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S.I. : GREENWASHING

Research on methods and strategies of green design carbon reduction for bicycle industry in Taiwan from perspective of product life cycle

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Abstract
Under the trend of environmental protection and carbon reduction, bicycles have become an important component of green urban transportation, and therefore, the net-zero emissions in the manufacturing process of the bicycle industry have become even more important. This study focuses on the green transformation of the bicycle industry in Taiwan and explores the carbon distribution of bicycles through the product life cycle. In order to understand the status of the industry, we invite four senior industry experts and three green design scholars. It conducts research and analysis on green design and carbon reduction in the bicycle industry through expert interviews and grounded theory. In the face of development challenges, we believe that the Taiwan bicycle industry should adopt a systematic approach, carry out phased carbon reduction tasks, and implement product life cycle carbon footprint verification in order to achieve a balance between business models and sustainable operations. In the present study, we formulate preliminary carbon reduction strategies for different-scale enterprises into four stages based on the current status of the industry: (1) product plan, (2) design and development, (3) manufacturing, and (4) collaborative carbon reduction. These strategies can be applied to different production stages of the manufacturer. In addition, we plan a green design carbon reduction flowchart for the bicycle industry from the perspective of life cycle, which allows them to think more comprehensively about product carbon reduction plans. In order to alleviate the international and internal pressure faced by the industry, we have also formulated three countermeasures: (1) risk reduction and increased implementation willingness, (2) transformation of product–service models, and (3) implementation of carbon footprint verification throughout the life cycle. Furthermore, the assembly of bicycle products depends on raw materials and parts from different countries. Therefore, carbon reduction in the bicycle industry is not a goal that can be achieved by single manufacturer or single stakeholder's efforts. Although this study focuses on the bicycle industry in Taiwan, when facing changes in the international market, it is crucial for enterprises to seize the opportunity to transition timely. The research findings can still provide reference for other countries facing similar challenges. Subsequent studies can also test the methods and strategies proposed in this research in actual industry settings, thereby providing more practical implementation suggestions and promoting green design and carbon reduction in the industry.

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Keywords Bicycle products · Product life cycle · Green design · Net-zero emissions

1 Introduction

In recent years, with the rise of environmental awareness, many countries have begun to prioritize the environmental impacts caused by production and manufacturing. They have gradually developed relevant eco-design processes and procedures, aiming to achieve carbon reduction or net-zero cities by 2050. Globally, transportation accounts for a quarter of the total carbon dioxide emissions, with many countries still heavily reliant on fuel-powered vehicles as the core means of transportation (Timperley, 2020). In the wake of the COVID-19 outbreak in 2019, compounded by the escalating risks associated with climate change, many cities have come to view bicycling as a viable solution for commuting. This approach not only minimizes the risk of mass infections in public transport settings but also reduces air and noise pollution, mitigates accident occurrences, and undeniably stands as a pivotal component in the vision for future sustainable cities (Santos et al., 2010). In a bid to encourage the public to adopt bicycling as an alternative means of transportation, governments across Europe, Asia, and the Americas have been actively promoting bike-sharing initiatives (Rojas-Rueda et al., 2011). For instance, the Australian government advocates for the control of urban development through pedestrianization and cycling as key modes of public transport, aiming to enhance environmental conditions (Gurran et al., 2015). The U.S. Department of Transportation, in its Bipartisan Infrastructure Law (BIL) of 2022, authorized a budget of 108 billion USD for the development of public transportation, paving the way for increased opportunities and funding for bicycling projects. Meanwhile, since the 1970s, Japan has been encouraging bicycle transportation in its transportation policies, enacting legislations to construct four distinct types of bicycle lanes to facilitate co-travel of pedestrians and cyclists (Chinese Institute of Transportation, 2011). Compared to cars or trucks, each bicycle trip results in a 14% reduction in carbon emissions (Brand et al., 2021). Bicycles have indeed become important means of transportation for green cities and carbon–neutral cities. As a result, achieving net-zero emissions in the manufacturing process of the bicycle industry has become even more significant.

In the past, the traditional supply chain focused primarily on product-oriented and low-cost production, neglecting the external costs of environmental pollution, which led to accelerated global warming. With the threat of ecological degradation, countries worldwide are under pressure to reduce carbon emissions, leading to strict carbon footprint regulations on the overall product life cycle of enterprises. In studies focusing on transportation modes, walking and cycling are commonly regarded as zero-carbon emission methods. However, from the life cycle perspective, these two modes of transportation also generate carbon emissions (Fabian, 2016). Life cycle assessment systematically evaluates and quantifies the energy use and waste emissions throughout various stages of products, including production, use, disposal, and recycling, to assess and quantify the environmental impacts and burdens. The ultimate goal of using product life cycle assessment systems is to record and reduce the negative environmental impacts of products. This approach has been widely adopted and promoted by numerous domestic and international businesses and research institutions (EPA NRMRL Staff, 2012; Liu, 2019; Wang et al., 2019). Bicycles, being products comprised of diverse components, still possess non-circular materials and designs that contribute to environmental pollution in a linear economy. Research indicates that the entire life cycle carbon footprint

of a bicycle is 34.56 kg of carbon dioxide. If a bicycle is directly landfilled, it takes 31 years to decompose. Furthermore, for a genuine net positive emissions reduction to be achieved, a user would need to ride the bicycle for 686 days (Chen et al., 2020). Wang (2021) conducted a life cycle analysis on shared bicycles in schools and found that the highest carbon emissions occurred during the raw material acquisition and maintenance stages (35%), followed by the recycling phase (15%), and the manufacturing stage (10%) (Table 1).

The bicycle industry in Taiwan has a history of over 60 years and possesses a complete industrial chain. With decreasing export sales and weakening price advantages, some domestic manufacturers have started adopting the OEM (Original Equipment Manufacturer) model, gradually facilitating industry transformation and upgrading (Giant, 2020). In recent years, the bicycle industry has made efforts to cultivate overseas markets, resulting in successful transformations. Both the sales prices and profits have shown stable growth, and global export demand has exhibited a stable trend (Ministry of Finance,R.O.C, 2022). In Taiwan, many bicycle components are manufactured by local factories for export. Due to the island's lack of natural resources, there is often a need to import metal materials, an aspect that has significant environmental impacts. Presently, global strategies in the bicycle industry predominantly emphasize 'sharing,' 'recycling and remanufacturing,' and 'reducing packaging.' By promoting shared bicycles and electric bikes, there is an effort to diversify and facilitate public transportation options (Sun et al., 2020). Additionally, the development of composite materials is pursued to enhance recyclability (Chen et al., 2022). However, in Taiwan, the emphasis is mainly on encouraging green consumption at the end of the consumption chain, with little change in the manufacturing process. Under the goal of promoting carbon reduction or achieving net-zero cities, the bicycle industry, despite reducing carbon emissions during the usage stage, lacks sufficient green design strategies in the raw material and manufacturing stages.

In recent years, there has been a global shift toward green supply chain management. As a result, designers and engineers no longer focus solely on the product itself but consider its entire life cycle in a chain-like manner (Shih & Dai, 2000). Compared to traditional design, green design emphasizes 'recyclability, low pollution, and energy efficiency.' It is not merely an independent design category or mode. Instead, it holds the potential to propel social and economic growth while mitigating environmental impact, achieving a win–win development. Numerous industry players have integrated green design into their operational strategies. For instance, in BizLink's 'Sustainability Report' (2021), there is a commitment to resource conservation, carbon reduction, and increased energy efficiency in product design, centering on principles of easy assembly, disassembly, and recyclability, implementing green design thinking throughout the product life cycle, showcasing exemplary circular economic performance. In contrast, Coretronic (2021) has chosen to focus on green raw material selection, introducing a green accounting system to collect and analyze procurement performance while actively purchasing green raw materials, thus fully implementing green supply chain management. It is evident that green design is not only effective in product design but also beneficial in corporate management. As consumer sensitivity to environmental conservation and social responsibility heightens, there is a growing willingness to pay a premium for green products (FirstInsight, 2020) offering a significant advantage for traditional industries in their transformation. In light of this, this study aims to explore the bicycle design process from the perspective of product life cycle assessment (LCA), conduct interviews with experts, analyze and evaluate the industry using grounded theory, and develop a set of green design and carbon reduction methods and strategies applicable to product design, development, and manufacturing processes, in

Table 1 Bicycle life cycle carbon emission ratio (Wang et al., 2021)

Life cycle stages	Raw material extraction	Manufacturing production	Transportation	Maintenance	Disposal recycling
Carbon emission ratio	35%	10%	5%	35%	15%

order to achieve the goal of green transformation and upgrading of bicycle industry. The specific research purposes of this study are as follows:

1. Explore the carbon distribution and design process of bicycle products from the perspective of product life cycle assessment.
2. Gain in-depth understanding of the current situation in the bicycle industry through expert interviews.
3. Analyze and evaluate green design and carbon reduction in the bicycle industry through grounded theory.
4. Develop green design and carbon reduction methods and strategies for the bicycle industry.

As the severity of the Earth's greenhouse effect intensifies, the range of products affected expands in complexity. Industries should bolster environmental management and enhance resource productivity, advocating for a reduction in environmental burdens. When considering carbon footprint management, it is vital not only to adopt a macro-perspective but also to implement proactive measures early on, preventing significant escalations in subsequent management costs. Amidst the impact of the COVID-19 pandemic and trade wars, it is crucial for Taiwanese companies to establish a strong brand image and enhance brand value, so as to strive for global market share. Currently, the industry faces the challenge of high-carbon emissions. In response to global environmental strategies, the bicycle industry should focus on the concept of sustainable manufacturing and aim to achieve carbon reduction and net-zero targets throughout the product life cycle. This direction not only is essential for the development of the bicycle industry but also contributes to the brand value of being a 'sustainable enterprise.'

2 Literature review

2.1 Manufacturing process and life cycle of bicycle

The manufacturing supply chain of most bicycle companies is dispersed worldwide, typically involving component production in Asia and assembly and sales in Europe and America (Adrienne, 2019). The production of a bicycle can generally be divided into six steps: (1) raw material acquisition, (2) metal frame preparation, (3) component welding, (4) painting, (5) frame assembly, and (6) packaging and shipping (Srivastava, 2020). In a speech by Rod Lo, a product designer at Giant Group in 2021, he presented the bicycle design and development process, which involves the participation of several key roles including product managers, engineers, designers, and factories. The product manager is responsible for formulating the bicycle project content, while the designer works on patterns, structures, and other designs (Fig. 1). The engineer ensures component compatibility, dimensions, and conducts safety tests. Effective communication among these three parties is crucial throughout the entire design and manufacturing process.

The life cycle of a bicycle product encompasses five stages: raw material acquisition, manufacturing, distribution and sales, utilization, and waste recycling. The raw material acquisition stage involves obtaining all the necessary raw materials for manufacturing. The manufacturing stage includes processes such as assembly, packaging, and waste management. The distribution and sales stage involves packaging and transportation of the

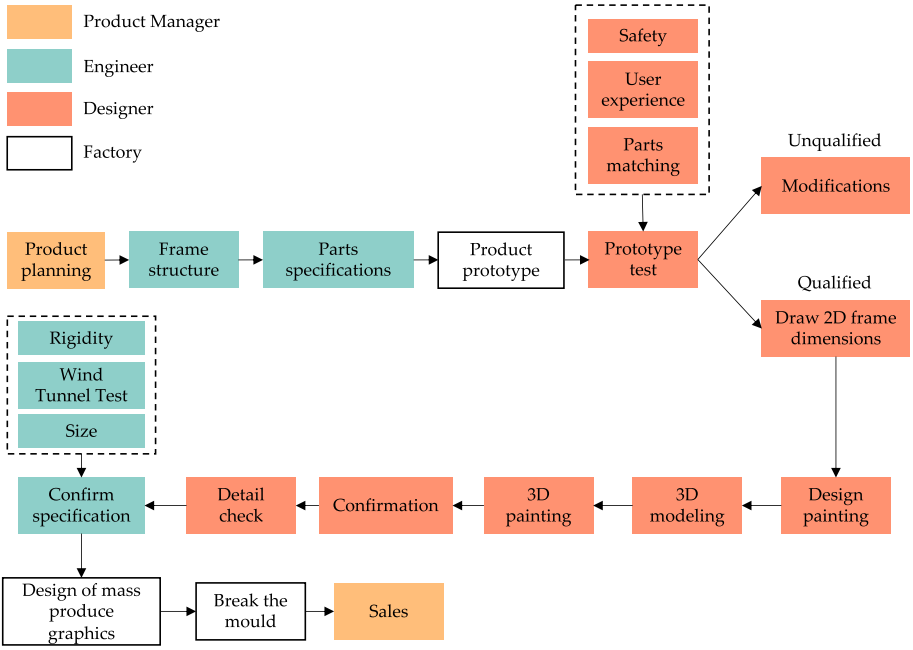

Fig. 1 Bicycle design and development process (Chinese Industrial Designers Association, 2021)

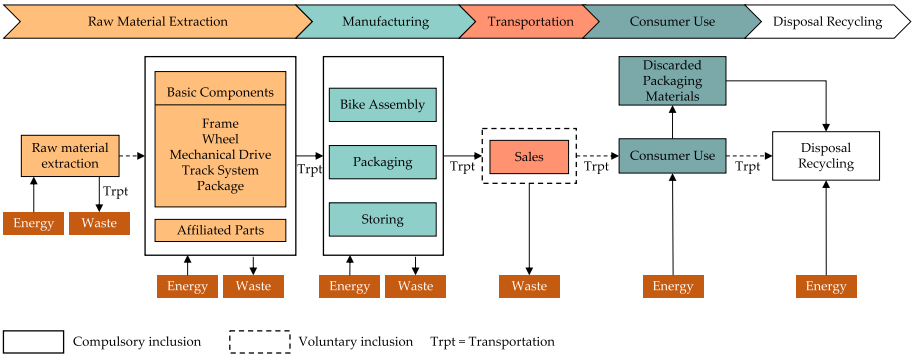

Fig. 2 Bicycle product life cycle process (Environmental Protection Administration, 2011)

products from the factory to the sales outlets. The utilization stage involves component maintenance and replacement. The waste recycling stage is assessed and calculated according to government regulations or program requirements. The specific process is illustrated in Fig. 2.

The advantage of life cycle analysis lies in its ability to comprehensively assess the complete supply chain and value chain formed during each stage of a product's life. By conducting a thorough investigation, it can identify 'hot spot issues' and subsequently improve process design. Therefore, this study incorporates the methodology of product life cycle analysis into the evaluation of bicycle products.

2.2 Distribution of carbon emissions in bicycle products

Bicycles are widely recognized as a green mode of transportation. However, they are not completely carbon emission-free. Throughout the product life cycle, greenhouse gas emissions are generated during the production, transportation, disposal stages, and even related infrastructure construction process (Chen et al., 2023; Lai et al., 2021; Roy et al., 2019; Seb, 2020). In response to societal demand, some manufacturers have begun conducting product inventory reports and analyses. For electric bicycles, a report by Ampler company revealed that the production of each Stellar model produced 815 kg of carbon dioxide, with the main emissions occurring during the component production process (27%) and the electricity usage process (54%) (Tanja, 2022). In 2021, Trek, an American bicycle company, chose three representative bicycles to track their carbon emissions (Table 2). The results showed that on average, the production of one kilogram of steel emitted 1.9 kg of carbon dioxide (Rizwan & Felipe, 2023). The production of one kilogram of aluminum emits a minimum of 6.8 kg of carbon dioxide (European Aluminium, 2022). Clearly, the environmental impact of bicycles is primarily derived from the material preparation stage, and the distribution of carbon emissions during this stage varies depending on the bicycle material. Higher-end products tend to have higher-carbon emissions.

In addition, bicycles also generate a certain amount of carbon emissions during the maintenance and recycling stages. If a bicycle is directly disposed of in a landfill, it takes 31 years to degrade, and it would take us over 600 days of using a bicycle to achieve true net-zero emissions (Chen & Chen, 2018; Chen et al., 2020). Therefore, finding alternative technologies, as well as applying and optimizing recycling and reuse methods, are crucial pathways to maximize the carbon reduction benefits of bicycle products.

3 Methods

3.1 In-depth interview

To ensure the comprehensiveness and professionalism of research data, the selection of interviewees should be guided by the research questions and expertise, taking both internal and external experts into account (Soest, 2023). Therefore, this study selected experts who have been working in the bicycle industry and green design field for more than five years, based on their extensive knowledge and experience. Among the participants, four industry experts have extensive experience in the bicycle sector, representing leading manufacturers, small- and medium-sized enterprises, and governmental departments. Their insights bring a multi-perspective that enriches the research content. The three scholars provide integrated analyses from management, engineering, and design viewpoints, offering a comprehensive perspective on the future development direction of the bicycle industry. The basic information of the interviewees is presented in Table 3.

Centered on the core of this study, the researcher has categorized the interview content into three dimensions. The aim is to understand Taiwan's current carbon reduction status and procedures through industry experts and to explore attitudes toward green carbon reduction from three distinct entities, hoping to identify methods conducive to future collaborative endeavors. Scholar interviews mainly focus on the impact of green design and life cycle research on the industry. Experts are requested to provide industry action

Table 2 Main carbon emission parts and the proportion of different bike models (Trek, 2021)

Model	Type	Carbon emission (kg)	Parts (%)
Marlin	Cross-country mountain bikes	116	Frame assembly (17%), fork assembly (15%), wheel (10%)
Fuel Ex	Trail mountain bikes	153	Frame assembly (18%), fork assembly (14%), crank assembly (8%)
Madone	Performance road bikes	197	Frame assembly (29%), wheel rear (21%), wheel front (15%)

Table 3 Expert interviewees

No	A-a	A-b	A-c	A-d	B-a	B-b	B-c
Fields	Industry	Industry	Industry	Industry	Academic	Academic	Academic
Organizations	Bicycle Wheel Components Manufacturer	Bicycle Parts Manufacturer	Cycling & Health Tech Industry R&D Center	Bicycle Product Distributors	Industrial Management, Sustainable Development	Industrial Engineering, Green Innovation	Environmental Management, Sustainable Development
Title	Senior manager	President	Supervisor	Manager	Professor	Professor	Professor
Qualifications	20 years	5 years	20 years	5 years	20 years	15 years	20 years

recommendations from an academic perspective. Ultimately, the study will integrate the insights of experts from both domains regarding the perceived value of green design carbon reduction in bicycles, analyzing commonalities and differences. The interviews lasted approximately 60–90 min. The interviews were recorded and supplemented with written notes to capture key points. The interview content was then transcribed, coded, and summarized. The interview dimensions are presented in Table 4.

3.2 Grounded theory

To make this research objective and systematic, grounded theory was adopted as the research analysis method. Grounded theory emphasizes the systematic collection and coding of research data and is a method of theory induction from phenomena, generating new theoretical frameworks through an iterative and evolving process (Chun Tie et al., 2019). Due to the nature of grounded theory, it requires researchers not only to actively interact with the industry to obtain genuine data but also to continually ruminate over. This aids in our understanding of the actual conditions and challenges faced by the industry, thereby establishing a carbon reduction method in green design that is both grounded in reality and specifically tailored for the bicycle industry in Taiwan. Therefore, in this study, grounded theory was chosen as the data analysis approach. The content of expert interviews was subjected to open coding, and the analysis process converged toward the development of a central theoretical framework.

The core analytical method of grounded theory is 'coding,' which involves categorizing, conceptualizing, and recombining data. There are primarily three methods: open coding, axial coding, and selective coding. Open coding refers to the conceptualization and categorization of interview data. In this study, 112 concepts (from a1 to a112) and 12 categories (from A1 to A12) were extracted from the data. Axial coding, on the other hand, connects the extracted categories, further elaborating on their properties and dimensions. In the axial coding phase of this research, a total of 6 main categories (AA1–AA6) were identified. Due to length constraints, the description of data coding is shown in Table 5.

4 Results

4.1 Key point of expert interviews

Based on the research objectives and framework, this study conducted literature review and adopted life cycle perspective in the first stage to understand the carbon distribution and design processes of the bicycle industry. In the second stage, expert interviews were conducted to gain insights into the current status of the bicycle industry and to explore the feasibility, evaluation, and potential of carbon reduction through green design in the

Table 4 Interview structure

Type	Industry	Academic
First dimension	Industry situation	Green design impact on industry
Second dimension	Carbon reduction program	Action recommendations
Third dimension	Cognition	Cognition

Table 5 Open coding instructions

Type	Level	Code	Instruction
Open coding	Level I	A-a, A-b, A-c...	A is a group of industry experts, Bis a group of academic experts, a, b,c... are different expert numbers.
	Level II	01,02,03...	Paragraph coded for transcript.
	Level III	1,2,3...	Coded order for transcript.
	Example	A-a-01-1	Industry experts a -first paragraph- first code.
Open coding	Conceptualization	a1, a2...a112	a1 Consumer motivation. a2 Future market trends. a3 Difficulty in recycling.…
	Categorization	A1, A2...A12	A1 Current status of productprocessing A2 Carbon reductionmotivation and customerdemands A3 Current carbon reductionaction of enterprises…
Axial codin	Main categories	AA1, AA2...AA6	AA1 Current carbonreduction status AA2 International carbonreduction policy AA3 Expert suggestions…

bicycle industry. Through data synthesis and analysis, the study will ultimately develop methods and strategies for carbon reduction through green design in the bicycle industry. By interviewing with seven experts and integrating their opinions, the study will identify similar views between the experts from both domains. This will provide valuable insights and recommendations for the application of carbon reduction through green design in the bicycle industry. Subsequently, this information can be used to develop methods and strategies for implementing green design procedures for carbon reduction (Table 6).

4.2 Current status of green design and carbon reduction implementation in Taiwan's bicycle industry

The current state of Taiwan's bicycle industry is still primarily focused on traditional development approaches, with carbon reduction measures mainly centered around replacing power-consuming equipment or adopting high-efficiency devices. However, in recent years, there have been distinctive carbon reduction actions. Some companies have started hiring professional green consulting teams to conduct comprehensive assessments of their overall carbon emissions. Additionally, they are guiding their employees toward a shared understanding of carbon reduction through education and training initiatives. For instance, the Giant Company, as one of Taiwan's largest bicycle enterprises at present, faces the global trend of carbon reduction. Its R&D center in Taiwan is actively implementing a carbon reduction plan, carrying out greenhouse gas inventories, and conducting life cycle assessments. Moreover, they periodically host environmental seminars. This not only allows them to uncover new directions and opportunities for carbon reduction during the learning process but also facilitates a consensus between the management and employees, ensuring they work collaboratively toward their goals. Furthermore, experts suggest the need for a positive drive to transform the mindset of top management, viewing climate change and the global net-zero trend as opportunities for business development. However, besides from these efforts, Taiwan currently lacks clear carbon reduction regulations or carbon tax legislation. As a result,

Table 6 Scope and concepts of expert interviews

Type of experts	Topics	Concepts
Industry experts	Status of development	Design-driven requirements Relatively little investments in new technologies in recent years Established regulatory requirements for bicycle production Current carbon emissions are primarily determined by the electricity consumption of factories Metal bicycle frames have a higher-carbon footprint in terms of raw material acquisition, while carbon fiber frames have a higher-carbon footprint during the manufacturing process The bicycle industry features intricate division of labor and is highly interconnected
	Motivation to carbon reduction	Customer-driven requirements It is influenced by regulations and policies related to export requirements
	Current carbon reduction status of enterprises	Large bicycle companies have started implementing carbon reduction measures, while small- and medium-sized enterprises show relatively little awareness or response The main measures taken include replacing factory equipment, utilizing green energy sources, reducing painting processes, and conducting carbon footprint verification Development of circular business model
	Incentives for carbon reduction	Government funding/investment Enhancing brand image Global trends
	Problems in execution	Immature recycling technologies and high costs Low consumer acceptance Difficulties in balancing quality Lack of initiative Lack of viable commercialization model Unwillingness to take risks

Table 6 (continued)

Type of experts	Topics	Concepts
Academic experts	Process of development	The primary carbon emissions of the product come from raw material acquisition Choosing different materials to reduce the carbon footprint of raw materials Development of lightweight bicycle design trends
	Suggestions for action	Green design and carbon reduction are two different concepts that require defining the points of concern Reducing materials, utilizing alternative energy and materials, standardizing specifications, embracing the principle of easy disassembly, lightweighting, adopting green business models, and extending product life cycles Establishing a robust circular business model Promoting collaboration between upstream and downstream manufacturers Implementing phased execution plans Systematizing carbon emissions data
	Perceived value	Building a positive corporate image Reducing carbon tax costs Linking industries for mutual profitability
	Recycling mechanism	Forming alliances with recycling businesses Enhancing the development of metal material recycling technologies Reducing recycling costs Standardizing recycling quality

proactive carbon reduction actions within the business sector are primarily focused on minor adjustments, particularly for small- and medium-sized enterprises that are customer-driven. Without customer demand, it is challenging for them to undergo significant changes. With the changing landscape of carbon taxation in the international market, Taiwanese companies are forced to respond reactively to carbon reduction initiatives. Experts believe that if the Taiwanese government introduces subsidies or tax policies specifically targeting carbon reduction in the future, it would greatly encourage industries to actively pursue energy-saving and carbon reduction measures. Faced with the changing trends in the international market, leading bicycle companies in Taiwan are gradually transitioning toward green design and carbon reduction in their production processes. However, there are still many areas where they can learn and draw inspiration from major bicycle manufacturers abroad.

In the manufacturing process of bicycles, design is an important determining factor. To apply green design and carbon reduction methods and strategies in the bicycle industry's manufacturing processes, most experts believe that there is a need for technological updates and breakthroughs. However, achieving this goal is challenging for a single company alone. It requires coordination among various levels of the supply chain to effectively implement green design and carbon reduction in bicycle products. However, due to differing motivations and interests between leading companies and small- and medium-sized enterprises (SMEs) in Taiwan, SMEs often follow a business model driven by customer demand. These enterprises consider the actual user experience as the primary production consideration. Therefore, there needs to be sufficient customer demand to motivate manufacturers to undertake carbon reduction initiatives. On the other hand, leading companies believe that implementing carbon reduction can create new value for their brand image. With the increasing recognition of environmental awareness in Taiwan society, 'green enterprises' are favored by consumers and are expected to generate more favorable benefits in the future. Hence, the implementation status, attitudes, and motivations of applying green design and carbon reduction in Taiwan's bicycle industry exhibit a polarized distribution (Fig. 3).

4.3 Feasibility analysis of green design and carbon reduction in the bicycle industry

With the increasing attention of governments worldwide to climate change issues, the demand for achieving net-zero carbon emissions has become imperative (B-a-02-10). Many international brands have already established green supply chains to promote green

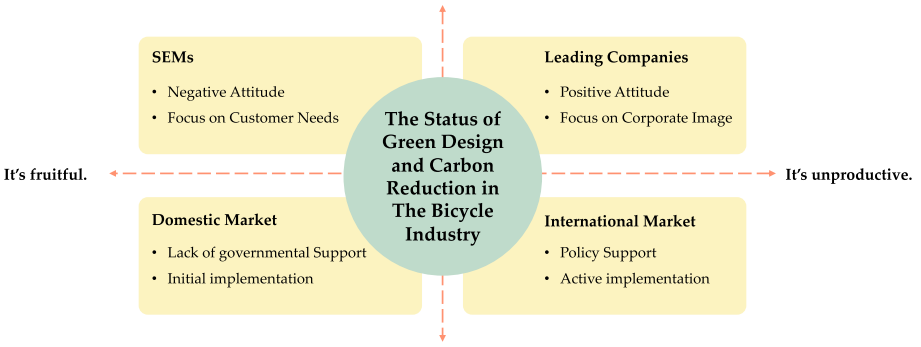

Fig. 3 Status of green design and carbon reduction in bicycle industry

production and consumption, aiming to fulfill business social responsibility and achieve the United Nations Sustainable Development Goals (SDGs). The European Union will officially implement the Carbon Border Adjustment Mechanism (CBAM) in 2026, which will establish corresponding carbon prices based on the average carbon trading price within the EU Emissions Trading System (EUETS). On the other hand, imported products to the EU will also need to pay the same carbon cost as domestically produced goods, offsetting the carbon emissions upon importation with CBAM certificates. The CBAM will include both direct and indirect greenhouse gas emissions, with a primary focus on industries such as cement, electricity, fertilizers, steel, and aluminum in 2026. It is expected that by 2030, the regulation will also cover carbon emissions from industries such as construction and the use of petrochemical fuels in transportation (European Commission, 2022). Consequently, for Taiwan's local industry primarily engaged in exporting bicycle components, the production costs will inevitably increase, creating a disadvantageous situation in terms of international market competitiveness. In order to facilitate better green product design and carbon reduction planning for Taiwan's bicycle industry, this study conducts an integrated analysis of the macro-environment and various internal and external factors using PEST and SWOT frameworks (Tables 7 and 8).

Through PEST and SWOT analysis, it has been identified that the bicycle industry in Taiwan is currently facing the influence of external carbon reduction policies and internal risk pressures. With the implementation of international carbon border policies, many foreign bicycle companies are required to disclosure of information such as carbon label and carbon emissions for imported products. To ensure the accuracy and authenticity of carbon emission data, verification by official agencies is required. Meeting carbon reduction standards entails time and financial investment for testing and modification. Furthermore, the European Union is a global leader and indicator in carbon pricing policies. An increasing number of countries, including the USA, the UK, and South Korea, are considering adopting mechanisms similar to the EU. The cumulative long-term impacts brought by these

Table 7 PEST analysis of carbon reduction in the bicycle industry through green design

Politics	Economy
1.Implementation of carbon reduction and net-zero emission policy and objectives. 2.Support the establishment of a comprehensive ecosystem in the bicycle industry to form a complete industry chain. 3.Greenhouse Gas Emission Control. 4.Promote collaboration among industry, government, academia, and research sectors. 5.Promote the adoption rates of green energy usage.	1.Rise of the sharing economy and circular economy. 2.Implementation of Carbon Border Adjustment Mechanism by the European Union. 3.Global raw material industries need to implement carbon reduction measures. 4.The bicycle industry, as a representative industry of Taiwan, has a significant impact due to its large-scale exports. 5.Increasing manufacturing costs in the bicycle industry.
Society	**Technology**
1.Rising environmental awareness. leads to the use of low-carbon products. 2.Favor toward green and circular enterprises. 3.Public support for bicycle riding.	1.Possessing strong capabilities in component manufacturing. 2.Possessing capabilities in complete bicycle design and development. 3.Committed to the development of mid- to high-end bicycle technologies. 4.Having a vast bicycle industry chain.

Table 8 SWOT analysis of green design and carbon reduction in the bicycle industry

Strengths	Weaknesses
1.Leading enterprises initiating carbon reduction actions and collaborating with midstream and downstream companies to establish green consensus in the industry chain. 2.Replacement of outdated equipment within the factory premises Implementation of subsequent secondhand recycling mechanisms and shared service initiatives. 3.Incorporation of modular design during the design and manufacturing process stage. 4.Utilization of low-carbon electricity. 5.Reduction of chemical spray painting and coatings. 6.Establishment of a visualized carbon footprint system.	1.High implementation costs of carbon reduction. 2.Extended product verification time required. 3.Challenges in developing and manufacturing recycled materials. 4.Limitations in recycling technologies for recycled materials. 5.Challenges in altering user behavior patterns. 6.Time-consuming process to achieve industry consensus. 7.Lack of awareness and preparedness in many small- and medium-sized enterprises regarding the crisis and countermeasures.
Opportunities	**Threats**
1.Development of a new green bicycle industry chain. 2.Enhancement of brand image and value. 3.Creation of new green business models and services. 4.Leading enterprises effectively driving carbon reduction methods in small- and medium-sized enterprises.	1.Difficulties in maintaining and controlling the balance of supply and demand in traditional industries. 2.Carbon reduction actions require investment of financial resources, and many small- and medium-sized enterprises are reluctant to implement them. 3.Uncertainty in consumer acceptance during the development of new products. 4.Imbalance between extending product life cycles and business interests. 5.Customers tend to choose manufacturers offering lower costs.

factors cannot be ignored by Taiwanese enterprises. The implementation of a carbon tax in Taiwan faces challenges, especially in the details of the system's formulation and the management of funds. The government should consider this from a macro-perspective, transforming the net-zero targets into financial tools to help alleviate the economic impact. This responds to the demands for green revitalization amidst the pandemic, alleviates the vulnerabilities under the climate impact, and promotes a just transition. Considering Taiwan's position as a major exporter of bicycle products worldwide, and in light of the promotion of net-zero carbon emission, the bicycle industry needs to collaborate with various sectors such as production, government, academia, and research. It is crucial to actively engage with industry-leading companies and establish a consensus on carbon reduction, which will facilitate the implementation of effective carbon reduction measures.

4.4 Green design and carbon reduction methods and processes in the bicycle industry

As a representative of green transportation, bicycles play a crucial role in achieving net-zero carbon emissions in the industry. It is essential to examine and plan for relevant specifications in green design and carbon reduction throughout the design and manufacturing processes. To achieve green design and carbon reduction goals in the bicycle industry, a comprehensive life cycle approach is necessary to effectively reduce carbon emissions.

This includes establishing robust strategies for green product design and extending the life cycle of products through recycling and regeneration stages.

Based on the product design and development process in the bicycle industry, the following green design and carbon reduction plan is proposed (Fig. 4):

4.4.1 Product planning phase

Companies need to identify the carbon emissions associated with each component of the product, as carbon footprint verification is a primary task for enterprises. If enterprises encounter difficulties during the initial implementation, they can seek assistance from third-party evaluation agencies, universities, and research centers to clarify the inventory procedures and methods. By doing so, they can achieve the best results with half the effort.

4.4.2 Design and development phase

Designers should collaborate with engineers to establish a shared understanding and consensus on carbon reduction. Incorporating the concepts and methods of green design throughout the design and engineering collaboration process, and targeting materials with higher-carbon emissions for alternative design and testing (such as marine waste materials, recyclable aluminum, etc.), or improving product packaging and transportation methods (such as reusable packaging, multi-functional packaging, reducing packaging materials and space, etc.) can reduce the overall environmental impact of product development by at least 70%.

4.4.3 Production and manufacturing phase

It is important to assess the carbon footprint at each stage of the product life cycle and set carbon reduction targets. For example, considering the carbon emissions associated with raw material sourcing during the initial design phase and selecting low-carbon, lightweight materials or utilizing recycled materials for processing and production. Modular and easy-to-disassemble designs can also help reduce recycling costs. Focusing on simplifying and

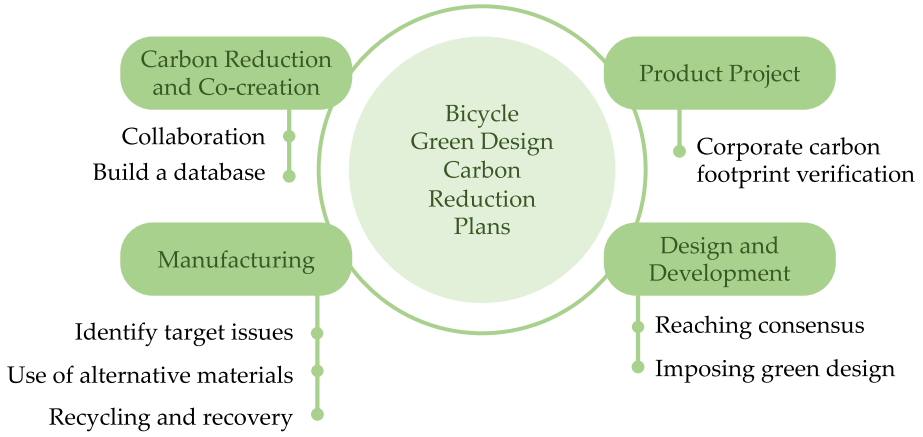

Fig. 4 Bicycle green design carbon reduction method

lightweighting specific aspects can contribute to overall carbon reduction, such as upgrading energy-consuming equipment, changing materials, reducing paint coatings, minimizing welding points, and reducing the number of bent tubes. Finally, at the end of the product life cycle, minimum energy should be used for recycling or regeneration.

4.4.4 Co-creation of carbon reduction

In addition to internal changes in design and production processes, collaboration with external companies or related industries is crucial. In the current business model, long-term cooperation among enterprises can have a significant impact. For example, suppliers focusing on carbon reduction in materials or proactively providing carbon-reducing materials to manufacturers can effectively drive upstream industries to take carbon reduction actions, indirectly influencing the entire production mode and carbon emissions of the industry chain. Therefore, companies can establish a shared carbon information platform within the existing system, systematically and quantitatively measure carbon emissions, and propose specific carbon reduction action plans. This collaborative approach can enhance the effectiveness of green carbon reduction in the industry.

Finally, this study presents the process flowchart for green design and carbon reduction in the bicycle industry as shown in Fig. 5.

4.5 Green design and carbon reduction strategies in the bicycle industry

In response to carbon reduction demands, the bicycle industry also needs to prioritize green design and carbon reduction processes and strategies for its products. 'Sustainability' is not only aimed at enhancing brand competitiveness and expanding international markets, but also assisting businesses in achieving sustainable operations and maintaining an environmentally friendly industrial ecosystem, thereby promoting collective progress throughout the industry value chain. Through the aforementioned research analysis, it can be observed that the bicycle industry is currently facing the impact of external carbon reduction policies and internal risk pressures. Consequently, we have formulated green design and carbon reduction strategies for the bicycle industry, providing reference for future industry actions.

4.5.1 Risk reduction and increased implementation willingness

When facing market changes, the primary consideration is the interests of the enterprise itself. Therefore, systematic thinking is necessary during the implementation process, as any change can have crucial impacts. Therefore, it is recommended that Taiwan's bicycle industry initiates carbon reduction actions led by industry leaders. By leveraging their significant influence, they can start with localized changes and continuously adjust and communicate, minimizing risks. Additionally, engaging third-party consulting teams can assist in carbon reduction implementation and further cultivate green thinking among internal employees. For small- and medium-sized enterprises, phased carbon reduction tasks can be initially implemented, setting gradual goals and making adjustments, which can facilitate the execution of subsequent carbon reduction strategies and mitigate internal risks. Following the footsteps of industry leaders, their execution processes and methods can be referenced to reduce the probability of errors. Furthermore, effective financial planning should be undertaken to assess costs and risks, thereby minimizing business losses.

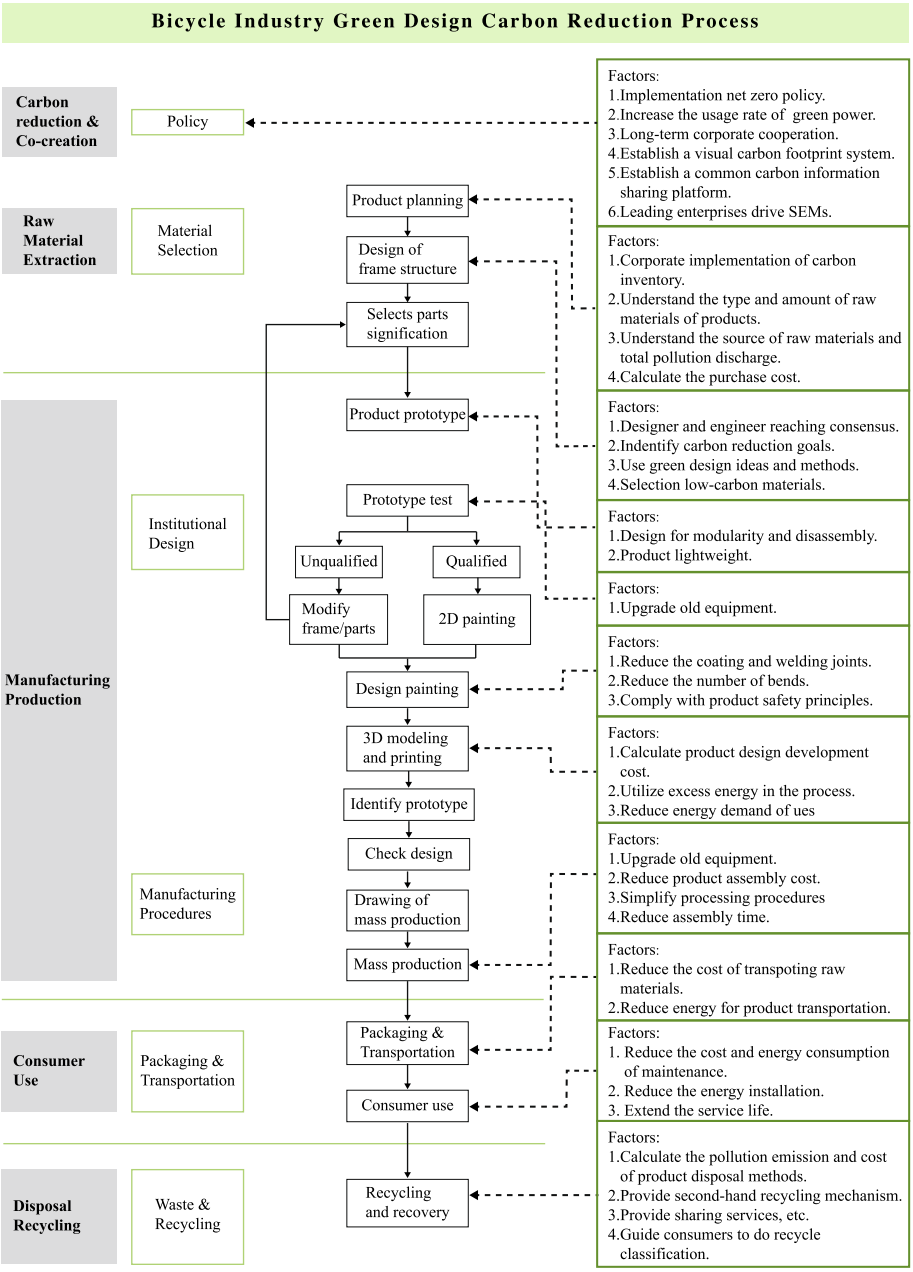

Fig. 5 Bicycle industry green design flowchart

4.5.2 Transformation of product–service models

Facing the market demand for carbon reduction, the bicycle industry needs to reconsider sustainable business models based on circular economy principles. It is recommended to

establish appropriate sustainable product–service systems. In line with changes in product usage and consumption patterns, diverse and high-quality product services should be provided, strengthening after-sales service and maintenance systems to enhance customer satisfaction and product life cycles. If consumers do not understand the carbon emissions of the production line well enough, they can easily mistake some products as eco-friendly. Therefore, industries should strengthen sustainable marketing and disclose green information to enhance consumer trust. This approach can enhance the company's image and market competitiveness, achieving a balance between business profits and environmental sustainability, and realizing the goal of sustainable operations.

4.5.3 Implementation of carbon footprint verification throughout the life cycle

Currently, Taiwan's bicycle industry is facing the challenge of achieving net-zero carbon emissions. 'Green design' and 'carbon reduction' are two different concepts, often unable to align their goals during implementation; thus, it is necessary for Taiwan's bicycle industry to anchor on a key problem and devise targeted solutions to successfully achieve carbon reduction targets. Thus, carbon footprint verification is an essential part of entering the green design carbon reduction process for enterprises. Through comprehensive analysis of each stage of the product life cycle, specific carbon emission issues can be identified, and carbon reduction strategies can be formulated accordingly, enabling the industry to continuously progress toward more specific carbon reduction objectives. Given the current situation in Taiwan, for bicycle carbon reduction initiatives, it is necessary to first assess the carbon emissions released during the product life cycle, identify specific impact points, and then modify designs or processes using green design principles and guidelines. This approach can also avoid large-scale projects, reducing cost investments. Although the progress is relatively slower, it can lay a solid foundation for the successful transformation of the enterprise in the future (Figs. 6 and 7).

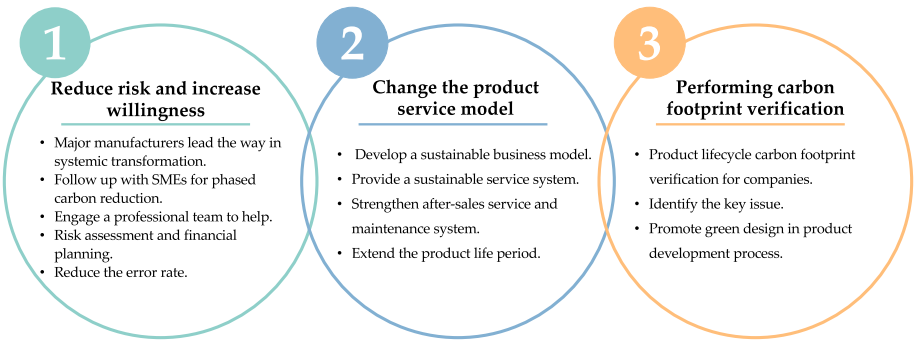

Fig. 6 Bicycle industry green design carbon reduction strategy

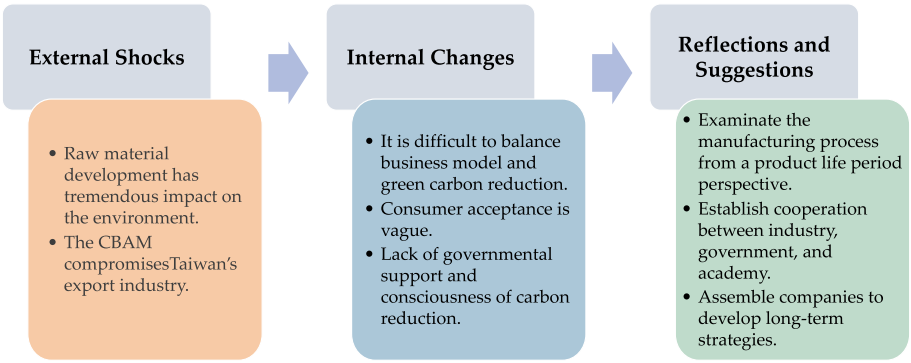

Fig. 7 Key point of bicycle industry

5 Conclusions

Compared to industries in other countries that have been implementing carbon reduction measures for several years, Taiwan is still in the early stages. Due to geographical factors, many industries in related fields in Taiwan primarily engage in contract manufacturing. However, the environmental impact of metal materials during raw material production and manufacturing processes should not be underestimated (Roy et al., 2019). Currently, many internationally renowned bicycle brands are demanding that Taiwanese factories implement carbon reduction plans due to the EU's carbon border tax. In order to reduce carbon emissions during transportation, some international brands are gradually merging manufacturing and assembly plants to minimize emissions generated during the transportation process (DECATHLON, 2023). This undoubtedly poses a significant challenge for the manufacturing industry in Taiwan. For small- and medium-sized enterprises, the difficulty in implementing green design and carbon reduction plans lies in the inability to balance the business model. High costs and prices reduce customer acceptance, making it necessary to consider suitable commercialization models to meet customer demands. Additionally, the industry lacks understanding of the implementation methods for green carbon reduction, leading to limited capabilities. However, it is worth mentioning that major bicycle manufacturers in Taiwan maintain an optimistic attitude while encountering the industry's shift toward green carbon reduction and hope to serve as leading companies driving the progress of Taiwan's industry.

Addressing today's environmental issues requires broad and comprehensive thinking. This research invites experts deeply involved in the bicycle industry and green design for in-depth interviews. The results of these interviews can help us understand some undisclosed industry conditions and challenges, and also facilitate discussions with academic experts regarding these issues, which is beneficial for future carbon reduction planning for both the industry and the government. Based on the interview results, we propose some forward-looking recommendations that provide solutions for various scenarios for Taiwan's bicycle companies. Additionally, a significant reduction in carbon emissions by businesses relies on collaborative planning stakeholders (Pee et al., 2018), so our research also presents possibilities for achieving consensus and future cooperation among companies. In addition to proposing green design and carbon reduction methods and strategies applicable to Taiwan's bicycle industry, this study also offers

some reflections and recommendations regarding the challenges and difficulties faced by the industry in green design and carbon reduction. In the early stages of implementing carbon reduction plans, after companies have just completed the internalization of carbon tax costs, they face relatively higher expenses. Given these challenges, businesses need the government to establish policy to balance out the price disparities, like carbon tax system or Carbon Dividend feedback mechanism, that can directly redistribute the carbon tax to the citizens, ensuring that everyone benefits from carbon reduction efforts. This approach promotes a collective consensus on carbon reduction, preventing the discussion from being confined solely to the industrial sector. Policy support has a positive impact on carbon emission reduction efficiency, and previous research supports this conclusion (Danish et al., 2020; Wu et al., 2022). Simultaneously, the industry should create new market demands. By introducing carbon-reducing products for specific consumer groups or establishing collaborative marketing platforms, larger brands can help elevate smaller ones, boosting Taiwan's brand reputation and its sustainable value. Moreover, it is beneficial to assess bicycle products from a life cycle perspective, which allows the industry to identify hot spots and issues more effectively, and then addressing these issues using green design principles, progressing steadily and strategically. To effectively achieve carbon reduction design strategies, collaboration and support from various sectors including industry, government, academia, and research are essential. Breaking the conceptual gap between the industry and academia is necessary to guide the industry in establishing a sustainable circular value concept, integrating new technological developments from experts and scholars, government policies, and consumer trends. By uniting upstream and downstream industries and jointly formulating long-term implementation plans, the industry can reduce transition risks, achieve carbon reduction goals, and create a new generation of bicycle products within a circular economic system.

Given that bicycles are composed of various parts, their production often depends on raw materials and components from different countries. As such, achieving carbon reduction in the bicycle industry is not a goal that can be realized solely by one entity. Although this study focuses on the bicycle industry in Taiwan, the research findings can still provide reference for other countries facing similar challenges. The Taiwanese industry can collaborate with OEM manufacturers in countries like Vietnam and Cambodia to jointly plan carbon reduction policies and strategies, ensuring carbon reduction right from the source. This study also conducts a feasibility analysis for the bicycle industry, presenting global development trends and potential future directions. Subsequent studies can also test the methods and strategies proposed in this research in actual industry settings. For instance, based on their financial capacity (whether leading large enterprises or SMEs), companies can undertake targeted carbon reductions, implementing green design carbon reduction plans proposed in this study in a phased manner for their entire production process. It is also hoped that this research can facilitate a consensus between the industry and academia, thereby providing more practical implementation suggestions and promoting green design and carbon reduction in the industry. The limitations of this study are that the research field is confined to the Taiwan bicycle market, which lacks a broader research perspective, and that we have adopted a purely qualitative study, which may be mired in a more subjective analysis. In the future, we aim to continue collaborating with the industry and government research centers. By approaching from a design perspective, we can assist the industry in green carbon reduction. Additionally, we can develop more carbon assessment tools or product checklists for industry use, simplifying the carbon reduction process, boosting industry confidence, and enhancing brand competitiveness.

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Author contributions J-CT, S-CL and P-CH were involved in conceptualization, validation, and project administration; S-CL and P-CH were responsible for methodology, formal analysis and investigation, data curation, and writing—original draft preparation; and J-CT and X-YZ contributed to writing—reviewing and editing, and supervision. All authors have read and agreed to the published version of the manuscript.

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Data availability The data in this study are available on request from the corresponding authors. The data are not publicly available due to the privacy.

Declarations

Conflict of interest The authors declare no conflict of interest.

Informed consent Informed consent was obtained from all subjects involved in the study.

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