Theory and Method for Rapid Carbon Footprint Accounting of Solid Wood Furniture

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Abstract

In response to global warming, increasing numbers of governments and global organizations have adopted the carbon footprint as an indicator to measure greenhouse gas emissions from products. However, the analysis of furniture carbon footprint data is time-consuming and difficult to practically implement in product development and production, leading to ineffective verification and limited emission reduction outcomes. This article proposes a method of rapid calculation of carbon footprint for solid wood furniture based on processing steps, including dividing operation units, collecting consumption data, establishing a carbon accounting model, adding individual emissions to obtain the sum, and developing calculation software. This method of decomposition and integration enables rapid calculation of the carbon footprint and effective emission reduction, facilitating precise emission reduction strategies and production optimization in the furniture industry.

Currently, addressing global warming has become an urgent issue worldwide (Kerr 2007). In order to actively respond to the impacts of climate change in various countries, increasing numbers of governments and global organizations have adopted the carbon footprint as an indicator to measure greenhouse gas emissions from products, providing a basis for decision-making on carbon reduction. At the same time, they are actively developing carbon labeling systems, using labels on products to indicate the carbon footprint and guide consumers in choosing products with lower carbon emissions. This approach aims to reduce greenhouse gas emissions and mitigate climate change (Zhao and Zhong 2015, Liu et al. 2016, Zhao et al. 2018, Rondoni and Grasso 2021).

China's furniture industry occupies an important position in the global furniture industry, and China is one of the main exporting and producing countries for furniture products (Xiong et al. 2017, Chen et al. 2021). At present, most of the carbon footprint calculations for furniture in China choose a furniture product as the research object, use the life-cycle assessment method to determine the system boundary of the research product, track the furniture production process in the furniture production factory, obtain first-hand data to calculate the carbon footprint of the furniture product, and analyze the results. Analyses indicate the link in the production process that releases more greenhouse gases, and then studies propose improvement suggestions for that link (Gamage et al. 2008, Kwangsawat and Rugwongwan 2017, Xie et al. 2024). Increasing efforts in

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This paper was received for publication in December 2024. Article no. 24-00058.

Forest Prod. J. 75(2):155–163.
doi:10.13073/FPJ-D-24-00058

carbon footprint assessment can help to better understand the environmental impacts of a furniture product throughout its life cycle, promoting green production and consumption. At present, factories produce furniture products in large quantities with long production cycles, and each process corresponds to different positions and staff. It is often a mixed production of multiple products, so collecting product data is difficult and requires a lot of time. At the same time, it is necessary to analyze these data, which requires a huge amount of work, and so it is challenging to obtain sufficient data to play a practical role in product development and production.

Currently, there is limited research on carbon footprint assessment in the furniture industry, both domestically and internationally. Most studies remain focused on the carbon footprint of individual products and offer general improvement suggestions. However, research on carbon footprint assessment methods and management system design has emerged in other industries, aiming to establish management systems that enable rapid prediction and assessment of product carbon footprints. These systems visualize product carbon footprints, saving time and steps in the assessment process and reducing workload for staff (Petsch et al. 2011, Chen et al. 2016, Chen 2022). In the construction industry, to quickly account for greenhouse gas emissions during the construction phase, a "Building Construction Carbon Footprint System" has been established using building information modeling technology and computer technology (Li et al. 2017). To measure the carbon dioxide emissions of individuals or households, a plethora of carbon footprint calculators are available online. Developers have created platforms for carbon footprint calculator applications, allowing users to understand their personal carbon footprints based on their activities and take corresponding actions (Rahman et al. 2011). The 2030 Calculator is a carbon footprint calculation tool developed by Omnical in partnership with Doconomy, a Swedish company, primarily used to quantify the carbon footprint of clothing, furniture, and household items ("2030 Calculator"; Omnical 2024). It aims to enable manufacturers and brands to calculate the carbon footprint of their products in an intuitive and rapid manner, without the expensive and time-consuming resources typically associated with life-cycle analysis. The 2030 Calculator guides users through a concise interface to input data such as materials, production processes, and transportation methods, and it utilizes a built-in emission factor database to quickly calculate the carbon footprint. The results are presented in charts and visual formats, helping users to intuitively understand the carbon emissions at each stage, as shown in Figure 1. Compared to traditional life-cycle analysis, which may take weeks, this tool can generate results within minutes. It is suitable for companies to quickly assess product carbon footprints, although the calculated results are estimates.

The purpose of this study was to find a method that can reduce the time and labor costs of product carbon footprint measurement, achieve rapid measurement and prediction of product carbon footprint, further analyze and evaluate the carbon reduction effect, and optimize production processes and energy utilization through the data obtained from the

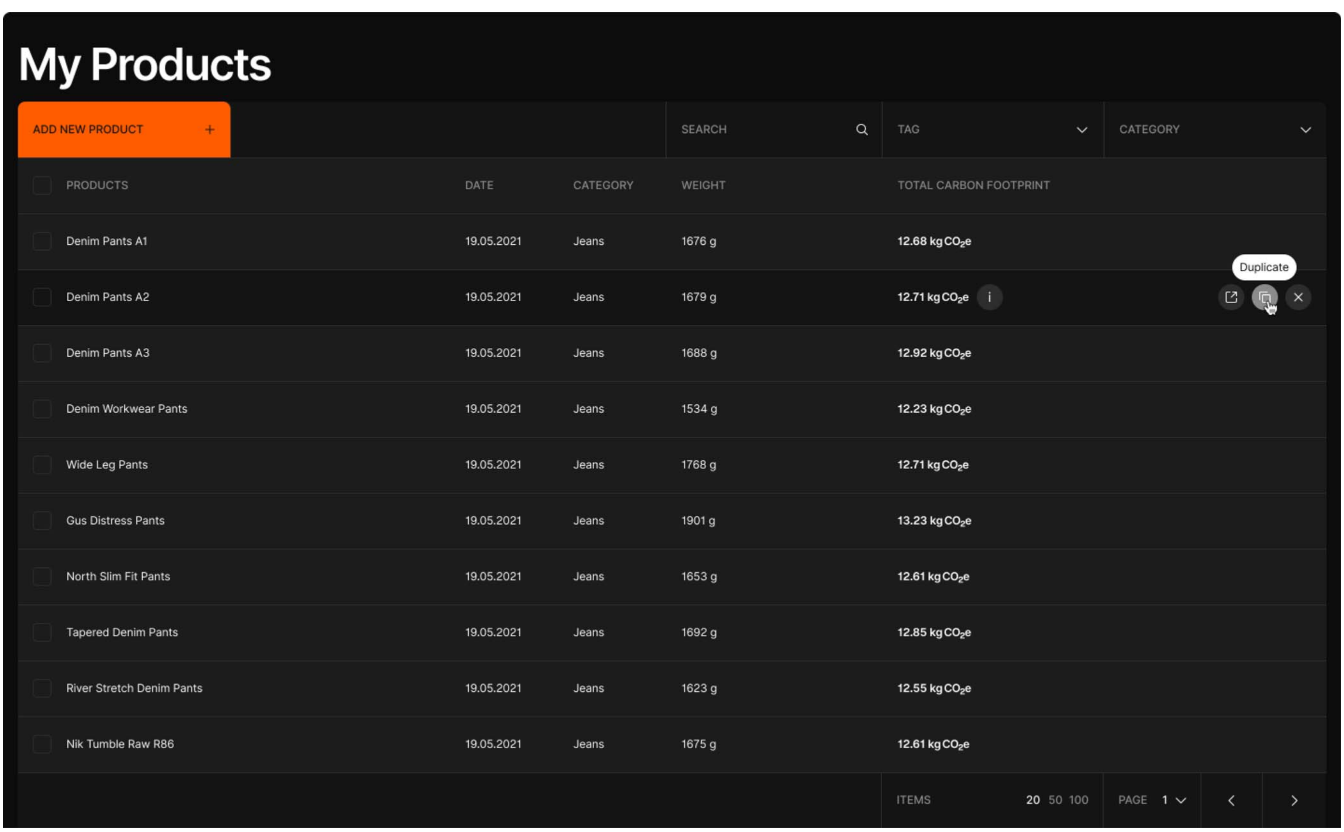


Figure 1.—2030 Calculator Web page (https://www.2030calculator.com/).

rapid measurements. This will provide data support for improving products and making reasonable decisions.

Research Method

This study drew on research methods from other industries to propose a carbon emission calculation method based on the production process. This method is based on International Organization for Standardization (ISO) standard ISO 14040 on life-cycle analysis (ISO 2006) and standard ISO 14067 on the carbon footprint of products (ISO 2018). From the perspective of process flow, this method enables an intuitive and rapid calculation of the product's carbon footprint. This method is divided into five steps: division, collection, modeling, calculation, and software system. The following text uses solid wood furniture production as an example to introduce this method in detail.

Division of operational units

Operational units are divided based on the processing stages and components of the processed products. Regardless of the production process of any product, dividing operational units based on processing stages and components of the processed products is crucial for product manufacturing. Detailed division of operational units can assist factories in more effectively managing production processes, optimizing production efficiency, and controlling production costs. Additionally, it facilitates the collection of data on production activities, providing fundamental information for carbon footprint calculations. Taking the solid wood furniture manufacturing process as an example, this process typically includes steps such as cutting, splicing, tenoning, drilling, painting, spraying, screwing, and packaging. Each of these steps is considered an independent operational unit, and the different components within each step are further divided into subunits. This division method makes the production process more visible and controllable, as shown in Figure 2.

Taking cutting as an example, in the production of solid wood furniture, cutting is an important part of the production process. Large solid wood furniture production companies usually have a fixed set of production processes and size standards, which can ensure product consistency and stability. In the cutting process, multiple fixed panel cutting sizes are also set. By dividing the cutting board into different subunits, it is possible to more accurately record the raw material and energy consumption of each component. This helps production managers track and analyze the usage of various energy consumption components, thereby providing a data basis for calculating the carbon footprint of each subunit in the later stage. In the process of tenoning, different types of tenons are subdivided into subunits to ensure that independent data can be obtained for each tenon.

For processes such as polishing and painting, it is not possible to obtain clear statistical data in the form of components like the previous processes. Furniture polishing and painting are usually carried out in the final stages of the production process. Generally speaking, furniture products that have been assembled and inspected will enter the polishing and painting process. At this stage, the processing of furniture is generally carried out in the form of a whole, so the process of this part is divided into a whole work unit. Overall, subdividing each step in the production process into work units and further dividing them into subunits can help factories better track production activities and provide a basic module for rapid carbon footprint measurement in the future.

Collection of material consumption data

Data on raw material and energy consumption for operational units are collected through methods such as operational measurements and regression analysis. After defining the operational unit, data collection is carried out on the unit content. The carbon emissions in the production and manufacturing process mainly come from the energy consumption of equipment and the carbon emissions generated by the consumption of raw materials. Taking the processing of solid wood furniture as an example, the energy consumption during the processing of solid wood furniture is mainly electricity. The collection of electricity data mainly consists of the power of processing machines and processing time, that is, time multiplied by machine power equals electricity consumption. The power of the machine can be found on the label on the body, which is relatively easy to collect. Time collection can be done using a stopwatch or electronic timer to directly and continuously observe the execution of the job over some time. This article takes a large solid wood furniture factory as an example to collect and calculate data on factory production activities. Compared with traditional manual workshop-style solid wood furniture factories, this factory uses advanced equipment such as precision push table saws, high-frequency splicing machines, and CNC tenoning machines, greatly improving production efficiency and output, and making it at the leading level in domestic furniture production, as shown in Figure 3.

Panel cutting serves as an illustrative example during which only machine processing power consumption is involved. To establish a scientific time standard for continuous

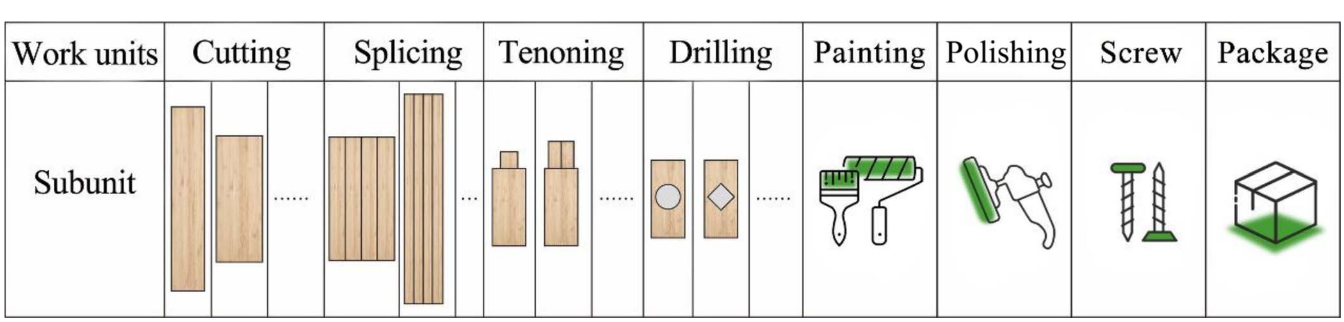


Figure 2.—Operational units are divided according to production processes.

Figure 3.—Furniture production equipment.

measurement of the panel-cutting process, a sufficient sample size is essential. Typically, for operations lasting less than 2 minutes, the observation frequency should not fall below 25 times. Consequently, for each type of panel being cut, 30 measurements were conducted, and outliers were eliminated using the three-sigma method. Subsequently, the average processing time for each operational unit and subunit component was calculated, providing the necessary data for subsequent carbon footprint calculations. The factory utilizes the Nanxing Precision Sliding Table Saw MJ1132F, which operates at a power of 5.5 kW. The power emission factor employed in this study is the 2021 national average carbon dioxide emission factor for electricity, as published by the Ministry of Ecology and Environment of China, which is 0.5568 $kgCO_2eq$ (kWh)(Ministry of Ecology and Environment of China and the National Bureau of Statistics 2024). As presented in Table 1, based on the collection and calculation of field data, a comprehensive carbon footprint database for the panel-cutting operation unit was established. Next, we determined the opening time, power consumption, and thus the carbon footprint based on the fixed size of the plate.

During the splicing process, both electricity and raw material consumption are significant factors. Initially, it is crucial to gather data on the adhesive utilized in the splicing process. By repeatedly measuring the quality of adhesive used for each fixed size of splicing, an average value can be obtained to determine the amount of adhesive raw materials consumed for each splicing size. Simultaneously, the time consumed by high-frequency splicing machines and other equipment during the splicing process should be recorded to calculate the electricity consumption for each splicing size. The factory employs the Era High-Frequency Splicing Machine GJB-PL-48A-JY, which has a maximum splicing size of 2440 by 1220 mm, operates at a power of 20 kW, and has a single operation time of 120 seconds. During operation, multiple groups of splicing boards of the same size enter the machine simultaneously, and the operation time must be evenly allocated among them. The adhesive used is white latex, commonly available in the market, with an emission factor of 31.6 $kgCO_2eq$ (m^3), as documented in the *Second National Pollution Source Census Production and Emission Accounting Coefficient Manual* (refer to Table 2). Based on the collection and calculation of on-site data, a comprehensive carbon footprint database for the splicing process was established.

As a traditional and effective method of woodworking joinery, mortising has been preserved and further technically improved and innovated in modern large-scale solid wood furniture manufacturing factories (Wu et al. 2021) by the introduction of advanced equipment such as efficient and precise numerical control mortising machines. These machines significantly enhance the efficiency and accuracy of mortising, thereby meeting large-scale production

Table 1.—Data collection table for cutting operations.

Number	Plate size (mm)	Plate	Sawing time (s)	Power consumption (kWh)	Carbon footprint (kg CO_2eq)
1	260 × 180 × 18		19	0.029	0.016
2	1000 × 358 × 18		38	0.058	0.032
3	760 × 300 × 18		31	0.047	0.026
4	730 × 460 × 18		34	0.051	0.023
5	820 × 174 × 18		29	0.045	0.025
6	440 × 110 × 36		22	0.036	0.020

demands. For processes such as mortising and drilling, field operation data were also collected based on work units, and corresponding carbon footprint databases were established, as shown in Table 3.

For processes such as painting, and spraying, the calculation of components is no longer used to collect them as a whole work unit. According to actual work analysis, the polishing time is mainly related to the polishing area. As the polishing area increases, the required time and power consumption also increase accordingly. Therefore, in the polishing process, the main focus was on studying the relationship between polishing area and time, and further exploring issues related to power consumption. The amount of paint used is also related to the spraying area, and the larger the area, the higher the amount of paint used. In this stage of research, the main focus was on exploring the relationship between processing area and paint usage, with a focus on solving the problem of raw material consumption. Regression analysis can handle the correlation between variables and provide mathematical expressions. It can also use empirical formulas to predict the value of another variable. Based on multiple measurement data, regression analysis can obtain the linear relationship between polishing time and polishing area (Fig. 4), the linear relationship between paint consumption and wood component area, and specific regression function formulas. This method provides data for calculating electricity and material consumption in the carbon footprint.

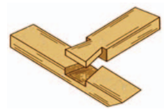
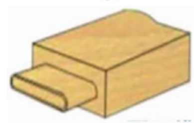
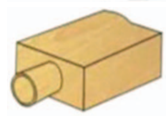
Establishing accounting models

We next establish a carbon accounting model for raw material and energy consumption and calculate the carbon emissions of each operational unit after collecting data. The calculation method for the carbon footprint adopts the widely used emission factor method proposed by the Intergovernmental Panel on Climate Change (IPCC 2006). The carbon

Table 2.—Data collection table for splicing operations.

Number	Plate size (mm)	Splicing plate	Splicing time (s)	Power consumption (kWh)	Adhesive (g)	Carbon footprint (kg CO_2eq)
1	1000 × 720 × 25		40	0.22	8	0.37
2	1200 × 760 × 18		40	0.22	13.82	0.56
3	440 × 440 × 18		15	0.08	4.07	0.2
4	940 × 240 × 18		15	0.08	5.41	0.21

Table 3.—Data collection table for tenoning operations.

Number	Tenon size (mm)	Tenons	Tenoning time (s)	Power consumption (kWh)	Carbon footprint (kg CO_2eq)
1	$20 \times 16 \times 16$		5	0.034	0.019
2	$32 \times 25 \times 25$		2	0.013	0.007
3	$30 \times 10 \times 20$		6	0.042	0.019
4	$10 \times 10 \times 20$		5	0.034	0.023

emission factor refers to the amount of greenhouse gas generated along with the consumption of a unit of mass substance, expressed in carbon dioxide equivalent and related activity units (e.g., kg CO_2eq per unit input). Carbon emissions were calculated based on the divided operational units and collected data, and the product of the input energy usage and emission factors was as the estimated carbon emissions for the emission project. The formula for calculating the carbon footprint is:

$$CE_i = AD_i \cdot EF_i$$

where CE_i is the carbon footprint; AD_i is the activity level of greenhouse gas emissions caused by substances; and EF_i is the carbon emission factor.

This formula is the basic formula for carbon accounting, which mainly involves raw material consumption and energy consumption in the product manufacturing process. Therefore, two types of carbon emission accounting formulas for components can be established.

Calculating carbon footprint

The carbon emissions of each step are progressively summed according to the manufacturing process to obtain the production carbon footprint of the product. Following the aforementioned steps, the carbon footprint value of each operational unit during each processing step can be calculated, forming a carbon footprint database for the factory. When calculating the carbon footprint of a specific product, it needs to be dismantled and analyzed step by step. For example, in the cutting stage, it is necessary to determine the size of the board to be used, which spliced board is utilized, and the type of tenon used. Additionally, the surface area of the product needs to be measured, and the carbon emissions generated during polishing, sanding, spraying, and painting processes should be calculated. Finally, the carbon footprint values from these processes are summed

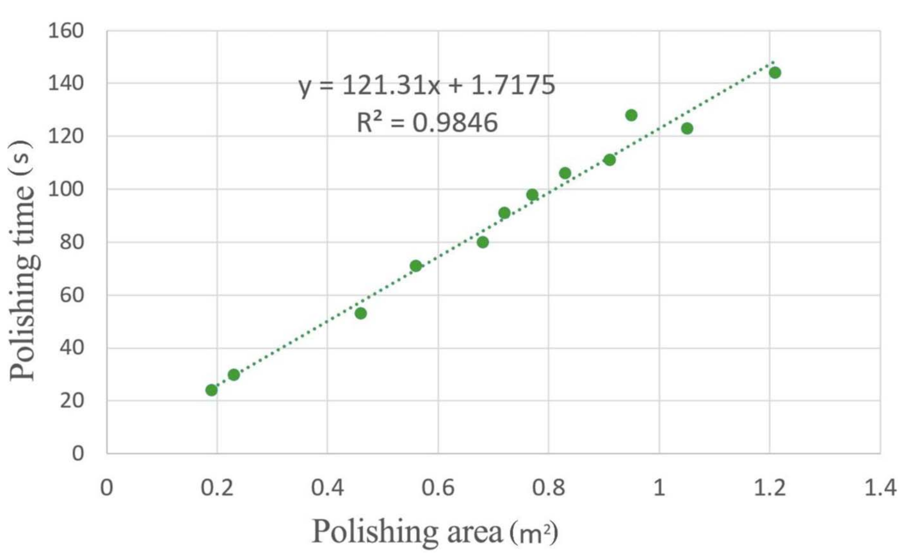


Figure 4.—Regression analysis chart of wood polishing time and area.

up to obtain the complete carbon footprint of the product, as shown in Figure 5.

Establish a Carbon Footprint Calculation System

A software system for carbon footprint calculation can be established to enable rapid estimation. Software technology can enhance management standards and efficiency. By developing accounting software, enterprises can be provided with carbon emission data management and visualize results and analyses. The accounting software adopted a B/S (browser/server) development architecture, comprising three logical layers: the application layer, the logic layer, and the data layer. The application layer encompasses the browser and user operations, the logic layer encompasses the accounting rules and processes of the software, and the data layer primarily focuses on the storage of the underlying database.

To establish a carbon footprint calculation system for solid wood furniture, the initial step involves configuring the software's basic structure based on the previously defined operational units and storing the production carbon footprint data for each unit within the company, ensuring a comprehensive backend database. Subsequently, the dismantled data for the furniture to be tested are obtained, and a new blank file is created. Carbon footprint data for each process are sequentially selected according to the manufacturing process, ultimately compiling a carbon footprint inventory for the product during its production phase. As shown in Figure 6, the carbon footprint inventory for Product X is rapidly established through the software system. Based on the dismantled details of Product X, operational units are selected on the left-hand data management page to form a summarized carbon footprint inventory for Product X. This software enables the rapid calculation of the carbon footprint for new products, providing data support for subsequent optimizations.

Discussion

This study focused on a prominent domestic solid wood furniture enterprise, selecting Product XYZ-013 as the research case. Utilizing the traditional field-based life-cycle assessment method, the data collection and calculation within the system boundaries were completed over a 10-day period, yielding a final carbon footprint measurement of 2.90 kg CO_2eq for the product. Subsequently, carbon footprint calculation software was employed to disaggregate the product's operational units into seven key processes, including material cutting, panel assembly, and others. By inputting the data into the software, the entire carbon footprint assessment process was completed in just 18 minutes, resulting in a measured carbon footprint of 2.69 kg CO_2eq, as shown in Figure 7.

A comparison of the results obtained from the two methods revealed that the difference fell within an acceptable range for engineering calculations. The core advantage of the method proposed in this study lies in its significant reduction of the heavy reliance on professionals typically required in traditional life-cycle assessment methodologies. With the aid of this software, even nonprofessionals can efficiently complete the carbon footprint accounting for complex products, guided by standardized procedures. This innovation provides an efficient and practical tool for

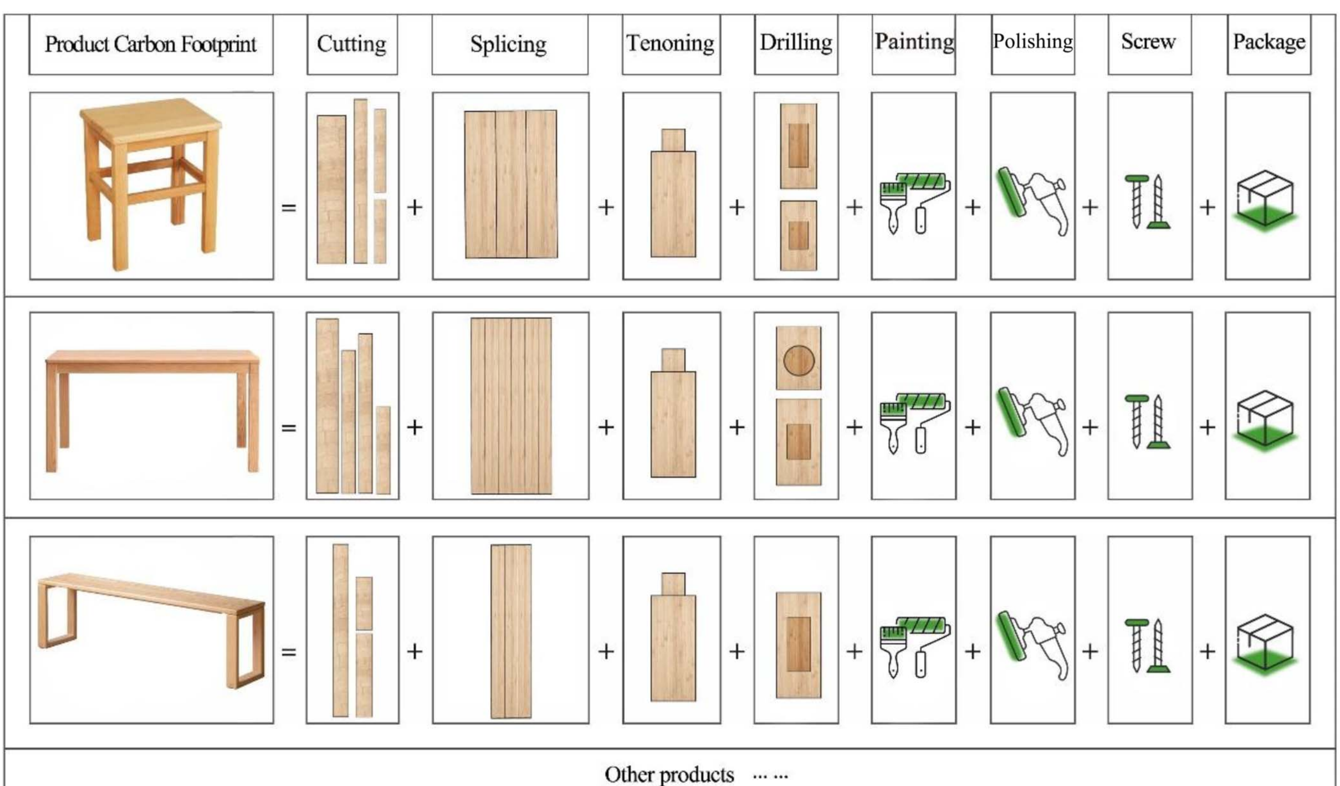


Figure 5.—Product carbon footprint summation calculation.

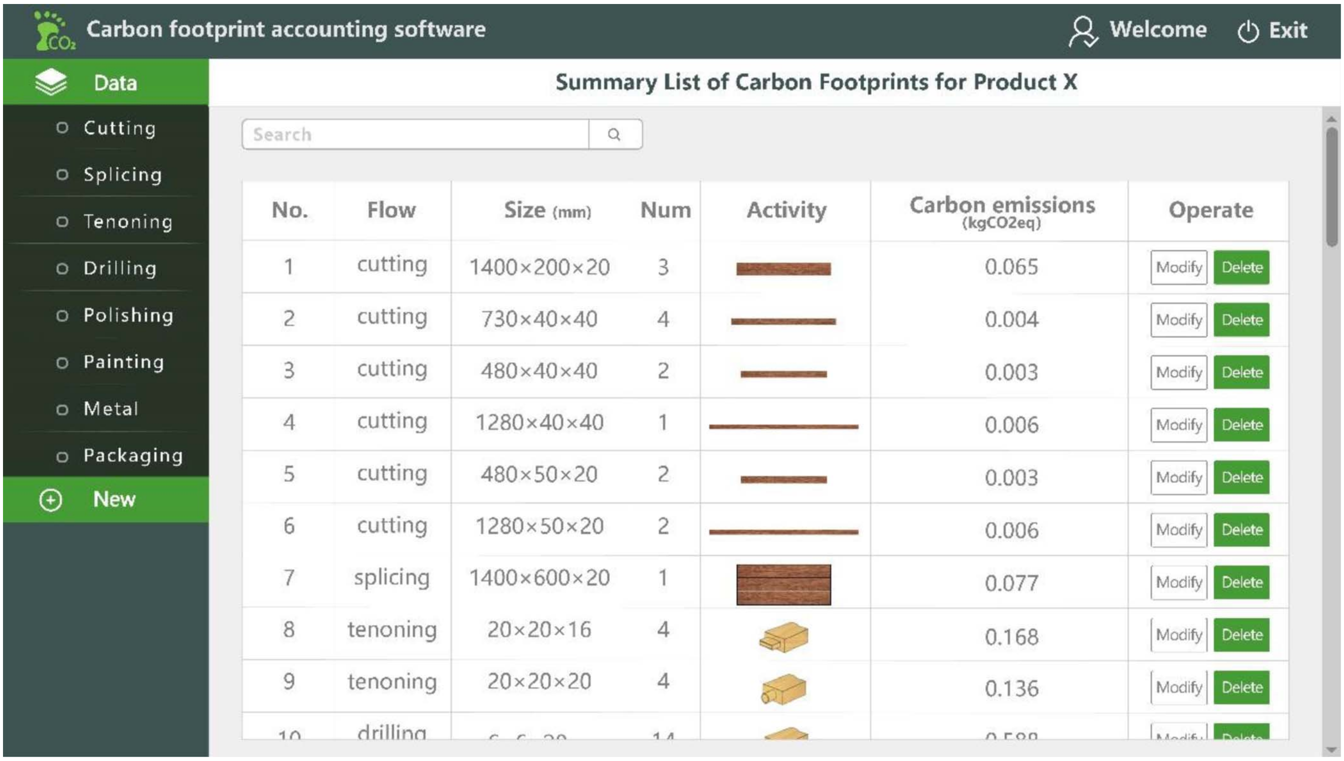


Figure 6.—Software system for carbon footprint accounting of solid wood furniture.

manufacturing enterprises to implement product carbon emission management. The findings of this study confirm that rapid carbon footprint calculation methods based on digital technology not only significantly enhance calculation efficiency, but also maintain the necessary calculation accuracy. This holds significant applied value for promoting low-carbon production practices among small- and medium-sized manufacturing enterprises.

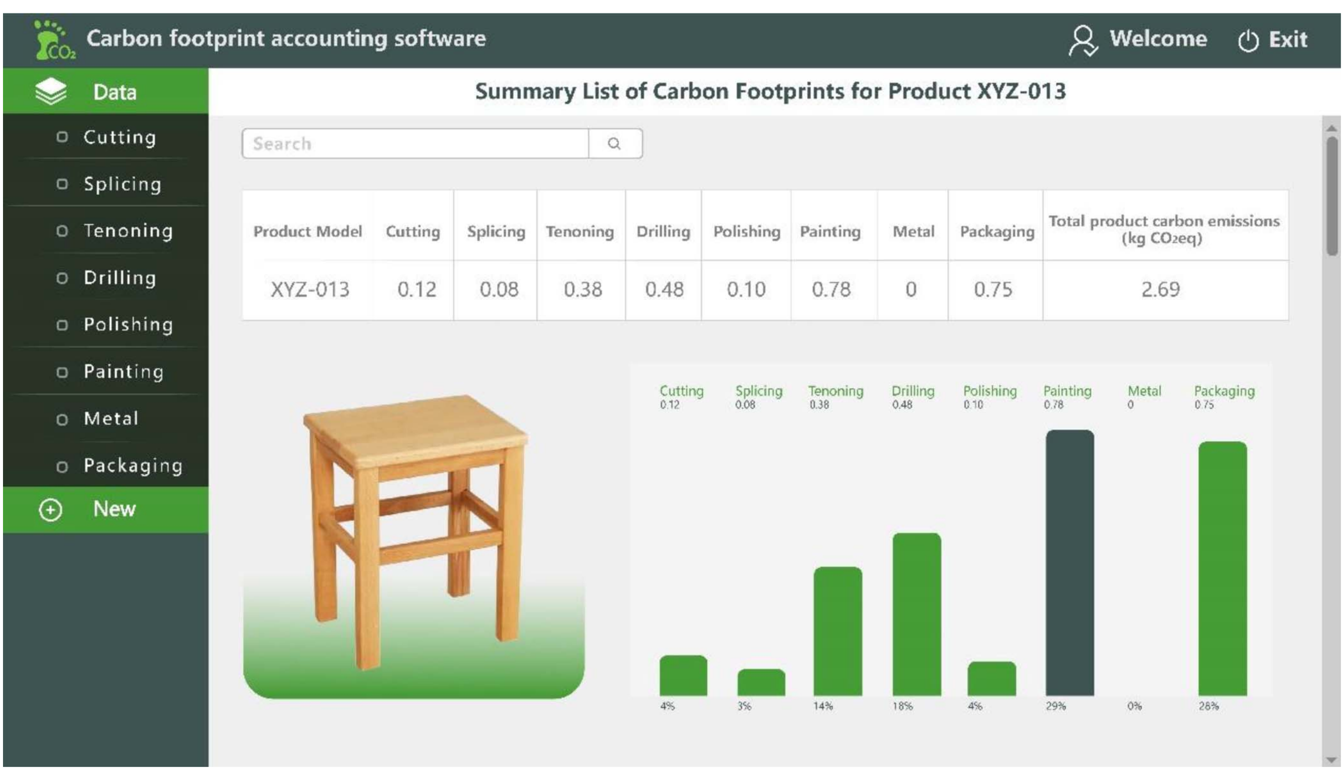


Figure 7.—The carbon emission result for Product XYZ-013.

Conclusion

This article takes solid wood furniture as the research object and proposes a rapid carbon footprint calculation method based on the manufacturing process. The core concept of this method is to establish an extensive database through extensive collection and calculation of factory data in the early stage. This database enables subsequent products to quickly retrieve the required carbon footprint data, thereby simplifying the entire calculation process. Compared to traditional methods for calculating product carbon footprints, this approach saves considerable time and human resources, as it eliminates the need for individual tracking and surveying of each product. Simply by obtaining the corresponding basic data from the database, the carbon footprint value of a product can be quickly obtained.

Furthermore, this method possesses the capability to predict the carbon footprint values that may arise during the product development process. By analyzing and calculating the product design drawings, the carbon footprint can be estimated before the actual production of the product. Such predictive capability provides an important reference for product improvement and production, enabling targeted consideration of emission reduction measures during the design stage, which can further enhance production efficiency and the effectiveness of emission reduction strategies.

Overall, this decomposition and reintegration approach provides significant assistance for rapid calculation of the carbon footprint and effective emission reduction. It not only simplifies the process of carbon footprint calculation, but also offers deeper optimization and improvement possibilities for product design and production, thereby actively contributing to the achievement of sustainable development goals.

Acknowledgments

This work was supported by the Natural Science Foundation of Jiangsu Province (grant number BK20230403, Jiangsu Provincial Department of Science and Technology) and the Qing Lan Project (Jiangsu Education Department).

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