_2eq \cdot kg_{-1}$ and 4.44 $kgCO_2eq \cdot kg_{-1}$, respectively. Linkosalmi *et al.* (2016) studied the greenhouse gas emissions during the life cycle of 8 different furniture products in 3 wooden furniture factories in Finland. In their kitchen cabinet (wooden) sample, the total GHG emissions were 129 $kgCO_2$-e, with the wooden base material accounting for 28.6 $kgCO_2$-e, the emissions of the chemical substances, *e.g.*, paints, adhesives, *etc.*, were 32.3 $kgCO_2$-e, and the emissions of the transportation and assembly processes were 6.16 $kgCO_2$-e and 61.7 $kgCO_2$-e, respectively. It was worth noting that the carbon sequestration of the entire cabinet reached 132.4 $kgCO_2$-e. Wenker *et al.* (2018) added that existing life cycle assessment (LCA) studies for furniture focus on single pieces of furniture and use a bottom-up approach based on their bill of materials (BOM) to build up the data inventories. This approach does not ensure completeness regarding material and energy fluxes and representativeness regarding the product portfolio. One of the results is that 10% of greenhouse gas emissions are not recorded. They put forward a life cycle assessment method of industrial furniture system that combines the top-down method and bottom-up method. The results show that the use of accessories and other metal parts significantly affects the LCA results. In addition, the use of wood and engineered wood products (EWPs) has a significant impact on LCA results, as wood materials represent most of the total mass of the products studied. In general, the supply of semi-finished products has the greatest impact on the results of LCA. Therefore, for furniture production companies, the choice of materials is most likely to reduce the environmental impact. Through the above-mentioned literature research, the high emission process in solid wood furniture manufacturing is clearly visible.

The potential of solid wood furniture emission reduction

The design and manufacturing process of solid wood furniture has a huge potential for emission reduction, which runs through the entire process, from design material selection to production and processing. The specific potential reduction points are shown in Fig. 1.

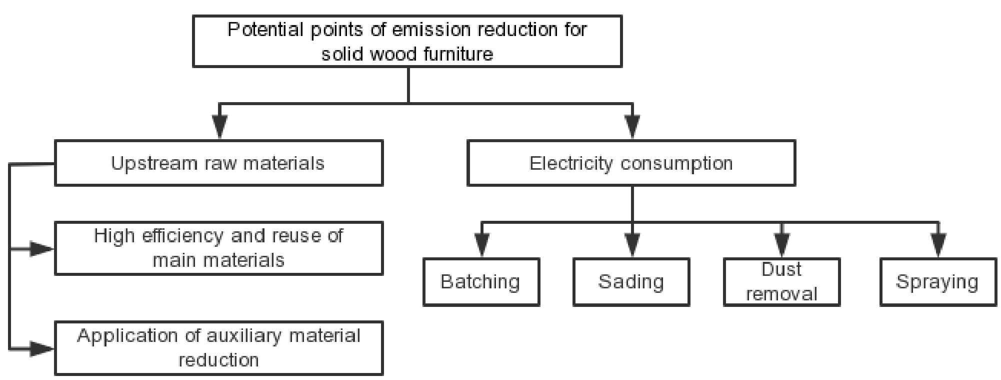

Fig. 1. Potential points for emission reduction of solid wood furniture

In terms of materials, the solid wood and laminated timber used in solid wood furniture have not undergone synthetic processing similar to wood-based panels, so the bio-carbon storage is relatively high. From the perspective of the entire life cycle, it also has low carbon emissions and a strong carbon sink capacity (Liu 2011). Compared with the main materials, auxiliary materials, *e.g.*, coatings, adhesives, hardware, and plastic glass, have to undergo multiple complex and energy-consuming processing to get from mineral resources to finished products, and therefore they have relatively high carbon emissions. However, due to the diversity of solid wood furniture processing technology, the involved mechanical equipment is also diverse with a long product production cycle, which leads to high energy consumption during solid wood processing. This is especially true during the spraying process and repeated painting and polishing processes, since they not only consume large amounts of energy and resources, but also have a considerable negative impact on the health of the operators. Therefore, the finishing process is the biggest goal in terms of reducing the emissions of solid wood furniture. From the above analysis, it can be concluded that the emission reduction of solid wood furniture can be started from two upstream aspects, the raw materials and power consumption, *i.e.*, the high efficiency and reuse of primary materials, the reduction of auxiliary materials, and the optimization of solid wood processing in term of on spraying and dust removal.

Carbon Reduction Design Methods of Solid Wood Furniture

With the increasing integration of digital technologies within the furniture industry, the design and manufacturing are inseparable; front-end design can reduce carbon emissions at the source, and it is also convenient for energy saving and emission reduction during processing and production. In this study, the authors summarized the design methods of solid wood furniture carbon reduction into four aspects, *i.e.*, an overview of the carbon reduction design methods, the carbon reduction material selection design, the carbon reduction production structure design, and the carbon reduction packaging design (as shown in Fig. 2).

Overview of the carbon reduction design methods

From a design perspective, reducing carbon emissions primarily starts with materials, then increasing revenue and reducing expenditure, and finally transitions to manufacturing services. This entire process must be guided by design methods.

Sustainable design (part 1)

It is particularly important to integrate sustainability principles into product design, manufacturing, as well as the entire system, which can help companies think about environmental, social, and economic issues in advance. Sustainable design in solid wood furniture carbon reduction is embodied in four sections: conceptual design, recyclable design, material saving, and energy saving design.

Conceptual design

Design affects global sustainability, so early design should take into account the entire life cycle of the materials, manufacturing processes, transportation, and recycling (Seyedmahmoudi *et al.* 2018). First of all, when designing products, it is recommended to avoid excessive functions and avoid all unnecessary decorative designs. Some furniture is extremely complicated in structure, and some furniture is complicated in crafts. The engraving of a part requires several hours of engraving machine work, which consumes a lot of electricity and is not equipped with high aesthetic value (Xu 2019). In addition, the stacking of functions will not only lead to the waste of materials, but also increase the price, thereby reducing the willingness of consumers to purchase.

Material-saving design

Material-saving design can reduce carbon emissions at the source. Proper product design based on the principle of subtraction is also one of the morphological characteristics of green furniture (Qian 2017). During the design of modern solid wood furniture, the number of components and cross-sectional areas are reduced without affecting the basic function and strength. This not only reduces the consumption of raw materials and the weight of the product, but also the energy consumption during product transportation. The specific design forms include reducing the number of solid wood components while ensuring the stability of the solid wood furniture and reducing the redundant size of solid wood components while ensuring the function of the solid wood furniture. This reduction in weight of solid wood components can be achieved by reducing the section size (Wang and Xu 2020). From this perspective, one should not only be limited to carbon sequestration, but also follow the design principles of modern green furniture.

Energy-saving design

Energy-saving designs consider the energy consumption during the production and transportation of the furniture. These savings can be achievable *via* considerations of the folding, stacking, and disassembly and assembly design. In addition, the furniture product requires a simple form, and the decoration eliminates complicated carvings, so as to achieve production-oriented design. Design and manufacture are closely connected, providing a guide for production activities, which is conducive to low-carbon manufacturing.

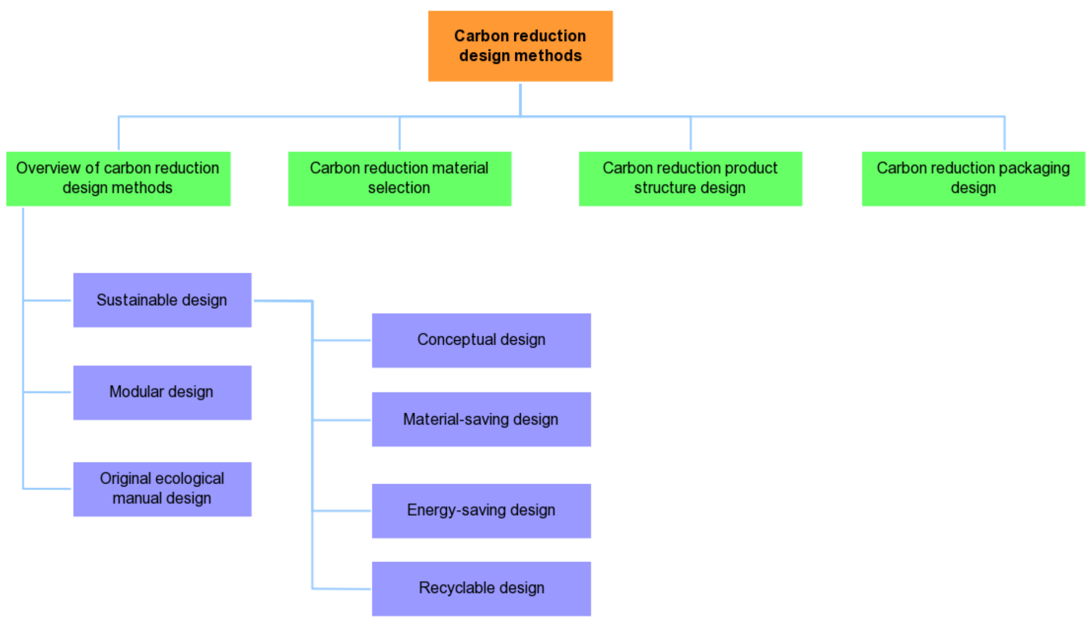

Fig. 2. Classification of the carbon reduction design methods of solid wood furniture

Recyclable design

Recyclable design is a primary component of the sustainable approach and the direction of furniture design. When designing, it is necessary to consider closed material recycling. Enterprises need to make their own recyclable strategies, simplify furniture installation and disassembly, and improve furniture renovation and recycling services, *e.g.*, disassembly and repair as well as the availability and warranty of spare parts, which help enhance the consumption experience of the consumer and the efficiency and success rate of recyclability (Wang *et al.* 2019; Xiong *et al.* 2020).

Modular design (part 2)

The contribution of modular design to carbon reduction is to standardize furniture components, reduce the types of solid wood components, and facilitate group processing, thereby reducing processing procedures, increasing the utilization rate of woodworking equipment, and reducing the number of adjustments and carbon emissions from equipment idling. This can be achieved by breaking the subordination relationship of the parts during the design. First, it is recommended to merge the similar dimensions without affecting the appearance and structural craftsmanship. Second, use the same width and thickness as much as possible for parts with the same function. Third, under the premise of satisfying the craft and function, choose a smaller size.

Original ecological manual design (part 3)

The most ideal state of the carbon reduction design of solid wood furniture is the original ecological manual design and production. Without mechanical processing, there is no electricity or energy consumption. The furniture made in this way has a strong feeling and is of commemorative importance, but it is not suitable for modern production. Such furniture, *e.g.*, rough wood furniture, is primarily made of natural materials, *e.g.*, branches, bamboo, rattan, shrub rhizomes, and waste wood, that have not undergone any processing. The processing and production are primarily manual, which not only saves energy, but also greatly reduces carbon dioxide output. The emissions fully reflect its low-carbon and environmentally friendly characteristics. For example, boat wood furniture mainly uses solid wood materials dismantled from scrap hulls. After selection, different forms of furniture are made according to needs. Such furniture has certain characteristics, corrosion resistance, stable structural strength, and weather-beaten visual effects (Lv *et al.* 2011).

Carbon reduction material selection

Wood is the primary material for solid wood furniture. It is renewable and has good carbon fixation properties, which make it a green environmental material. After wood is processed into furniture, the amount of bio-carbon contained in it depends on the furniture and elapses when the furniture is scrapped after degradation by bacteria or by burning with the production of CO_2; therefore, the longer the service life of the furniture, the less carbon emissions during its life cycle will be (Yu and Shen 2015). Currently, the mainstream materials for solid wood furniture on the market are black walnut, ebony wood, ash, oak, and walnut. These woods have a fine texture and excellent performance, which can be perfectly integrated with a corresponding design style so that the furniture has high aesthetic value. The materials used with them are rubber wood, pine wood, and walnut wood (Wang and Xu 2020). Furniture items made of different materials have different final carbon storage capacities. There is some evidence linking higher carbon storage values to higher carbon sequestration capacities of the material and lower carbon emissions during the material life cycle. Therefore, without affecting the aesthetic requirements of solid wood furniture, wood with higher carbon storage values can be selected during the overall material selection, and wood with higher carbon storage values can be selected for load-bearing components, *e.g.*, frame structures, which can improve its structural strength and durability, extend the service life of the furniture, and is convenient for secondary use.

Low-grade wood with high carbon content can be used for the wood utilized in the hidden part of the furniture, which can reduce the material cost while reducing carbon emissions.

The use of waste materials and recycled materials is one of the strategies for reducing carbon emissions of solid wood furniture, *i.e*., starting from the source of raw materials, reducing the use of upstream raw materials, and redesigning recycled materials. (Yuan *et al.* 2019) Such approaches not only can reduce carbon emissions, but also they follow the guidelines of sustainable design. For example, oil palm trunks with no commercial value in the palm oil industry chain usually decays into waste, but using them to make furniture can effectively reduce greenhouse gas emissions, although the energy consumption of wood processing is higher due to material properties (Rettenmaier *et al.* 2014)

Compared with wood materials, the auxiliary materials of solid wood furniture are all high-emission materials. Therefore, reducing the use of chemical agents and metal connectors is the primary goal. When necessary, it is recommended to choose auxiliary materials with low emission factors and buy green and environmentally friendly materials, *e.g.*, low-carbon adhesives and low-carbon paints. In addition, choose material suppliers that effectively control carbon emissions, especially during the procurement of coatings.

Carbon reduction product structure design

Under the influence of fast-paced modern society, compared with the convenience of connectors, a tenon-and-mortise structure is a bit cumbersome, and its precision and meticulousness hinder its own development, making it difficult to be considered by furniture manufacturers (Ge *et al.* 2020). Nowadays, many middle and low-grade solid wood furniture manufacturers will choose to use some hardware connectors or glue to connect, but the hardware connectors will wear the wood, greatly reduce the life of the wood, and accelerate the exhaustion of carbon quality. Therefore, innovative tenon and tenon structure designs, *e.g.*, dovetail tenons and three-way mitered tenons, have been manufactured with the goals of designing a tenon and tenon structure suitable for modern processing, thus reducing the use of glue and metal connectors. This reduces the carbon footprint of solid wood furniture and also inherits and innovates traditional culture (Wang *et al.* 2019). In this era of the rapid development of logistics, reducing logistics costs can provide considerable benefits to enterprises. Especially for the solid wood furniture industry, the furniture structure is designed to be detachable, which can reduce the volume of furniture packaging as well as the carbon emissions from packaging materials and transportation. If the component is damaged, it can be replaced separately, which will not affect the function of the entire furniture and extend the service life of the furniture (Xiao *et al.* 2019).

Carbon reduction packaging design

Packaging design should be based on reducing the amount of packaging materials and material regeneration or the reuse of materials, *e.g.*, avoiding excessive packaging and only providing appropriate protection for the product (Zhu and Wu 2013). During the structural design, the convenience of packaging is considered, so that the packaging structure is reasonable, with the least amount of material consumption. For products that are transported small distances from the factory warehouse directly to the installation site, try to use simple packaging, *e.g.*, blankets and paper skins, that can be used multiple times. In addition, reasonable packaging can reduce storage space and transportation energy consumption, as well as reducing carbon emissions (Shi and Zhou 2018).

Carbon Reduction Manufacturing Technology of Solid Wood Furniture

Carbon reduction technology in the manufacturing process of solid wood furniture can be primarily summarized in terms of the process and equipment, as shown in Fig. 3. The other factors are summarized in the section of Carbon Reduction Management Measures for Solid Wood Furniture, as shown in Fig. 4. Other aspects of environmental impacts will be considered briefly.

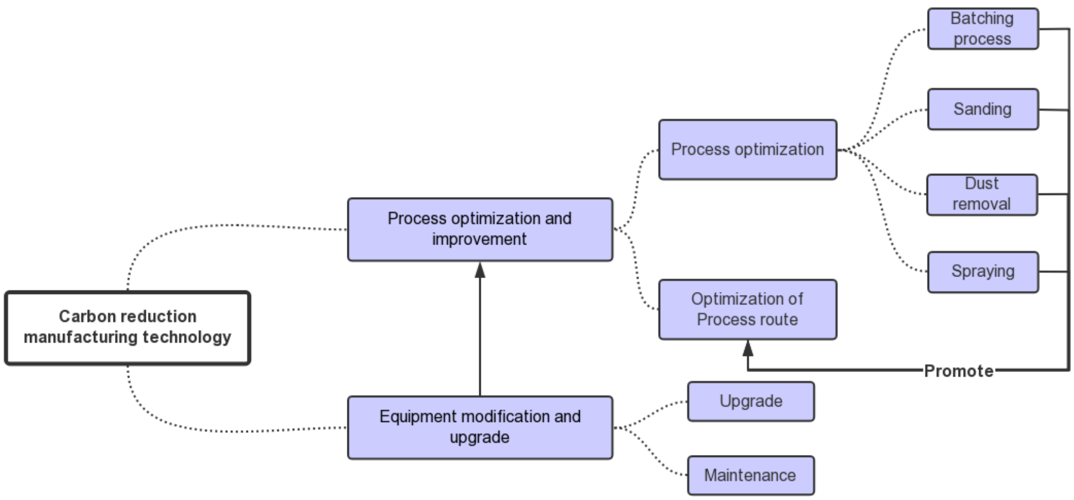

Fig. 3. Direction of the carbon reduction technology in the manufacturing process

Process optimization and improvement

The processing process of solid wood is complex and diverse, with a high consumption of energy. The most important energy-consuming process is spraying, followed by sanding, dust removal, and batching. Modifications of these four processes can effectively reduce carbon emissions.

Process optimization (part 1)

Batching process

The batching process of solid wood furniture refers to the process of processing square plates into net materials. Optimizing the batching process can increase the yield of raw materials. For example, using a preferred cross-cut saw can increase the yield by 10% compared to a cross-sectional circular saw (Liang and Li 2017). The small bandsaw or joiner's bandsaw used in traditional manual batching is replaced by CNC curved band saw batching, and the CNC mechanical automatic batching is carried out for curved parts, which drastically improves the material yield and production efficiency of the board. With the development and innovation of technology, an intelligent batching production line composed of an automatic scanner, optimization saw, automatic finger jointing machine, four-sided moulder, and automatic high-frequency splicing machine, as well as other equipment, can better achieve the goal of carbon reduction (Wu 2019).

Sanding

The sanding process is a grinding method for surface treatment of wood products to reduce the surface roughness. This process will generate a large amount of dust, which may be present many times in a set of processes. However, the surface quality of the grinding surface in the sanding process is sometimes not as good as the cutting surface, and consumes a large amount of materials. In the solid wood processing, the cutting accuracy should be improved as much as possible, the amount of grinding should be reduced, as a means to cut down the energy consumption of grinding. On the other hand, optimizing the finishing process, improving the sanding accuracy and reducing the frequency of sanding can be conductive to reduce carbon emissions.

Dust removal

The dust removal system ensures the normal operation of furniture production. As long as there are workshops in operation, the dust removal system must be turned on, which leads to considerable power consumption. Therefore, a low-energy dust removal system that conforms to the factory production plan should be established, and the dust removal port and production equipment should be switched on and off by an intelligent monitoring system, through a production state start-stop action module to save energy, which can effectively reduce corporate carbon emissions. To determine whether the dust collector saves energy, a comprehensive evaluation should be made from four aspects (excluding the electronic control system): the dust collector itself, the pipe network, the fan, and the electric control system. The design filter area of the dust collector body should be large enough so the filter wind speed (air-to-cloth ratio) will be low, and the resistance will be small. The network design should minimize the elbow and shorten the pipe length and the fan should be customized according to the factory needs.

Spraying

The spraying process is a commonly used decorative method for the surface treatment of solid wood furniture. It is suitable for modern production processes and has high production efficiency, but the utilization rate of coatings is exceptionally low and consumes a lot of energy. By establishing an intelligent robotic spraying line, the uniformity of the coating film can be guaranteed, and the amount of over-spraying and cleaning solvent can be reduced, correspondingly improving the quality of spraying and material usage. Electrostatic spraying absorbs the paint to the surface of the work piece through electrostatic positive and negative attraction. It has a large production capacity, and the oil volume can reach 90%, which saves costs, although its applicability on furniture is currently limited. The panel parts can be changed from spraying to UV roller coating, which not only saves energy, but also reduces the consumption of paint (Wu and Shen 2020).

Optimization of the process route (part 2)

Currently, many solid wood furniture factories lack professional knowledge and the process route is unreasonable. Therefore, the process route sequence of solid wood furniture parts should be optimized to make production more efficient and reduce energy usage. As such, the technological process should be simplified, *e.g.*, the cutting process of some parts can be processed by a four-sided planer simultaneously, and complex components can be formed by a CNC machine simultaneously. Finally, an advanced production line can be used to replace an old production line to save energy and materials in all aspects. On account of most factories operating continuously during working hours, optimizing this process can reduce the idle time of product processing and improve energy efficiency (Lian *et al.* 2002).

Equipment modification and upgrade

The improvement of the automation level of processing equipment will no doubt help improve material utilization and processing accuracy, and further reduce energy consumption in each process. For example, the use of a fully automatic high-frequency splicing machine saves the amount of glue applied and can reduce the amount of glue over usage in comparison to traditional glue application methods. At the same time, a clamping and pressure method can minimize the thickness difference of the splicing board as well as the required amount of sanding, thus improving the processing quality and yield rate. The establishment of a CNC machining center can achieve high-precision machining (up to 0.05 mm to 0.1 mm), stable machining quality, highly flexible machining, multi-axis linkage, and complete one-time machining of furniture parts. Especially for special-shaped parts, CNC machining saves a lot of processes, which reduces energy consumption and carbon emissions during processing. In addition to advanced machinery and equipment, effective maintenance is also crucial. All equipment must be maintained regularly to ensure adequate engine lubrication, reduce machine tool product failure rates, and avoid poor production.

Carbon Reduction Management Measures for Solid Wood Furniture

Energy-saving utilization of raw materials

During solid wood furniture processing, a large amount of solid waste will be generated, *e.g.*, leftovers, dust, paint residue, waste activated carbon, and waste packaging materials. At the same time, a large amount of waste gas and waste liquid will be generated. If these wastes are planned for resource utilization, the amount of carbon emission and environmental pollution can be effectively reduced.

Generally speaking, only 65% of the tree remains in the form of logs after being harvested, and the efficiency of processing logs into square lumber is only 70%. After an enterprise purchases the square lumber, roughly 30% to 40% of the raw materials is lost in the batching process to obtain a semi-finished product, and during the fine processing of a final wooden furniture product, 10% to 20% is lost. The total volume of the final processed solid wood furniture is only approximately 50% to 70% of the original square plate. The loss is primarily in the form of dust and leftover materials (Wu 2019). For large-shaped leftover materials, *e.g.*, wood planks, wood strips, *etc.*, after sawing, planning, and drilling, they can be directly reused as raw materials. After the sawdust and shavings produced *via* planning and drilling are compacted, they can be combined with wood boards or other materials through adhesives to make wood-based panels. The scrap and sawdust can be directly used as fuel after being dried. In addition, they can be extruded into certain pellets or blocks under high temperatures and high pressures, among other specific conditions, to produce fuel ethanol or under bio-fermentation to produce fuel ethanol. It turns out that the biggest contribution in terms of carbon dioxide reduction is the substitution of wood for coal in energy production (Sikkema and Nabuurs 1995). The heat recovery (to produce electricity) from burning waste is used to reduce carbon dioxide emissions during the burning of fossil fuels (Vogtländer *et al.* 2014); it can also be used as an activated carbon adsorbent to make wood-plastic products or ferment into organic fertilizers (Sun and Li 2019). During the spraying process of solid wood furniture, a large number of non-effective spray areas are involved, which not only increases the material cost, but also increases the carbon emissions during the production process. Therefore, the paint mist can be recovered, and the coating can be recycled, which can effectively reduce the carbon emissions of this process.

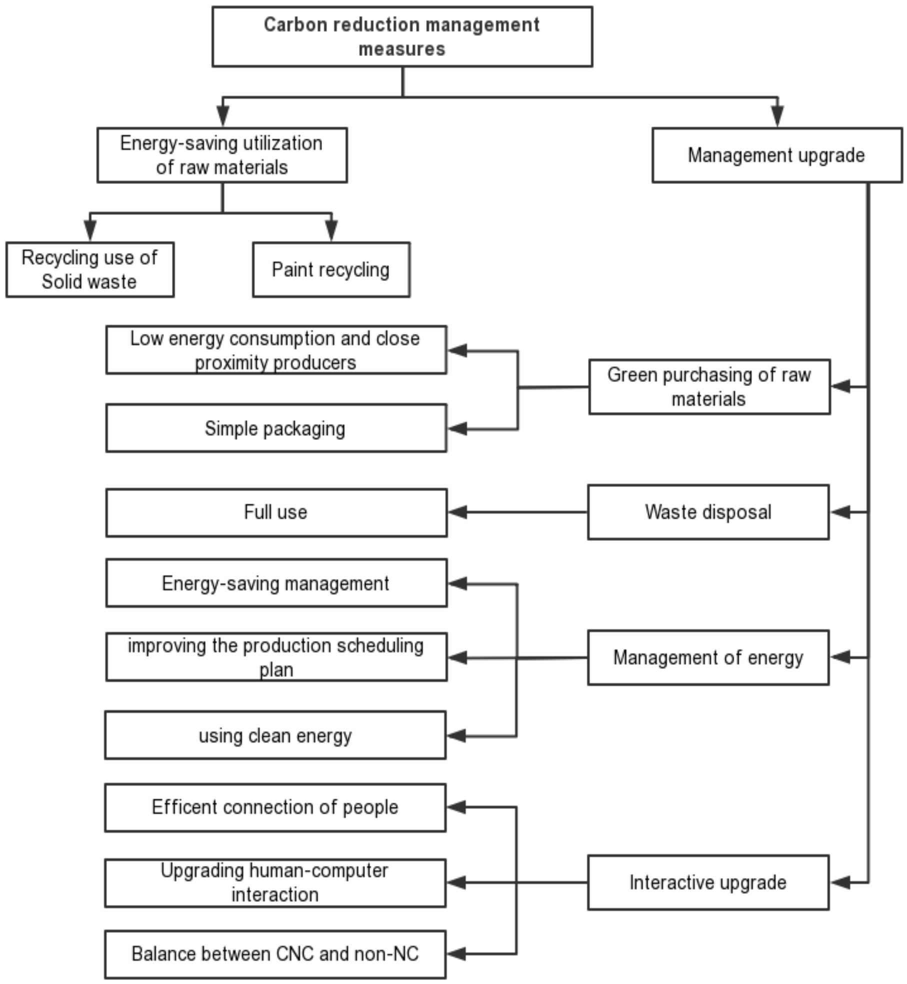

Fig. 4. Content of the carbon reduction technology in management

Management upgrade

Energy conservation and emission reduction is a strategic design of an enterprise, which must be integrated with enterprise management, starting with optimizing the enterprise management system, implementing green procurement methods for raw materials, waste disposal, strengthening energy management, and upgrading the internal interaction system. When purchasing raw materials, it is recommended to buy low-carbon materials and choose low-carbon manufacturers, *e.g.*, low-energy wood manufacturers (different cutting methods and cutting section sizes of a log affect the power consumption, so the lumber factory should establish the optimal energy consumption model), use simple material packaging, and choose close suppliers as much as possible to reduce transportation costs (Chan 2016). In addition, to improve the waste management system, consider transportation energy consumption for reuse outside the plant, and avoid incineration as much as possible. Reasonable use and disposal of thinned wood and wood waste can effectively reduce carbon dioxide emissions (Etoh *et al.* 2011).

In terms of energy management, clean energy should be used where conditions permit, *e.g.*, wind power instead of thermal power. Energy-saving management should be strengthened to reduce all unnecessary power consumption, *e.g.*, improve the production scheduling plan to avoid idling equipment and chaotic management caused by the reworking of parts and components, which increases the carbon emissions of a single product. For instance, during the formation of solid wood furniture, wood drying is not only a high carbon emission process, it is also an indispensable process (Wang and Lo 2016). Generally, the sawn wood purchased by furniture manufacturers conforms to the local equilibrium moisture content, and it only needs to be properly stored and treated with anti-corrosion or fire prevention when necessary, which can effectively reduce the mold rate and improve the biochar content (Hsu and Lee 2008). Some sawn timber needs to be manually dried and processed in a drying kiln. At this stage, the heat and steam generated by the drying of the wood can be used indirectly as a source of power generation, which can power the electric saw motor (Bergman *et al.* 2014).

Finally, the carbon reduction concept needs to be practiced from top to bottom by improving the interaction of various elements within the enterprise. Specific measures can be taken in aspects of enabling efficient docking of employees between departments and positions, upgrading human-computer interaction, reducing operation error rate, ensuring the balance between CNC and non-CNC, and optimizing processes.

DISCUSSION

At present, the furniture industry is at a key node of digital transformation, and advanced intelligent manufacturing technology will bring obvious effects on carbon emission reduction in the manufacturing process (Tian *et al.* 2016). Some companies have integrated carbon footprint calculations into digital production systems, and through data management functions, real-time records of product materials, process, and structure of carbon emissions in all aspects of the product production process are used to continuously improve and optimize products. At the same time, combined with technologies such as digital twins, it is possible to determine the best structure of the product, the best production line, the best equipment parameters, improve production efficiency, and reduce energy consumption before processing.

The next stage is to move towards carbon neutrality, which is also the direction of national policy. Solid wood furniture companies must plan for long-term investment. National policies will inevitably develop in a low-carbon direction, and low-carbon environmental certification will also become a mandatory certification requirement. However, the current certification standards are not standardized. The furniture industry can give priority to the construction of a furniture carbon footprint certification system to encourage green production and break industry barriers. In the future, furniture companies can integrate corresponding carbon reduction specifications with manufacturing software, optimize production data, and finally affix carbon labels to products to promote product promotion and internally promote low-carbon production methods.

CONCLUSIONS

1. This paper analyzes the carbon footprint of the solid wood furniture processing process to obtain specific emission reduction potential points, as follows: (1) the efficient utilization and reuse of lumber; (2) reducing the use of hardware and chemicals; and (3) the reduction of power consumption during high-emission processing, *e.g.*, ingredients, sanding, spraying, and dust removal.

2. Analysis of the carbon footprint of the solid wood furniture processing process to obtain specific emission reduction showed that the following aspects are critically important: (1) the efficient utilization and reuse of lumber; (2) reducing the use of hardware and chemicals; and (3) the reduction of power consumption during high-emission processing, *e.g.*, ingredients, sanding, spraying, and dust removal.
3. Utilizing all aspects of the solid wood furniture design and manufacturing process analysis, the present work has summarized the entry point of carbon reduction technology: the carbon reduction design methods and principles, the carbon reduction manufacturing suggestions, and the enterprise carbon reduction management measures, all of which will provide ideas for the development of low-carbon processes in the furniture industry.

CONFLICT OF INTEREST

The authors declare no conflicts of interests.

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