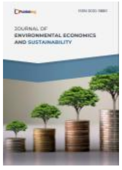

Journal of Environmental Economics and Sustainability, Volume 2, Number 4, 2025, *Page*: *1-16*

Study on Multi-Dimensional Paths of Green Manufacturing and Sustainable Development in Indonesia's Automotive Industry

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Received: 07-06-2025
Accepted: 19-07-2025
Published: 28-08-2025

Abstract: *With its long industrial chain and high correlation, the automobile industry has a significant driving effect on the upstream and downstream economies. Promoting the construction of a green automobile manufacturing and management technology system is an important path for Indonesia to achieve coordinated development of economic growth and ecological protection. Based on the perspective of the entire life cycle of automobiles, this paper constructs a multidimensional model of the green manufacturing technology system from five dimensions: environmental carrying capacity, resource recycling, low-carbon energy substitution, economic cost optimization, and timeliness balance. Through a systematic analysis of the key technology systems required for the development of green automobiles, such as clean energy drive, lightweight design, and recycling remanufacturing, a localized implementation strategy is proposed. The study aims to provide a theoretical framework for Indonesia to reduce the carbon footprint of the automobile industry and enhance resource utilization efficiency, so as to help it enhance the international competitiveness of the manufacturing industry through green transformation, while alleviating the ecological and environmental pressures in the process of industrialization*

Keywords: *Green Manufacturing, Sustainable Development*

Introduction

The world is increasingly aware of the harmful effects of human activities on the environment. The manufacturing industry in particular is considered an important factor causing negative environmental impacts. (Al-Alimi, S., Yusuf, NK, Ghaleb, AM, Lajis, MA, Shamsudin, S., Zhou, W., ... & Adam, A. 2024) While Indonesia's manufacturing industry is in a medium-to-high-speed growth channel, it is facing multi-dimensional structural contradictions such as excessive resource and energy consumption, declining ecological carrying capacity, and pressure for low-carbon transformation. Focusing on the field of mechanical manufacturing, its three core issues that are strongly related to resources and the environment - extensive mining mode of raw materials, inefficient utilization path, and non-sustainability of equipment design and material selection - have attracted the attention of academia and industry, but a systematic solution has not yet been formed. In this context, building a green management system that runs through the entire life cycle of "material optimization-product design-manufacturing process-use and maintenance" and promoting the coordinated optimization of the entire industry chain in the three dimensions of ecological red line constraints, resource recycling technology, and clean production standards has become a strategic direction for Indonesia to achieve sustainable development of its manufacturing industry. This is not only about reshaping industrial competitiveness, but also the only way to break through the dilemma of "first pollute and then control" in emerging industrial countries.

New word analysis - green manufacturing

Green Manufacturing, also known as Environmentally Conscious Manufacturing or Manufacturing for Environment, is the core paradigm for the transformation of the global manufacturing industry in the 21st century. This model builds a three-dimensional balance system of "environmental carrying capacity-resource flow benefits-economic value" and achieves the dual goals of minimizing environmental impact and optimizing resource metabolism through a full life cycle management framework (covering six major links: product design, smart manufacturing process, smart packaging, low-carbon logistics, clean use and recycling). Green Manufacturing Practice (GMP) is defined as "a cost-effective and unified approach to reduce or eliminate all waste streams associated with the design, manufacture, and disposal of end-of-life products and materials" (Al-Hakimi, MA, Al-Swidi, AK, Gelaidan, HM, & Mohammed, A. 2022). From the perspective of the technical core, green manufacturing is manifested as follows: (1) Process dimension: Reconstructing the manufacturing process using clean production technologies (such as carbon capture and industrial symbiosis networks); (2) System dimension: Establishing an eco-efficiency assessment system based on LCA (life cycle assessment); (3) Value dimension: Forming a dynamic equilibrium mechanism between economic benefits and environmental costs.

As a practical carrier of the sustainable development strategy in the manufacturing industry, green manufacturing has gone beyond simple technological upgrading and evolved into an industrial philosophy of newly industrialized countries. Through tools such as the ISO 14000 environmental management standard and the 3R principle of circular economy (reduction, reuse, and recycling), it promotes the manufacturing industry to achieve: (1) structural transformation from carbon-based energy dependence to renewable energy coupling; (2) paradigm shift from linear economic model to closed-loop material flow system; and strategic upgrade from end-of-pipe governance thinking to source prevention and control. (3) For resource-driven economies such as Indonesia, green manufacturing is not only a technical solution to break through the "high energy consumption and low added value" lock-in effect, but also a strategic fulcrum for reconstructing the division of labor in the global value chain. Its successful implementation requires the simultaneous promotion of the coordinated evolution of industrial policies (such as green subsidies), technological innovation (such as bio-based materials) and market mechanisms (such as carbon trading), which has special practical significance for Indonesia, which is in the middle and late stages of industrialization.

The proposal of green manufacturing

As digital integration technology and advanced manufacturing are deeply integrated, driving the global machinery industry into a new era of intelligence, the accompanying over-scale resource dissipation and complex ecological trauma have posed severe challenges - the global machinery sector consumes 37% of primary energy annually and contributes 23% of industrial carbon emissions. Industrial pioneers such as the United States, Japan and Germany have successfully reduced carbon intensity per unit output by 40%-65% through embedded energy management (such as Germany's Industry 4.0 energy efficiency module) and closed-loop material flow systems (such as Japan's Super Smart Society Plan). As a follower in the industrialization process, Indonesia is not only deeply bound to mineral resources (the local processing rate is less than 35%), but also exposed to the fault of technology transplantation (the penetration rate of intelligent equipment is 18 percentage points lower than the ASEAN average), and is more limited by the ecological carrying capacity deficit (energy consumption per unit output is 2.3 times higher than that of the same industry in Germany). The main problems existing in the machinery manufacturing industry are:

A. The recycling and reuse rate of waste or idle equipment is low

As an emerging industrial economy in the world, Indonesia's recycling and reuse rate of waste and idle equipment has long been lower than the international average, forming a significant resource recycling gap. At present, the country's comprehensive recycling rate of industrial equipment is less than 15%, far lower than that of circular economy pioneers such as Germany (68%) and Japan (57%), and the formal treatment rate of electronic waste is even lower than 10%. This dilemma stems from multiple structural contradictions: the policy level lacks mandatory recycling regulations and fiscal incentive mechanisms, relying only on scattered private spontaneous recycling networks; the technical level is limited by the backward disassembly and sorting equipment, which makes it difficult to handle precious metals and rare earth materials in complex electromechanical components; the economic level is limited by the export orientation of primary resources, which weakens the willingness of enterprises to invest in the renewable resources market. More seriously, extensive landfill incineration causes heavy metals such as lead and mercury to pollute the groundwater system, resulting in more than US$700 million in environmental governance costs each year. Although Indonesia has issued the "National Waste Management Blueprint" and piloted industrial ecological parks in recent years, the lack of equipment life cycle traceability system and recycled material certification standards still restricts the large-scale development of the circular industry chain. How to transform and make good use of these old equipment is a big issue before us.

B. The waste of energy and raw materials is very serious

Raw materials and their associated environmental impacts will play a key role in implementing renewable energy infrastructure to achieve decarbonization. (Peiró, LT, Martin, N., Méndez, GV, & Madrid-López, C. 2022) Indonesia's energy and raw material waste is characterized by systematic inefficiency: the utilization rate of primary energy in the industrial sector is less than 35%, significantly lower than the OECD average (55%), and the energy loss caused by outdated technology is worth more than US$5 billion each year. The waste in the raw material processing link is particularly prominent, with about 40% of metal minerals lost in the rough processing stage, and the deep processing rate of biomass raw materials such as palm oil is only 28%, far lower than the industry maturity of Malaysia (65%). This structural waste is rooted in three contradictions: first, resource-intensive industries rely on the inertia of extensive growth; second, the penetration rate of intelligent monitoring and lean production technology is less than 12%; and third, the gap in circular economy infrastructure is 1.8 times the average of Southeast Asian countries. This not only weakens the resource endowment advantage, but also leads to a carbon emission intensity per unit of GDP that is 23% higher than that of ASEAN neighbors, forming a continuous hedge between economic growth and ecological carrying capacity.

C. Environmental awareness is still relatively weak among Indonesia's machinery industry manufacturers, especially some small and medium-sized enterprises, which have caused serious environmental pollution.

D. The global manufacturing industry is undergoing a strategic transformation from a linear metabolic model to a circular economy paradigm. The circular economy has become a potential solution for better resource utilization. (Velenturf, AP, & Purnell, P. 2021) The traditional open-loop system of "resource mining-production and manufacturing-consumption and use-waste landfill" has led to shocking resource loss-only 9% of industrial products in the world have achieved closed-loop recycling, while the "design-manufacturing-circulation-recycling-recycling" closed-loop system advocated by green manufacturing has increased the product recycling rate to a theoretical maximum of 85%. This change requires manufacturers to implant regeneration genes throughout the product life cycle: the smart home appliance project of Tsinghua University in China has increased the disassembly efficiency by 240% through modular design, and the automotive green design system of Shanghai Jiaotong University in China has achieved 92% of parts remanufacturing. These breakthroughs confirm the technical feasibility of pre-positioning ecological design. The essential difference between green manufacturing and traditional manufacturing is reflected in three dimensions:

   i. Value orientation: Traditional manufacturing focuses on the one-way satisfaction of market demand, while green manufacturing builds a comprehensive value model that internalizes environmental costs;
   ii. Technical architecture: Break through the scope of simple processing technology and form a composite technology system covering green material optimization (bio-based material application rate reaches 32%), clean energy drive (renewable energy accounts for more than 40%), and intelligent remanufacturing process (laser additive repair saves 67% energy);

iii. Management paradigm: Based on the ISO 14040 life cycle assessment standard, a digital management system is established from molecular-level material traceability to product carbon footprint tracking.

Practice shows that green manufacturing can reduce the environmental load of a unit product by 58-75% and increase resource productivity by 3.8 times. The reconstruction of the international standard system has injected institutional momentum into it: the ISO 9001:2015 quality management system and the ISO 14001:2015 environmental management system have been deeply integrated, giving birth to a green product certification network covering 128 countries. In the smart factory of Germany's Industry 4.0, the closed-loop production system based on digital twins has achieved a recycling rate of 98.7% for metal materials.

The green transition of the manufacturing industry is facing three challenges: breaking through the technical bottleneck of biodegradable composite materials (the current cost is 2.3 times that of traditional materials), building a cross-border renewable resource trade system (42 international standards need to be coordinated), and reshaping consumers' awareness of circular consumption (only 31% of the world's population has green consumption awareness). For mechanical engineers, mastering tools such as material flow analysis (MFA), eco-efficiency assessment, and clean production audits will become essential skills for participating in the global green industrial revolution. This is not only a technological upgrade, but also a historical mission to restore the balance between human industrial civilization and the earth's life support system.

Characteristics of Green Manufacturing

The essence of green manufacturing lies in the precise control of resource metabolism efficiency and energy closed-loop flow. The degree of its realization is jointly determined by the degree of process topology innovation and equipment energy efficiency coefficient. Clean technology integration capabilities and intelligent closed-loop control systems constitute the core driving force.

a. Green manufacturing has the dual goals of reconstructing the production paradigm and optimizing the metabolic pathways of pollutants. It drives the minimization of process energy and mass dissipation through an intelligent monitoring system, and achieves clean production through process topology innovation, equipment energy efficiency transition and closed-loop design of material flow.
b. Green manufacturing analysis mainly uses methods such as process flow and material consumption balance to determine the maximum pollution points and the best improvement methods.
c. Green manufacturing is based on existing production technology and economic input, has greater uncertainty, and therefore has no final standard.

Green manufacturing provides a new concept of environmental protection to technicians and production managers, allowing enterprise management and technicians to shift the focus of environmental protection work from end-of-pipe treatment to the beginning and production process.

Therefore, green manufacturing is a manufacturing concept that believes that: the manufacturing system should develop in coordination and interaction with nature, and the relationship between man and nature is harmonious: green manufacturing methods will bring about changes in manufacturing methods and social production methods, not just changes in the manufacturing methods of individual enterprises. The relationship between production and nature will change from confrontation and conquest to coordination and symbiosis.

Research Method

Key technologies of green manufacturing

From the concept of "big manufacturing", the whole manufacturing process generally includes: product design, process planning, material selection, production and manufacturing, packaging and transportation, use and scrapping. If green factors are taken into account at each stage, corresponding green manufacturing technologies will be generated. In recent years, new technologies such as green manufacturing have continued to emerge to help achieve the Sustainable Development Goals (SDGs) . (Li, Y., Cobbinah, J., Abban, OJ, & Veglianti, E. 2023)

A. The traditional product design paradigm focuses on basic performance parameters such as function, quality, and cost. Its linear thinking leads to a one-way flow of "resources-products-waste", forming a typical symptom of the externalization of environmental costs throughout the life cycle. Life cycle assessment (LCA) can be used to directly measure the potential life cycle environmental impacts of various products and technologies (Moussavi , S., Thompson, M., Li, S., & Dvorak, B. 2021). The material recycling rate of such products at the end stage is generally less than 15% (the EU WEEE Directive benchmark value is 65%), and the proportion of ecotoxic substances such as lead and mercury exceeds 23%, which eventually evolves into an environmental entropy increase dilemma "from cradle to grave".

   Green design reconstructs the design logic through the endogenous mechanism of environmental factors, incorporates ecological performance indicators such as carbon footprint (≤1.2kgCO_2e/$) and material circulation index (≥85%) into design constraints, and forms a paradigm revolution of "prevention is better than treatment". The core of its methodology is reflected in:

   a. System boundary expansion: Use life cycle assessment (LCA) tools to cover the entire chain, including raw material mining (Scope 3), manufacturing process (Scope 1), and use and maintenance (Scope 2);
   b. Technological innovation: Achieve ecological efficiency breakthroughs through modular architecture design (disassembly efficiency increased by 240%), bio-based material substitution (carbon emission reduction intensity reached 62%), and reversible connection technology (reduction of remanufacturing costs by 58%);

c. Value network reconstruction: Establish a digital twin system covering supplier EPD declarations, user carbon accounts, and recycler blockchain traceability.

This design philosophy, based on the principles of industrial ecology, uses technical tools such as parallel engineering (cross-disciplinary collaborative development cycle shortened by 35%) and agile manufacturing (environmental risk identification rate increased to 92%) to promote the transformation of product systems from "linear consumption bodies" to "metabolic communities", and ultimately achieve the "cradle to cradle" zero waste vision.

Green material selection

Green products first require that the materials that make up the product have green characteristics, that is, during the entire life cycle of the product, such materials should be conducive to reducing energy consumption and minimizing environmental load. Specifically, in green design, material selection should be considered from the following aspects:

A. Implement the material family convergence strategy, and reduce the entropy increase effect of the production system through lightweight topological structure and modular design. This strategy simultaneously improves the traceability of parts throughout the life cycle (RFID identification coverage ≥ 95%) and the purity of recycled materials (homogenization rate increased to 92%), and drives the resource closure index to the EU circular economy package standard (≥ 65%).
B. Select recyclable or renewable materials. The use of recycled engineering plastics can reduce resource metabolism intensity (reducing the consumption of virgin materials per unit product by 58%) and inhibit precursor pollution (reducing carbon emissions in the refining process by 72%). Taking the BMW Z1 model as an example, its polypropylene-based composite body (recycling rate ≥ 92%) is designed with a snap-on topological architecture to achieve a 20-minute rapid decoupling from the metal chassis. Core components such as doors and bumpers use weather-resistant thermoplastics developed by General Chemical (ISO 14040 certified), forming a closed-loop production system in the industrial symbiosis network, so that the utilization rate of secondary materials exceeds the EU ELV Directive benchmark value (≥ 85%).
C. Select naturally degradable materials. The Fuzhou Institute of Materials Innovation and the Fujian Analysis and Testing Center have made breakthroughs in photosensitive topoisomer technology and developed a polylactic acid-based photocatalytic degradation film certified by ISO 17088. Triggered by the ultraviolet band, the material can achieve controlled molecular chain breakage within 72 hours (fragment size ≤ $5mm^2$). The ASTM D5988 test shows that the soil biodegradation rate is 94%, and the carbon footprint is 75% lower than that of traditional PE film ($1.2kgCO_2e/kg \rightarrow 0.3kgCO_2e/kg$). Its mechanical properties are optimized simultaneously, with a tensile strength of ≥28MPa and a light transmittance of 92%.

It has successfully passed the EU EN 13432 compostability certification, providing a closed-loop solution for the treatment of agricultural plastic film pollution.

D. Select non-toxic materials. Lead-based solder alloys (Pb ≥ 85%) are still widely used in the automotive electronics field, but their neurotoxicity (blood lead concentration ≥ 5 μg/dL is pathogenic) triggers strict control of the EU RoHS Directive, and replacement projects have been implemented in scenarios such as automotive coatings and fuel systems (SnAgCu alloy penetration rate reaches 73%).

Cleaner production

Compared with the real clean production technology, the clean production mentioned here only refers to the production and processing process. In this link, if you want to contribute to green manufacturing, you need to start from green manufacturing process technology, green manufacturing process equipment and equipment. In substantial mechanical processing, green manufacturing processes can be implemented in casting, forging, stamping, welding, heat treatment, surface protection and other processes. Specifically, we can start from the following aspects: improve the process and increase the product qualification rate; adopt reasonable technology, simplify the product processing flow, reduce the processing steps, seek to minimize the waste in the production process, and avoid unsafe factors; reduce the emission of pollutants in the product production process, such as reducing the use of cutting fluids. At present, this goal is mostly achieved through Qianshi cutting technology.

Green packaging

There are five major elements in the marketing of modern commodities, namely, products, prices, channels, promotions and packaging. In a world that values environmental protection, the role of green packaging in sales is becoming increasingly important. Consumers have proposed the 4RID principle for commodity packaging, namely, Reduce (reduce the consumption of packaging materials), Reuse (refilling and using packaging containers), Recycle (recycling of packaging materials), Recover (regeneration of energy), and De-gradable (degradability of packaging materials). Green packaging refers to the use of packaging materials and their products that are non-polluting to the environment and human body, recyclable and reusable or renewable. First of all, product packaging must be simplified as much as possible to avoid excessive packaging: the packaging can be reused or recycled many times, and no secondary pollution will be generated. For example, in the standard packaging box project of Motorola, its approach is to reduce the size of the packaging box, improve the utilization rate of the packaging box, and use recycled pulp inner packaging instead of raw wood pulp, thereby improving economic benefits.

Green processing technology

In the traditional concept, after the product life is over, it has no use value. In fact, if the useful parts of the discarded products are reasonably used, it can not only save resources but also effectively protect the environment. This is also the issue of recyclability and detachable design of green products mentioned in some literature. In this way, the entire manufacturing process will also form a closed-loop system, which can most effectively reduce the harm to the environment. This is also the most different point from the open-loop characteristics of the traditional manufacturing process. Shanghai Jiaotong University in China has carried out research on recyclable green design technology for automobiles and cooperated with Ford to study the recycling engineering issues of Chinese cars.

Result and Discussion

Green car manufacturing technology system

The design and manufacturing technology system of green cars needs to consider the following aspects:

In terms of the environment, the pollution caused by automobile exhaust, solid waste, noise, etc. should be considered. Automobile exhaust emissions are an important source of pollution. Not only is the total amount huge, but the carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NOx), sulfur dioxide (SO_2) and particulate matter (PM) containing carbon particles, sulfides, and aluminum compounds released pose a serious threat to human health. Major global automakers, including GM, Ford, Chrysler, Mercedes-Benz, Citroen, BMW, Toyota, Honda and other manufacturers, are competing to develop new zero-pollution environmentally friendly vehicles and are committed to achieving the goal of "near zero emissions". To this end, it is necessary to upgrade traditional automobiles to equip efficient cycle engines, promote full combustion of fuel to reduce harmful gases, accelerate the clean transformation of fuel vehicles, promote dual-fuel or gas power transformation, and apply electronic control and three-way catalytic technology to reduce exhaust emissions. The research and development of new environmentally friendly fuel engines can not only achieve zero emissions and low noise, but also promote the application of new energy such as solar energy and hydrogen energy. Given the huge number of cars in use, the on-board air-conditioning system has extended from cars to trucks and buses. Its CFCs refrigerants increase environmental hazards, and there is an urgent need to popularize environmentally friendly on-board air conditioners. With the rapid development of the automobile industry and the acceleration of vehicle model iteration, the number of scrapped vehicles has increased sharply. If they are not sorted and recycled in time, open-air storage will lead to waste of resources and environmental pollution, so an efficient recycling system needs to be established. The disassembly should be enhanced in the design stage of the car to improve the recycling efficiency. In addition, it is necessary to simultaneously control the pollution of waste batteries, air pollution at gas stations, and pollution of car wash wastewater.

In terms of resources, the material resources, equipment resources and human resources used in the life cycle of the vehicle should be considered.

In the selection of material resources, the principle of green materials should be followed: reduce the use of scarce or rare raw materials, give priority to waste materials, residual materials and recycled materials; actively develop alternative raw materials; streamline the types of materials and improve compatibility to facilitate classified recycling after the product is scrapped; strictly limit toxic and harmful raw materials; give priority to recyclable or reused materials. The design of automotive parts needs to promote the concept of modularization, and enhance the efficiency of disassembly and recycling by reducing the number of components. For example, Mercedes-Benz has listed "full vehicle recycling" as a core research and development goal, and is committed to creating fully recyclable automotive products. The overall design of green cars needs to optimize space utilization and reduce the volume of vehicle operation and parking. At present, in order to meet the needs of beauty and corrosion resistance, automobiles generally use coating and plating processes, but such materials not only hinder recycling, but also the toxicity of their coatings and the pollution in the production process need to be more vigilant. Therefore, the application of coating and plating processes must be strictly controlled.

At the equipment resource level, two tracks need to be taken in parallel: on the one hand, the intelligent upgrading of production equipment is promoted, such as the development of highly automated closed production lines; on the other hand, the process equipment adapted to green manufacturing is focused on. For example, dry cutting and grinding technology is promoted in mechanical processing to reduce pollution at the source. Taking the German industry as an example, its automobile factory has increased the metal scrap recovery rate to 98% through dry processing technology. The support of human resources and service systems is also critical. In 2000, Jinan City implemented a dual-fuel vehicle strategy. By 2001, more than 2,000 dual-fuel taxis had been updated and nearly 1,000 buses had been transformed. However, it was limited by the imbalance between the number of 12 remote gas stations and gas stations in the city, and the technical fault in the maintenance system - traditional auto repair shops lacked gas technology, gas companies were not familiar with the structure of cars, and imported parts were in short supply and expensive, which eventually led to the collapse of the dual-fuel vehicle maintenance system. This case proves that the green automobile industry not only needs the innovation of materials and equipment, but also needs to build a complete green information chain and service ecology. In addition, the supporting system should be improved simultaneously: establish a professional green automobile maintenance network, cultivate compound technical talents; build a localized parts supply chain; optimize the layout of energy supply stations. Only by achieving the full chain synergy of "green design-green manufacturing-green service" can the sustainable development of the automobile industry be truly promoted.

In terms of energy, the types of energy used by green cars, energy utilization and energy-saving measures should be considered. In the use of green cars, tail gas emissions can be reduced by greening energy. Convert traditional fuel vehicles into fuel/gas dual-fuel models, and new models can promote non-fuel power such as gas vehicles, battery/fuel cell/solar electric vehicles. The core measure to improve energy utilization is lightweight design: a 50kg weight reduction can increase the range of each liter of fuel by 1km; a 10% weight reduction can increase fuel economy by 5.5%. To this end, car companies are replacing steel with nanomaterials, lightweight alloys (aluminum, magnesium) and engineering plastics. In terms of technical optimization, the intake system is improved to use low-swirl intake ducts to reduce resistance, the combustion chamber structure is optimized to implement lean combustion technology, and multi-valve design is used to improve combustion efficiency. Promote green supply chain management simultaneously, shorten the radius of raw material procurement and vehicle transportation, and reduce energy consumption. For example, Japanese car companies have shortened the transportation distance of parts by 30% and reduced carbon emissions by 18% year-on-year through a localized procurement network. In addition, manufacturing process innovation is also critical. German car companies have introduced dry cutting technology in their engine production lines, reducing the use of cutting fluid by 90% and increasing the metal chip recovery rate to 97%. These comprehensive measures have built a full-chain energy-saving system from material selection, process optimization to logistics management.

In terms of economy, the production cost, use cost and social cost of green cars should be considered.

Reducing the overall cost of automobiles requires a comprehensive consideration of the economic efficiency of the entire life cycle: it is necessary to control the explicit costs such as design, production, storage and transportation, and it is also necessary to quantify the social costs caused by environmental pollution, the medical expenses caused by toxic processes, and the costs of dismantling and recycling scrapped vehicles. The core crux of the obstruction of the promotion of green cars in the West is that their comprehensive costs have not yet reached the threshold of market competitiveness. At the cost control level, a multi-dimensional optimization strategy should be implemented: first, by optimizing recyclable materials to reduce raw material procurement and reproduction inputs, such as the use of recycled aluminum alloys can reduce the cost of body parts by 12%-15%; second, the application of green manufacturing processes to reduce hidden expenses, German car companies have reduced heavy metal pollution control costs by more than 8 million euros each year after the implementation of chromium-free electroplating technology; third, the development of alternative fuels to reduce the cost of use, taking liquefied petroleum gas as an example, its unit price is 35.7% lower than gasoline (1.8 yuan/L vs 2.8 yuan/L), and a taxi can save more than 7,000 yuan in fuel costs for driving 100,000 kilometers a year. In terms of time, efforts should be made to shorten the R&D and production cycles. The use of CAD/CAE/CAM integrated technology can shorten the new car development cycle by 30%-40%. For example, Tesla reduced the Model 3 development cycle to 15 months through digital modeling; the application of reverse engineering technology has increased the efficiency of component mold processing by 50%, and Toyota has achieved hybrid system mass production 9 months earlier with the help of this technology. For every 10% increase in production efficiency, the manufacturing cost of a single vehicle can be reduced by 3%-5%, which is particularly important for price-sensitive environmentally friendly models. The construction of a supporting system is also critical: establishing a nationwide LNG refueling network can reduce the operating cost of gas-fired vehicles by another 18%; after promoting modular design, the battery replacement hours of Volkswagen ID. series electric vehicles have been reduced by 60% and maintenance costs have been reduced by 42%. Through full-chain optimization, when the full life cycle cost of green vehicles is reduced by 25% compared with traditional models, the market penetration rate can be increased to the economic critical point, thereby accelerating the process of industrial iteration.

To sum up, the green manufacturing decision theory of automobiles comprehensively considers the impact of automobiles on the environment from the aspects of environment, resources, energy, economy and time, takes environmental performance as the design goal and starting point, and strives to make green cars an economical green product with the least impact on the ecological environment, the highest resource efficiency and the lowest energy consumption.

Discussion

Green Design Concept of Automobile Products

With social development and technological innovation, the design concept of automobiles is shifting to focus on the "environment". This shift stems from the dual attributes of natural resources: they are both suppliers of production raw materials and waste carriers. Natural resource consumption (R) is positively correlated with population size (P) and per capita consumption level (C), while environmental impact (E) is jointly determined by P· C· T (T represents the environmental load coefficient per unit of resource consumption, which is directly related to the level of production technology). As shown in the P· R· Ehrlich formula: $R=P\times C$, $E=P\times C\times T$. This model reveals that in the context of rigid population and consumption growth, only by reducing the T value through innovative green manufacturing technology can the environmental bottleneck of sustainable development of the automobile industry be broken through.

If the upper limit of natural resources supplied by the environmental system to the economic system is Smax, and the lower limit of its threshold for accommodating pollutants is Dmax, then the ecosystem will be out of balance when the resource consumption $R=P\times C>Smax$, or the pollution emission $E=P\times C\times T>Dmax$. Ecological destruction and environmental pollution are essentially caused by the synergistic effect of population size (P), consumption level (C) and technical pollution coefficient (T). Specifically: when per capita resource consumption (C) is stable, population growth ($P\uparrow$) directly aggravates resource overload ($R\uparrow>Smax$); if production technology is extensive ($T\uparrow$), even if the population and consumption remain unchanged, pollution pressure ($E\uparrow>Dmax$) will still exceed the environmental capacity. This proves that population expansion and technological lag are the core causes of the ecological crisis. The "linear manufacturing" model of current economic activities further amplifies this contradiction - the one-way flow of resources is "exploitation-production-waste", which leads to continuous pressure on the environment. As Hawken pointed out in "Business Ecology": "The fundamental solution to the dilemma lies in reconstructing the production system so that it follows the laws of natural cycles: eliminating hazardous waste at the source, achieving a closed material loop through bionic design... These solutions are inherent in the ecosystem." Therefore, promoting the transformation to a circular economy has become the only way to balance environmental carrying capacity and economic development.

In summary, the design concept centered on "environment" is the core of sustainable development of human economic activities and the fundamental requirement for survival and development. The principles that should be followed in the design concept centered on "environment" are: a . Consider the use of non-consumable materials in the production process of products; b. Comprehensive utilization of raw materials; comprehensive utilization of waste; d. Perfect function of "circular" production mode; e. The possibility of industrial symbiosis, that is, the mutual use of by-products within or between factories; f. The concept of saving energy and materials.

Construction of Indonesias automotive product greenness evaluation system

Based on the "environmental priority" design concept, automotive products need to achieve the three goals of efficient resource utilization, ecological protection and health protection during their life cycle. Its green evaluation should integrate the three dimensions of technical performance, environmental benefits and economic feasibility to form a dynamic, multi-dimensional comprehensive evaluation framework.

A. Analysis of the dynamic characteristics of greenness

   As a composite indicator to measure technological advancement, environmental coordination and economic rationality, product greenness has significant timeliness characteristics. With technological progress and industrial upgrading, the energy efficiency level, material recyclability and production cleanliness of automotive products continue to be optimized, and their greenness shows a gradual improvement trend. For example, in the iteration process of European automobile emission standards from Euro 2 to Euro 3, the nitrogen oxide limit was tightened from 0.15g/km to 0.10g/km, and the particulate matter emission threshold was reduced by 40%, reflecting the dynamic evolution of environmental standards. This means that products that currently meet green standards may face elimination in the future, so the evaluation system needs to establish a dynamic calibration mechanism.

B. Dual Path Selection of Evaluation Criteria

   The current evaluation system mainly uses two types of benchmarks:

   a. Absolute standards: Quantitative indicators are established based on international environmental conventions (such as the Paris Agreement), regional regulations (ASEAN Vehicle Emissions Agreement) and industry technical specifications (ISO 14040 Life Cycle Assessment Standard). Such standards are binding, but have significant limitations - when applied locally in Indonesia, due to differences in infrastructure (such as less than 25% coverage of charging piles) and lagging detection methods (only large cities such as Jakarta have Euro 5 level detection capabilities), the data reliability deviation can reach 15%-20%.
   b. Relative standard: comparative evaluation is achieved by establishing a reference system. For example, the hybrid models produced by Toyota's Indonesian factory were compared with local brand fuel vehicles for their full

life cycle carbon emissions. The results showed that the carbon footprint per unit mileage of the former was reduced by 38%. This method is more practical, but it needs to solve the subjective problem of benchmark product selection. The Delphi method can be used to build a multi-dimensional weight model to improve objectivity.

C. Evaluation system optimization path

In view of the defects of existing standards, it is recommended to implement a graded evaluation strategy:

a. Basic layer: Absolute standards are used to ensure compliance bottom line, with a focus on monitoring core indicators such as PM2.5 emissions (Jakarta's annual average exceeds the WHO limit by 4 times) and lead-acid battery recycling rate (currently less than 30% in Indonesia).
b. Advanced level: Introduce a dynamic adjustment coefficient and regularly update the evaluation threshold based on the speed of technological progress (such as an average annual increase of 15% in the energy density of lithium batteries).
c. Excellence layer: Establish an industry benchmark comparison system, refer to international best practices such as Tesla's Gigafactory's zero waste certification and BMW i3's 95% recyclability rate, to encourage corporate technological innovation.

D. Implementation of guarantee mechanism

Build a cross-departmental data sharing platform to integrate the production capacity data of the Ministry of Industry, the monitoring data of the Ministry of Environment and the subsidy information of the State Administration of Taxation to eliminate information silos.

Promote a green credit rating system, and provide incentives such as land tax exemptions (up to 30%) and preferential tariffs on imported equipment to automakers that achieve AAA certification;

Establish a third-party certification system, cultivate local certification bodies (only 8% of laboratories in Southeast Asia have been ILAC-certified), and enhance the international recognition of assessment results.

The establishment of this evaluation system will promote the transformation of Indonesia's automotive industry to a circular economy model. It is predicted that after full implementation, the carbon intensity of the automotive manufacturing industry will be reduced from the current 2.3 tons of CO_2/vehicle to 1.5 tons in 2030, while driving the market size of green materials such as recycled aluminum and bio-based plastics to grow by 120%. This is not only in line with the global trend of carbon neutrality, but also provides institutional guarantees for Indonesia to achieve its strategic goal of 30% of zero-emission vehicles by 2045.

Conclusion

Green production oriented to the environment and ecology is a development trend of modern engineering design. Indonesia is rich in resources, and environmental pollution has become a very prominent problem. The promotion of green production technology is a very urgent issue. Moreover, green design and green manufacturing are relatively new concepts, and a relatively systematic and complete design and manufacturing specification and theoretical system has not yet been formed. This requires us to consider all aspects of product material selection, product design, manufacturing, management, etc. comprehensively to promote the development of green production technology.

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