Precision Machinery Product Development Based on Green Design Concept

Haolong Song, Lingxia Zeng, Wuyi Ming

Abstract—**Amid increasingly severe environmental challenges, the precision machinery manufacturing industry must achieve sustainable development by adopting green design. This paper systematically examines the core elements and methodologies of green design in the development of precision machinery products and validates its practical applicability. Firstly, the concept of green design and the principle of full lifecycle application are analyzed, highlighting their critical role in resource efficiency and pollution reduction. Subsequently, the study discusses four dimensions—material selection, energy efficiency optimization, modular design, and recycling and remanufacturing—and introduces various green design tools. Finally, through case studies of Audi's electric vehicles and semiconductor equipment, the effectiveness of green design in mitigating the environmental impacts across the entire lifecycle and enhancing resource efficiency is verified. Furthermore, the study explores the strengths and limitations of green design, identifies challenges specific to precision machinery, and proposes future directions such as optimizing material properties, reconciling technological conflicts, harmonizing policies, and integrating emerging technologies. The study demonstrates that the green design concept not only fosters the low-carbon transformation of the precision machinery manufacturing industry but also offers a comprehensive solution to global sustainable development objectives.**

Index Terms—**Green design, precision machining, mechanical engineering, material selection, sustainable development**

I. Introduction

GREEN design represents an irreversible trend in the advancement of contemporary and future mechanical manufacturing. In the context of global warming, increasing frequency of natural disasters, and the continuous degradation of the ecological environment [1], public awareness of environmental protection has steadily increased. Consequently, the concept of green design has emerged as a pivotal element in facilitating the transformation and advancement of the machinery manufacturing industry. In the field of precision manufacturing, green design enhances processes through pollution reduction, energy saving, emission reduction, resource optimization, and cost control. This approach not only mitigates negative environmental impacts [2], but also lowers manufacturing costs, fosters technological innovation, and improves product performance.

Nevertheless, the precision machinery manufacturing industry continues to encounter significant environmental challenges during both design and production stages. According to studies by the International Energy Agency (IEA) and the Netherlands Environmental Assessment Agency (PBL), manufacturing has been a primary contributor to greenhouse gas emissions from human activities [3] (Fig. 1 illustrates the estimated global GHG emissions by sector in recent years, revealing that energy systems and industries related to precision machinery contribute a significant share). In addition, energy- intensive processing technologies, extensive consumption of non- renewable resources, inadequate recycling mechanisms, and process-related pollution (including waste trimmings, chips, discarded products, effluents, residues, and greenhouse gas emissions) continue to intensify environmental degradation ([5], [6], [7]). As early as the 1970s, Papanek [8] introduced sustainable design for environmental protection, and Kurk and Eagan [9] subsequently applied industrial design principles to mitigate environmental issues in precision machinery manufacturing through green design. Therefore, during the initial stages of product design, designers must comprehensively assess potential environmental impacts. Mechanical products—essential equipment across industries—play a critical role in energy conservation and emission reduction; accordingly, robust design strategies are crucial for controlling environmental pollution [10].

This study aims to optimize the precision machinery manufacturing industry by integrating green design principles to achieve environmental sustainability and maximize resource efficiency. The specific objectives are to adopt environmentally friendly materials, develop energy- efficient designs, implement modular design strategies, and optimize recycling systems. These measures not only reduce product environmental impacts and enhance resource utilization, but also facilitate maintenance, disassembly, reuse, recycling, and regeneration, thereby promoting the sustainable development of the precision machinery manufacturing industry [11].

Moreover, the significance of green design resides in its capacity to generate novel opportunities and pathways for transforming and upgrading the precision machinery industry. The promotion and implementation of green design catalyze

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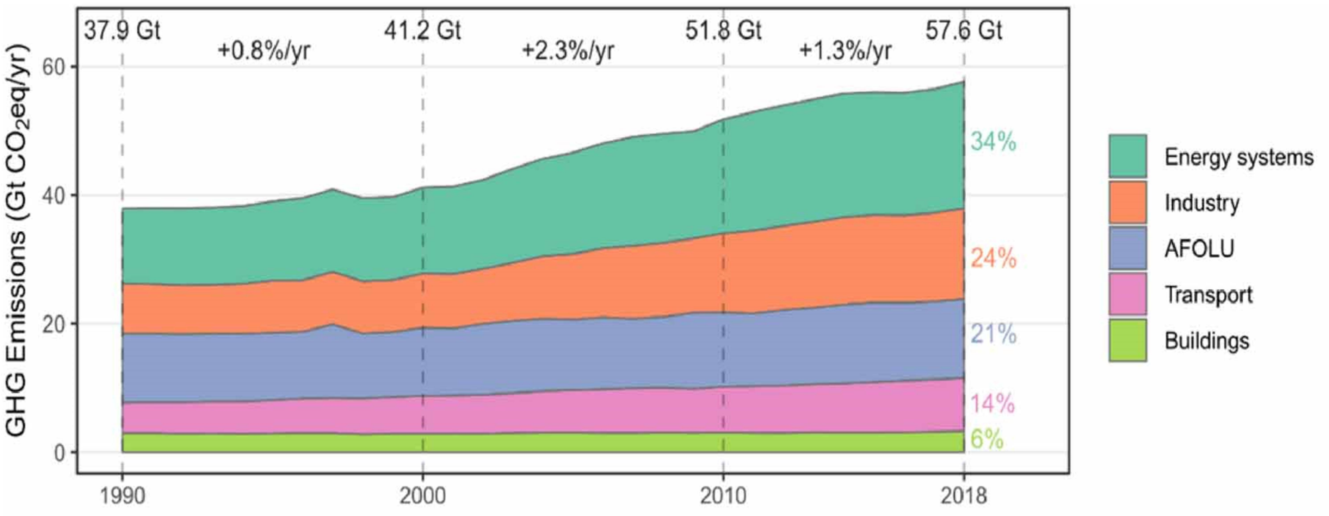

Fig. 1. Estimated global greenhouse gas emissions by sector ([4] and the owner states clearly that it can be used without permission).

technological advancements in precision machinery manufacturing and underpin efforts to achieve global sustainable development goals.

II. BASIC CONNOTATION, PRINCIPLES AND APPLICATION OF GREEN DESIGN

Green design differs fundamentally from traditional design by addressing a product's entire life cycle—from concept development and manufacturing to usage and post-disposal recycling. Its essence lies in maximizing resource efficiency and minimizing environmental pollution during design, while satisfying essential functional, quality, and cost requirements to enhance product value and reduce expenses [12]. Therefore, the core objective of green design is to minimize resource consumption and environmental impact through innovative design and optimized production processes, thereby ensuring sustainable social and economic development. The principles of green design aim to achieve both environmental protection and economic efficiency by reducing negative environmental impacts across a product's life cycle [13]. This approach requires integrating environmental considerations at the design stage, including selecting eco-friendly materials, optimizing energy efficiency, ensuring recyclability, and applying energy-saving and emission-reduction technologies.

Green design plays a crucial role throughout a product's life cycle, encompassing multiple stages of manufacturing, usage, and recycling. The following are applications of green design at various stages:

1) During manufacturing, green design prioritizes the use of eco-friendly materials and the adoption of energy-saving and emission-reduction processes to minimize energy consumption and pollutant emissions. For example, Pham et al. [14] found that applying eco-friendly materials in architectural contexts can significantly reduce greenhouse gas emissions. Additionally, the vanishing-mold and moldless casting techniques described in [15] significantly reduce material and energy consumption while improving throughput and efficiency. Green manufacturing encourages the adoption of eco-friendly packaging wherever feasible. Green packaging materials, typically fabricated from bio-composites, exhibit high tensile strength, low cost, and low density, and generate reduced CO_2 emissions, thereby reducing resource consumption [16].

2) During the usage phase, resource consumption can be substantially reduced by designing durable, maintainable products that promote environmental protection. For example, Ardente et al. [17] proposed a methodology for environmental assessment of product durability (Fig. 2 presents two scenarios: Scenario 1 assumes that Product A is replaced by a new Product B after its average lifetime (T), while Scenario 2 assumes that the lifetime of Product A is extended by X time units and that it is replaced by Product B only after this extension) and demonstrated with a washing machine case study that extending product lifespan provides life-cycle environmental benefits. Additionally, Mesa [18] introduced an engineering tool for cyclicity and durability design by reviewing Design for X (DFX) literature—DFCD (Fig. 3). Managing product environmental impact can also be achieved through modifying user behavior, such as implementing customized power-saving modes on smartphones to conserve energy [19].

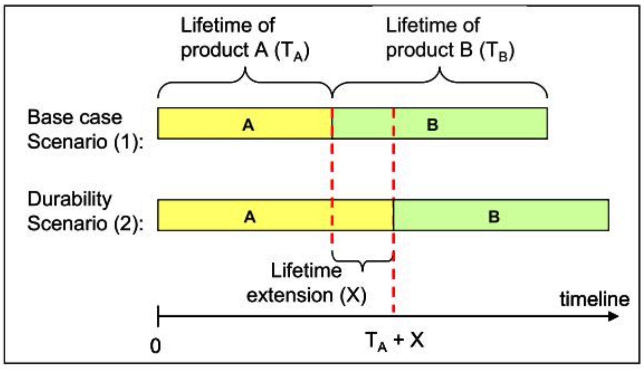

Fig. 2. Durability assessment scenarios ([17] and the owner states clearly that it can be used without permission).

3) During the recycling phase, product design should prioritize disassemblability and recyclability to ensure efficient material recovery and reuse. A study [20] examined component assembly and disassembly by varying part quality and reliability parameters, concluding that enhanced disassemblability is critical for effective part recycling. This finding underscores the importance of disassembly in the

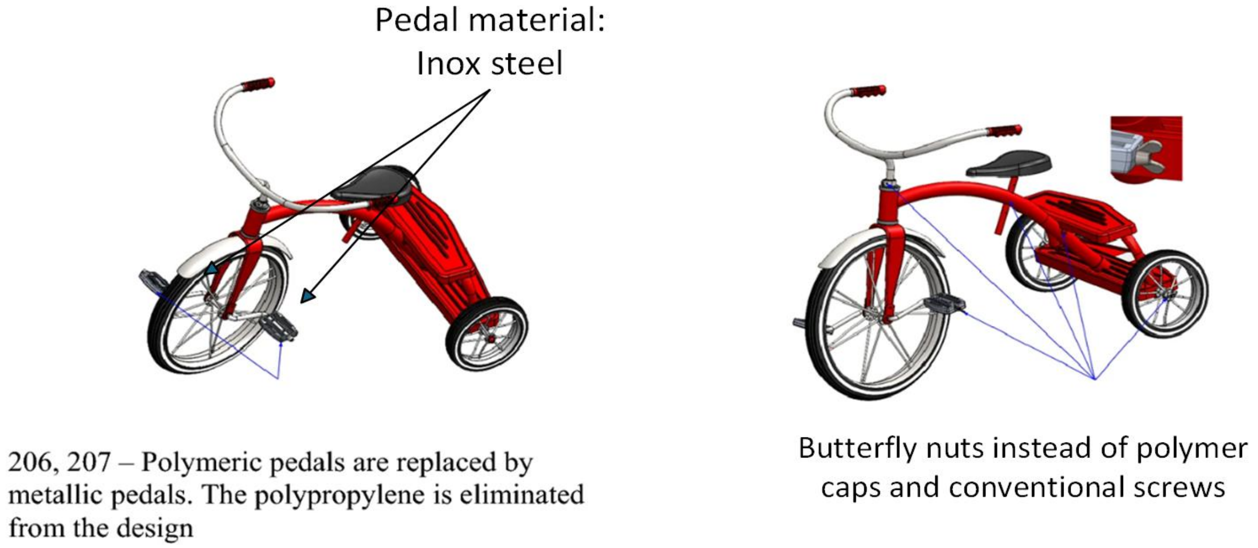

Fig. 3. Partial modifications to tricycles based on DFCD guidelines ([18] and the owner states clearly that it can be used without permission).

recycling process. Additionally, selecting recyclable or degradable materials can greatly increase recycling rates and mitigate environmental pollution.

III. KEY ELEMENTS OF GREEN DESIGN FOR PRECISION MACHINERY PRODUCTS

A. Material Selection

Compared with traditional mechanical design, green design for precision mechanical products must not only focus on mechanical properties, economic efficiency, and processing technology of materials, but also consider their impact on the ecological environment. Therefore, when selecting materials for green design, the following fundamental principles should be followed:

Principle of Good Usability: Prioritize materials that fulfill functional requirements and maintain superior performance across the product's life cycle. This entails evaluating mechanical, physical, and chemical properties, while accounting for the product's operating-environment requirements [21].

Principle of Good Processing: Material processing directly influences product performance, quality, and resource efficiency. For example, additive manufacturing technologies such as Fused Deposition Modeling (FDM) (Fig. 4) eliminate chemical post-processing and resin curing, utilize cost-effective equipment and materials, and provide a more environmentally friendly process compared to conventional methods [22].

Principle of Optimal Economy: Material selection affects procurement, assembly, and recycling costs during product manufacturing. Literature [23] introduces a decision-support model for selecting eco-friendly and cost-effective materials. Analysis of materials such as aluminum indicates that reduced material costs facilitate recycling and enhance product environmental benefits.

Principle of Minimizing Life-Cycle Environmental Impact: The life cycle of a material encompasses all stages, from raw-material extraction to post-use recycling, disposal, or discarding [24]. The life-cycle environmental impact of materials is a crucial consideration. Materials chosen for mechanical products during preparation, processing, manufacturing, usage, recycling, disposal, and reuse should aim to minimize environmental pollution [25].

Material selection involves numerous, often interrelated and conflicting factors (e.g., steel's toughness versus stiffness), making it challenging to identify an optimal combination of properties. Therefore, a multi-objective decision-making approach is necessary to weigh each parameter's importance and determine an overall optimal solution. For example, the fuzzy analytic hierarchy process (FAHP) [26] can score each objective; however, it may introduce subjective bias. To enhance objectivity, the entropy-weighting method [27] can be integrated with FAHP. Additionally, Zhang et al. [28] propose a fuzzy multi-criteria group decision-making (MCGDM) method integrating 2-tuple linguistic modeling, linguistic hierarchies, and Quality Function Deployment (QFD). This approach can evaluate the relative importance of each objective in the material selection process. In conclusion, mathematical methods are essential for material selection, enabling the development of high-performance products in minimal time and at reduced cost.

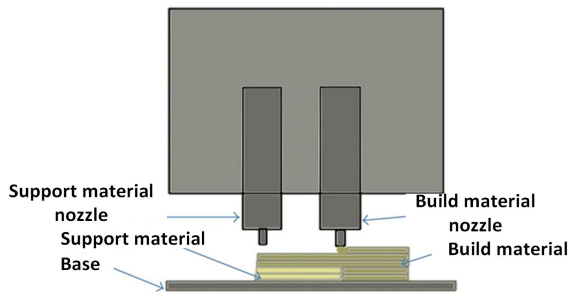

Fig. 4. Fused deposition molding process ([22] and the owner states clearly that it can be used without permission).

1) Recycled Steel

Recycled steel is an eco-friendly material, notably because it reduces carbon emissions and lowers energy consumption during production. Recycled steel, or scrap steel, is primarily obtained from waste streams such as end-of-life vehicles, household appliances, construction debris, and processing by-products (e.g., edges and chips). Recycled steel finds

TABLE I
ADVANTAGES OF RECYCLED STEEL OVER VIRGIN STEEL

Reference	Findings	Advantages of recycled steel	Weaknesses of primary steel
Broadbent, [31]	Reduction of 1.5 kg of CO_2 emissions per 1 kg of recycled steel scrap Saving of 13.4 MJ of primary energy and 1.4 kg of iron ore.	Significant reduction of CO_2 emissions during production, saving mineral resources and primary energy.	High carbon emissions from the blast furnace process.
Liu, [29]	ARS501 grade with nickel-chromium (⩾7% nickel) for corrosion-resistant precision machinery.	Divided into 18 classes (e.g. MRS202, BRS501, ARS501) to meet diversified industrial needs.	Single raw material, low application flexibility.
Johnson, [30]	Energy consumption will be reduced by 67%, while carbon monoxide (CO) emissions will decrease by 70%.	Reduction in significant energy consumption and pollution emissions.	Higher levels of energy consumption and pollution emissions.
Yellishetty, [33]	EAF energy consumption is only 32-40% of BOF.	Low energy consumption due to the electric arc furnace (EAF) process.	High energy consumption due to reliance on the Blast Furnace - Converter (BOF) process.

applications in diverse industries, including construction, automotive, rubber, and precision machinery manufacturing. It is classified into 18 distinct grades. For instance, MRS202-grade recycled steel is used in manufacturing precision mechanical components. BRS501-grade fusion-recycled steel is suitable for fabricating mechanical components. Additionally, ARS501-grade recycled steel, derived from nickel-chromium stainless steel components or machining by-products containing ≥7% nickel, is employed in producing corrosion-resistant precision mechanical components [29].

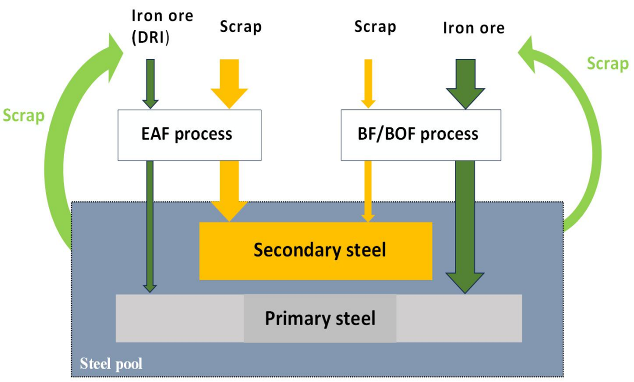

Fig. 5. Connection between primary and secondary steel production ([31] and the owner states clearly that it can be used without permission).

Using recycled steel significantly reduces energy consumption. For instance, producing austenitic stainless steel entirely from scrap can reduce energy consumption by 67% and lower CO emissions by 70% compared with virgin-material production [30]. Scrap recycling partially offsets virgin steel production needs. Experimental data show that per kilogram of end-of-life scrap recycled, 1.5 kg CO_2 emissions are avoided, 13.4 MJ primary energy is conserved, and 1.4 kg iron ore is preserved [31] (Fig. 5). In addition to conserving mineral and energy resources, recycled steel reduces steelmaking costs. Regarding raw-material costs, scrap-based recycled steel generally has a more stable, lower price than iron ore. By contrast, primary steel production relies on iron ore, whose volatile international price introduces cost uncertainty. From a production-cost perspective, recycled steel is predominantly produced via the electric arc furnace (EAF) process, which is simple and energy-efficient, whereas primary steel production relies on the blast furnace-converter (BOF) route, which is complex and energy-intensive [32]. Yellishetty et al. [33] found that EAF steelmaking requires 9–12.5 GJ/tcs, whereas the BOF process consumes 28–31 GJ/tcs, indicating a substantial increase in energy demand. Thus, recycled steel not only reduces raw-material costs but also substantially decreases production energy consumption, thereby alleviating the steel industry's economic burden. TABLE I highlights the advantages of recycled steel over virgin steel.

Furthermore, in the context of recycled steel applications, isothermal forging and additive manufacturing (AM) technologies can improve material utilization and reduce processing waste. Isothermal forging offers several advantages over traditional stamping, including uniform temperature distribution, reduced metal strain rate, and lower deformation forces. This process yields forged components with enhanced dimensional accuracy while minimizing material waste, aligning with green precision machining principles. He et al. [34] conducted a semi-closed die isothermal forging study on AZ80 magnesium alloy support beams. The results showed that the forgings were well-filled with smooth surfaces, achieving high accuracy and material utilization. Similarly, Konstantinov et al. [35] combined computer simulation with isothermal forging to manufacture 5083 aluminum alloy rack components, increasing metal utilization from 0.44 to 0.77. Additive manufacturing builds solid components layer by layer, providing greater design flexibility, improved forming efficiency, and enhanced material utilization compared to traditional subtractive and deformation-based processes. For instance, in electric motor production, additive manufacturing optimized the winding structure by replacing semicircular ends with right-angled ends, reducing copper consumption by 15% [36]. Li et al. [37] developed a hybrid manufacturing process combining wire arc additive manufacturing (WAAM) with milling, increasing material utilization in fascia machining from 34% to 91% (a 57% increase) while reducing construction time from 166 minutes to 102 minutes (a 32% reduction).

2) Bio-based Materials

Bio-based materials, increasingly employed in precision mechanical products, are derived partially or entirely from biological resources. For instance, biofibers, including sisal, palm fiber, hemp, and oil palm, are widely used in textile production [38]. Relevant literature [39] examines diverse types of bioplastics and their corresponding production processes, such as bio-enriched polyurethanes synthesized from modified vegetable oils and polyethylene monomers derived through bioethanol dehydration. Traditional petroleum-based materials not only exacerbate environmental challenges but are also vulnerable to oil price volatility due to their reliance on non-renewable resources,

Fig. 6. Future research directions for natural FRP composites ([50] and the owner states clearly that it can be used without permission).

TABLE II
MECHANICAL PROPERTIES OF NATURAL FIBERS FOR COMPOSITES [42]

Natural fibers	Tensile strength (MPa)	Elongation at break (%)	Young's modulus (GPa)
Jute	200–800	1.16–8	10–55
Banana	529–914	3	27–32
Sisal	80–840	2–25	9–38
Kenaf	119–295	3.5	2.86

high pollution levels, and limited biodegradability. In contrast, bio-based materials markedly reduce dependence on petroleum-based alternatives owing to their renewable, biodegradable, and environmentally benign characteristics [40].

Bio-based materials demonstrate remarkable mechanical properties; for instance, coconut fibers can be utilized to fabricate bio-composites exhibiting significant mechanical strength [41]. TABLE II illustrates the mechanical properties of various natural fibers utilized in composite applications [42], suggesting that plant-based natural fibers constitute viable alternatives to costlier and non-renewable synthetic fibers, such as glass, as reinforcements in polymer composites. Previous studies have demonstrated that E-class automotive interior components composed of various natural fiber composites effectively balance mechanical strength and comfort [43]. Akande et al. [44] found that the damping properties of bio-composites significantly reduced vibration, thus improving the stability of precision equipment, including CNC machine tools and aerospace machinery. Zulhanafi et al. [45] reported that under lower load conditions, the bio-based lubricant palm medium oil (PMO) exhibited superior pressure resistance compared to mineral oil (SAE 40). Under higher load conditions, the performance difference between the two was minimal; however, PMO exhibited superior thermal resistance and a lower coefficient of friction across all test conditions, making it a promising candidate for precision bearings, high-precision guides, and other mechanical devices.

Bio-based materials offer enhanced environmental compatibility. For instance, polylactic acid (PLA)-based plastics are biodegradable and synthesized via the polymerization of lactic acid, positioning them as eco-friendly alternatives. PLA decomposes rapidly within a few months under industrial composting conditions, while conventional plastics may take several decades to break down [46]. Studies indicate that bio-based materials emit, on average, 45% fewer greenhouse gases over their entire life cycle compared to petroleum-based materials [47], thereby presenting a sustainable solution for material applications. In the automotive industry, substituting 50% of glass fiber composites with bio-based alternatives could yield substantial decreases in non-renewable resource consumption and CO_2 emissions. Specifically, annual savings during material manufacturing could reach 1.01 Mt of CO_2 and 0.39 Mt of crude oil, while additional fuel savings—attributed to the lightweight nature of the bio-based materials—could further reduce CO_2 emissions by 2.06 Mt and crude oil use by 0.8 Mt [48]. Boland et al. [49] demonstrated that replacing 30% of glass fibers in automotive components with cellulose fibers (30%) or jute fibers (40%) resulted in weight reductions of 11.7% and 7%, respectively. Consequently, the life-cycle energy demand for cellulose-based components decreased by 9.2%, and greenhouse gas emissions by 18.6%, whereas jute-based components exhibited reductions of 6.0% and 10.7%, respectively. These findings highlight the significant energy-saving and carbon-reduction potential of bio-based materials and indicate that cellulose outperforms jute in emissions reduction by a factor of 1.7.

Moreover, bio-based materials find diverse applications within the domain of precision machinery. Notably, in the aerospace sector, natural fiber-reinforced composites are employed in the structural components of aircraft, satellites, and missiles. In the biomedical field, these materials serve as components for artificial hearts, implants, sensors, and other medical devices, thereby facilitating tissue repair or replacement and enhancing patients' quality of life. Within the electrical and electronics industry, bio-based materials demonstrate high strength, low thermal expansion, and superior electrical and thermal conductivity, rendering them suitable for manufacturing heat sinks, connectors, printed circuit boards, and other critical components. These attributes markedly improve equipment performance and reliability [50]. Fig. 6 outlines prospective research directions for

TABLE III
ADVANTAGES OF BIO-BASED MATERIALS

Strengths Category	Performance/Application	Key data/cases	Reference
Mechanical property	High strength, vibration damping, good lubrication performance.	The vibration-damping properties of bio-composites enhance stability in CNC machine tools and aerospace equipment, while PMO lubricant offers a low friction coefficient and excellent thermal resistance.	Kumar S, [41] Cheung H, [42] Akande I G, [44] Zulhanafi P, [45]
Environmental	Biodegradable, emission reduction, lightweight energy saving.	PLA degradation in months, 45% reduction in life cycle GHG; automotive lightweighting: 11.7% weight reduction in cellulose (18.6% reduction), 7% weight reduction in jute (10.7% reduction).	Xie B, [46] Zuiderveen E, [47] Pervaiz M, [48] Boland C S, [49]
Wide application	Aerospace, biomedical, electrical and electronics.	Aircraft/satellite structural components, artificial hearts/implants, heat sinks/circuit boards (high-strength, thermally conductive).	Maiti S, [50]

natural fiber-reinforced composites. Due to their advantageous characteristics, bio-based materials play a crucial role in advancing the sustainable development of precision machinery. TABLE III presents a comprehensive overview of the benefits associated with bio-based materials.

B. *Energy Efficiency*

The machinery industry is a highly energy-intensive sector, with energy consumption accounting for a substantial proportion of total industrial energy consumption. In particular, coal is the primary component of China's energy infrastructure (Fig. 7) [51]. Enhancing energy efficiency is vital not only for conserving energy and reducing emissions, but also as a prerequisite for the sustainable development of precision machinery manufacturing.

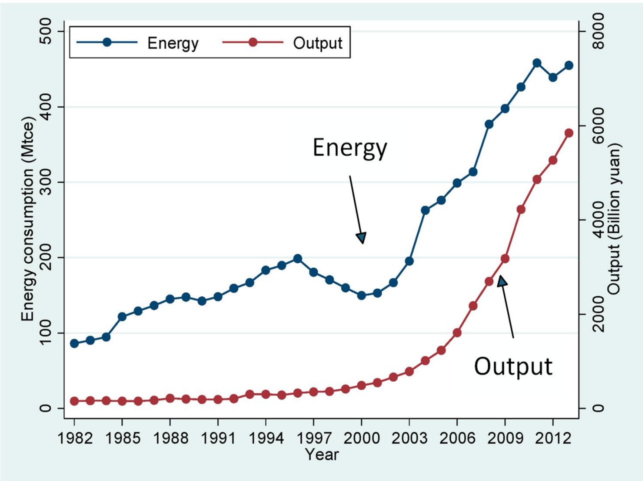

Fig. 7. Energy consumption and production in China's machinery industry, 1982-2013 ([51] and the owner states clearly that it can be used without permission).

Energy consumption during the development of precision machinery products occurs primarily across multiple stages, including raw material processing (e.g., smelting, casting, and forging), all of which demand substantial amounts of heat and electricity (Fig. 8 illustrates the forging process and its energy consumption, with heating before forging representing the highest share, accounting for approximately 20–25%, followed by 30–35% for heat treatment, 25–30% for billet machining, and 15–20% for auxiliary energy use). For example, the melting and metal treatment processes in cast iron production are major energy consumers, with the cupola furnace accounting for 50% of total energy consumption and the induction furnace consuming up to 70% [53]. Moreover, during the manufacturing phase, surveys indicate that up to 54% of electrical energy is consumed by production processes, with production machinery accounting for a significant share [54]. This demand remains significant in machining operations—such as turning, milling, and grinding—which entail high energy consumption. To promote sustainable development, it is imperative to optimize production processes and deploy advanced technologies to minimize energy consumption.

1) *High-efficiency Powertrain*

The deployment of high-efficiency equipment—including high-performance motors and energy-efficient machine tools—plays a pivotal role in mitigating energy consumption. High-performance motors can significantly lower energy consumption compared to conventional counterparts [55]. These motors achieve efficiencies of up to 95% or higher, generate minimal heat, consume less energy, and offer extended operational lifespans [56]. A literature case study [57] demonstrated that energy-efficient machine tools can reduce energy demand by up to 30%, and in some scenarios, by as much as 52%, through various energy-saving strategies. These energy reductions do not compromise machine tool operational performance. Fig. 9 presents strategies for improving the energy efficiency of machine tool operations.

In summary, the adoption of hybrid powertrains plays a pivotal role in enhancing energy efficiency. Although conventional internal combustion engine (ICE) powertrains exhibit low efficiency and elevated emissions, hybrid powertrains substantially improve energy efficiency by optimizing energy utilization. Fundamentally, hybrid powertrains combine the advantages of internal combustion engines and electric motors: at low or idle speeds, the electric motor propels the vehicle with zero tailpipe emissions, and at higher speeds or under heavy loads, operation switches to the internal combustion engine to avoid inefficiencies. Moreover, the electric motor supplements the internal combustion engine during acceleration or inclines, alleviating peak loads and ensuring that the engine operates within its optimal efficiency range. Furthermore, hybrid systems effectively reduce environmental pollution by limiting exhaust emissions and diminishing reliance on fossil fuels. This reduction in fuel consumption directly lowers carbon dioxide (CO_2) emissions and substantially reduces harmful pollutants—such as nitrogen oxides (NO_x) and particulate matter (PM)—compared to conventional fuel-powered vehicles [58]. Anton et al. [59] introduced a series hybrid vehicle powertrain. Compared to a conventional ICE vehicle consuming an average of 5.62 L/100 km, the proposed series-parallel hybrid configuration conserved 2.09 L/100 km,

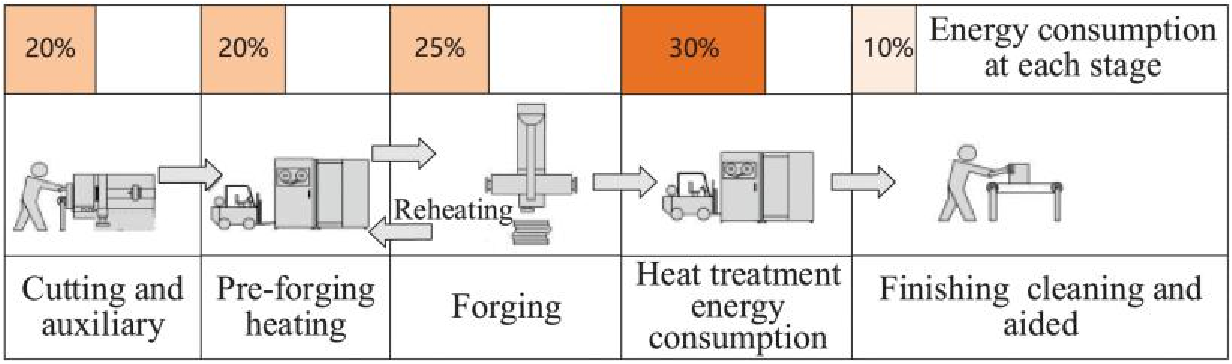

Fig. 8. Forging core process and energy consumption. [52] and the owner states clearly that it can be used without permission.

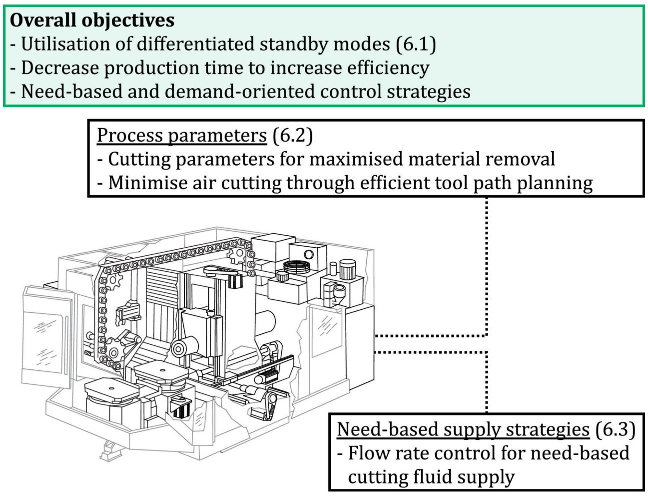

Fig. 9. Measures for improving energy efficiency in machine tool operations ([57] and the owner states clearly that it can be used without permission).

yielding an efficiency improvement of approximately 38%. Furthermore, hybrid systems have broad applications and are well-established in domains such as power generation and maritime transportation. For instance, integrating a diesel generator with a dedicated recirculating battery can reduce fuel and maintenance costs by up to 66%, while achieving comparable reductions in CO_2 emissions [60]. Moreover, Geertsma et al. [61] concluded that hybrid ship architectures, when integrated with advanced control strategies, could decrease fuel consumption and emissions by 10–35%, while also enhancing noise reduction, maintainability, maneuverability, and overall comfort. In summary, hybrid power systems represent a critical technology in modern transportation, balancing environmental sustainability with operational performance through efficient energy utilization and pollution control.

2) Advanced Processing Technology

Energy consumption can be minimized through the optimization of machining processes. For example, a material melting process study [62] examined novel technologies aimed at minimizing both energy consumption and material waste in traditional aluminum-silicon alloy melting. Moreover, optimizing Computer Numerical Control (CNC) machining—which is extensively employed in aerospace, automotive, and medical-device industries [63]—enhances processing speed, automation, and accuracy, thereby reducing errors due to manual intervention. The ongoing development and deployment of advanced manufacturing technologies have substantially decreased machining time while boosting efficiency and accuracy [64]. Currently, CNC machining optimization can be achieved by refining toolpaths and adjusting cutting parameters. For instance, research [65] presents a CNC hole-machining optimization model, demonstrating up to a 50% reduction in energy consumption and processing time through parameter optimization. Similarly, optimizing laser-cutting technology enables mass production while minimizing material waste. Compared to conventional methods, laser cutting offers greater flexibility and precision [66]; however, its low energy efficiency (≈30%) leads to high energy consumption, increased costs, and a substantial environmental impact [67]. Therefore, optimizing the laser-cutting process is imperative. For example, Jiang et al. [68] developed a parameter-optimization model for laser remanufacturing, which effectively reduces energy consumption, improves powder utilization, and ensures high-quality cladding.

The adoption of Minimum Quantity Lubrication (MQL) addresses energy loss caused by friction in machining processes. Friction generated by equipment movement is a major source of energy loss in machining. It not only generates heat but also accelerates tool wear and increases energy consumption. Effective lubrication substantially reduces energy consumption and lowers manufacturing costs for automotive components. Inadequate lubrication leads to friction, which is both energy-intensive and contributes to tool degradation and safety risks [69]. Conventional lubrication methods rely on high fluid volumes, resulting in excessive resource consumption and environmental pollution from waste disposal. In contrast, MQL effectively minimizes friction and wear, reduces energy consumption, and diminishes environmental impact by delivering precise lubricant volumes [70]. Compared to flood and dry cutting, MQL can reduce production costs by ≥15%, decrease cutting forces by 15%–70%, lower cutting temperatures by 5%–30%, and mitigate tool wear by 20%–50%. Furthermore, MQL has achieved a 20% reduction in energy consumption [71]. Fig. 10 illustrates a comparison of energy consumption across various cutting conditions. The adoption of MQL overcomes the limitations of conventional cutting methods, delivering high efficiency while adhering to sustainable manufacturing principles.

3) Energy Recovery and Reuse

Energy utilization can be enhanced through the implementation of heat recovery technologies, particularly waste heat recovery and heat pump systems. Waste heat recovery entails capturing heat that would otherwise be lost

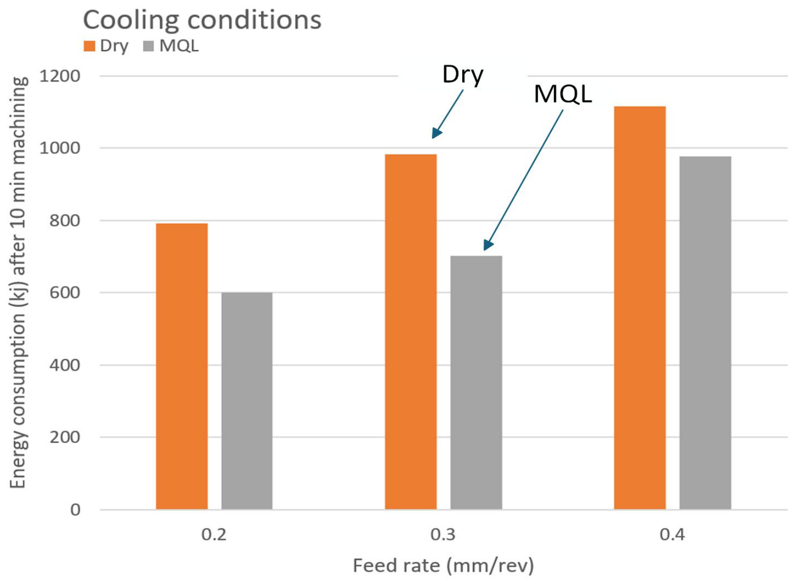

Fig. 10. Energy consumption comparison between dry cutting and MQL machining ([72] and the owner states clearly that it can be used without permission).

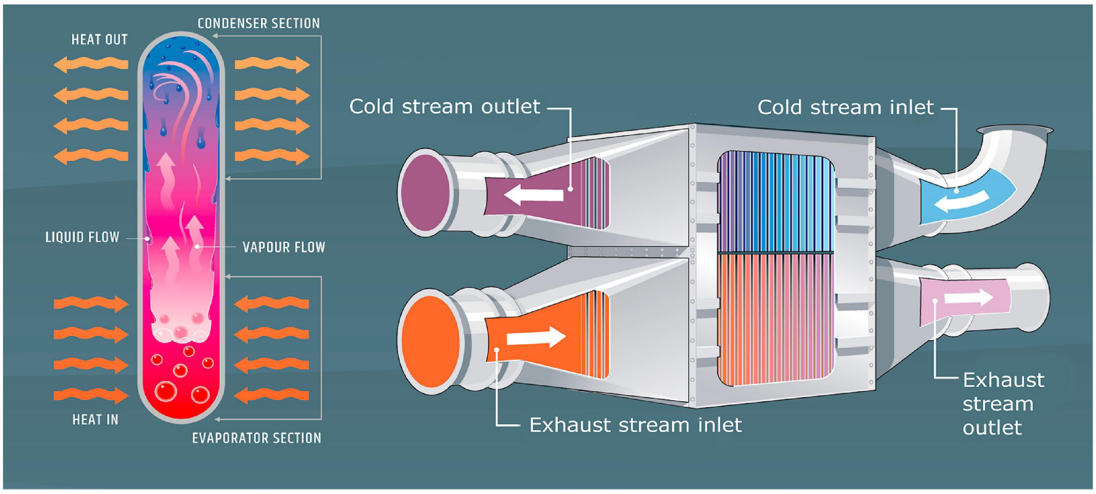

Fig. 11. Role of heat pipes and heat pipe heat exchangers ([74] and the owner states clearly that it can be used without permission).

to the environment, which can then be repurposed for heating or other applications [73]. For example, research [74] discusses the use of heat pipe heat exchangers (HPHE) in the aluminum die-casting industry (illustrated in Fig. 11). This technology is capable of reducing energy consumption by up to 476 MWh and CO_2 emissions by 86 tons per year. Furthermore, heat pump technology enables the recovery and reuse of thermal energy from industrial processes and cooling systems, facilitating both heating and cooling operations. This dual-function process not only supplies the necessary heat but also minimizes energy losses. In precision manufacturing, heat pump technology is employed for material preheating and coating curing. A representative example is adsorption heat pump coating technology [75], which efficiently cures coatings by supplying heat as required and removing excess heat from the process.

The adoption of regenerative braking energy recovery technology, commonly employed in vehicles, aims to maximize energy recovery during braking while maintaining vehicle stability. Sandrini et al. [76] proposed a regenerative braking strategy to enhance braking energy recovery and optimize braking force distribution. Simulation results demonstrated that vehicles incorporating this strategy achieved a 29.5% to 30.3% reduction in fuel consumption under the WLTC driving cycle, compared to vehicles without regenerative braking systems. In specialized vehicles—such as mining trucks—conventional hydraulic braking poses safety risks and results in considerable energy losses, particularly of gravitational potential energy, underscoring the importance of regenerative braking. Han et al. [77] introduced a regenerative braking force distribution and control strategy for rear-wheel parallel hybrid mining trucks, developing and simulating a model using the ADVISOR software. The study indicated that the system's maximum regenerative braking energy recovery reached 65.01% across initial charging currents of 10 A, 30 A, 50 A, and 70 A, respectively. This technology enables mining trucks to ascend unloaded and descend fully loaded, thereby conserving electrical and diesel energy by harnessing gravitational potential energy.

4) Design and Structural Optimization

Structural optimization techniques, such as topology optimization, can significantly enhance product energy efficiency. This approach involves the systematic removal of excess material to decrease mass, thereby reducing power or fuel consumption, while maintaining sufficient strength and

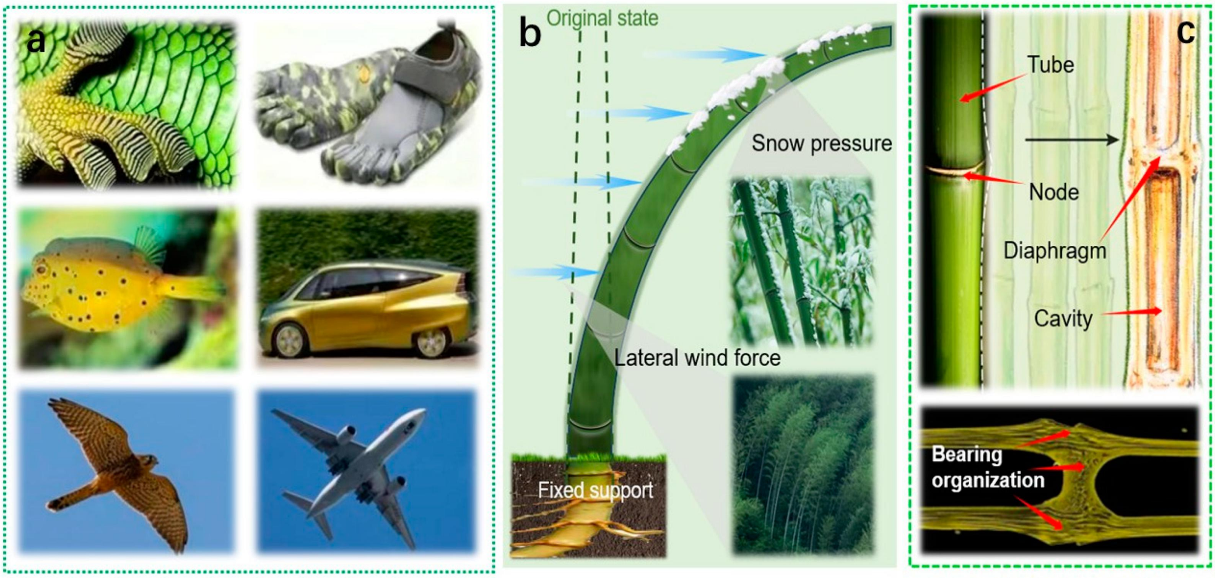

Fig. 12. Bionic design examples and structural features of bamboo ([82] and the owner states clearly that it can be used without permission).

stiffness to preserve product integrity [78]. Topology optimization is extensively utilized in aircraft and aerospace structural design, with four primary applications: fuselage material layout optimization, reinforcement rib optimization for aircraft panels, multi-component structural system design, and structural design incorporating joint load constraints. Htet's topology optimization study on wing ribs achieved an 81.64% weight reduction relative to the original structure [79]. Similarly, Munk et al. [80] demonstrated that topology optimization methods enabled a 40% reduction in overall structural weight compared to conventional design approaches, while still adhering to international aviation regulations.

Structural bionic optimization can be achieved by emulating efficient load-bearing structures in nature, which provide valuable insights for bionic design [81]. The study in [82] describes the optimization of a conventional cantilever beam via a bamboo-inspired bionic design, exhibiting enhanced mechanical properties and load-bearing stability owing to its multiscale architecture. Fig. 12 illustrates an example of bionic design and the structural characteristics of bamboo, including: (a) a bionic design example, (b) the structural advantages of bamboo, and (c) the macrostructural characteristics of bamboo. Ma et al. [83] developed a dragonfly-inspired flapping micro-vehicle mimicking dragonfly biomechanics, featuring four tandem, independently controllable wings that generate a sustained lift of 10 gf per wing at 28 Hz frequency and 180° amplitude. The robot incorporated attitude sensing, RF wireless communication, four motor controllers, and onboard flight control, achieving a notable reduction in overall weight. The prototype successfully lifted off from a balance beam, validating the feasibility of applying bionic principles to precision machinery. TABLE IV summarizes energy efficiency optimizations achieved using various energy-saving technologies.

C. *Modular Design*

Modular design entails decomposing complex systems into simplified, interoperable modules, thereby enabling a diverse range of products [84]. When implementing modular mechanical design, three fundamental considerations must be addressed: vertical, system-level, and horizontal design. These principles facilitate seamless transformations among modules or product variants, while ensuring that all parameters adhere to specified requirements. Each module is designed for a dedicated function, allowing the system to be upgraded through module replacement or addition. Modules interconnect via standardized interfaces, ensuring compatibility, autonomy, and flexibility. Employing identical modules permits the integration of a limited set of distinct components, facilitating the creation of diverse products with minimal modifications. Modularity also aids the management of numerous interfaces, which is crucial for cultivating design knowledge, controlling complexity, facilitating upgrades, enhancing evolvability, enabling parallel development, and simplifying component replacement [85].

During the early stages of product development, modular design facilitates the establishment of clear functional relationships among components, thereby ensuring product quality and enabling continuous product evolution through iterative updates. This approach is particularly effective when proven modules are reused or incrementally enhanced. Based on the number of modules integrated, modular systems can be classified as hybrid or fully modular. As implied, hybrid systems predominantly consist of non-modular components, whereas fully modular systems comprise only modules [86]. These two categories are prevalent in mechanical modular design. To address user requirements, modules are divided into user requirement analysis and functional modification [87]. This strategy enables the modularization of complex products, facilitating rapid and efficient responses to user requirements. Product modularization is a foundational technology that supports user customization, extending its impact from individual enterprises to broader societal contexts. Modularity offers advantages such as enabling sustainable design across the product life cycle, reducing material diversity, minimizing tooling requirements, lowering inventory levels, and eliminating process redundancies, while enhancing product modification feasibility and strengthening resilience to future uncertainties

TABLE IV
OPTIMIZATION OF ENERGY EFFICIENCY IN PRECISION MACHINERY WITH VARIOUS ENERGY-SAVING TECHNOLOGIES

Research Direction	Measures	Improvement Effect	Application	References
High-efficiency powertrain	High-efficiency motors	High efficiency exceeding 95%, low heat dissipation, and energy consumption reduction of 30%–52%	Machine tools, industrial equipment	[55], [57]
	Hybrid systems (vehicles)	Fuel consumption decreased by 2.09 liters per 100 km (38% fuel savings), accompanied by substantial reductions in CO_2 and other pollutant emissions	Automotive, marine, power generation	[59], [60], [61]
Advanced processing technology	CNC machining optimization	Energy consumption and processing time reduced by 50%	Precision machining for aerospace, medical equipment	[65]
	Micro Lubrication Technology (MQL)	Production costs reduced by 15%; cutting force decreased by 15%–70%, operating temperature lowered by 5%–30%, and tool wear reduced by 20%–50%	Manufacture of automotive parts, cutting and machining	[70], [71]
Energy recovery and reuse	Regenerative braking energy recovery technology	Fuel consumption decreased by 29.5%–30.3%, with an energy recovery rate of 65.01% for mining trucks	Automobiles, special vehicles (e.g., mining trucks)	[76], [77]
	Heat Recovery Technology	Significant improvement in aluminum die-casting energy efficiency and reduction in greenhouse gas emissions	Industrial waste heat recovery, coating curing	[74], [75]
Design and structural optimization	Topology optimization (wing rib design)	Structural weight reduction of 18.36%–40%, leading to lower power and fuel consumption	Aerospace, aircraft airframe design	[79], [80]
	Optimization of bionic structures (dragonfly vehicles)	Monoplane lift increased to 10 gf, enhancing lightweight characteristics and mechanical performance	Micro air vehicle, bionic machine design	[83]

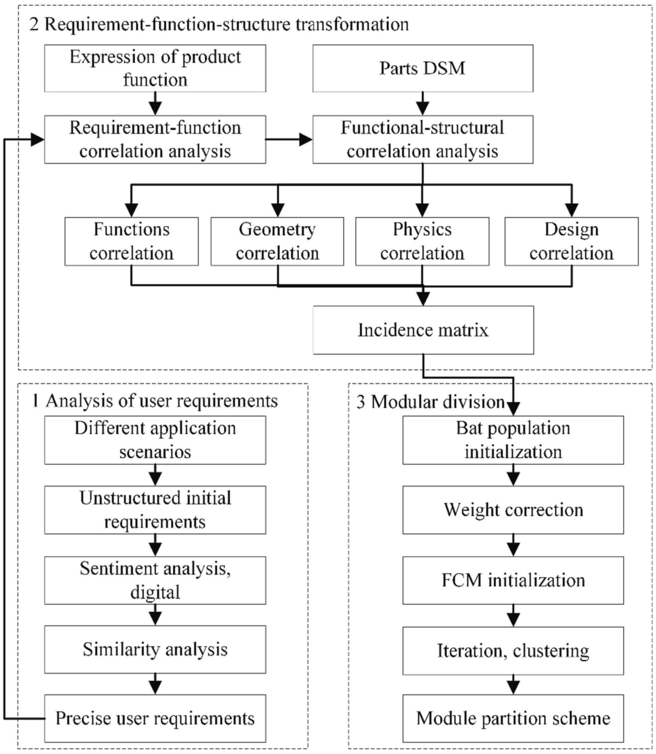

Fig. 13. Flowchart of the module partitioning method ([87] and the owner states clearly that it can be used without permission).

[88]. Moreover, modularization streamlines system workflows, reduces design errors through functional segmentation, and improves product reliability and reparability [89]. Fig. 13 illustrates the module division process. TABLE V provides a comprehensive summary of advantages associated with each phase of modular design.

These advantages of modularity have enabled widespread application in the development and design of diverse electromechanical products. Ma et al. [90] implemented a modular design for a coffee maker, demonstrating that modularization improves disassembly and assembly efficiency, particularly at the end-of-life stage, thereby facilitating recycling. Maintenance time for the filter basket and heater modules was reduced by more than 50%. Recycling costs for the main housing module, achieved through standardized interface design, were 30% lower than those of traditional monolithic designs. Moreover, independent modules—such as the glass jug module—could be readily sorted and recycled, achieving an 80% recycling rate, compared to only 35% in traditional designs. Zhang et al. [91] demonstrated that, in the modular design of optical microscopes, localized component replacement (e.g., the rear set of thick, curved moon lenses) obviates the need to discard the entire system. Statistical data indicate that modular design reduces waste generation by 30%, streamlines assembly processes, and lowers production costs by 20%. Wang et al. [92] proposed a modular design process for the HTC2550hs machine tool, demonstrating that modularization facilitates remanufacturing, thereby extending the machine's life cycle. Key components—such as guideways and spindle boxes—can be replaced individually, reducing maintenance costs by 25%, shortening the remanufacturing cycle by 30%, and increasing the material recycling rate to 85%. Shneor [93] demonstrated that modularized subsystems enable rapid switching between machining modes, thereby minimizing machine downtime and reducing retrofit costs. Installation of the polishing module requires only fixture and control system adjustments, resulting in a 60% reduction in retrofit costs.

D. Recycling and Remanufacturing

The traditional linear economic model generates substantial waste, exerting a detrimental impact on the

TABLE V
ADVANTAGES OF THE VARIOUS STAGES OF MODULAR DESIGN

Stage	Modularity Advantage
Production	1. Enhancing transportation and storage efficiency by minimizing both the quantity and dimensions of goods. 2. Enhancing the adaptability of product modifications while maximizing equipment utilization. 3. Reducing material variety while enhancing compatibility. 4. Facilitating inter-organizational collaboration to enhance technological adaptability and foster innovation.
Manufacturing	1. Facilitates disassembly for efficient recycling and reuse. 2. Ensures high functional independence and streamlined remanufacturing.
Application	1. Streamlining the maintenance process for improved cost-effectiveness and efficiency. 2. Facilitates maintenance, enhances service quality, and reduces costs. 3. Enables seamless upgrades, adaptations, and modifications while maintaining system continuity.

environment. In contrast, the circular economy, also termed zero-waste manufacturing [94], presents a sustainable alternative by promoting remanufacturing, reuse, and recycling of products at end-of-life. Recycling entails the collection of waste materials and their repurposing, a process often described as the reuse of discarded resources [95]. This process encompasses various methods to recover waste or transform it into new products, materials, or useful components [96]. Recycling techniques include chemical and physical methods, with hybrid approaches frequently employed to address the specific characteristics of processed materials. For example, in e-waste recycling, physical recycling technologies—such as shredders and separators—are initially employed to disintegrate materials and increase surface area. Subsequently, chemical recycling processes are applied to separate organic matter from metals, thereby facilitating efficient recovery of precious metals [97].

Recyclability and reusability are essential considerations in product design. In precision machinery production, which is energy-intensive and emission-intensive, recycling and reusing waste materials can significantly reduce CO_2 emissions and mitigate environmental impact. For example, the recycling of lithium-ion batteries offers substantial environmental benefits [98]. Moreover, recycling promotes market growth, generates economic benefits by lowering production costs, creates revenue streams from recycled materials, and provides employment opportunities along the value chain, thereby driving economic expansion [99]. In automotive applications, an integrated recycling-technology model has been developed (Fig. 14). This model incorporates diverse recycling technologies for electrical and electronic equipment, plastics, glass, and metals, addressing their commonalities, limitations, and strengths to optimize overall efficiency [100].

With the continuous advancement of science and technology, recycling and reuse technologies have

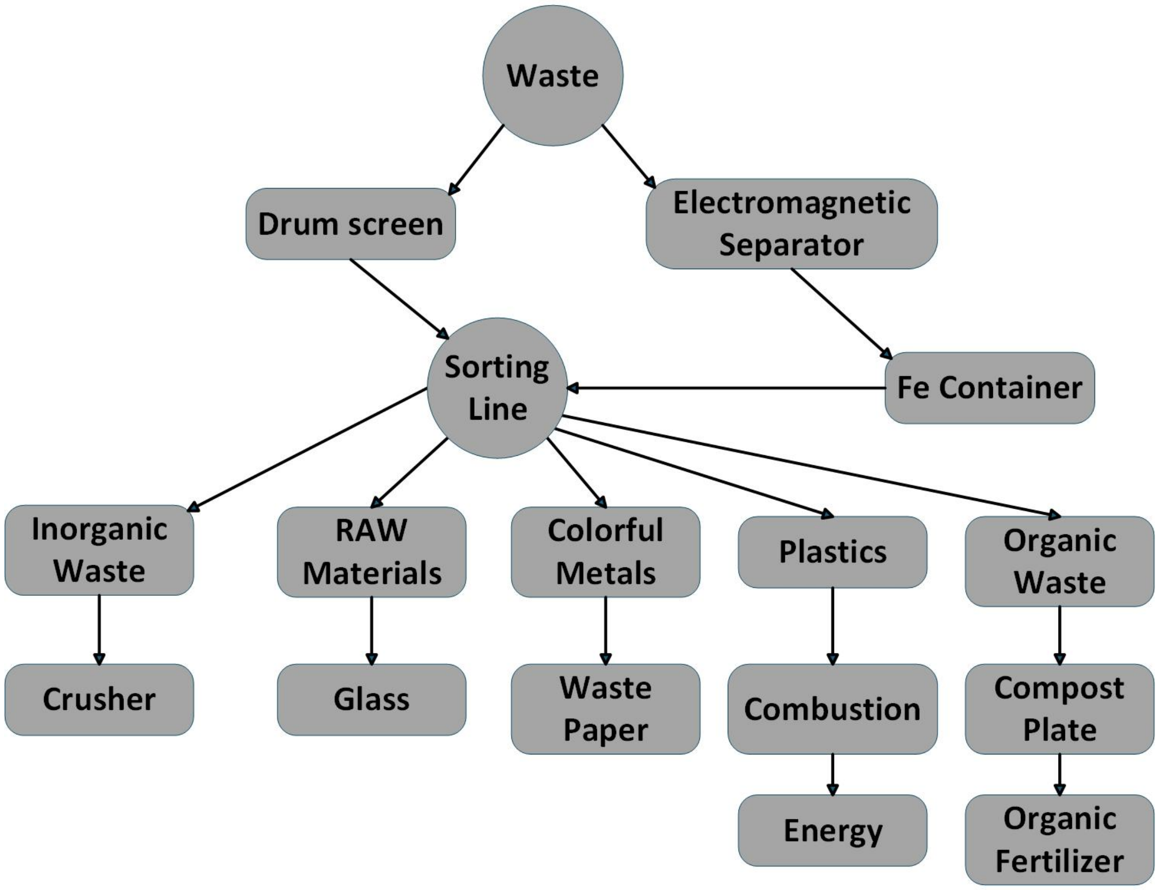

Fig. 14. Recycling technology modeling with automotive parts.

TABLE VI
ENVIRONMENTAL BENEFITS OF RECYCLING AND REMANUFACTURING PRECISION MACHINERY

Research Direction	Findings	References
Reduced consumption of resources	Engine remanufacturing reduced raw material consumption to below 10%.	[103], [104]
Energy conservation	Engine remanufacturing achieved an 83% reduction in energy consumption.	[103], [104]
Emission reductions	Engine remanufacturing reduced CO_2 emissions by 87%. Battery recycling led to a net reduction of 4.5 tons of CO_2 emissions per ton of material processed.	[103], [104], [110]
Cost reduction	The remanufacturing cost of core components was 50% of that of brand-new parts. Lithium recycling costs were reduced by 30%.	[105], [110]
Good performance	The microhardness of aerospace blades increased by 56% after remanufacturing. Recovered carbon fiber retained 80.3% of its original strength and 87.6% of its modulus. The capacity of recovered batteries was restored to 92% of the original value.	[106], [108], [110]
Waste recycling	Engine remanufacturing resulted in a 70% reduction in waste generation. The use of chemicals was reduced by 92% in the remanufacturing process. The lifespan of batteries was extended by 5 to 8 years through recycling and optimization.	[103], [104], [109]

progressed through ongoing innovation. Previous studies [101] have highlighted significant technological breakthroughs in waste stream separation, facilitating the recovery of valuable chemicals, such as precious metal ions (e.g., Au, Ag), from industrial wastewater while simultaneously reducing pollutant loads. These innovations not only reduce environmental impacts and enhance sustainability but also bolster corporate competitiveness. Technologically advanced companies can significantly reduce costs and strengthen their market competitiveness [102]. Research indicates that remanufacturing of used automotive components substantially lowers resource consumption and minimizes environmental impact. For instance, in the case of engines, the remanufacturing process achieves reductions of 83% in energy consumption, 87% in carbon dioxide emissions, 92% in chemical usage, and 70% in waste generation relative to new engine production, while requiring less than 10% of the raw materials required for new engine manufacturing ([103], [104]). From an economic perspective, the cost of core components, such as transmissions and engines, remains approximately 50% of the cost of a new component after performance restoration through processes such as cleaning and surface treatment [105]. In the aerospace industry, laser fusion repair is applied to aero-engine blades, resulting in repaired wheel discs and blades (TC6 and TC4 titanium alloys) with smooth, defect-free surfaces and a 56% increase in microhardness. In contrast, conventional repair techniques generate large heat-affected zones and deformations, making them unsuitable for high-precision components. These findings indicate that remanufacturing not only reduces resource consumption and lowers the frequency of replacing expensive components but also yields considerable cost savings [106].

For certain advanced and emerging high-performance products, optimizing recovery technology is crucial. For example, conventional pyrolytic recovery of carbon fibers suffers from inefficient matrix removal, high energy consumption, fiber damage, and gas emission [107]. Wei et al. [108] enhanced matrix conversion and minimized energy waste by optimizing the temperature range (410–425°C), heating rate, nitrogen flow rate, and isothermal duration. This method achieved a carbon loss of less than 1%, reduced surface corrosion and diameter shrinkage, and significantly improved the tensile strength (80.3%) and modulus (87.6%) of recycled carbon fibers. Another example pertains to the recycling of new energy vehicle batteries. Typically, retired batteries retain only 70–80% of their original capacity and can be sorted and repurposed to enhance their capacity for use in energy storage systems (e.g., home storage, grid peaking), thereby extending their operational lifespan by 5 to 8 years [109]. Moreover, recycling cobalt, nickel, and other metals from batteries offers significant environmental benefits. For instance, Redwood Materials implements a thermal process to recover nickel and cobalt alloys with a purity exceeding 99% and adopts a wet process to extract lithium with a recovery rate greater than 80%. Tesla's wet recycling process at its Nevada Gigafactory has led to a 4.5-ton reduction in CO_2 emissions per ton of batteries and a 30% decrease in lithium recovery costs compared to conventional mining. Additionally, the anode SBTs can be restored via electrolyte injection and in-situ lithium deposition. Similarly, lithium deposition may be utilized to restore the anode SEI film through electrolyte injection and in-situ lithium deposition, thereby restoring battery capacity to 92% of its original value [110]. TABLE VI presents a summary of the environmental benefits associated with the recycling and remanufacturing of selected precision machinery.

IV. GREEN DESIGN TOOLS

A. Computer-aided Tools

CAD design tools, extensively utilized for geometric modeling and engineering analysis, are instrumental in the development of precision mechanical products. These tools support product designers by integrating life cycle assessment (LCA) within the CAD system at the early design stages, enabling the evaluation of a product's environmental impact. Moreover, the integration of LCA and life cycle optimization modules with CAD/CAE systems facilitates the development of eco-design methodologies, seamlessly embedding environmental considerations into the product design process [111]. CAD tools can assist in material

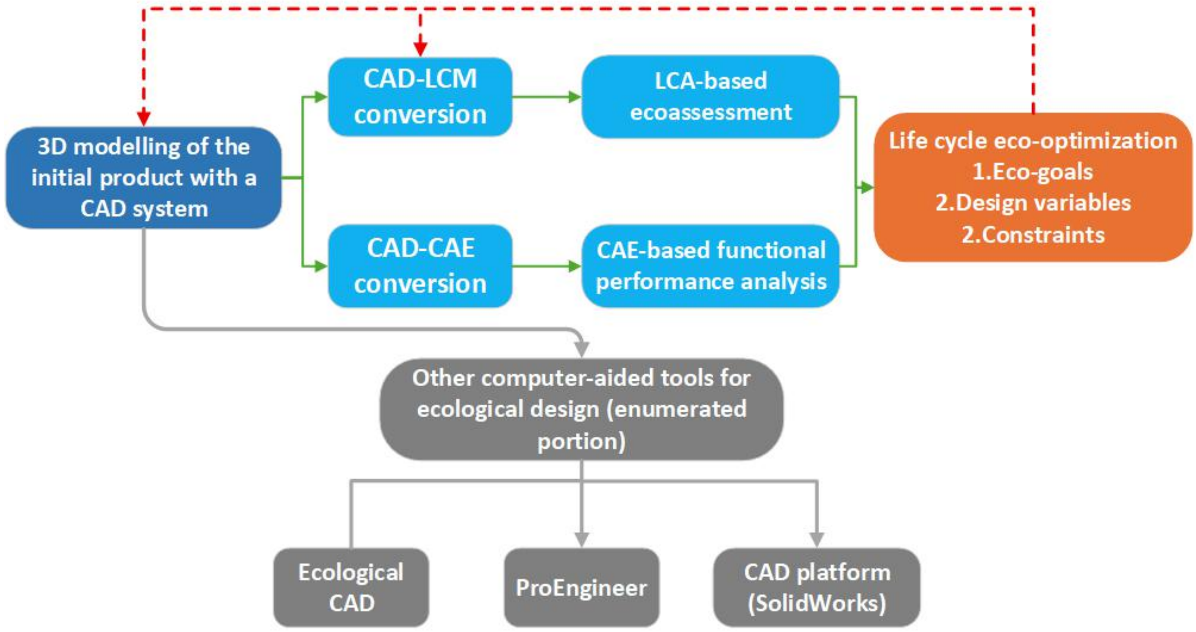

Fig. 15. CAD/CAM-integrated eco-design framework and computer-aided tools.

selection and optimization by utilizing data from material databases to determine recyclable and biodegradable options, thereby ensuring a comprehensive sustainability assessment [112]. Additionally, CAD enhances product structural optimization by employing 3D modeling to identify the optimal design solution, taking into account a given design volume, boundary conditions (e.g., loads, constraints), and predefined objectives. For instance, optimizing beam thickness can improve material efficiency, reduce weight, and maintain the required bending stiffness [113]. Fig. 15 shows the CAD/CAE integrated eco-design methodology framework and some of the other computer-aided tools for eco-design.

The implementation of computer-aided manufacturing (CAM) software in green manufacturing enables engineers to evaluate diverse machining strategies and pinpoint the most energy-efficient and waste-minimizing approaches. For instance, CAM software streamlines cutting paths, reduces idle strokes, and improves cutting efficiency, thereby decreasing energy consumption [114]. Additionally, when machining complex components such as engine assemblies and body parts, CAM software simulates and refines cutting parameters—including cutting speed, feed rate, and depth of cut—to reduce energy consumption and tool wear during manufacturing. This process enhances material utilization while reducing waste [115]. Kumar et al. [116] examined the application of CAM software in optimizing cutting paths, showing that energy consumption and waste generation can be significantly reduced by shortening cutting distances and fine-tuning cutting parameters. Building on this, the integration of CAD and CAM, particularly CAD/CAM integration techniques, holds significant potential for modern machine manufacturing applications. Optimizing the CAD/CAM process enables seamless integration between design and manufacturing, improving both quality and performance in new product development by combining the advanced simulation and analysis capabilities of CAD with the precision machining capabilities of CAM [117].

B. Digital Twins and Simulation

The implementation of digital twin technology as an advanced manufacturing tool allows manufacturers to proactively detect potential issues and enhance system performance by creating virtual representations of physical systems, enabling multi-scenario simulation and predictive analysis [118]. In green manufacturing, its core value lies in analyzing and optimizing energy consumption and environmental impact. Engineers can accurately forecast resource consumption, waste generation, and ecological footprint during real production by leveraging virtual machining process simulations, thus formulating more sustainable process strategies [119]. Furthermore, the sustainable digital supply chain twin framework proposed by Kamble et al. [120] broadens the application scope of this technology. Studies have demonstrated that this framework improves the collaborative efficiency of supply chain networks by consolidating, integrating, and dynamically distributing manufacturing resources, significantly increasing resource utilization and overall supply chain sustainability.

The implementation of simulation software significantly improves design accuracy and efficiency. By conducting simulations and analyses during the early stages of precision mechanical product development, potential issues can be detected and addressed to enhance the design. This approach reduces the labor, cost, and time associated with physical testing [121]. For instance, finite element analysis software, such as ANSYS, is capable of simulating stress distribution under various loading conditions. Fatigue analysis can estimate the lifespan of a product subjected to repeated loading under various configurations, facilitating the selection of more durable and long-lasting designs. This approach decreases the frequency of replacements, lowers waste generation, and improves product reliability [122]. For products requiring airflow considerations (e.g., cooling systems for aerospace gas turbines, aerodynamic design of automotive profiles [123], Computational Fluid Dynamics tools can model aerodynamic performance, decrease air resistance, and consequently enhance energy efficiency.

C. *Environmental Impact Assessment*

Aligned with the principles of green design, the utilization of environmental impact assessment tools in precision machinery product development facilitates the evaluation and optimization of product performance throughout the design phase. Notably, these tools include Life Cycle Assessment (LCA), Energy Efficiency Assessment (EEA), and Material Flow Analysis (MFA).

Life Cycle Assessment (LCA) tools evaluate the environmental impacts of a product by analyzing its entire life cycle—from raw material acquisition, throughout production and use, to final disposal. One notable application of LCA is the life cycle analysis of precision machine tools, where the environmental impacts during the use phase are particularly significant. For machine tools, the LCA process consists of four phases: scoping, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), and result interpretation. Zendoia et al. [124] refined the LCI and validated it through machine tool case studies to improve the transparency and consistency of LCA data, thereby illustrating that LCA can function as a decision support tool for assessing the life cycle impacts of products manufactured using machine tools.

Energy efficiency assessment tools are employed to analyze industrial processes, and the methodology is typically divided into three phases: energy analysis (E1), energy assessment (E2), and energy conservation measures (E3). E1 comprises an initial diagnosis to identify energy consumption patterns, whereas E2 involves a more comprehensive analysis of energy usage within the production process, evaluating its impact on energy efficiency and environmental objectives. E3 focuses on identifying and evaluating potential improvements to reduce energy consumption and alleviate environmental impacts in manufacturing [125]. Gopalakrishnan et al. [126] developed the ISO 50001 Analyzer software—an advanced energy analysis tool that has demonstrated exceptional performance in practical applications.

Material Flow Analysis (MFA) represents a crucial tool for managing complex waste streams, as it systematically traces the entire flow path of substances (e.g., metals, plastics, chemicals) from raw material extraction through processing, manufacturing, and use to disposal, while also quantifying the throughput within these process chains. Generally, MFA provides a systematic analytical framework for examining various interrelated processes and material flows, thereby facilitating the strategic and prioritized development of management measures [127]. Shahbudin et al. [128] performed a material flow analysis of heavy metals in a wastewater system, assuming a treatment efficiency of 95%, and demonstrated that the treatment plant's performance was below standard. Their findings suggested that MFA could function as an alternative tool for enhancing water quality monitoring. Deshpande et al. [129] utilized MFA to investigate the material flow of typical fishing gear employed in commercial fishing. Their study revealed that discarded gear and parts account for approximately 380 tons of plastic waste annually. The findings effectively tracked the destination of material flows and demonstrated that MFA aids in the recovery of resources such as plastics, metals, and chemicals. In conclusion, MFA presents numerous advantages, including systematic analysis, quantitative assessment, cost-effectiveness, and enhanced visualization. It is particularly suitable for promoting the sustainability of resource-intensive, high-value-added products.

V. CASE STUDIES

A. *Case 1-Implementation of Audi's Green Design*

In recent years, the automotive industry has been actively exploring ways to reduce carbon emissions. Leading automotive brand Audi has introduced the all-electric e-tron GT model, which incorporates green design concepts throughout the design and manufacturing process to minimize the vehicle's environmental impact throughout its life cycle.

The Audi e-tron GT incorporates a range of environmentally friendly interior materials, including bio-composites and cellulose fibers in carpets and floor mats, thereby reducing reliance on petroleum-based materials and mitigating environmental impact [130]. Lightweighting has become a primary focus in the automotive industry [131]. To decrease body weight and improve range, the Audi e-tron GT wheels are fabricated from low-carbon aluminum [132] manufactured via Elysis' smelting technology [133], which eliminates the direct CO_2 emissions associated with conventional smelting. Moreover, using carbon fiber–reinforced polymers (CFRPs)—which double stiffness and flexural strength and halve weight relative to traditional steel frames [134]—further reduces vehicle mass. A Life Cycle Assessment (LCA) evaluated the material's service life, and Finite Element Analysis simulated material stresses, verifying compliance with strength and stiffness requirements while maintaining environmental friendliness and lightweight characteristics. To extend driving range, the Audi e-tron GT implements electric decoupling, minimization of residual braking torque, and a highly adaptable thermal management system [135] (Fig. 16).

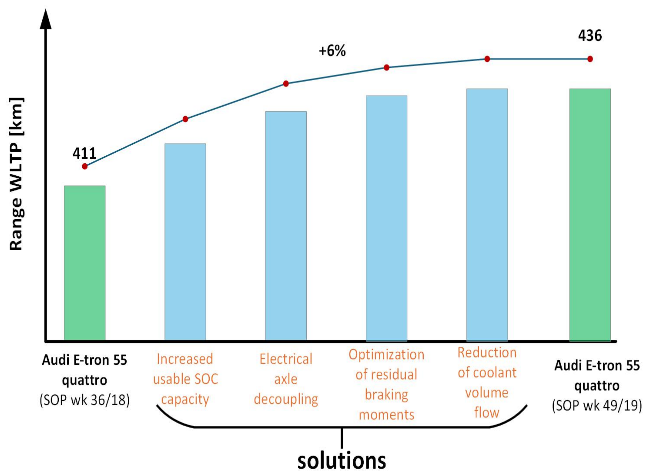

Fig. 16. Measures to extend the range of the E-tron series.

TABLE VII
THE ENVIRONMENTAL BENEFITS OF THE AUDI E-TRON GT WITH ITS GREEN DESIGN VERSUS THE OLDER 2019 MODEL([137], [145], [146]).

Research Direction	2019 Audi e-tron	Audi e-tron GT	Improvement
Battery performance	Battery capacity 83.7kWh，fast charging power 150kW.	Battery capacity 93kWh，fast charging power 270kW.	An 11% increase in battery capacity enhances range optimization, improves energy efficiency management, and enables 80% faster charging.
Aluminum recycling	No closed-loop recycling.	100% closed-loop recycling.	Achieving a 30% reduction in carbon emissions.
Energy recovery	Recovery power of 230kW.	Recovery power of 265kW.	A 15% improvement in recycling efficiency is achieved.
Interior materials	Mainly petroleum-based materials.	Over 30% recycled materials.	This results in a 40% reduction in the carbon footprint.

The Audi e-tron GT features a highly efficient powertrain, with a front motor generating 175 kW and a rear motor producing 335 kW, delivering a combined output of 440 kW and 830 N·m of torque. In boost mode, the output temporarily increases to 475 kW. This powertrain maintains an efficiency of over 90% under most driving conditions [136]. The e-tron GT also employs advanced lithium-ion battery technology, offering high energy density, extended service life, and superior charging and discharging capabilities. According to Audi's official website, the vehicle is powered by a 93 kWh lithium-ion battery, providing a range of more than 400 kilometers under WLTP conditions [137]. The vehicle supports DC fast charging at rates up to 270 kW, enabling the battery to reach 80% charge in about 23 minutes. The integration of fast charging technology plays a crucial role in enhancing the vehicle's performance [138]. Additionally, the e-tron GT incorporates an energy recovery system: when the driver releases the brake and accelerator pedals, the intensity of energy recovery in regenerative braking mode can be adjusted via a toggle on the steering wheel, with two selectable intensity levels, enabling a maximum energy recovery of about 265 kW during braking [139]. The vehicle's aerodynamics have been optimized through wind tunnel testing and CFX (Computational Fluid Dynamics) simulations, achieving a sleek design with a low drag coefficient of 0.24. This optimization not only enhances the vehicle's energy efficiency but also elevates the overall driving experience [140].

In terms of modular design, the e-tron GT's electric drivetrain exemplifies this concept. A modular and scalable system is utilized in battery production, allowing the reuse of identical or modified components in future projects. This approach enhances both battery maintenance and product durability. The battery pack consists of multiple modules, with each module housed in individual compartments within the frame structure, ensuring exceptional mechanical strength for the high-voltage batteries. Flexible modular connectors ensure well-balanced tolerance for the high-voltage connections between individual battery modules, thus enhancing safety. Furthermore, certain vehicle functions, such as vibration damping and skid control, can be modularly integrated into the power electronics, resulting in improved performance, including increased acceleration and enhanced stability on icy roads [141].

Finally, in terms of product recycling and reuse, Audi aims to conserve resources across the entire value chain. To achieve this, Audi has introduced a new remanufacturing method as part of its Exchange 2.0 program, enabling the company to save up to 80% of parts in the value chain [142]. Audi also repurposes packaging waste, converting it into tools and fixtures for production use. This waste is processed into filaments suitable for 3D printing, allowing the creation of components such as actuators and fixtures [143]. Additionally, Audi launched a pilot program in 2020 focused on plastic recycling, in which partially obsolete plastic parts—such as fuel tanks, decorative hubcaps, and radiator grilles—are chemically recycled into pyrolysis oil. This oil, comparable in quality to traditional petroleum-based products, can be used to manufacture new automotive parts [144]. As illustrated in Fig. 17, automotive bioplastic parts can be processed through both recycling and biodegradation pathways, enabling cost-effective reuse and environmentally sustainable material disposal. Furthermore, Audi has established a dedicated battery recycling system, the "Second Life" program, ensuring proper and eco-friendly disposal of used batteries. Some batteries are repurposed for energy storage systems or other low-power-demand applications, maximizing resource utilization while minimizing environmental impact.

According to Audi's official data, the Audi e-tron GT, compared to its predecessor, the 2019 Audi e-tron, implements closed-loop aluminum recycling, reducing the demand for virgin aluminum. The use of recycled aluminum yields energy savings of up to 95% compared to virgin aluminum [145]. The battery capacity has been increased to 93 kWh (net 86 kWh), providing a WLTP range of 488 km. Energy consumption has been further reduced through an efficient thermal management system. It supports 270 kW fast charging, enabling the battery to charge from 5% to 80% in just over 20 minutes, compared to 30 minutes for the previous generation. The regenerative braking system can recover up to 265 kW of energy, boosting efficiency by 15% compared to the previous generation. It supports three levels of manual adjustment and integrates with the driver assistance system, enabling intelligent deceleration, thereby increasing the range by 30%. The utilization of waste heat and advanced drying equipment in the paint shop at Audi's Changchun production site reduces CO_2 emissions by approximately 100,000 tons annually. Additionally, the implementation of ultra-modern E-Cube paint separation technology at the Foshan Audi production plant substantially lowers energy demand and water consumption, reducing CO_2 emissions by approximately 26,500 tons annually, contributing to the establishment of a low-carbon, environmentally friendly facility [146].

TABLE VII presents the environmental benefits of the Audi e-tron GT, enhanced by the Green Design Update, in comparison to the older 2019 model.

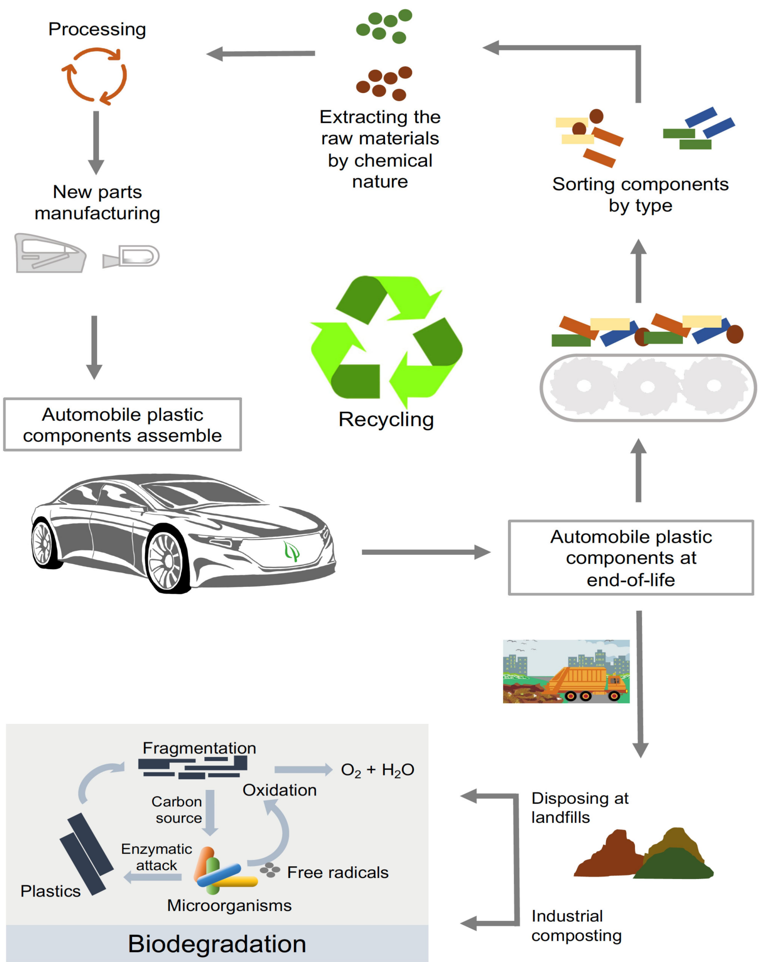

Fig. 17. End-of-life disposal pathways for automotive bioplastic parts ([144] and the owner states clearly that it can be used without permission).

B. Case 2-Implementation of Green Design for Semiconductor Equipment

The environmental impact of semiconductor equipment is wide-ranging and multi-dimensional, encompassing energy consumption, chemical use, waste disposal, and greenhouse gas emissions. The semiconductor industry is under increasing environmental scrutiny, particularly regarding resource utilization and the environmental footprint of the manufacturing process.

Modern semiconductor manufacturing equipment is progressively integrating eco-friendly materials. For example, various coating materials applied to equipment surfaces are specifically designed to improve corrosion and wear resistance, thereby prolonging the equipment's lifespan. However, conventional coatings, such as those based on chromium and nickel, may contain harmful substances that present potential risks to both environmental sustainability and operator health. In contrast, ceramic coatings are free from hazardous chemicals, demonstrate exceptional resistance to oxidation and erosion at elevated temperatures, and exhibit superior thermal and electrical properties [147]. In addition to advancements in coating technologies, the widespread adoption of lead-free solders has substantially enhanced the eco-sustainability of semiconductor packaging processes. Traditional solders typically contain lead, a toxic heavy metal that presents health and environmental hazards during the soldering process. The transition to lead-free solders ensures compliance with environmental standards while reducing the risk of lead contamination [148]. Furthermore, emerging semiconductor manufacturing techniques are playing a significant role in reducing chemical waste. For example, photoresists, essential in photolithography, have traditionally been composed of polymers, solvents, sensitizers, and other additives. In contrast, block copolymer (BCP) and brush-coated lithography methods eliminate the need for sensitizers and other hazardous additives, thereby substantially minimizing chemical waste generation [149].

Several strategies can be employed to improve the energy efficiency of semiconductor equipment. For example, adopting more energy-efficient chiller models can reduce energy consumption by 40% to 50%. Furthermore, installing variable speed drives (VSDs) for pumps in chilled water systems can result in energy savings of up to 30%. Moreover, improved process integration can streamline operations and eliminate energy-intensive steps, leading to substantial energy reductions [150]. Temperature and humidity control plays a critical role in semiconductor manufacturing, as it ensures the proper functioning of equipment. Therefore, optimizing air conditioning and cooling systems—major energy consumers—is essential. Fans and chillers are the primary energy-intensive components of these systems, contributing to approximately 80%–90% of total energy consumption. Moreover, most modern systems require thermal and cooling compensation, resulting in additional heating and cooling demands [151]. To address these challenges, recent studies have proposed a generalized

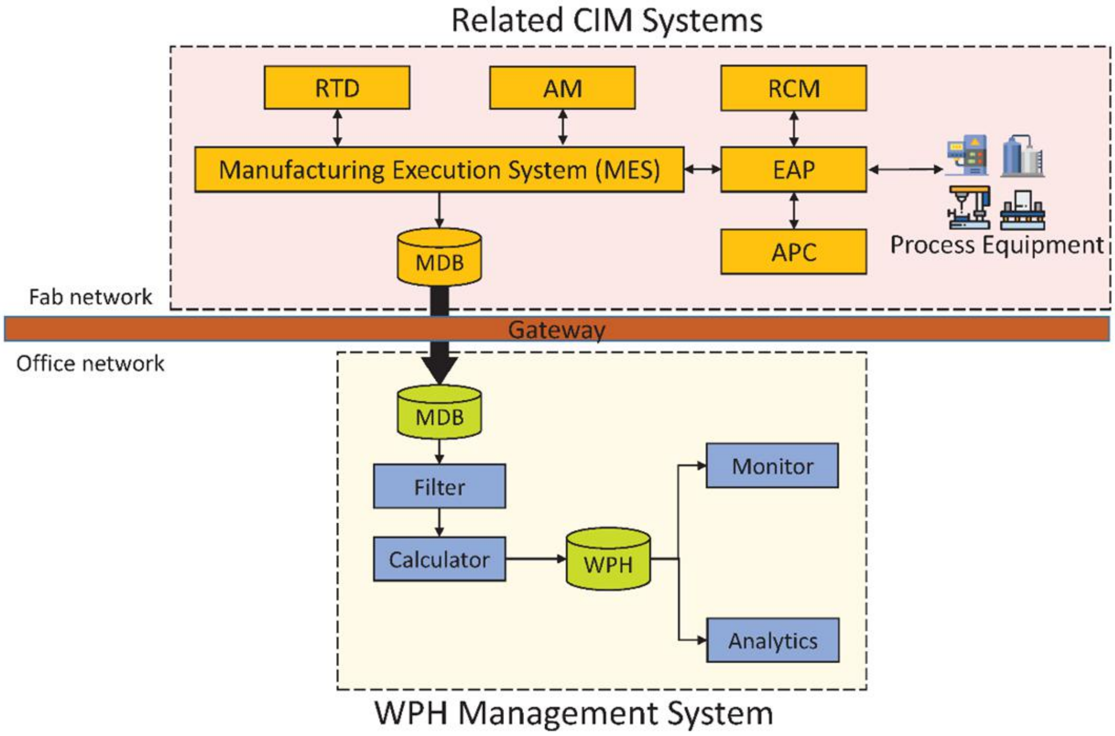

Fig. 18. System architecture of the WPH management system ([153] and the owner states clearly that it can be used without permission).

framework for the optimized design of semiconductor cleanroom air-conditioning systems. This framework integrates heat recovery and free cooling technologies on both air and water sides, effectively addressing heat and cooling compensation issues. It improves cooling efficiency under various weather conditions, cooling loads, ventilation rates, and climatic scenarios. Research findings indicate that, compared to conventional designs, this method results in energy savings ranging from 2.3% to 33.1%, with a primary energy reduction of up to 15.8 GJ/m² per year [152].

From a modular design standpoint, the semiconductor wafer fabrication equipment throughput management system focuses on optimizing wafer flow and handling throughout the entire manufacturing process. This modular approach offers flexibility, scalability, and improved operational efficiency, enabling the system to adapt to the growing complexity of production environments in modern semiconductor fabrication facilities. The Wafer Processing and Handling (WPH) management system, as introduced by recent studies [153], automates and optimizes wafer flow via intelligent scheduling, precise control, and real-time monitoring. The system architecture is depicted in Fig. 18. The system comprises four primary modules: filtering, computation, monitoring, and analysis. By integrating these modules, the WPH system significantly improves the alignment between planned and actual capacity, increasing the correlation coefficient of the capacity allocation model from 0.6548 to 0.9587. Accurate capacity planning reduces equipment idle time, leading to a conservatively estimated 5%–10% reduction in unproductive energy consumption. Furthermore, the mean-square error in wafer production count decreases from 4,614.96 to 2,834.88, thereby minimizing wafer rework and scrap rates. Assuming a 2% reduction in wafer scrap, this improvement yields significant annual raw material savings. The modular design of the WPH system not only enhances its flexibility, scalability, and reliability but also reduces both cost and system complexity. This design approach not only meets the current demands of semiconductor manufacturing but also establishes a robust foundation for future technological advancements and system expansions, positioning it as a critical direction in modern intelligent manufacturing.

In the semiconductor manufacturing industry, numerous high-cost, complex equipment units with extended service lives are regularly recycled or refurbished for reuse. These units retain their value and, with appropriate maintenance and upgrades, can continue to meet evolving production requirements. However, the chemical waste streams generated during semiconductor production pose a more significant environmental threat than the equipment itself, primarily due to the substantial volumes of sulfuric acid waste and spent etchants. Approximately one billion cubic meters of etchant waste is generated annually, with copper chloride and alkaline etchants accounting for the majority of this waste. Several regeneration methods have been developed, including chemical precipitation, flocculation–precipitation, electrolysis, and membrane separation technology [154]. Reference [155] describes sulfuric acid treatment methods employed in semiconductor manufacturing plants, such as atmospheric pressure distillation and low-pressure distillation, which achieve effective recycling performance and high output quality. Specifically, when atmospheric pressure distillation is employed, the recovery rate of sulfuric acid waste exceeds 95%, the recovery concentration surpasses 97%, and the residual impurity levels in the recycled sulfuric acid are equivalent to those found in industrial-grade sulfuric acid used in electronics applications.

Leading semiconductor manufacturers, including TSMC, Intel, and Samsung, are actively mitigating greenhouse gas emissions produced during fabrication processes. All three companies have procured Renewable Energy Certificates

(RECs), resulting in an average CO_2 emissions reduction exceeding 40%. Additionally, TSMC has deployed carbon capture technologies to remove residual CO_2 during purification processes, capturing 500 metric tons of CO_2 in 2022. Intel has implemented process optimization strategies, such as deactivating idle equipment, achieving a reduction of 16,000 metric tons of CO_2 annually and a cost savings of $408 per ton; moreover, its cooling technology upgrades (e.g., installation of variable frequency drives) and HVAC retrofits have decreased emissions by 1,200 and 800 metric tons per year, respectively. Samsung has enhanced building energy efficiency—such as by adopting LED lighting—to reduce CO_2 emissions by 1.32 million metric tons per year and has utilized liquid biofuels and geothermal energy to achieve additional reductions of approximately 7,500 and 28,500 metric tons annually, respectively [156]. These initiatives underscore the positive impact of green design strategies on advancing sustainability objectives within the semiconductor manufacturing industry.

C. Summary

The integration of green design principles in Audi's vehicles and semiconductor equipment underscores their broad applicability and significant impact on contemporary industries. Green design transforms the environmental performance of precision machinery through material innovation, energy efficiency optimization, and recycling technologies, demonstrating its potential for achieving systematic reductions in emissions in automotive and semiconductor manufacturing. The Audi e-tron GT employs closed-loop substitution of bio-based materials (e.g., 100% recycled aluminum scrap), carbon fiber lightweighting (reducing weight by 50%), and 270 kW intelligent fast-charging technology, resulting in a 40% reduction in life-cycle carbon emissions. These measures confirm the feasibility of improving eco-efficiency in precision machinery through material flow reengineering and energy management. Audi’s green design initiative not only enhances its brand image and market competitiveness but also provides a valuable benchmark for other automakers. In comparison, semiconductor equipment achieves a 20% reduction in carbon footprint per wafer through ceramic coatings (60% emission reduction), lead-free solder (65% energy savings), and a modular wafer system design (10% reduction in inefficient energy consumption), further supplemented by etchant recycling (95% sulfuric acid recovery) and pyrolysis oil conversion technology. This example demonstrates how green design transforms the environmental impact of precision machinery from a linear model to a circular, closed-loop system through multidimensional technological innovations, markedly improving resource conversion efficiency while maintaining precision performance. Furthermore, it establishes a replicable technological paradigm for the low-carbon transformation of high-precision manufacturing.

VI. DISCUSSION

This review synthesizes the application of green design concepts to the design and development of precision mechanical products. It highlights four core elements—material selection, energy efficiency, modular design, and recycling and remanufacturing. It then introduces essential methods and tools, including computer-aided manufacturing (CAM), digital twins, simulation, and environmental impact assessment. Furthermore, it demonstrates the effectiveness of green design in mitigating environmental impacts and enhancing resource efficiency across the product life cycle via case studies of Audi electric vehicles and semiconductor equipment. These findings underscore the value of integrating green design strategies to mitigate environmental burdens and optimize resource utilization in precision machinery products.

A. Green Design Synergies

By integrating the four major elements of green design—material selection, energy efficiency, modular design, and recycling and remanufacturing—in existing studies, researchers have demonstrated that these elements significantly enhance the environmental benefits, economic value, and technological innovation potential of precision machinery products through the multidimensional integration of technologies, materials, and strategies, resulting in a “1+1>2” synergistic effect and ultimately achieving full life cycle sustainability. Below, we detail the synergistic effects of selected green design elements:

1) Synergies exist between material selection and energy efficiency optimization. For example, the Audi e-tron GT in Case 1 employs carbon fiber composites and recycled aluminum to reduce body weight, thereby reducing energy consumption. This lightweighting directly reduces the load on the drivetrain and synergizes with hybrid technology, achieving a 38% fuel saving and enhancing overall energy efficiency, thereby demonstrating the dual benefits of lightweight materials; furthermore, the application of bio-based lubricants (e.g., PMO) in precision bearings not only reduces friction and machining energy consumption but is readily biodegradable, thus minimizing environmental impact and achieving dual optimization of material environmental friendliness and process energy efficiency.

2) The synergistic effect of modular design, recycling, and remanufacturing is significant. Modular design promotes the circular economy by standardizing connections and simplifying disassembly, thereby significantly improving material recycling rates. For example, the glass pot of a coffee maker can be recycled at up to 80% through modular design, compared with only 35% under traditional design [90]. Furthermore, the modular components of an optical microscope (e.g., the moon-shaped lens set) allow localized replacement rather than complete scrapping, reducing waste generation by 30% and enhancing functional independence and maintenance efficiency [91].

B. Contradictions and Conflicts in Green Design

In the process of green design and development of precision machinery, numerous challenges arise, primarily in material selection, manufacturing technologies, and structural optimization. First, regarding material selection, although recycled steel demonstrates advantages in reducing energy consumption and carbon emissions compared with virgin steel, its mechanical properties remain unstable due to significant fluctuations in impurity levels. To address this issue, a precision smelting process is required; thus, recycled steels are currently limited to low- and mid-range

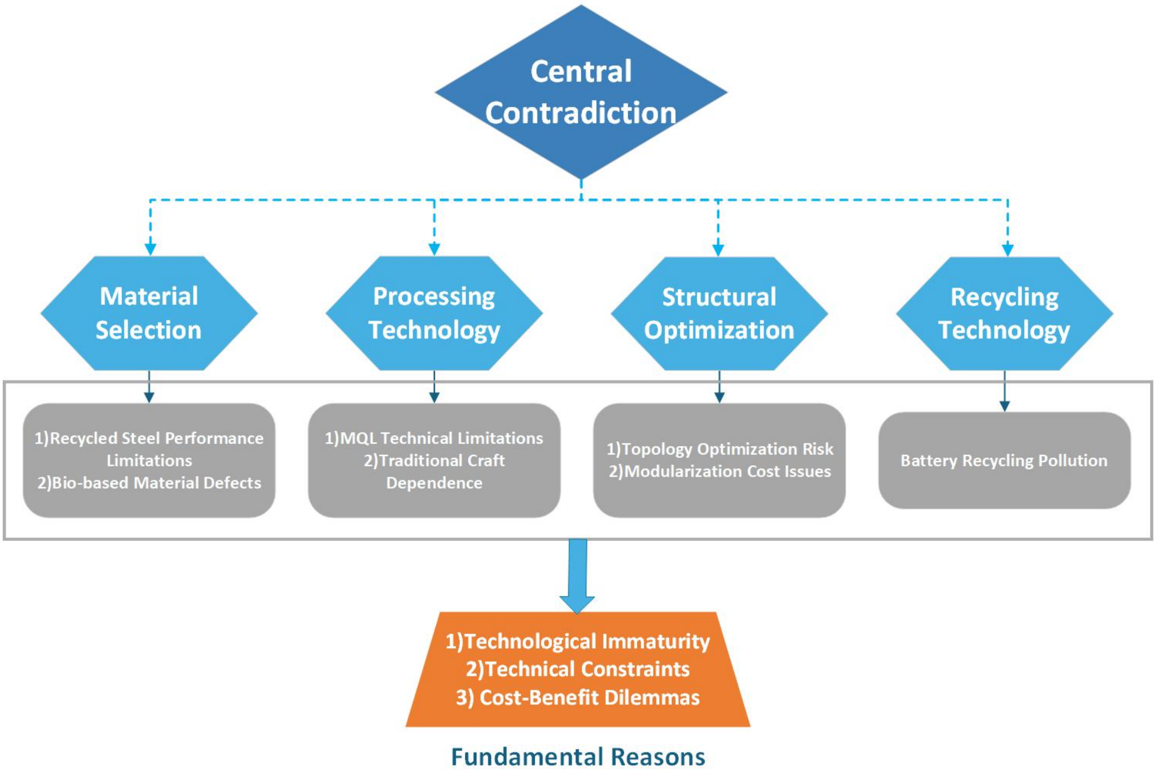

Fig. 19. Causes of multidimensional contradictions and conflicts in green design of precision machinery.

components that do not demand high mechanical performance, such as structural elements. Components with stringent requirements, such as aerospace-grade steels, continue to rely on primary smelting processes [157]. Similarly, bio-based polymers (e.g., polylactic acid (PLA)) offer environmental benefits but are constrained by thermal sensitivity and hygroscopicity, which complicate achieving consistent molding quality and dimensional accuracy [158]. Additionally, although bio-based lubricants exhibit favorable environmental properties, they are susceptible to oxidation and degradation in high-pressure precision bearings; their service life is significantly shorter than that of mineral oils, and frequent replacements elevate maintenance costs [159].

Secondly, regarding machining technology, micro quantity lubrication (MQL) effectively reduces energy consumption; however, its lubrication film is prone to rupture under extreme conditions—such as high speed, high pressure, and high temperature—resulting in increased tool wear. Consequently, conventional cutting methods remain indispensable for machining special materials, such as titanium alloy aerospace components [160].

Furthermore, in structural optimization, topology optimization techniques, while significantly reducing weight, may induce stress concentrations, thereby compromising the reliability of mechanical systems—particularly under high precision, high load conditions—thus exacerbating this potential risk [161]. Meanwhile, modular design enhances maintainability and recyclability, but its implementation in precision machinery is constrained by high initial investment, complex design procedures, and increased manufacturing costs [162].

Finally, recycling and reuse technologies are still in the early developmental stage, posing inherent environmental risks. For example, pyrometallurgical recycling of lithium-ion batteries consumes substantial energy and generates significant greenhouse gas emissions and toxic by-products, thereby heightening the risk of secondary pollution if improperly managed [163].

These contradictions and conflicts reveal that the root causes lie in the immaturity of technological development, intrinsic technological limitations, and the mismatch between economic feasibility and market mechanisms. On one hand, some green materials and processes remain at the research or early application stage, making it difficult to satisfy precision machinery performance and reliability requirements; on the other hand, certain green technologies cannot supplant traditional solutions in specific scenarios due to intrinsic material properties or fundamental physical constraints. Furthermore, even when technically feasible, commercialization remains constrained by high costs, low efficiency, and limited market acceptance. Only by addressing these fundamental issues can the contradictions and conflicts in the green design process be resolved. Fig. 19 illustrates the multidimensional contradiction and conflict analysis in the green design of precision machinery.

C. Challenges to Green Design of Precision Machinery

Although existing research demonstrates the potential of green design in precision machinery, its industrialization continues to encounter significant technical, economic, and policy challenges (Fig. 20).

Technical aspects: Existing research prioritizes the environmental performance of individual materials; however, it insufficiently optimizes critical attributes—such as mechanical strength and heat resistance—as well as associated production processes. In particular, the absence of systematic investigations into multi scale composites (e.g., nano reinforced biomaterials) prevents resolution of the "high strength, low environmental impact" dilemma. In the field of high-precision machining, the application of

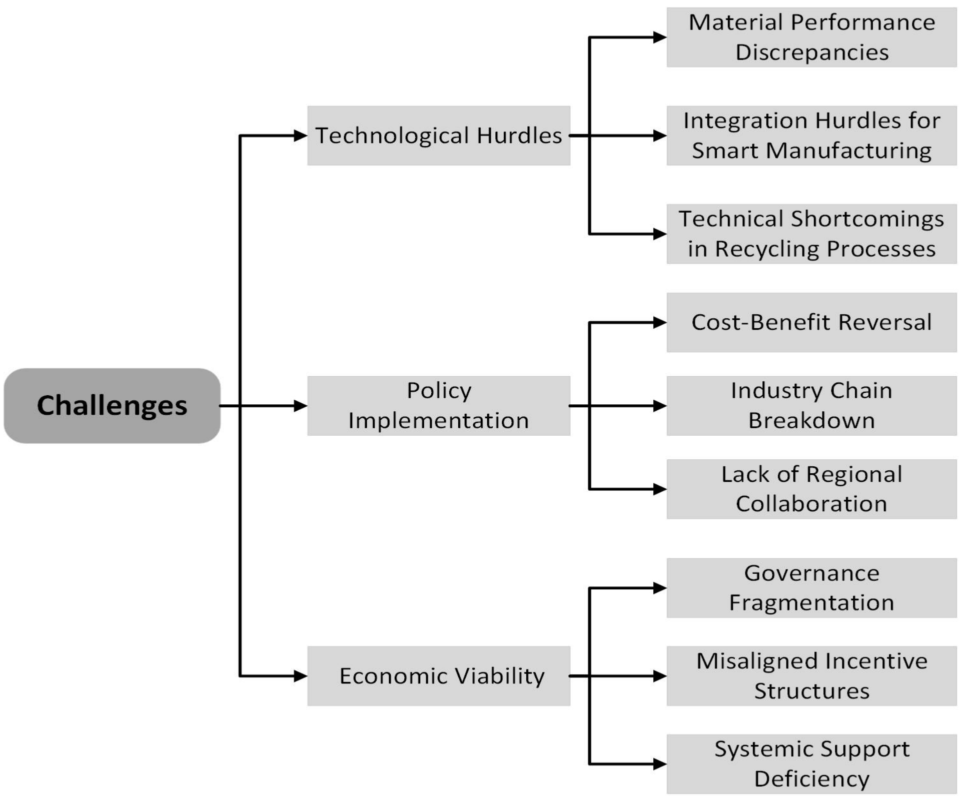

Fig. 20. Analytical framework for challenges in green design of precision machinery.

energy-efficient technologies is still relatively limited, and the actual results are not satisfactory. Nowadays, the development of artificial intelligence and industrial IoT brings new possibilities for energy efficiency optimization, but these new technologies must be integrated with the existing old systems in factories, and there are still many difficulties, such as real-time data collection and feedback control. For small and medium-sized enterprises, they would like to use modular design to improve efficiency, but the interface standards are not uniform and the initial investment cost is too high, which makes it difficult to eliminate the problem of low precision of products after recycling and remanufacturing in production. In addition, the whole recycling process has a relatively large impact on the environment, and there is a certain risk of secondary pollution.

Economic aspects: The development of green design in precision machinery encounters various constraints, including high costs, low returns, and significant investment risks. The elevated costs of green materials, prolonged investment return cycles for energy-saving technologies, substantial initial investments in modular design, and limited economic returns from recycling and remanufacturing undermine the endogenous motivation for implementing green strategies in actual industrial operations. Moreover, existing research primarily remains at the theoretical exploration stage, hindering the formation of a comprehensive industrial support system; additionally, studies on cross-industry synergy mechanisms remain relatively underdeveloped. The absence of a regional circular collaboration system diminishes resource flow efficiency and allocation, thereby impeding the industrialization and large-scale application of green design innovations.

Policy aspects: In the context of applying and advancing green design concepts for precision machinery, technological innovation predominantly captures mainstream attention. However, most existing research primarily examines individual national or regional policies (e.g., the European Union's Ecodesign Directive or China's "dual-carbon" goal), neglecting cross-regional synergy mechanisms. Most literature investigates the impact of short-term government subsidies while overlooking the formulation of market-driven mechanisms. Consequently, firms may deviate from green development trajectories when financial support diminishes, owing to reduced profitability. Therefore, assessing the influence of fiscal incentives and binding regulations on the industrialization of green technologies is essential to addressing the "technology-market disconnect." In the absence of comprehensive policy frameworks, fragmented technological applications impede the formation of an integrated industrial ecosystem, thereby constraining the full realization of environmental benefits.

VII. Outlook

With the continued global emphasis on sustainable development, technological advances, policy support, and shifts in market demand, the concept of green design will become a core strategy for the future development of the precision machinery manufacturing industry and a key factor in sustainable growth. Considering the limitations of existing research and the challenges of industrialization, future studies should develop a multidimensional theoretical framework and a technological roadmap for green design, focusing on the following directions:

(1) Achieving innovation and process optimization of high-performance green materials is essential. Future research should focus on developing multiscale composite materials that integrate bionics and nanotechnology to

produce gradient-structured materials—for example, bamboo fiber-reinforced polylactic acid (PLA)—which, through the synergistic effects of natural fibers and bio-based polymers, not only compensates for PLA's low compressive strength but also significantly enhances its toughness, thermal stability, and degradation properties [164]. Such materials offer unique advantages in environmental protection, resource sustainability, and functionality, making them an important direction for green materials research and development. Future research should also develop intelligent green processes—such as hybrid manufacturing technologies that combine additive and subtractive methods for complex geometries and high-quality surface finishes—to achieve comprehensive improvements in production efficiency, processing accuracy, and resource utilization, thereby providing green solutions for aerospace, biomedical, and other high-end applications [165]. Only by achieving breakthroughs in material properties and process methodologies can the widespread application of green design in high-end manufacturing scenarios be truly realized.

(2) Applying emerging smart manufacturing technologies, such as artificial intelligence (AI) and digital twins—holds great potential for advancing green manufacturing and overcoming the technical and economic bottlenecks of conventional models. Through deep learning and machine learning algorithms, AI can accelerate green materials R&D, optimize manufacturing process parameters, and significantly enhance material performance, processing accuracy, and production efficiency while reducing R&D costs and resource consumption. This dual advantage improves energy efficiency and minimizes waste [166]. For example, Soares et al. [167] demonstrated that AI can optimize bio based lubricant performance, reduce operating costs, and enhance sustainability, thereby providing a feasible route to replace non degradable lubricants. Rahman et al. [168] further reported that AI significantly improves efficiency and product quality in both subtractive and additive manufacturing through real time monitoring, dynamic control, and data driven optimization. In addition, digital twin technology provides an efficient virtual verification platform for green design and manufacturing, enabling designers to rapidly identify and resolve physical world issues, optimize product structures and manufacturing processes, and thus accelerate product iteration and enhance value creation efficiency [169]. Future integration of AI and digital twins will further enhance green manufacturing's capabilities in intelligent decision making and full life cycle management.

(3) Address the trade- off between precision- machinery product performance and environmental protection. In the green- design process for precision machinery, pursuing higher performance may shorten product lifespan, while stringent processing requirements can complicate manufacturing, thereby increasing energy consumption and waste generation. For example, in the automotive sector, increased engine displacement yields greater power but also results in higher emissions. In this context, powertrain reconfiguration—through the development of variable- compression- ratio engines—can increase power while reducing emissions [170]. Moreover, integrating AI- driven emission- control systems that optimize combustion parameters in real time can further improve fuel- utilization efficiency [171]. Future work should focus on optimizing designs and fostering technological innovation to advance the green and sustainable development of precision machinery while satisfying high- performance requirements.

(4) Future research should emphasize interdisciplinary collaboration. The green design of precision machinery is essentially a multidisciplinary, cross- disciplinary systems- engineering endeavor, requiring deep collaboration among mechanical engineering, materials science, economics, computer science, and related fields. For example, in precision CNC machine tools, optimizing structural design and motion- control systems, developing environmentally friendly, high- performance cutting fluids or lubricant substitutes, conducting economic- feasibility assessments of green- performance products, and leveraging software algorithms and information technology to develop intelligent management systems all require a multidisciplinary approach. Only through multidisciplinary collaborative research can we systematically resolve the trade- offs between performance and environmental protection, technology and economics in green design, and promote the effective implementation and sustainable development of green manufacturing concepts in precision machinery [172].

(5) The government should proactively implement diversified incentive mechanisms. Through policy guidance and market- driven instruments, enterprises can be encouraged to adopt low- carbon development strategies and embed the concept of green design in precision machinery throughout their operations. The core of economic incentives is not direct intervention in firms' technological pathways or emission standards, but rather the use of price signals and reward structures to incentivize firms to adjust their behavior autonomously and transition to green production methods. This approach not only enhances firms' flexibility in resource allocation but also advances environmental objectives while safeguarding economic growth, thereby fostering a development model that harmonizes economic and ecological benefits [173]. Therefore, future research and practice should prioritize policy support and guidance to ensure the broad adoption and development of green design across the precision- machinery sector.

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