

Experimental and Numerical Assessment of Sustainable Machine Tool Design: A Life Cycle Perspective on Structural Optimization and Energy Performance

Nagendra Singh^{1*}, Sanjeev Kumar Verma², Diksha Jain³, Gopal Sharma⁴,
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Abstract

Machine tools are high-mass, energy-intensive systems with long service lives, contributing significantly to the carbon footprint of manufacturing. Enhancing their sustainability requires integrated structural and energy optimization without compromising functionality, accuracy, or productivity. While sustainable design has been studied broadly, systematic reviews from an experimental and applied mechanics perspective remain limited. This paper reviews sustainable machine tool design through a life cycle lens, emphasizing mechanics-based strategies and assessment methods. Key technologies are categorized by life cycle stage and evaluated for their impact on structural integrity and energy consumption. Component-level structural optimization via topology optimization and bionic design for light weighting. Modular configurations and layout optimization to improve stiffness-to-mass ratio. Reduction of cutting fluids through minimum quantity lubrication, dry machining, and cryogenic techniques, and their effect on thermal-mechanical loads. Experimental modeling of energy use during cutting and idle states. Design for reuse, remanufacturing, and recycling to minimize material waste. Sustainability assessment methods such as experimental energy modeling, life cycle costing, and structural life prediction are discussed. This review provides designers with mechanics-driven strategies to enhance machine tool sustainability, linking structural design choices to life cycle energy and environmental performance. The study identifies critical gaps in experimental validation of sustainable design techniques and proposes directions for future applied mechanics research.

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INTRODUCTION

Sustainable Manufacturing and Design

Over the past thirty years, sustainable manufacturing has been accepted as the principal industrial development trend, bringing benefits such as reduced resource and production costs, easier job creation, and enhanced safety, since manufacturing influences product sustainability across their life stages. Therefore, as demands for sustainability grow, design and manufacturing engineers must integrate sustainability considerations into their

work. Every manufacturing process embedded in a product produces environmental effects through its use of energy and materials, and life-cycle thinking must cover all product stages that consume resources and produce waste and emissions [1]. Design and process planning offer substantial latitude in decisions about machine and factory operations. Accordingly, this paper examines detailed methods for designing sustainable machine tools (MT) to support sustainable manufacturing and production.

Sustainable manufacturing also requires industry to weigh economic efficiency, environmental protection, and social benefits in process planning, using advanced manufacturing technologies to strengthen a product's competitiveness. Consequently, the sector should choose more sustainable machines, those with high energy and resource efficiency, low waste generation, and similar attributes. Previously, research on eco-design for machine tools has been extensive but focused primarily on environmental factors, particularly energy use during the operational stage [2]. Even though energy performance in the use phase has been incorporated into design procedures, comprehensive methods for defining sustainability of machine tools during early design phases remain lacking. The research concentrates on the machine tool itself, rather than on the parts produced by it.

Machine tools and their operators are widely recognized as playing a crucial role across numerous industrial sectors, since machine tools serve as the fundamental "mother machines" in manufacturing industries. In response to sustainability concerns, the machine tool industry has introduced various directives and standardization measures that address certain aspects of sustainability. For instance, the European Union has continuously developed standards and regulations concerning energy-consuming products, including Directive 2009/125/EC, which establishes energy consumption requirements for machine tools and related equipment, and Directive 2005/32/EC, which focuses on the eco-design of energy-using products [3]. The European Association of the Machine Tool Industries (CECIMO) has promoted a Self-Regulatory Initiative that encourages manufacturers within the European Union to reduce the environmental footprint of machine tools (MTs). This initiative recognizes eco-design as an effective approach for improving sustainable design performance and strengthening the long-term competitiveness of the machine tool industry, with the objective of enhancing energy efficiency while considering the technical requirements and characteristics of machine tools. Furthermore, CECIMO has launched the "Blue Competence Machine Tools" project to encourage more efficient use of energy and other resources by both machine tool manufacturers and users. In addition, ISO 14955-1:2017 provides guidelines for implementing eco-design principles in machine tools. Although these directives and standards offer valuable guidance to the machine tool industry, they are not legally mandatory [4]. In the future, machine tool manufacturers are expected to provide essential sustainability-related information in addition to functional specifications and purchase costs.

From an environmental perspective, the majority of research has concentrated on energy efficiency, including energy-saving measures during the operational phase and the analysis of energy consumption by key machine tool components such as the main spindle and drive system. The second area of focus is resource efficiency, which encompasses the utilization of raw materials, water, coolants, and lubricants. A third important aspect is the assessment of carbon emissions. While conventional design processes primarily emphasize initial costs, sustainability evaluations should incorporate life-cycle costs. In contrast, the social dimension of sustainability in machine tools has received comparatively limited attention at the product design stage [5]. Therefore, a sustainable design approach should aim to achieve an appropriate balance among the environmental, economic, and social dimensions of sustainability while ensuring that the required functional performance is maintained.

Therefore, to achieve genuinely sustainable machine tool design, designers must incorporate all three dimensions of sustainability throughout the design process. The core technologies that support sustainable manufacturing include environmentally friendly and energy-efficient machine tools, high-performance cutting tools, advanced green machining technologies, and the optimization of manufacturing processes for sustainability. Improving the sustainability performance of machine tools

while simultaneously satisfying technical and functional requirements presents several challenges and requires the implementation of these key technological solutions.

Challenges and Opportunities of Sustainable Machine Tool Design

As manufacturing systems continue to evolve toward greater complexity and higher performance, the demands placed on machine tools have increased significantly. These requirements include enhanced speed, accuracy, intelligence, modularity, reliability, and environmental sustainability [6]. At the same time, global consumption of energy and natural resources is steadily rising, leading to the depletion of non-renewable resources, degradation of the ecological environment, and increased carbon dioxide emissions. Figure 1 illustrates the major challenges associated with sustainable machine tool design. Furthermore, the manufacturing sector accounts for approximately 37% of the global energy demand, highlighting the importance of improving sustainability in this field.



Figure 1. Key challenges of sustainable machine tools design [7].

Machine tools, which are essential equipment in product manufacturing, are considered typical high-energy and high-carbon systems because of their substantial mass, extended life cycles, and significant consumption of resources and energy. As a result, the environmental impacts associated with machine tools are especially pronounced. Consequently, the machine tool manufacturing industry must focus on minimizing the use of non-renewable resources, improving energy efficiency, and reducing environmental pollution to address the growing challenges posed by resource limitations and environmental concerns.

In particular, the design stage represents a critical phase of industrial production, as it largely determines the performance of a product throughout its entire life cycle. During this stage, more than 70% of the characteristics that influence manufacturing, operation, recycling, and end-of-life disposal are established. These characteristics include positioning accuracy, structural stiffness, thermal behavior, pulse equivalent, spindle speed, production cost, environmental impact, and health-related effects [8]. As a result, sustainable machine tools have emerged as an important development in modern manufacturing. Their key features include the use of renewable components, a reduction of more than 50% in total machine weight, a decrease of over 30% in overall power consumption, a reduction of more than 50% in waste emissions, and the potential for complete material recyclability. Green machine tools are characterized by minimal environmental impact, high energy efficiency, and low levels of carbon emissions and waste generation. In general, electricity consumption represents the largest share

of the environmental burden associated with machine tools (MTs). However, sustainable machine tools are not limited to meeting environmental protection objectives; they must also deliver economic viability and social benefits to fulfill the broader goals of sustainable development. Achieving a sustainable transformation of the manufacturing industry requires designers to develop innovative strategies for the design of new sustainable machine tools while simultaneously enhancing the productivity and performance of existing machine tool systems [9].

To address these challenges, machine tool (MT) designers are adopting a range of design approaches, including eco-design methodologies, energy-efficient design, resource-efficient design, and low-carbon design strategies. While several of these technologies, particularly those aimed at reducing energy consumption during the operational phase of machine tools, have already been commercialized, they still need to be systematically integrated into the design process and adapted for practical use by design engineers. **Figure 2** illustrates the key technologies involved in sustainable machine tool (MT) design [10]. The sustainability of machine tools encompasses technological, environmental, economic, and social dimensions, which can be achieved through the implementation of various advanced techniques. These include lightweight design methods, such as bionic and topology-optimization approaches, modular design based on microsystem technologies, and comprehensive sustainability assessment methodologies.

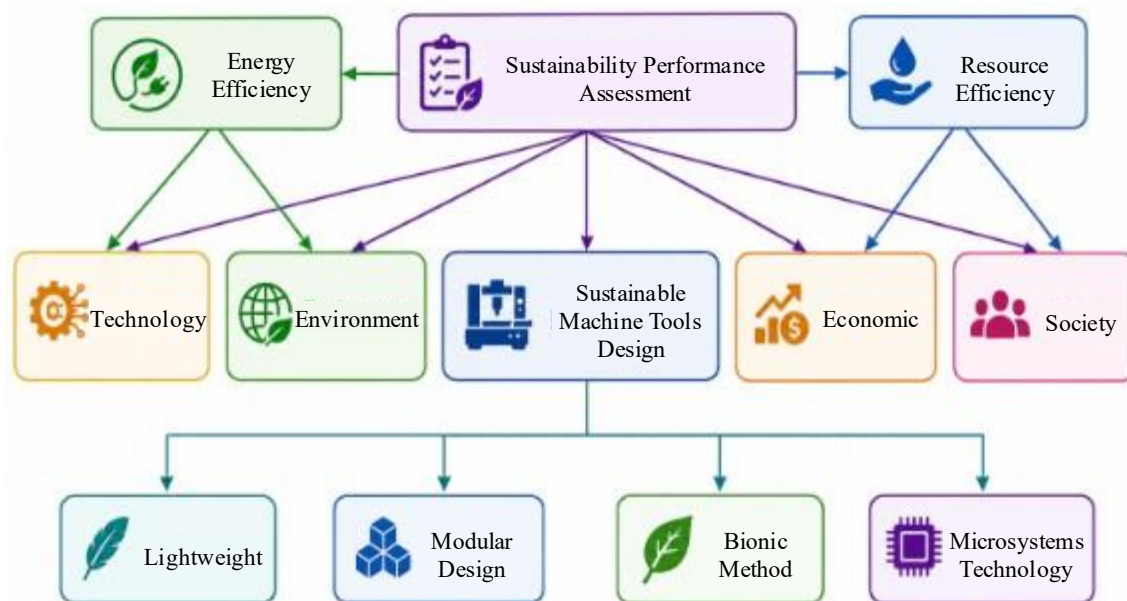


Figure 2. The key technologies of sustainable machine tools design [11].

Accordingly, this review examines the key technologies associated with the sustainable design of machine tools during the early stages of the design process. One objective is to summarize the sustainability dimensions relevant to machine tools—namely technological, environmental, economic, and social aspects—to provide guidance for designers during the conceptual and preliminary design phases. Another objective is to discuss specific design strategies for sustainable machine tool development, analyze the underlying design principles and their relationship to sustainability, and highlight future trends and directions in the advancement of sustainable machine tools.

RESEARCH METHODOLOGY

The literature related to sustainable machine tool design was reviewed using a structured and reproducible methodology. The initial step involved defining and focusing the research question, which concerns the sustainable design techniques applied to machine tools. Given the extensive body of literature available on sustainable development, sustainable design, and sustainable manufacturing, this

study seeks to clarify the concept of sustainable design and identify the techniques that are employed to achieve sustainability objectives in machine tool applications [12]. The second stage involved collecting data from major online databases, including Elsevier, IEEE Electronic Library, John Wiley, ProQuest, Springer, ASME, Taylor & Francis, MDPI, and other relevant sources. The third stage focused on assessing the quality of the retrieved literature and excluding low-quality studies based on evaluations of their abstracts, methodologies, and practical applications. The final stage consisted of interpreting the review findings and providing recommendations for future research and development. The search process employed keywords such as *sustainable development*, *sustainable product development*, *sustainable design*, *sustainable product design*, *sustainable manufacturing*, *sustainable machining*, *sustainable machine tool design*, *machine tool alternatives*, *energy efficiency in machine tools*, *green machine tool design*, *coolant systems*, *machine tool structural design*, *lightweight design*, and *modularity for sustainability*. Using these keywords, a wide range of scientific publications was retrieved from the selected databases. Based on an evaluation of the titles, abstracts, and methodological approaches, the collected literature was further filtered to focus specifically on machine tool design and its applications, with particular emphasis on sustainability considerations.

DIMENSION OF SUSTAINABLE MACHINE TOOLS

In the manufacturing sector, the design and development of sustainable products have been recognized as essential strategies for achieving sustainability and promoting sustainable manufacturing practices [13]. Therefore, incorporating the three dimensions of sustainability—environmental, economic, and social aspects—along with technical requirements during the early design stage can help ensure that products operate with minimal environmental impact while remaining economically viable and socially acceptable. In the field of green machine tool design, however, the majority of research has primarily concentrated on environmental considerations. Recently, researchers have expanded sustainability assessments of machine tool systems beyond environmental aspects alone. For example, **Avram et al.** evaluated the sustainability of a machine tool system during its operational phase by considering economic, technological, and ecological dimensions at both the system and process levels, as summarized in **Table 1**. Furthermore, **Azkarate et al.** proposed a decision-making framework for the design stage of sustainable machine tools, incorporating economic factors such as life-cycle cost and value creation, environmental factors including electricity consumption, lubricants, coolants, materials, and transportation, as well as social factors such as safety, user-friendliness, and ergonomics, as presented in **Table 1**.

Table 1. The dimensions of sustainable machine tools [14].

Dimension	Criteria for Machine Tools	Corresponding Influence Factors	Process Level
Technology	Precision	Evaluated through factors such as positioning accuracy and tool storage capacity, with cutting force serving as an important process-level indicator.	Cutting Force
	Flexibility	Influenced by the type of CNC (Computer Numerical Control) system, part complexity, number of pallets, and idle power consumption, while surface roughness reflects process-level performance.	Surface Roughness
	Power/Energy	Assessed through total rated power and part-program energy requirements, with cutting power representing the corresponding process-level parameter.	Cutting Power
Environment	Emissions Control	Determined by features such as mist collectors and enclosure design, while cutting fluid usage, air consumption, and air quality are important process-level considerations.	Cutting Fluid, Consumption Air Quality
	Material	Related to material selection and its environmental implications throughout the machine tool life cycle.	

Dimension	Criteria for Machine Tools	Corresponding Influence Factors	Process Level
	Productivity	Influenced by tool-to-tool change time, rapid feed rate, and initial investment cost, with tool life serving as a key process-level indicator.	Tool Life
Economy	Cost	Evaluated through maintenance and operational expenses, while machining time significantly affects process-level economic performance.	Machining Time
	Safety	Considered an important factor influencing both machine operation and overall production efficiency.	Safety
Society	User-Friendliness	Assessed by the ease of programming and operation of the machine tool.	
	Ergonomics	Evaluated through the level of support provided for manual operations, with user-friendliness and ergonomic considerations playing a crucial role in process-level performance and operator well-being	User friendliness, Ergonomics

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 Economy	 Cost	Evaluated through maintenance and operational expenses, while machining time significantly affects process-level economic performance.	 Machining Time
	 Safety	Considered an important factor influencing both machine operation and overall production efficiency.	 Safety
 Society	 User-Friendliness	Assessed by the ease of programming and operation of the machine tool.	 User Friendliness
	 Ergonomics	Evaluated through the level of support provided for manual operations, with user-friendliness and ergonomic considerations playing a crucial role in process-level performance and operator well-being.	 Ergonomics

Figure 3. (a) Graphical Representation of Tool Life Cycle [15].

Technology Factors

The scientific and technological advancement of the machine tool (MT) industry is widely regarded as a key indicator of a nation's overall level of technological and industrial development. Machine tools, which consist of standard interchangeable components as well as specialized parts, achieve material shaping and machining through the use of cutting tools. Consequently, the development of the machine tool industry is considered a strategic priority in many countries graphical Representation of Tool Life Cycle mentioned in Figure 3 (a).

Current technological trends in machine tools emphasize high precision, enhanced efficiency, greater flexibility, and increased automation [15]. As a result, machine tool products must first satisfy users' functional requirements, including machining accuracy, service life, productivity, operational flexibility, and overall performance.

Nevertheless, technological advancement remains the primary consideration in fulfilling the functional requirements of machine tools. Numerous studies have focused on improving technological aspects to achieve highly efficient and high-performance machining through various optimization measures. A machine tool consists of control systems, drive mechanisms, and sensing technologies that work together to produce workpiece surfaces with superior accuracy, high-speed operation, enhanced productivity, and improved environmental performance while minimizing ecological impacts [16]. The principal objectives of machine tool structural design are illustrated in **Figure 3 (b)**.

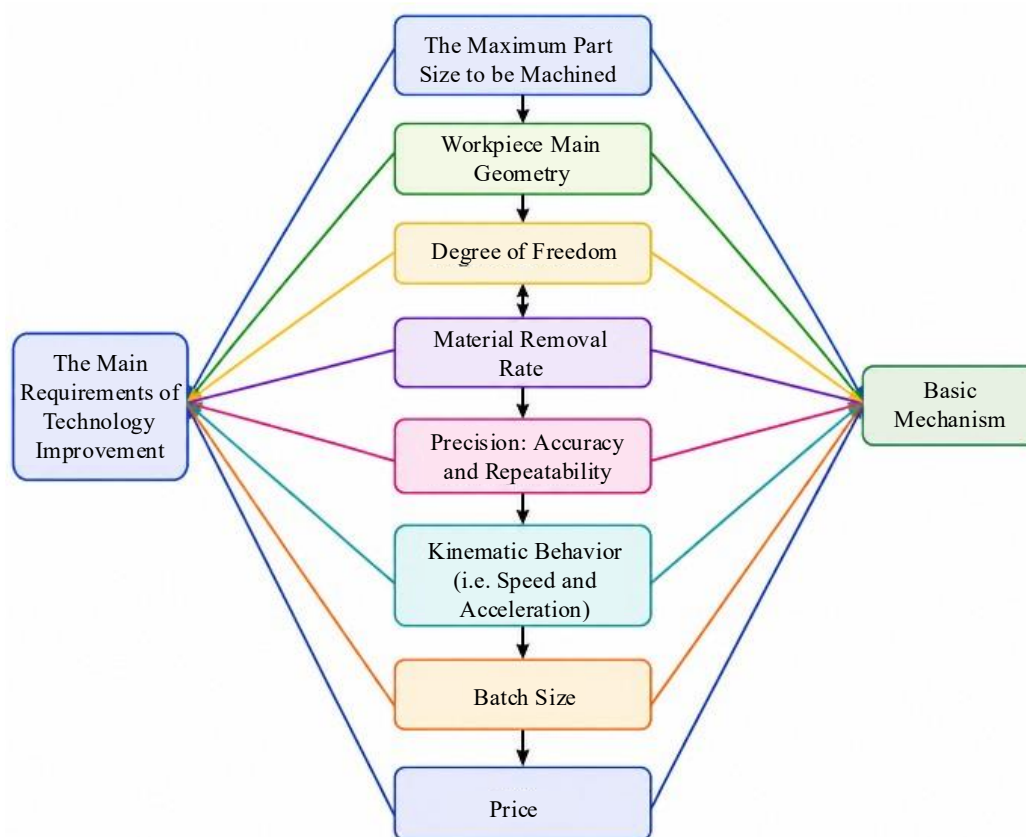


Figure 3. (b) The main objectives of machine tool (MT) structure [17].

During the design and configuration of machine tools (MTs), manufacturing quality and productivity are among the most critical objectives, as they significantly influence the static, dynamic, and thermal performance of the system. Key evaluation criteria include accuracy, repeatability, uncertainty, and functional performance, which are assessed based on geometric and kinematic models [17].

Environmental Factors

The environmental impact of machine tools is commonly evaluated by considering three direct factors—energy consumption, resource utilization, and waste generation—and one indirect factor, namely carbon emissions. Together, these factors provide a comprehensive assessment of the environmental performance of a machine tool throughout its life cycle. Energy consumption is one of the most significant environmental indicators because machine tools require substantial electrical power during operation. Energy is consumed by various subsystems, including the spindle, feed drives, hydraulic and pneumatic systems, cooling units, control systems, and auxiliary equipment.

Reducing energy consumption lowers operating costs and decreases the environmental burden associated with electricity generation. Strategies such as energy-efficient motors, optimized machining parameters, regenerative drives, and intelligent power management systems can significantly improve energy efficiency. Resource utilization refers to the consumption of materials and natural resources throughout the machine tool's life cycle, including manufacturing, operation, maintenance, and end-of-life stages. Efficient resource utilization aims to minimize material consumption while maximizing productivity and product life [18]. Lightweight structural designs, recyclable materials, modular components, and extended tool life contribute to improved resource efficiency.

Waste generation encompasses all unwanted outputs produced during machine tool manufacturing and operation. Excessive waste not only increases disposal costs but also causes environmental pollution. Waste reduction strategies involve recycling metal chips, reusing coolants, implementing minimum quantity lubrication (MQL), improving tool life, and adopting cleaner production technologies. Carbon emissions are generally considered an indirect environmental factor because they are largely associated with the energy and resources consumed by machine tools rather than being emitted directly by the machine itself [19]. Carbon emissions are commonly measured as carbon dioxide equivalent (CO₂-eq) and are evaluated using Life Cycle Assessment (LCA) methods. Since energy consumption is often the largest contributor to a machine tool's carbon footprint, improving energy efficiency is one of the most effective ways to reduce greenhouse gas emissions.

Energy Efficiency

Energy efficiency is regarded as the most critical environmental factor associated with machine tools because of their substantial electricity consumption. The drive to improve the energy efficiency of machine tools is influenced by several factors, including rising energy costs, increasing environmental awareness among consumers, significant opportunities for reducing energy use and operating expenses, the need to lower CO₂ emissions, growing emphasis on life-cycle cost evaluation of machinery and equipment, and evolving environmental regulations and policies. Throughout the machine tool life cycle, the operational or usage phase generally contributes the greatest environmental impact [20]. Consequently, considerable research and innovation efforts are currently focused on enhancing the energy efficiency of numerically controlled (NC) and CNC machine tools to support sustainable manufacturing practices. The development of energy consumption models and the evaluation of energy efficiency in machine tools are essential aspects of energy-saving research in manufacturing. Existing studies primarily focus on improving energy efficiency during the operational phase by optimizing machining parameters and process conditions. In addition, research efforts have addressed energy monitoring and management, structural configuration improvements, lightweight design, and energy optimization of moving components. Since machine tools are extensively used across various industrial sectors, even minor environmentally oriented design improvements can lead to significant enhancements in the overall sustainability performance of machine tools.

Despite these advancements, machine tool engineers seldom adopt comprehensive design strategies that address sustainability from a full life-cycle perspective. Several studies have developed dynamic energy consumption models for machine tools by considering multiple resource inputs and the dynamic characteristics of the machining process. These models facilitate the identification of energy-efficiency

improvement measures at both the machine tool and process levels [21]. Furthermore, **ISO 14955** focuses on the environmental performance of machine tools, with particular emphasis on identifying and implementing opportunities to reduce energy consumption, which is recognized as one of the most significant environmental impacts associated with machine tool operation. A comprehensive overview of environmental aspects integrated into the design and development process can serve as valuable guidance for sustainable machine tool design. Current research increasingly focuses on predicting energy demand during the design stage to facilitate the development of more energy-efficient machine tools. From this perspective, energy-saving strategies for green machine tools can be categorized into six levels, including energy evaluation and modeling, software-based optimization and control technologies, machining and cutting process improvements, hardware-based optimization, and environmentally conscious design approaches [22]. These strategies collectively contribute to enhancing the environmental performance and sustainability of machine tools.

Energy-efficiency optimization can be classified into three levels: the **component level**, the **system level**, and the **control level**. The component level focuses on physical characteristics and performance improvements of individual machine elements, such as enhancing the efficiency of power converters and reducing friction losses. The system level addresses aspects related to machine kinematics and system integration, while the control level emphasizes energy management and optimization of operational requirements. Both the system and control levels primarily aim to minimize energy losses arising from interactions among machine components, thereby improving the overall energy efficiency of the machine tool [23]. The energy consumption during the operational phase of a machine tool is affected by several factors, including material properties, machining process parameters, and the inherent characteristics of the machine itself. It is also influenced by processing time, standby duration, and average power consumption. In contrast, the energy required for cutting operations depends largely on the accurate determination of cutting-force models and the power characteristics of the machine tool. Current research is increasingly focused on optimizing process parameters to reduce energy consumption during machine tool operation. These studies primarily establish mathematical relationships between the material removal rate and specific energy consumption through experimental investigations, enabling more energy-efficient machining strategies.

Research efforts have primarily focused on energy transfer during the machining process, as well as on energy consumption analysis, energy-efficiency evaluation, and information monitoring, based on calculations of power usage and efficiency within the main drive system. In addition, power balance equations for the main drive system of machine tools equipped with frequency-controlled motor speed regulation have been developed through investigations of machine tool energy-flow characteristics [24]. These studies have revealed the complex nature of dynamic load losses occurring within the main transmission system during machine tool operation. Factory-integrated machine tools have been investigated to quantify energy consumption at the factory level and to better understand their contribution to overall manufacturing energy use. Several studies have explored methods for improving machining processes to achieve higher productivity, superior quality, and reduced costs while simultaneously considering the relationship between machining performance and energy efficiency. As a result, energy consumption has become an important factor in process planning, alongside traditional considerations such as machining time, product quality, and electrical power usage. In general, machining operations are performed using machine tools that share similar structural configurations, operating principles, and consumables, including cutting tools, lubricants, and coolant fluids [25].

Furthermore, for the operational phase and specific working conditions of machine tools, it is important to establish functional relationships among unit energy consumption, fixed power requirements, and processing power demand, which is often associated with the material removal rate. Several studies have investigated the relationship between energy demand and machining parameters using experimental data to quantify the energy requirements of specific machine tools. These investigations have confirmed that fixed energy consumption constitutes a fundamental component of

the general energy consumption model. However, the fundamental characteristics of different machine tools vary, which imposes limitations on their range of applications. Although improvements in manufacturing energy efficiency have been achieved through energy-efficiency assessment methods, relatively little attention has been given to energy conservation through structural design optimization aimed at reducing machine tool energy losses. Energy efficiency should be considered an evaluation criterion of equal importance to traditional performance indicators such as accuracy, productivity, cost, and reliability [26]. Consequently, a multiscale integrated design approach can help balance performance, reliability, and energy efficiency throughout the entire design process, thereby enhancing overall product competitiveness.

Resource Efficiency

Resource efficiency is a fundamental aspect of sustainable manufacturing and plays a significant role in the design and operation of machine tools. It refers to the effective utilization of materials, energy, water, and other resources while minimizing waste generation and environmental impact. Since machine tools are among the most resource-intensive manufacturing systems, improving their resource efficiency contributes directly to both environmental sustainability and economic profitability [27]. The primary resources consumed by machine tools include raw materials used in machine construction, cutting tools employed during machining operations, cutting fluids and lubricants required for cooling and friction reduction, and water utilized in cooling systems. During the life cycle of a machine tool, substantial quantities of these resources are consumed, making their efficient utilization an important design objective.

One important area of resource optimization is **material utilization**. Designers seek to reduce material consumption by employing lightweight structures, topology optimization, and advanced engineering materials that provide high strength with lower mass. Such approaches reduce the amount of raw material required during manufacturing while maintaining machine performance and structural integrity. Another important aspect is **process planning optimization**. Efficient process planning minimizes unnecessary machining operations, reduces material removal requirements, shortens production cycles, and decreases tool wear [28]. By selecting appropriate machining parameters and process sequences, manufacturers can improve productivity while reducing resource consumption.

Lubrication and coolant management also significantly affect resource efficiency. Traditional machining processes often consume large quantities of cutting fluids and lubricants, which increase operational costs and create environmental disposal challenges. Sustainable alternatives such as Minimum Quantity Lubrication (MQL), dry machining, and advanced coolant recycling systems help reduce fluid consumption while maintaining machining quality. At the machine level, manufacturers increasingly focus on developing **compact machine tools**, **bench-top systems**, and **micro-factory concepts**. These solutions require fewer construction materials, occupy less space, and consume less energy and auxiliary resources [29]. Compact designs also reduce transportation and installation requirements, contributing to lower environmental impacts throughout the machine's life cycle.

Resource efficiency extends beyond individual machines to the **shop-floor level**. Effective machine layout planning can minimize material handling distances, improve workflow efficiency, and reduce transportation energy requirements within manufacturing facilities. Additionally, optimizing machine footprints enables better space utilization, allowing more efficient use of factory infrastructure. Environmental conditions within manufacturing facilities also influence resource efficiency. Proper lighting systems reduce electricity consumption, while optimized ventilation and climate control systems improve workplace conditions without excessive energy use. Efficient use of factory space and environmental resources contributes to overall sustainability performance.

From an economic perspective, improved resource efficiency reduces operating costs by lowering material consumption, decreasing waste disposal expenses, extending tool life, and minimizing

maintenance requirements. Environmentally, it reduces resource depletion, pollution generation, and ecological impacts associated with manufacturing activities [30]. Therefore, resource efficiency is not only an environmental objective but also a strategic factor that enhances the competitiveness, sustainability, and long-term profitability of machine tool manufacturing systems. By integrating resource-efficient principles into machine design, process planning, and factory operations, manufacturers can achieve significant improvements in both economic and environmental performance.

Waste

Waste management is a critical component of sustainable machine tool design and manufacturing. Throughout the life cycle of a machine tool, waste is generated during production, operation, maintenance, and end-of-life disposal stages. Reducing waste not only minimizes environmental impacts but also improves resource efficiency and lowers operating costs. Consequently, waste reduction has become an important objective in sustainable manufacturing systems. During the **use phase** of machine tools, several types of waste are produced. One of the most significant sources is **cutting fluids and lubricants** [31]. These fluids are used to cool the cutting zone, reduce friction, and improve surface quality. However, after prolonged use, they become contaminated with metal particles, oils, and other impurities, making disposal necessary. Improper disposal of these fluids can lead to soil and water pollution, posing environmental and health risks.

Another major waste stream consists of **worn cutting tools**. Cutting inserts, drills, milling cutters, and other tooling components gradually lose their effectiveness due to wear, thermal damage, and mechanical stresses. If these tools are discarded without recycling, valuable materials such as tungsten carbide, cobalt, and high-speed steel are lost. **Polluted wastewater** generated during cleaning, cooling, and machining operations also contributes to industrial waste. This wastewater often contains oils, metal particles, chemical additives, and other contaminants that require treatment before discharge [32]. Effective wastewater management is therefore essential for environmental protection.

At the **end-of-life stage**, machine tools generate waste in the form of obsolete or damaged components. Some parts can be recycled or remanufactured, while others may be difficult to recover due to material degradation, complex assemblies, or poor design choices. Consequently, sustainable machine tool design emphasizes the principles of **Design for Reuse (DfR)**, **Design for Recycling (DfRcy)**, and **Design for Remanufacturing (DfRem)**. To support these principles, designers must consider sustainability requirements during the **early design stage**. Components should be designed for durability, easy disassembly, and material recovery [33]. Excessive wear of critical parts should be minimized through improved material selection, surface treatments, lubrication systems, and optimized operating conditions. Such measures increase component lifespan and improve the feasibility of reuse and remanufacturing.

Another important strategy is reducing **component scrapping**. Defective or prematurely failed components represent a direct waste of materials, energy, and labor. Improving design quality, manufacturing precision, and maintenance practices can significantly reduce scrap generation. **Machine idle time** also indirectly contributes to waste. When machines remain powered but inactive, they continue consuming energy and resources without producing value. Reducing idle periods through effective production scheduling and machine management improves resource utilization and lowers environmental impacts. In addition, **process optimization** plays a key role in waste reduction [34]. Optimized machining parameters can minimize material removal, reduce tool wear, lower coolant consumption, and improve product quality. This results in less scrap material, fewer rejected parts, and more efficient use of resources.

Overall, waste reduction in machine tools requires a life-cycle approach that integrates design, manufacturing, operation, maintenance, and end-of-life management. By emphasizing reuse, recycling, remanufacturing, process optimization, and efficient resource utilization, manufacturers can

significantly decrease waste generation while improving both environmental and economic performance [35]. Such practices are essential for achieving sustainable manufacturing and supporting the transition toward a circular economy.

Carbon Emission

Greenhouse gas (GHG) emissions have become one of the most widely used indicators for evaluating the environmental sustainability of manufacturing systems, including machine tools. These emissions are commonly expressed as **carbon dioxide equivalent (CO₂-eq)**, a standardized metric that combines the effects of various greenhouse gases into a single value based on their global warming potential. CO₂-eq emissions provide a comprehensive measure of the environmental impact associated with a machine tool throughout its entire life cycle. The carbon footprint of a machine tool is closely linked to three major factors: **energy consumption**, **resource utilization**, and **waste generation** [36]. Among these, energy consumption—particularly electricity use during machine operation—typically contributes the largest share of total greenhouse gas emissions. Machine tools require substantial electrical energy for spindle drives, feed systems, cooling units, hydraulic systems, control electronics, and auxiliary equipment. Because electricity generation often relies on fossil fuels, higher energy consumption directly translates into increased CO₂ emissions.

The **usage phase** of a machine tool generally represents the most environmentally significant stage of its life cycle. Studies have shown that the electricity consumed during years of machine operation frequently exceeds the environmental impacts associated with manufacturing and transportation. Consequently, improving energy efficiency during operation is one of the most effective methods for reducing the carbon footprint of machine tools. Another important contributor to greenhouse gas emissions is **resource consumption**. The extraction, processing, transportation, and manufacturing of raw materials such as steel, cast iron, aluminum, and copper require substantial amounts of energy. Similarly, the production of consumables such as cutting tools, lubricants, and coolants generates additional emissions [37]. Therefore, efficient material utilization and longer component lifetimes contribute significantly to carbon reduction. **Waste generation** also affects environmental performance. Disposal of used cutting fluids, worn tools, scrap materials, and non-recyclable machine components often requires energy-intensive treatment processes. Reducing waste through recycling and reuse minimizes both environmental pollution and associated greenhouse gas emissions.

Economic Factors

Economic performance metrics primarily focus on **life-cycle cost (LCC)** and **value creation**. In modern manufacturing, the conventional concept of cost evaluation must be expanded beyond initial production expenses. Life-cycle cost analysis has emerged as a comprehensive approach that incorporates costs associated with raw material acquisition, manufacturing, transportation, operation, maintenance, and end-of-life recovery [38]. Material efficiency is linked to the proportion of recycled materials used in the product, requiring designers to determine and quantify this contribution during the design stage. Furthermore, operational costs are mainly influenced by the consumption of electricity, cutting fluids, and lubricating oils required for producing a given workpiece under specified machining conditions. Labor costs are generally excluded from the analysis because they vary considerably among different countries and regions. Metrics related to **value addition** reflect the practical usefulness and performance of a product, including factors such as productivity, service life, accuracy, and reliability. Productivity is typically evaluated based on parameters such as maximum spindle speed, tool-change time, and feed rate. Since service life depends on specific operating conditions and application environments, it should be assessed from a life-cycle perspective. Furthermore, energy consumption and economic cost are closely interrelated in machine tools, and this relationship can drive improvements and innovations in machine tool structural design and development. Furthermore, a **life-cycle cost (LCC) assessment method** has been developed for machine tools to support decision-making during the design phase. This approach extends beyond the initial purchase price and incorporates costs associated with operation, maintenance, repair, and end-of-life disposal throughout

the machine's entire service life [39]. The distribution of these costs varies among different types of machine tools. For example, transfer machines exhibit a particular life-cycle cost structure, as illustrated in **Figure 4**, whereas grinding machines show a different cost distribution, as presented in **Figure 5**. In general, life-cycle cost analysis has evolved beyond traditional cost-calculation methods, providing a more comprehensive evaluation of the economic performance of machine tools over their entire lifespan.

Social Factors

Currently, the social aspect of machine tool design primarily focuses on operational safety, usability, and ergonomics to safeguard the well-being of machine tool operators. These factors affect people such as employees, consumers, and suppliers. Usability mainly refers to the ease of programming as well as assistance during manual operation. Ergonomics, which includes the working environment, layout, color schemes, and the morphological features of both machine tool hardware and software interface design, has a significant impact on the health and well-being of workers [42]. The operational safety of machine tools mainly considers clamping safety, chip removal systems, and mist collectors used during manufacturing processes. Since social factors involve non-deterministic elements, they are difficult to quantify and are therefore typically represented using linguistic terms.

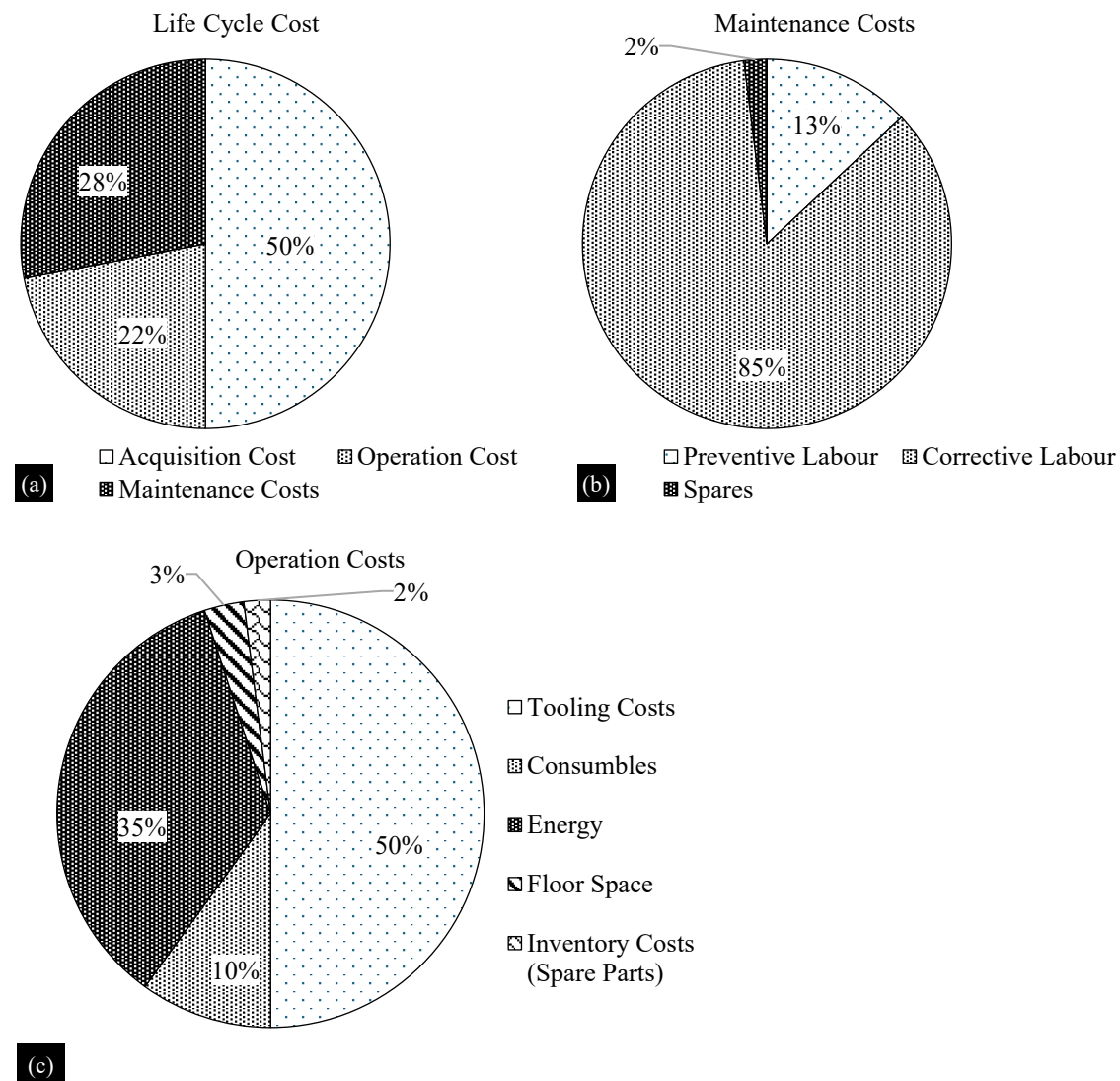


Figure 4. The life cycle cost for transfer machine. (a) Maintenance costs; (b) life cycle cost; (c) operation costs [40].

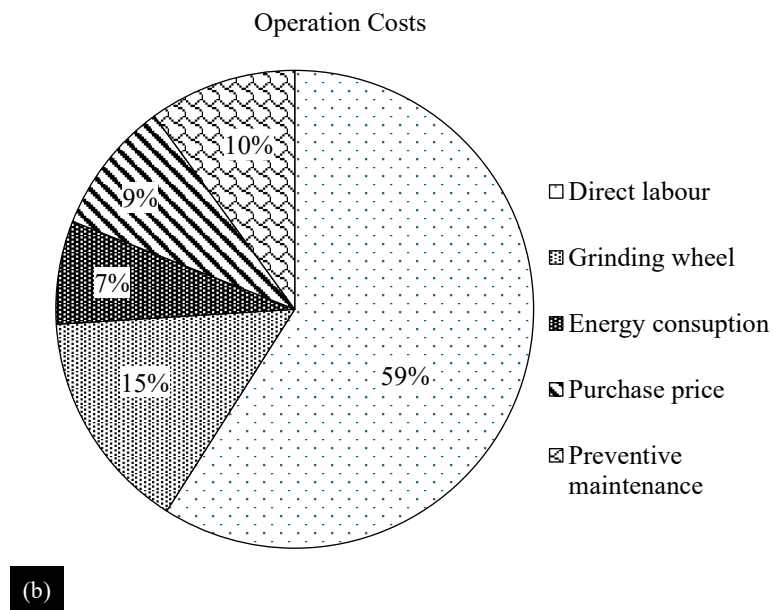


Figure 5. The life cycle cost for a grinding machine [41].

The Analysis Result

The objective of Section 3.5 is to examine the relationship between key techniques and sustainable machine tool design across different life cycle stages. The benefits are addressed within each sustainability dimension for all stages, including production, use, and end-of-life. A review of sustainable design and assessment studies for machine tools from 2003 to 2019 was conducted, moving from partial dimension approaches toward integrated approaches [43]. A total of 44 relevant papers were analyzed, of which 93.2% employed partial methods, while only 6.8% incorporated all three sustainability dimensions, as illustrated in Figure 6. In addition, 71.8% of the studies focused solely on energy, whereas 28.2% considered energy along with other factors.

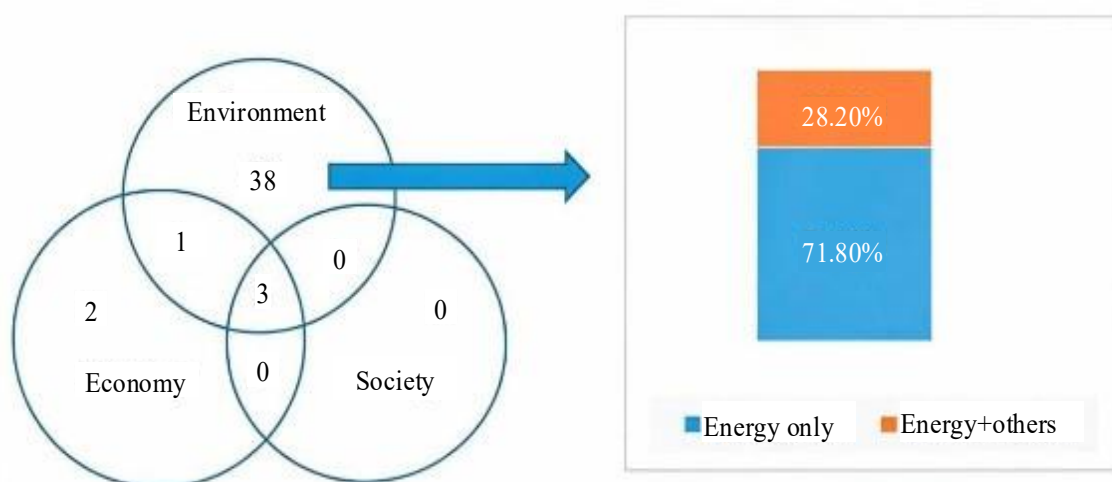


Figure 6. Classification of the focus dimensions of sustainable machine tools design [44].

STRATEGIES AND TECHNOLOGIES FOR SUSTAINABLE DESIGN OF MACHINE TOOLS

As manufacturers and customers become increasingly aware of sustainability issues, sustainable machine tool design and manufacturing will become a key selling point. Manufacturing should shift from extensive production focused only on achieving high quality and low cost to sustainable

manufacturing that maintains high quality while minimizing environmental impact. The strategies and techniques can be categorized into partial design tools that address one or two sustainability aspects, and comprehensive approaches that cover all three dimensions.

The former approach is relatively more mature and standardized than the latter during the early design stage, owing to the presence of uncertain factors at this phase [45]. At the same time, it is necessary to consider whether the machine tools are newly designed or already in use. If the machine tools are to be designed or upgraded through an innovative approach, this represents the best opportunity to integrate sustainability aspects. Otherwise, the focus should mainly be on process optimization methods, such as cutting parameters, tool paths, and machining time after the machine tools have entered their service period. Strategies and technologies are identified progressively, starting from individual components and extending to the product and system level.

Lightweight Techniques of Structural Components

High-speed and high-precision performance requires moving components with low mass and high stiffness. Therefore, improving the specific stiffness of moving parts such as the bed, beam, and spindle box has become an important issue. The lightweight and high-stiffness design of structural components like the bed and column contributes to improved quality, speed, and accuracy, while also enhancing environmental and economic performance by reducing energy consumption and raw material usage. Lightweight machine tools primarily focus on optimizing structural components, moving parts, the overall machine structure, and material selection. New structural concepts such as parallel kinematic machines (PKMs) and box-in-box configurations are continuously emerging and contribute to weight reduction [46]. At the same time, the development of new materials also supports lightweight design, including advanced aluminum alloys, quasi-isotropic fiber-reinforced plastics, and resin concrete (also known as artificial granite). The research group of Campa and Zulaika has made significant contributions to improving machine tool performance by suppressing chatter vibrations in large horizontal lathes, while maintaining high productivity, better surface finish, and enhanced stability. In addition, the dynamic performance of servo drives has also been analyzed.

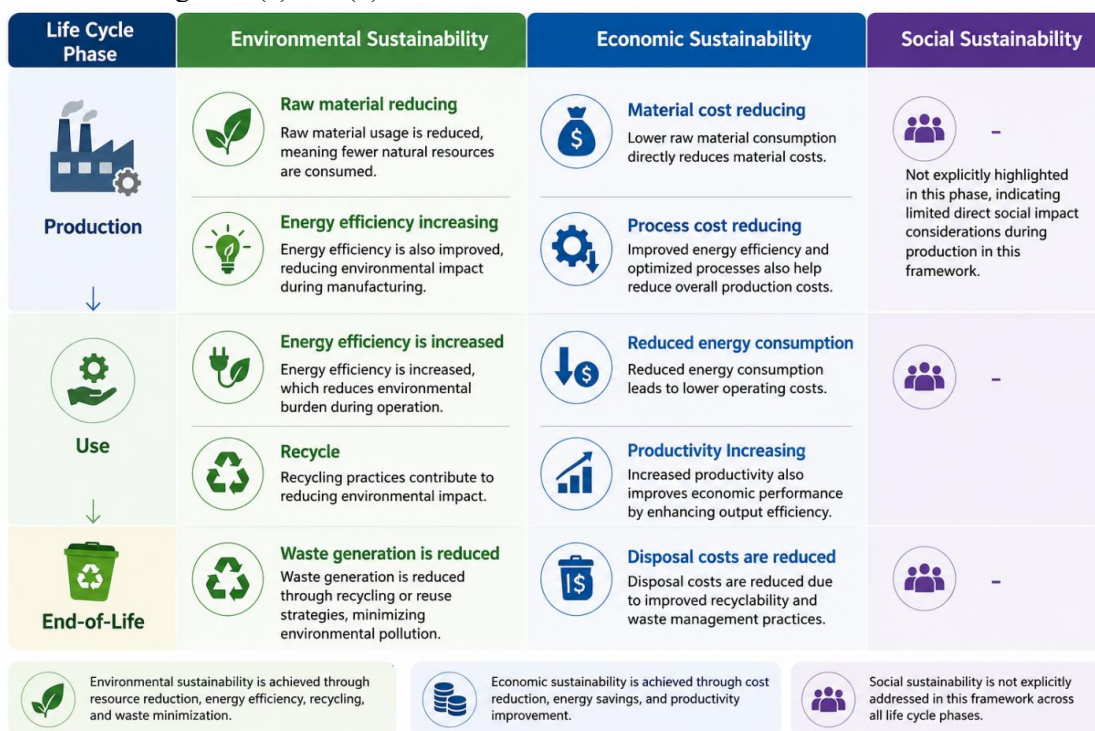
Additionally, lightweight milling machines are developed to achieve the desired productivity with minimal structural mass and reduced energy consumption, and this concept has already been applied in the redesign of existing machine tools. The moving parts of machine tools are made as light as possible to lower driving power requirements, improve energy efficiency, and reduce production and transportation costs. Structural components must still maintain sufficient stiffness to ensure machining accuracy [47]. They should also possess good damping and vibration reduction characteristics to prevent chatter and thereby enhance metal cutting rates. At present, lightweight design methods primarily focus on reducing energy consumption and carbon emissions. This is because reducing the weight of machine tool components can directly and indirectly improve energy efficiency by analyzing energy losses in feed drives and auxiliary systems, as well as by lowering the basic load of the machine tool.

Meanwhile, lightweight structural design plays an important role in reducing manufacturing costs in machine tool factories as well as improving overall machine performance. Structural components such as the bed and feed drive systems can be redesigned using appropriate lightweight strategies based on static stiffness considerations, and the complete machine tool can then be developed by taking dynamic behavior into account. Furthermore, reducing the weight of machine tools can significantly decrease material consumption. Reducing mass helps decrease reactive energy and friction losses, while also improving axis acceleration and guide bandwidth. Increasing stiffness enhances process stability and further improves guide bandwidth. The implementation of lightweight design in machine tools can be achieved through material selection and structural optimization techniques such as topology optimization and bionic design [48]. The benefits of lightweight design for the sustainability of machine tools across each life cycle phase are presented in Table 2.

Table 2. Benefits of light weight for sustainability of machine tools in each life cycle phase [49].

Life Cycle Phase	Environmental sustainability: Raw material usage is reduced, meaning fewer natural resources are consumed. Energy efficiency is also improved, reducing environmental impact during manufacturing.	Economic sustainability: Lower raw material consumption directly reduces material costs. Improved energy efficiency and optimized processes also help reduce overall production costs.	Social sustainability: Not explicitly highlighted in this phase, indicating limited direct social impact considerations during production in this framework.
Production	Raw material reducing	Material cost reducing	-
	Energy efficiency increasing	Process cost reducing	-
Use	Energy efficiency is increased, which reduces environmental burden during operation. Additionally, recycling practices contribute to reducing environmental impact.	Reduced energy consumption leads to lower operating costs. Increased productivity also improves economic performance by enhancing output efficiency.	-
	Recycle	Productivity Increasing	-
End-of-Life	Waste generation is reduced through recycling or reuse strategies, minimizing environmental pollution.	Disposal costs are reduced due to improved recyclability and waste management practices.	-

The selection of materials must be carefully considered during the design of machine tool structures to achieve high accuracy, high productivity, and environmental friendliness. The materials used in machine tool structures significantly affect moving mass, moment of inertia, static and dynamic stiffness, vibration behavior, and thermal characteristics [50]. Therefore, when comparing new materials with conventional ones, energy and resource efficiency as well as environmental and economic factors should be taken into account. The lightweight design approach for machine tools is illustrated in Figure 7 (a) and (b).

**Figure 7.** (a). Sustainability of machine tools in each life cycle phase [51]

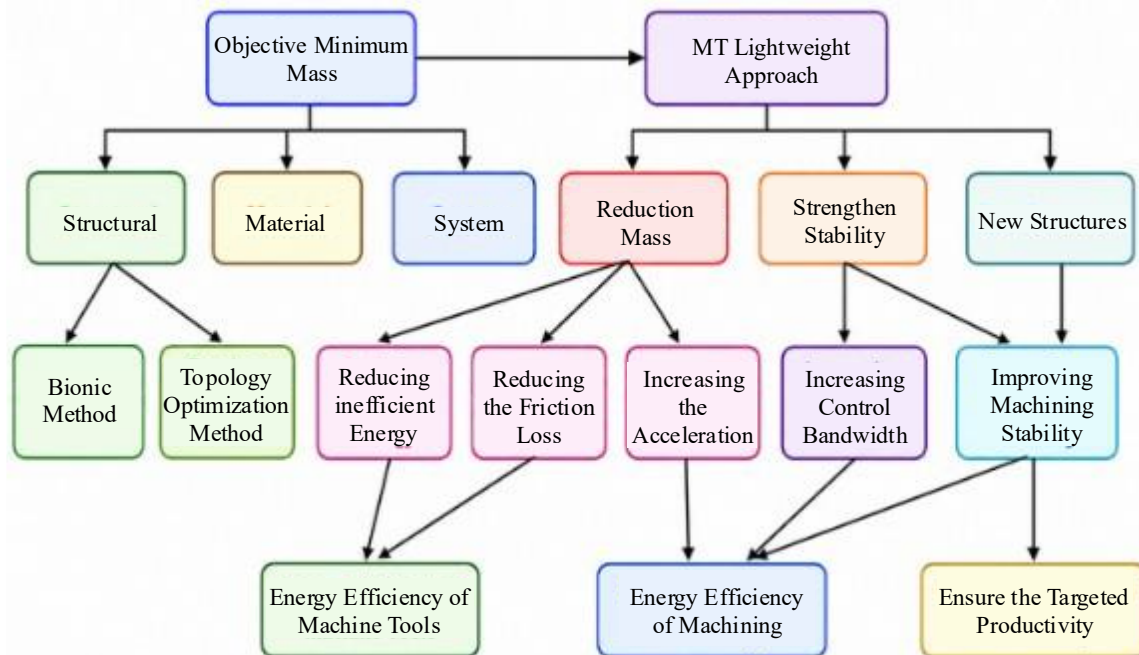


Figure 7. (b). The solution of the lightweight design method for machine tools [51].

The bionic method is an effective approach for accelerating the innovation cycle in modern machine tool design. At the same time, bionic structural design offers a new way to modernize traditional design concepts and achieve maximum structural efficiency. Lightweight technologies applied to moving components not only reduce material consumption in machine tools but also improve operational efficiency. The lightweight design of structural elements such as the bed and upright column is carried out under constraints of strength and stiffness, while also considering the relationship between bed weight and system stability [52]. The strength, stiffness, modal interactions, and weight of key machine tool components are analyzed under various dynamic performance conditions. In addition, the energy flow within machine parts is evaluated to optimize the lightweight design of moving components while ensuring that dynamic performance requirements are satisfied. It is important to note that lightweight strategies for different types of machine tools are primarily determined by the application scenario and machine size.

Structure Principle

Machine tool performance determines the quality of manufactured products and other equipment, involving not only accuracy and surface quality, but also environmental impact and cost efficiency. The energy efficiency of machine tools at the system level is linked to production systems. The structure and layout of machine tools also play a significant role in sustainability through interactions among components as energy converters [53]. In addition to selecting efficient components, the most relevant factors influencing sustainability performance must also be taken into account. Tool path strategies and machine tool axis configurations are considered during the machining process to improve the utilization efficiency of machine tools, which helps reduce energy consumption and material waste. In addition to analyzing the machining process and machine tools separately, the interaction between the machine tool and the manufacturing process should be evaluated through simulation. The functional description of machine tools is generally independent of both the machine tool design and the machining process being implemented [54]. The mapping of functions to machine components is specific to each machine tool, particularly for metal-cutting machines, as illustrated in Figure 8.

Although machine tools differ in their functions and operating conditions, they generally share common elements such as machine tool frames that provide the basic structural foundation. The

production of these frames requires costly engineering, extensive testing, and high-precision manufacturing, and once manufactured, conventional cast or welded structures are difficult or impossible to modify. At present, reconfigurable machine tools have gained acceptance because they allow products to be updated at the fastest rate and at the lowest cost. Machine tools are characterized by complexity, diversity of types, and variability in functions, whereas modular design can shorten the development cycle by enabling disassembly and reuse within reconfigurable manufacturing systems. At the same time, it supports economic efficiency, functional and physical feasibility, upgrading of outdated machines, material recycling, and improved maintenance performance [56]. Therefore, modular design plays a crucial role in the development of sustainable products at the end-of-life stage or during upgrading. Modular machine tools offer advantages in updating and reuse during the use phase and across their life cycles, providing a foundation for various manufacturing sectors.

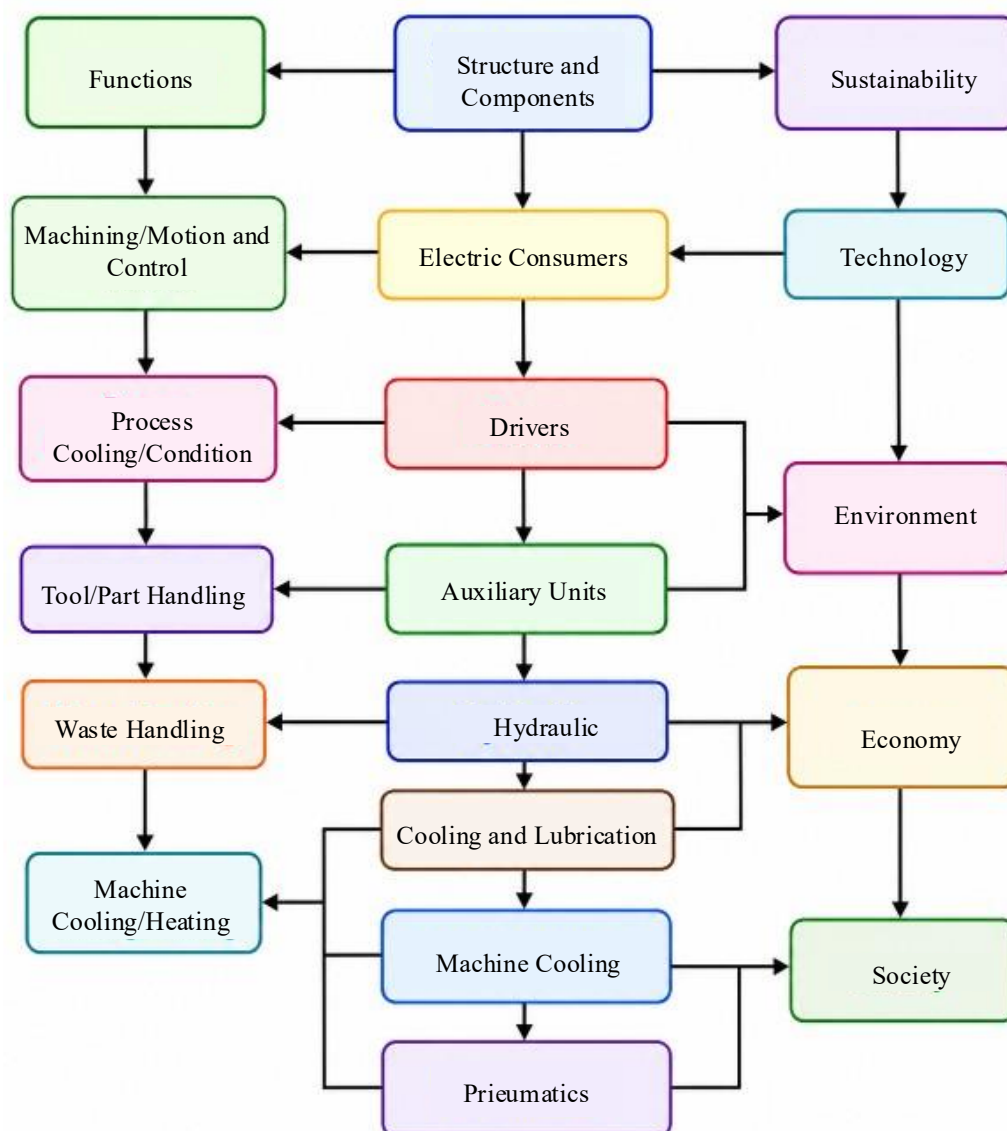


Figure 8. Machine functions to machine structure and components, and sustainability [55].

Machine tool frames are the primary structural elements for enhancing the sustainability performance of machine tools and therefore require greater attention during the design process. In general, machine tools are fixed in operation, whereas flexible manufacturing systems are capable of handling multiple production scenarios. Thus, there is a risk of over-engineering, involving increased labor hours, material

usage, and auxiliary resources, which leads to greater environmental impact and higher costs for manufactured products. Once the design is finalized and produced, it cannot be altered [57]. To address sustainability challenges fundamentally, improvements in machine tool structure and energy efficiency must be considered during the design phase by manufacturers and engineers.

The modular design of machine tools can achieve reconfigurability according to different usage scenarios and also supports reuse or remanufacturing at the end-of-life stage. In some cases, mechanical or electrical components perform multiple functions; for example, a coolant system is used both for machine cooling and process conditioning. In such cases, the energy consumption of these components can be allocated to different basic functions or sub-functions. For instance, the spindle unit of a machine tool, as one of the key components, has the potential to enhance energy efficiency through an optimized electric drive system. Similarly, energy-efficient cooling systems are a key technology in sustainable machine tool design, and hydraulic units should also incorporate energy-saving strategies [58]. Based on structural characteristics, the reinforced plate layout can be improved using advanced optimization methods, and the resulting lightweight design of the machine directly or indirectly enhances the energy efficiency of the machine tool. Considering energy and environmental aspects during the design phase can directly and indirectly improve efficiency, enabling flexibility and versatility while maintaining constraints related to quality and rigidity. Since structural information is defined at the design stage, it is important to identify the relationship between energy distribution and structural characteristics to address conflicts in energy performance. The sustainability benefits of modular machine tools across each life cycle phase are presented in Table 3.

Table 3. Sustainability benefits for modular machine tool in each life cycle phase [59].

	Sustainability for Environment	Sustainability for Economy	Sustainability for Society
Production	Material: Efficient use and selection of raw materials to reduce resource depletion.	Manufacturing cost: Total cost involved in producing machine tools, including labor, energy, and materials.	-
	Carbon emission: Greenhouse gases released during manufacturing processes.		-
	Variety: Diversity of materials or components used, where higher variety can increase environmental complexity (sorting, recycling difficulty).		-
	Supply Chain: Environmental impact of sourcing, transportation, and logistics of materials and components.	Fair wage: Ensuring workers in production receive fair and ethical compensation.	-
	Manufacture: Working conditions and safety during manufacturing processes.		-
	Maintenance: Ease and safety of maintaining production equipment and systems.		-
	Repairability: How easily machines or components can be repaired, affecting worker workload and safety.		-
Use	Upgrades: Ability to improve or modernize machine tools to reduce waste and extend life cycle.	Maintenance cost: (environmental link implied in table context): Resource use (energy/materials) required for maintaining machines.	Operator safety and health: Protection of workers from hazards, fatigue, vibration, noise, and ergonomic risks during machine operation.
	Functionality: Efficient operation that minimizes energy use and environmental impact during use.		
	Services: Support systems such as lubrication, cooling, and software updates that influence operational efficiency.		

	Sustainability for Environment	Sustainability for Economy	Sustainability for Society
End-of-life	Recycle, reuse, remanufacture, updated: Strategies to recover materials and components, reduce waste, and extend product life.	Recycle, reuse, remanufacture, updated: Cost savings achieved through material recovery and product life extension strategies.	Operator safety and health: Ensuring safe handling during dismantling, recycling, and remanufacturing processes, reducing occupational risks.

Cooling and Lubrication Technique

The cooling and lubrication system is a key factor in achieving the required levels of precision and stability, as well as in reducing friction in contact zones and maintaining thermal stability. In general, machine tools equipped with cooling and lubrication subsystems can protect contact areas and extend the service life of both tools and machines, which benefits economic performance. However, these systems also increase environmental impact due to the use of electricity or compressed air [60]. There are two primary sources of heat generation: electrical losses in motors and friction in bearings, along with the cutting process itself. To address this issue, several methods are used, such as minimum quantity lubrication (MQL) systems, dry machining processes, and cooling of the control cabinet, water coolers, cooling pumps, and the cooling/heating of guideways. The cooling and lubrication techniques are illustrated in Figure 9.

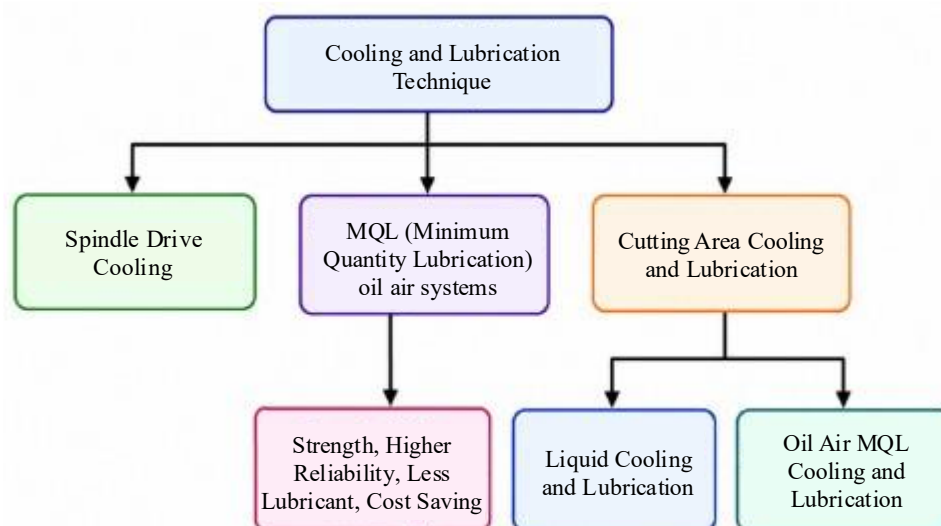


Figure 9. The cooling and lubrication technique [61].

The study compares the power consumption of conventional cooling, minimum quantity lubrication (MQL), and high-pressure lubrication, showing that traditional cooling uses the highest amount of energy. The main challenges of dry machining are related to tool life, workpiece geometric accuracy and surface integrity, material machinability, and machining processes. Different cooling system designs for motor spindles lead to varying sustainability outcomes, as the main spindle must control thermo-elastic deformations to ensure the accuracy and production quality of the manufactured products. Osman et al. review minimum quantity lubrication (MQL) techniques for improving sustainable machining, focusing on surface roughness, tool life, and cutting temperature. The study also investigates a cooling system incorporating a hot gas bypass to enhance energy efficiency, demonstrating that it is an effective approach for optimizing cooling equipment based on cooling capacity [62].

Additionally, dry machining and cryogenic machining are compared in terms of their ability to reduce cost and environmental impact for sustainable manufacturing. Conventional cutting fluids are not only hazardous to operators but also harmful to the environment and contribute to higher manufacturing

costs. In contrast, cryogenic cooling can enhance the quality of both manufactured workpieces and machines over their long service life, thereby improving environmental and economic performance. Dry machining eliminates the use of hazardous cutting fluids during machining operations, thereby benefiting environmental performance and reducing manufacturing costs. However, dry machining presents several challenges related to tool life, workpiece geometric accuracy, surface integrity, material machinability, and machining processes [63]. In addition, lubrication selection strategies are also reviewed with respect to improving environmental and health benefits. With the advancement of nanotechnology, nanofluid-based MQL is being applied in turning processes, considering factors such as surface roughness and power consumption. It also developed a sustainability evaluation model under nanofluid MQL conditions to enhance machining performance. Other fluids have likewise been introduced to improve surface quality while using minimal cutting fluid, such as neat-oil metalworking fluids. In summary, a cooling-lubrication system consists of components such as filters, containers, pumps, MQL units, exhaust systems, and cooling systems, which contribute to energy savings, waste reduction, and lower pollution emissions [64]. The system design focuses on optimizing core chiller configurations, including hot gas bypass, digital-scroll compressors, speed- and inverter-controlled compressors, and cold water mixing, as well as basic hydraulic system design and exhaust system design.

Reuse Techniques for Outdated Machine Tools

If the machine becomes outdated, its functions can still be utilized. In such cases, manufacturing enterprises or recycling companies can upgrade or reuse machine tools to increase added value through processes such as disassembly, cleaning, inspection, remanufacturing, and reassembly. The main objective of upgrading conventional outdated machines is generally to improve accuracy and productivity while reducing manufacturing time through high-speed machining as a sustainable solution. The reuse efficiency of an old machine can be evaluated using a holistic approach that considers technological and economic feasibility, along with the environmental benefits of machine tool remanufacturing. It demonstrates the effectiveness of remanufacturing machine tools in reducing waste, carbon emissions, energy consumption, material usage, and overall costs [65]. However, in the remanufacturing process of machine tools, several issues must be considered, such as uncertainties regarding internal component damage and the assessment of remanufacturability. To better implement remanufacturing and green manufacturing, the technical specification for metal-cutting machine tool remanufacturing (GB/T 28615-2012) provides relevant guidelines. Therefore, there are still several challenges that need to be addressed in future research to promote the reuse of components and machinery.

Sustainable Strategy for Machining Process

There are also other studies on machining process optimization aimed at improving the utilization efficiency of machine tools, which consider four indicators: specific cutting energy, tool wear rate, surface roughness, and material removal rate. The optimization objectives of a sustainable machining process focus on cutting parameters under specific machine tool conditions, such as spindle speed, depth of cut, and feed rate in turning operations. Existing literature mainly focuses on developing different machining strategies, such as turning and milling, for various types of machine tools [66]. In general, production machines and auxiliary machine peripherals are rarely considered in energy efficiency optimization.

A comprehensive review of sustainable machining has been developed, covering aspects such as cutting conditions, materials, optimization algorithms, costs, occupational health, and safety, among others. The *International Journal of Advanced Manufacturing Technology* has published additional studies on sustainable machining technologies, including reducing environmental impacts, determining optimal cutting parameters, cryogenic machining, sustainable machining of round-shaped microgroove patterns, energy-efficient machining systems, process planning, multi-objective job scheduling, and sustainable turning [67]. In sustainable-related technologies for machine tools, several other methods

are also applied. For example, the energy prediction model of machine tools uses the drilling process as the study objective, integrating feed power and material drilling power into a single model. The average prediction accuracy can reach 95.0% in case studies. In addition, empirical modeling is employed to improve the accuracy of energy consumption prediction, making the transition of physical parameters easier and supporting sustainable manufacturing. Therefore, this paper does not repeat this work in order to save time.

Other Technologies

With the development of high-speed networking and smart manufacturing technologies, new requirements have emerged in machine tool design for real-time monitoring of machine condition signals and real-time early warning systems. For example, 5G networks not only support the development of wireless monitoring platforms for machine tool systems but also enhance real-time acquisition of signal characteristics related to improved energy efficiency. Big data analytics for various types of machine tools can also support future design improvements and innovation, and it has already been applied in sustainable smart manufacturing [68]. In summary, emerging network technologies will inevitably play a key role in accelerating the implementation of sustainable machine tool design in industrial applications. The intelligent design of machine tools is mainly reflected in state monitoring, maintenance, and diagnostics through wireless methods. The concept, characteristics, and system structure of intelligent machine tools provide detailed technological information. Figure 10 illustrates the integration process between intelligent technologies and machine tools. Intelligent techniques can assist designers in extracting potential improvement information related to sustainable machine tool design, particularly for CNC machines [69]. This includes big data monitoring from control systems that are widely used, such as Siemens and FANUC series. A key step in achieving intelligent manufacturing is obtaining real-time monitoring data, which involves data acquisition through standard communication interfaces, PLC (Programmable Logic Controller), and electrical circuit methods, as well as data packaging, transmission buses, operation, and storage.

Nevertheless, the objective of intelligence should be considered during the design of the structure, control system, and sensor placement in order to improve machine tool functionality. The design of smart sensors for machine tool structural components, as a critical step, must be taken into account while ensuring data reliability and improving signal quality, such as in capacitive displacement measurement systems [70]. Additionally, integrating intelligence into machine tool design supports decision-making in sustainable machining planning. Chang et al. reviewed the application of artificial intelligence algorithms in smart machine tools, which can serve as a reference for sustainable machine tool development [71]. Therefore, intelligent techniques will become an essential component of sustainable machine tool design for acquiring real-time monitoring data such as energy consumption, cutting temperature, noise, tool wear, and other relevant parameters. They facilitate the application of sustainable machine tools in sustainable manufacturing, smart manufacturing, intelligent manufacturing, and smart factory environments [72]. Overall, the use of intelligent technologies in sustainable machine tools should consider several aspects, including the selection of highly reliable sensors, data acquisition, data packaging and transmission buses, data storage, and data processing using artificial intelligence algorithms. At the same time, the installation positions of sensors must be carefully determined due to spatial constraints. Figure 10

In another aspect, there are also techniques that enhance function reconfiguration, networked control systems, stiffness, and high precision. The manufacturing processes of key components also play a significant role in sustainable machine tool design and production, such as the manufacturing of bearings. Optimization of moving components like guideways and spindle systems can reduce energy consumption by lowering mass through the use of new structures or materials [74]. Technological innovation in machine tool design, focused on improving productivity, remains an important research direction and a key driving force. At the same time, high-precision design is also a major research focus to meet the requirements of micro-scale workpiece manufacturing and surface quality, through analysis of machine stiffness and the effects of cutting tool design.

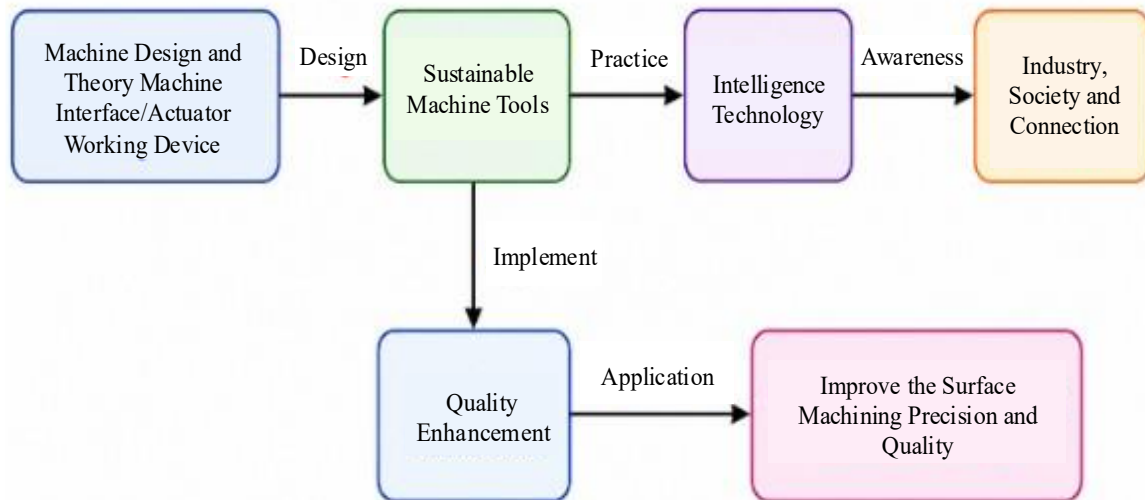


Figure 10. The integration of intelligent technology and machine tools [73].

CONCLUSIONS AND FUTURE RESEARCH DIRECTIONS

In this literature review, strategies and techniques are categorized into partial design tools that address one or two sustainability aspects, and comprehensive approaches that cover all three dimensions (environment, economy, and society). The former is more mature and standardized than the latter during the early design stage, due to the presence of uncertainties at this stage. Meanwhile, it also considers whether the machine tools are newly designed or already in use. If machine tools are to be designed or upgraded using an innovative approach, this provides the best opportunity to integrate sustainability aspects. Otherwise, the focus should primarily be on process optimization methods, such as cutting parameters, tool paths, and machining time, during the machine tool service period. Additionally, the influences on the three sustainability dimensions have been examined separately for machine tools from a life cycle perspective. Strategies and technologies are identified progressively, starting from individual parts and components and extending to the product and system level. Partial design strategies, such as lightweight and modular design, are incorporated into integrated sustainable design methods that consider all three sustainability dimensions. Sustainability assessment methods for machine tools are used to support decision-making in the early design stage. However, both categories face the challenge of simultaneously addressing the three sustainability dimensions across different life cycle stages. Most research primarily focuses on environmental impacts, particularly energy efficiency, whereas sustainable product design emphasizes the importance of all three sustainability dimensions while maintaining functional requirements. Key techniques are categorized into lightweight design, modular design, and cooling and lubrication systems, all of which provide benefits to sustainable machine tool design across different life cycle stages. Simulation techniques also improve design efficiency before manufacturing, as well as during the use and end-of-life phases. With the development of new types of sensors, wireless monitoring technology will be used to track machine tool operating conditions, including energy consumption, fault diagnosis, coolant fluids, lubricant oil, and other parameters. A unified standardization for machine tool energy efficiency should be developed based on standard components to enable accurate evaluation and decision-making. The network environment will also provide greater opportunities for collecting existing machine tool data, which can be used to improve the design of next-generation or new products.

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