Review

The Analysis of Key Technologies for Sustainable Machine Tools Design

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Abstract: Machine tools as indispensable tools for manufacturing products are typical high-energy, high-carbon manufacturing systems due to their larger mass, longer life cycles and huge resources and energy consumption. The current research trend of sustainable machine tools aims to reduce cost, energy consumption and increase sustainability without compromising their functionality, usability, productivity, accuracy, etc. However, there is a lack of systematic reviews about what are the key technologies for sustainable machine tools design. Thus, a comprehensive literature review of machine tool design for sustainability is needed in order to make clear how to design and evaluate sustainable machine tools from the viewpoint of life cycle sustainability analysis. The aim of this paper is to review the sustainable design and assessment aspects of machine tool design from partial goals to integrated aims according to whole sustainability dimensions such as the environment, economy and society, as well as involving key techniques in different life cycle stages. Recent research and study on improving directly or indirectly sustainability performance of machine tools according to focus points could be summarized as: design optimization of components such as lightweight using topology and bionic methods; structure design with modular design and layout; reducing cutting fluids and lubricant oil by employing minimum quantity lubrication, dry and cryogenic machining; reducing energy consumption; waste reduction by reusing, remanufacturing and recycling; sustainability assessment i.e., energy model, life cycle cost and life cycle social benefit. This paper assists designers and manufacturers to improve sustainability of machine tools by specific optimization measures in their activities.

Keywords: machine tools; sustainable design; life cycle; sustainable manufacturing

1. Introduction

1.1. Sustainable Manufacturing and Design

Sustainable manufacturing has been widely recognized as the main development trend of industries for three decades with the benefit on lower resource and production costs, easier employment and increasing safety because manufacturing industry impacts the sustainability performance of manufactured products in different life stages [1]. Thus, with incoming requirements for sustainable dimensions, design and manufacturing engineers should take into account sustainability in their activities. Each product-integrated manufacturing process has environmental impacts including energy and materials, while life cycle thinking should involve each stage of the product’s life which consumes energy and other resources and generates waste and emissions [2]. Design and process planning have great flexibility in making decisions for machine and factory operation [3]. Therefore, this paper addresses how to design sustainable machine tools (MT) utilizing detailed approaches in order to achieve the goal of sustainable manufacturing and production.
Additionally, sustainable manufacturing needs manufacturing industries to consider economy efficiency, environment and society benefits through process planning utilizing advancing manufacturing technology to promote a product’s competitive position. Hence, the industrial sector needs to select more sustainable machines, such as high energy efficiency and high resource efficiency, low waste, and so on. In the past, the eco-design of machine tools has been well studied and addresses only the environmental aspect especially energy consumption in use stage [4,5]. Although the energy aspect of a machine tool in the use stage was integrated into the design process, there is lack of comprehensive methods to define sustainable machine tools in the early design stage. The research objective is the machine tool itself, not the products machined on the machine tool.

It is well known that machine tool design and subsequently the machine tool operators play an important role in most industrial fields, as it has been used widely in factories as the mother machines. The machine tool industry’s directives and standardizations involving a partial sustainability dimension have already appeared. For example, it is worth noting that the European Union develops constantly standards and policies related to energy-using products, such as Directive 2009/125/EC [6] related to energy consumption standards for machine tools and related machinery products, and Directive 2005/32/EC [7] involving eco-design of energy-using products. The Self-Regulatory Initiative promoted by the European Association of the Machine Tool Industries (CECIMO) in European Union indicates that manufacturers should improve the ecologic footprint of manufactured MT. This regards eco-design as an effective action to enhance sustainable design performance and competitiveness in the long life of the MT industry to achieve the aims of increasing energy efficiency whilst taking into account the technical characteristics of machine tools. Moreover, CECIMO is also operating the ‘Blue Competence Machine Tools’ [8] project to promote utilization ratio for energy and other resources of MT and customers. Additionally, ISO 14955-1:2017 [9] proposed the application of eco-design standards of MT. The directives mentioned above are guidance for machine tool industries, but not mandatory requirements. In future, MT builders should supply some essential data related to sustainability performance except function and purchasing cost.

As regards the environmental realm, most research focuses on energy efficiency, including the energy efficiency measures in the use stage [4,10,11], the energy map of the main components [12] such as main spindle, driving system; second, on resource efficiency, involving raw material, water, cooling and lubricant fluids [13,14]; third, on carbon emissions [15]. Nevertheless, cost is considered in the traditional design process, while life cycle cost should be conducted in the sustainability assessment. The social dimension of sustainability performance for machine tools has received less attention related to the product design level. However, a sustainable design solution should consider balancing the three dimensions of sustainability on the condition of satisfying functional attributes. Thus, if designers want to achieve truly sustainable machine tools design, they must integrate all three sustainability aspects in the design process. The key technologies of sustainable manufacturing include green and high-energy efficient machine tools; high-performance cutting tools; green and high-performance cutting technology; and sustainable manufacturing process optimization.

The following Section 1.2 highlights the challenges and key technologies encountered in machine tools design for improving sustainability performance on the condition of meeting technical requirements.

1.2. Challenges and Opportunities of Sustainable Machine Tool Design

With the development of manufacturing systems of high complexity and high performance, there are higher requirements for the performance of machine tools, such as speed, precision [16], intelligence level, compositionality, reliability, and green degree. Meanwhile, global energy and resource consumption are gradually increasing, reflected in decreasing total non-renewable resources, the deterioration of ecological environment, and growing of carbon dioxide emissions [17]. More importantly, manufacturing consumes 37% of global energy demand [5,18]. Machine tools as one of the indispensable tools for manufacturing products are typical high-energy, high-carbon
manufacturing systems due to the larger mass, longer life cycle with huge resources and energy consumption, and hence, environmental problems are particularly acute [19]. Therefore, the machine tool manufacturing industry must reduce non-renewable resources and energy consumption [20], and decrease environmental pollution [21], in order to alleviate the serious problem of resource constraints. In general, the key challenges of sustainable machine tools design are summarized as follows:

- High performance;
- High energy consumption;
- High carbon manufacturing systems;
- Environmental burden;
- Waste volumes;
- Economy efficiency;
- Public health;
- Social benefits.

Specifically, the design stage is one key step in the process of industrial production, which also determines product performance of most stages of the whole life cycle. In the design stage, the product performance such as positioning accuracy, stiffness [22], thermal characteristics, pulse equivalent, spindle speed, cost, environmental impact and health effects, have been determined for more than 70% of the manufacture, use, recycling and waste disposal phases [23]. Hence, sustainable machines arise at an historic moment, with the main performance including parts that are renewable, reducing more than 50% of the total weight, reducing more than 30% of the total power consumption, reducing more than 50% of waste emissions, and 100% material recycling [24]. Green machine tools have little environmental effect with high energy efficiency, low gas carbon emission and waste. Generally, electrical consumption accounts for most of the environmental burden of MT. However, sustainable machine tools not only satisfy environmental protection requirements, but also have the economic and social efficiency in order to achieve the sustainable development requirements. To achieve the sustainable change of industry, designers must present innovative strategies for new MT design for sustainability while improve productivity of existing machine tools.

In short, the problems associated with the sustainability performance in the life cycle of machine tools can be summarized as follows:

- What is sustainable design of machine tools?
- How to design sustainable machine tools?
- What degree of sustainability performance is there for machine tools?

Designers of MT are attempting to handle the above issues by employing various design strategies, such as eco-design tools [25], energy minimum design [26], resource efficiency design [27], and carbon emission design [28]. Although some technologies have already been commercialized, especially for energy saving during the use stage of machine tools, they still need to be arranged in the design process, and also be applicable to design engineers. Figure 1 presents the key technologies of sustainable MT design. The dimension of sustainable MT involves technology, environment, economic and society, which will be achieved by some key techniques such as lightweight methods (bionic and topological approaches) [29,30] and modular design using microsystems techniques, as well as sustainability assessment methods.
Figure 1. The key technologies of sustainable machine tools design.

Hence in this review, key technologies of sustainable design of machine tools in the early design stage are reviewed. One aim is to summarize sustainable dimension related to MT, that is, technology, environment, economy and society in order to provide guidelines in the early design process. Another aim is to discuss the detailed design strategies in connection with sustainable machine tools design, analysis of the design principles and the relationship with sustainability, and the development tendency towards sustainable machine tools. In addition, sustainability assessment methods of machine tools is also discussed.

2. Research Methodology

Section 2 shows how we collect, analyze, and choose the related sustainable machine tools design literature employing a structured, reproducible approach [31] to carry out the process. The first step defines and focuses on the research question, which is related to the sustainable design techniques for machine tools. Because there is a large amount of work in the literature about sustainable development, sustainable design and manufacturing. This paper aims to identify what is sustainable design, and what techniques are used in the application objectives for machine tools. The second step is the sources of data collection mainly from online databases that are Elsevier, IEEE Electronic Library, John Wiley, ProQuest, Springer, ASME, Taylor & Francis, MDPI, etc. The third step is quality assessment for all references and eliminating low quality studies through the contents of abstract and method with application. The last step gives the interpretation for review results and future development suggestion. The searching keywords include “sustainable development”, “sustainable product development”, “sustainable design”, “sustainable product design”, “sustainable manufacturing”, “sustainable machining”, “sustainable machine tools design”, “machine tools alternatives”, “energy efficiency for machine tools”, “green machine tools design”, “coolant system”, “structure design of machine tools”, “lightweight design”, “modularity for sustainability”. According to these keywords, a variety of scientific literature is obtained from the aforementioned databases. From the contents of title, abstract and methods application, the collected references are shortened concentrating on machine tools design, application with the consideration of sustainability. The detailed information about sustainable machine tools is described as follows.

3. Dimension of Sustainable Machine Tools

In manufacturing industry, it has been proved that design and production of sustainable products are significant strategies to achieve sustainability and sustainable manufacturing. Thus, considering three dimension of sustainability in early design as well as technology requirement could ensure the product use with lowest environmental burden under economic and society feasibility. For green machine tool design, most research focuses on the environmental factor. Currently, Avram et al. [32] conducted the sustainability assessment of a machine tools system in the use stage, which considers economy, technology and ecology in the system level and process level as shown in Table 1. Moreover, Azkarate et al. [33] promote a decision-making approach in the design stage of designing sustainable
MT, which consider economic (life cycle cost and value added), environmental (electricity, lubricants and coolants, materials and transportation) and social (safety, user-friendliness and ergonomics) factors as shown in Table 1.

### Table 1. The dimensions of sustainable machine tools.

| Dimension | Criteria for Machine Tools | Corresponding Influence Factors | Process Level |
|-----------|----------------------------|---------------------------------|---------------|
| 1. Technology | Precision | Positioning accuracy | Cutting force |
| | Flexibility | Tool storage capacity | |
| | | CNC (Computer Numerical Control) type | |
| | | Part complexity | |
| | | Number of pallets | |
| | | Idle power | |
| | Power/Energy | Total rated power | |
| | | Part program energy | |
| 2. Environment | Emissions control | Mist collector | |
| | | Enclosure type | |
| | Material | Material selection | |
| | | Spindle maximum speed | |
| | Productivity | Tool-to-tool time | |
| | | Rapid feed rate | |
| | | Initial cost | |
| 3. Economy | Cost | Maintenance cost | |
| | | Operational cost | |
| | Safety | | |
| 4. Society | User-friendliness | Easiness of programming | |
| | Ergonomics | Support in manual operations | |
| | | | |

It is well known that MT have the characteristics of complexity, multicomponent and multipurpose, and hence, dimensions of sustainable machine tools not only include technology, but also environment, economy and society. From the life cycle sustainability viewpoint, the manufacturers should consider four dimensions as follows.

#### 3.1. Technology Factors

The science and technology level of the MT industry are typical symbol of comprehensive development level for new technology era. MT with interchangeable parts and special parts achieves the aim of shaping using cutting tools. Therefore, most countries in the world highlight the development of the machine tool industry [34]. The technology development trend of machine tools is high precision [35], high efficiency, high flexibility and automation. Therefore, the product firstly suits the functionability purpose of the users in terms of accuracy, use lifetime, productivity, flexibility, etc. Anyway, the technology is always regarded as the priority to meet the functional requirement. There are some studies that focus on increasing the technology issues for achieving highly efficient machining by different measures in order to high performance machining. MT is composed of control, drives and sensitization to finish workpiece surfaces with the characteristics of better precision, high speed, ecological benefit with minimum environmental impact and maximum productivity and precision. The main objectives of the MT structure are described as Figure 2.
In the design and configuration process of MT, the manufacturing quality and productivity problems are the most key targets to determine the static, dynamic, and thermal behavior [36]. The detailed criteria are accuracy, repeatability, uncertainty, and functional point based on geometric and kinematic models.

3.2. Environmental Factors

The environmental impact is assessed considering the three direct factors and one indirect factor, which is energy, resource, waste, and carbon emission.

3.2.1. Energy Efficiency

Energy efficiency is the most important environmental influence due to electricity consumption. The motivation for increasing the energy efficiency of MT includes energy costs growth, consumer awareness change, considerable potential for reducing energy consumption and costs, reduction of CO$_2$ emissions, examination of life cycle costs of machinery and equipment, changes in the legal framework, etc.

In the life cycle, usage has the most significant environmental impact for the general machine tool. At present, the research and innovation practice of energy efficiency of the numerical control equipment are actively carried out. The energy consumption model and the energy efficiency evaluation of MT is very important for manufacturing energy-saving research [11]. The existing research pays more attention to the energy efficiency optimization in the use stage through optimizing process parameters and conditions, and at the same time includes monitoring and management of energy efficiency, structure configuration, lightweight, energy optimization in the moving parts, etc. Because machine tools have been widely applied in industrial sectors, smaller design improvement oriented to environment could have large influences on whole sustainability performance of MT [37]. Nonetheless, engineers of MT enterprises rarely try to improve holistic design strategies from the lifecycle viewpoint [38]. The dynamic energy modeling of an MT is established in reference [39] considering multi-source resource and dynamic characteristic in the machining process. As a result, Zhang [40] reviewed the energy efficiency techniques of a machining process in order to provide the improvement measure both in MT and in process.

ISO14955 concentrates on the environmental impact of MT, specifically the possibilities to reduce the energy consumption as the most significant environment impact. ISO/TR 14062:2002 [41] gives the overview of holistic environmental aspects integrated into the design and development process.
which could be used as guidance for machine tool design [42]. The research is paying more attention to predicting energy demand from the design angle, and energy saving strategy of green machine tools can be divided into six levels as evaluation and modeling, optimization and control technology based on software, cutting improvement, based on the hardware optimization, and the environmental design.

The energy efficiency optimization could be divided into component level (physical effect), system level (kinematics, system integration), and control level (energy management, requirements optimization). The components layer is mainly internal component characteristics such as energy efficiency of the converter, the improvement of the friction coefficient, while the control and system layer are mainly to minimize energy loss interaction between components [43]. The energy consumption of the use stage is influenced by material characteristics, machining process parameters and the characteristics of the machine itself, also related to the time of processing and standby, and average power, while cutting energy consumption relies on the precise measurement of the cutting force model and machine tool unit power characteristics. Currently, further research in underway into the processing parameter optimization method of the energy consumption of MT of use process, mainly through the experiment established mathematical relationship between the material removal rate and unit energy consumption [44]. The studies concentrate on the energy transfer in the machining process, energy consumption and energy efficiency analysis and information monitoring, etc., based on the power and efficiency calculation of the main drive system. Furthermore, power balance equations of the main drive system frequency control of motor speed machine tool is established through the research of machine tool energy flow characteristics [45], which reveals the complex features of dynamic load loss of the main transmission system during the operation process of machine tools [46]. The factory-integrated machine tools are studied [47] to quantify the energy consumption at the level of the factory.

There is research studying how to improve machining process for achieving the aim of high productivity, high quality and low cost with consideration of the link between machining and energy efficiency. Energy consumption in machining has become a necessary factor in the process planning except for machining time and quality, as well electric energy consumption in machines. Generally, the machining process is conducted by machine tools with similar frames, operation basis, and consumables such as cutting tools, lubrication fluids, and coolant fluids.

In addition, for the use process and specific operating environment of machine tools, it is necessary to set up a function of machine unit energy consumption and fixed power requirements, and processing power demand (material removal rate) [18]. Some research describes the relationship between the energy demand and the processing parameters based on the experimental data to quantify the energy needs of a specific machine tool [48], which confirm that the fixed energy is part of the universal model. However, the basic factor of different machine tools is different limits to their use range. Although energy efficiency of manufacturing process is improved through energy efficiency evaluation, the research focuses less on energy conservation and to optimize the structure design to reduce the energy loss of machine tools. The energy efficiency factor as evaluation criterion for energy saving are equally important with classical evaluation criteria such as performance, accuracy, cost, reliability and so on. Therefore, the multiscale fusion can ensure product competitiveness between performance reliability and energy in the entire design stage.

3.2.2. Resource Efficiency

Resource efficiency is another key indicator due to any manufactured product consumer resource, especially MT, which benefits environment protection and the economy [49]. Therefore, MT builders have adopted some techniques to raise the competitive of MT. For machine tools, the resources include raw material, tools, cutting fluids [50] and lubrication oil [51], water, and so on. The optimization of resource utilization ratio include materials processed, process planning, lubrication in processes, and resources for machine building, bench-top machines and the micro factory in the level of
machine/processes. Additionally, at the shop-floor level, machine layout planning, machine footprint, space, lighting, and ambient working environment should be taken into account.

3.2.3. Waste

The waste includes the fluids, used tools and polluted water during the use stage as well as the non-recyclable components after the end of life of machine tools. If a designer wants to reuse, recycle, and remanufacture the used components for machine tools, it is necessary to consider the demands in early design stage to prevent some components worn badly [52]. Component scrapping, machine idle time, and process optimization are considered into reduce waste discharge.

3.2.4. Carbon Emission

The environmental metrics could also be quantified using greenhouse gas emission (CO$_2$-equivalent emission) through energy and resource consumption, and generated waste. The greenhouse gas emission generated by the electrical consumption in the life cycle of MT is regarded as the greatest impact on the environmental burden [53], while the recovery of used product could reduce greenhouse gas emissions [54]. Recovery metrics involve the activities of reuse, remanufacture, and recycle of used product. There is a different calculation process for CO$_2$-equivalent emission [55] in different life cycle stages due to different regions. Therefore, CO$_2$-equivalent emission for manufacturing, usage and the recovery phase should be considered separately. In the tracking of carbon footprint, cutting tools also are studied in reference [56] in order to identify the impact of cutting tools of MT.

The research trend of existing literatures focus on the equivalent conversion between the carbon footprint and other resources involving energy, material, waste in life cycle.

3.3. Economic Factors

Economic metrics mainly consider life cycle cost and value added. In particular, the concept of traditional cost in manufacturing processes has to be changed [57]. Life cycle cost (LCC) consider the cost of raw materials, manufacturing, transportation, operation and recovery, which is becoming the main cost analysis approach. Material efficiency is related to the proportion of recycled material which need the designers to determine the quantitative value, while operation cost mainly considers the cost of power, cutting fluid [58], and lubricant oil [59,60] used for the same test part. The cost of labor due to difference values between countries is generally neglected. Value added metrics contributing to products’ practicability involve productivity, service life, accuracy and so on. Productivity commonly is determined by maximum spindle speed, tool change time and feed rates. Service life is different for different use environments, and hence the main point should be considered from the life cycle perspective [61]. Moreover, the energy and cost have the greater correlation for MT [62], which could promote the development of the machine body structure.

Additionally, the life cycle cost calculation method for machine tools is proposed to support design phase decisions, which does not just include purchase cost but also the cost of use, repairing, and disposing of life cycle. Different machines have different proportions for each part of life cycle cost, such as the transfer machines given by Enparantza [63], as shown in Figure 3, while the grinding machine has another life cycle cost proportion, as shown in Figure 4. Generally, the contents of life cycle cost are increasingly based on traditional calculation degrees.
3.4. Social Factors

Currently, the social dimension for machine tools design mainly considers operational safety, user-friendliness and ergonomics to ensure the well-being of MT operators [33]. The factors have influences on the human such as employees, consumers, and suppliers. User-friendliness mainly involves easiness of programming and support in manual operation. Ergonomics including operation environment, layout, color, and morphological characteristics with machine tools hardware and software interface design, have a great influence on health and wellness of workers. Operational safety of MT mainly consider clamping safety, chip removal equipment and mist collector during manufacturing other products. The social factors are not easily quantifiable due to non-deterministic elements, and hence, they could be expressed by linguistic terms.

3.5. The Analysis Result

The objective of Section 3.5 is to explore the intersection between key techniques and sustainable machine tools design in different life stages. The benefits are claimed in each dimension of sustainability of every life stage (production, use, and end-of-life) as shown in Table 2.
Table 2. The analysis result related to dimensions of sustainable machine tools.

| Environment | Economy | Society | Integrated Method |
|-------------|---------|---------|-------------------|
| Specific strategy | Energy | Life cycle [10,64–66] Design stage [37,44,67–70] Complete machine [12,23,71] Use stage [4,13,72–78] Partial components [45,79–82] | Use cost [72] |
| Resource | Carbon emission | Review | Energy-saving [11,42] |
| Integrated strategy | Interaction between environment and economy | Energy-saving [5,14,78,84–87] | Life cycle cost [63] |

We reviewed sustainable design and assessment articles for MT from 2003 to 2019 from a partial dimension to an integrated dimension. Then, 44 relevant papers are discussed of which 93.2% of these are partial method while only 6.8% contain three sustainability dimensions as shown in Figure 5. Meanwhile, 71.8% of these took an energy only approach while 28.2% were energy and others factors.

![Figure 5. Classification of the focus dimensions of sustainable machine tools design.](image)

4. Strategies and Technologies for Sustainable Design of Machine Tools

As the manufacturer or customers are conscious of sustainability issues, sustainable MT design and manufacturing will be their selling point. Manufacturing should change from extensive manufacturing with the highest qualities and lowest costs to sustainable manufacturing with the highest qualities and little environmental burden. The strategies and techniques could be classified into partial design tools involving one or two sustainability aspects, and those covering three dimensions. The former is more mature and standard compared to the latter in the early design stage, due to uncertain elements of early design. Meanwhile, we also consider whether or not the machine tools have been designed and used. If the machine tools need to be designed or upgraded through an innovative approach, then it is the best opportunity to integrate the sustainability aspects, else it should consider mainly the processing optimization method such as cutting parameters, tool path, and machining time after machine tools.
service period. Strategies and technologies are identified from one part of the components, then to the product and system.

4.1. Lightweight Techniques of Structural Components

The high speed and high-accuracy performance need a moving component with less mass and high stiffness. Therefore, increasing the specific stiffness in moving components (such as bed, beam and spindle box) has become a significant issue. Lightweight and high stiffness of structural parts such as a bed and column are benefits to quality, speed and accuracy, as well as improving environment and economy performance through reducing energy consumption and raw material. Lightweight machine tools mainly focus on the optimization of structure components, moving components, whole structure, as well as material selection. The new structure emerging continuously like parallel kinematic machines (PKMs), box-in-box contribute for reducing weight. Meanwhile, new material also promote lightweight development like new aluminum alloys, quasi-isotropic fiber-reinforced plastics, and resin concrete (or man-made granite). The group of Campa and Zulaika make a great contribution to promoting machine tool performance on preventing chatter vibrations of large horizontal lathes [89], on the condition of high productivity and surface finish with greater stability. The dynamic performance of the servo drives is also analyzed by Ansoategui [90]. Additionally, lightweight milling machines are designed by Zulaika [91] in order to obtain targeted productivity with minimum structure mass as well as energy consumption, which has been applied in the redesign of actual machine tools.

The core concept related to lightweight parts include:

1. Machine tool moving parts are light as possible for reducing driving power, increasing energy efficiency, and decreasing production and transport costs.
2. The structure components should have enough effective stiffness in order to guarantee machining precision.
3. The structure components should have good damping and vibration reduction performance avoiding chatter to improve the metal cutting rate.

Currently, the lightweight method mainly focus on decreasing energy consumption and carbon emission. Because MT components lightweight could promote directly and indirectly energy efficiency through analysis energy losses of feed drives and auxiliary systems, reducing the basic load of MT. Meanwhile, the lightweight design of structure has also great significance to reduce manufacturing costs of machine tool factory as well as promote whole machine performance. Structural components such as bed and feed drive components could be redesigned employing corresponding lightweight strategies based on static stiffness, then the complete machine tools could be implemented considering dynamic behavior. Moreover, the light weight of machine tools could increasingly reduce material consumption. The reduction in mass has the benefit of reduction in reactive energy and friction losses, increasing the axis acceleration and guide bandwidth. The increase in stiffness could increase the process stability and guide bandwidth. The realization of lightweight design in machine tools could be achieved by material selection and structural optimization design such as topology and bionic design [68,92]. Benefits of light weight for the sustainability of machine tools in each life cycle phase are shown in Table 3.

| Sustainability for Environment | Sustainability for Economy | Sustainability for Society |
|-------------------------------|-----------------------------|---------------------------|
| Production                    |                             |                           |
| Raw material reducing         | Material cost reducing      | -                         |
| Energy efficiency increasing  | process cost reducing       |                           |
| Use                           |                             |                           |
| Energy efficiency increasing  | Energy cost reducing        | -                         |
| End-of-life                   | Recycle, waste reducing     | Disposal cost reducing    | -                         |
The selection of material must be considered accurately when designing machine tool structures, in order to achieve high accuracy, high productivity, and eco-friendliness. The material of machine tool structures has great influence on the moving mass, inertia moment, stiffness of static and dynamic, vibration mode and thermal properties. Therefore, we should consider the energy and resource efficiency, environment and economy factor when comparing material properties of new materials and traditional materials [93]. The solution of the lightweight design method for machine tools is shown in Figure 6.

![Figure 6. The solution of the lightweight design method for machine tools.](image)

The bionics method is a kind of effective method to speed up the innovation cycle in the modern machine tool design process. Meanwhile, bionic structure design provides a new method to update the traditional design concept and achieve maximum structure efficiency [92]. The lightweight technologies of moving parts both reduce the material consumption of machine tools and improve the operation efficiency [37]. The light weight of the structure such as bed body and upright column is carried out under the constraint condition of strength stiffness [68], and considers the relationship between the weight of the bed and the stability of the system. The strength, stiffness, contradiction between modalities and the weight for key components of machine tools are analyzed under different dynamic performances. Furthermore, the energy flow of the machine parts is gained to optimize the lightweight structure of the moving parts under the condition of meeting the requirements of dynamic performance. It is worth note that lightweight strategies for different kinds of MT are mainly based on use scenario and the size of the machine.

4.2. Structure Principle

Machine tool performance decides the quality of manufactured products and other machinery, which not only involve the properties of accuracy and surface quality, but also environmental effect and cost efficiency. Energy efficiency of machine tools on the system level is related to production systems [44]. The structure or layout of machine tools have also an important effect on sustainability through interaction between components as energy converters. Besides the selection of efficient components, what will be most relevant for the effectiveness of sustainability performance has to be considered. The tool path strategies and machine tool axes configurations are considered in machining process [94] for enhancing use efficiency of MT, which could reduce energy and material waste. Except the analysis of machining process and MT individually, the interaction between MT and manufacturing process [95] should be analyzed through simulation.

The functional description of machine tools is general and independent from the design of MT, and also independent from the machining process implemented. The mapping from functions to machine components is machine tool-specific for a metal-cutting machine tool as shown in Figure 7.
Although different machine tools have different function and use circumstances, generally they have similar elements such as machine tool frames to provide fundamental structures. The production of machine tool frames need expensive engineering, testing and high-precision manufacturing, which are limited and cannot be altered after manufacturing for conventionally casted or welded structures. Currently, reconfigurable MT has been accepted due to update product with fastest speed and lowest costs. Machine tools have the characteristics of complexity, type diversity, and functional variability, while modular design could shorten the development period with the advantage of disassembly and reuse in the reconfigurable manufacturing system. Meanwhile, it benefits economic efficiency, functional and physical feasibility, upgrading outdated machine, material recycle and maintenance performance [96]. Therefore, a modular design method plays an important role in the development of sustainable products when at the end-of-life or ungraded. A modular machine tool has the benefit on updating and reusing at use-phases and the corresponding life-cycles to provide the basis for different manufacturing sector.

Machine tool frames are the key structures to increase the sustainability performance of MT, in particular, and must gain more attention in the design process. Generally machine tools are static, while flexible manufacturing system could handle several production situation. Thus, there is the possibility of the over engineering issue with more hours, material and auxiliary resources, which generates a more environmental burden and cost for manufactured products. Once made, this cannot be changed. For solving the sustainability problem radically, the improvement of machine tool structure and energy efficiency must be considered in design phase by manufacturers and engineers. The modular design of MT could achieve the reconfigurable aim according to different use scenarios as well as benefit on reuse or remanufacture in the end-of life.

Sometimes mechanical/electrical machine components fulfil several functions, e.g., a coolant system is used for machine cooling and for process conditioning. Then the energy consumption of this component can be assigned to different basic functions or sub functions. For example, a spindle unit of MT as one of the key components has the potentials of improving energy efficiency through an adapted electric drive train [45]. Similarly, cooling systems of MT with energy conservation are also a key technology for sustainable machine tool design [81], and also hydraulic units should consider energy-efficient strategies [80]. According to the structure characteristics, reinforced board layout could be improved utilizing advanced optimization methods, and then the light weight of machine directly or indirectly improves energy efficiency of the machine tool [97]. Considering energy and environmental factors in the design phase could directly and indirectly promote efficiency in order to achieve flexibility and versatility under the constraints of quality and rigidity. Due to structure information determined in the design phase, it is necessary to identify the relationship of the energy distribution and structure.
characteristics in order to solve the problem of energy performance conflicts [98]. The benefits for sustainability of modular machine tools in each life cycle phase is shown in Table 4.

Table 4. Sustainability benefits for modular machine tool in each life cycle phase [99,100].

| Sustainability for Environment | Sustainability for Economy | Sustainability for Society |
|--------------------------------|-----------------------------|---------------------------|
| Production                     | Material                    | Manufacturing cost        |
|                                | Carbon emission             |                           |
|                                | Variety                     | Fair wage                 |
|                                | Supply Chain                |                           |
|                                | Manufacture                 |                           |
|                                | Maintenance                 |                           |
|                                | Repairability               |                           |
| Use                            | Upgrades                    | Maintenance cost          |
|                                | Functionality               | Operator safety and health|
|                                | Services                    |                           |
| End-of-life                    | Recycle, reuse, remanufacture, updated | Recycle, reuse, remanufacture, updated | Operator safety and health |

4.3. Cooling and Lubrication Technique

The cooling and lubrication system is an important factor for obtaining necessary levels of precision and stability as well as reducing friction in contact zones and maintaining thermal stability. Generally, machine tools with cooling and lubrication subsystems could protect the contact area and maximize tools and machine life, which benefits the economy aspect and increases the environmental burden through electrical or compressed air form. There are two main sources of heat generated by the electrical losses of motor and the friction of bearings, as well as the cutting process. In order to solve the problem, there are several methods such as minimum quantity lubrication (MQL) systems, dry-machining processes, as well as cooling of control cabinet, water cooler, cooling pumps, cooling/heating of guideways. The cooling and lubrication technique is shown in Figure 8.

Figure 8. The cooling and lubrication technique. (a) The cooling and lubrication technique; (b) proportion of power consumption.

The research [101] compares the power usage of traditional cooling, MQL and high-pressure lubrication, which shows that traditional cooling consumes the greatest energy. The challenge of dry machining mainly is oriented tool life, work-piece geometrical accuracies and surface integrity, machinability of materials, and machining processes. The different cooling system designs of motor spindles have different sustainable results, due to the main spindle needed to control thermo-elastic deformations for guaranteeing accuracy and production quality of the manufactured product. Osman et al., review the minimum quantity lubrication techniques for enhancing sustainable machining, involving surface roughness, tool life, and cutting temperature [102]. The study [81] carried out one technique of a cooling system with a hot gas bypass to increase energy efficiency, which
shows that it is an effective measure for optimizing cooling equipment according to cooling capacity. Additionally, dry and cryogenic machining are compared according to the capability of reducing cost and environmental burden for sustainable manufacturing [103]. The conventional cutting fluids not only are harmful for operating personnel, but also harmful to the environment and increase the manufacturing cost. However, cryogenic cooling could improve manufactured workpieces as well as machines’ quality in the long use life, which benefit on corresponding environmental and economic performance. Dry machining could eliminate hazardous cutting fluids during machining operations, which benefit the environmental factor and manufacturing cost [104]. Dry machining, however, poses many challenges to the tool life, work-piece geometrical accuracies, work-piece surface integrity, machinability of materials and machining processes. Furthermore, selection strategies of lubrication are also reviewed in the reference [105] to improve the environmental and health benefit. With the development of nanotechnology, nanofluid MQL [106] is used to assist the turning process considering the criteria of surface roughness and power consumption. It also established the sustainability evaluation model under the condition of nanofluid MQL for improving the machining performance. Other fluids also have been developed to improve surface quality using little cutting fluids such as neat-oil metal working fluids [107].

In a word, a cooling lubricant system involves a filter, container, pumps, MQL, exhaust, and cooling system contributing to energy saving, waste reduction, and pollution emission. The design optimizes a focus on basic chiller design of hot gas bypass, digital-scroll compressor, speed and inverter controlled compressor, and cold water admixing, as well as basic hydraulic system design and exhaust system design.

4.4. Reuse Techniques for Outdated Machine Tools

If the machine is outdated, the function could still be used. Then manufacturing enterprise or recycling companies could upgrade or reuse the machine tools for increasing value-added through disassembly, cleaning, detection, remanufacturing and reassembly. The aim of upgrading conventional outdated machines generally is to increase accuracy and productivity, and decreasing manufacturing time with high speed machining as sustainable solution [108]. Du et al. [109] evaluated the reuse efficiency of an old machine with a holistic method considering technology and economic feasibility, as well as environmental benefits of MT remanufacturing. It proved the validity of remanufacturing MT on the reducing waste and carbon emissions, energy consumption, material use, and cost. However, in the remanufacturing process of MT, some issues need to be considered like uncertainty about inner damage to components and the calculation for remanufacture-ability. For better implementing remanufacturing, China creates a set of standards such as Quality Management Requirements for Machinery Products Remanufacturing (GB/T 31207-2014), and green manufacturing, the technology specification for metal-cutting machine tool remanufacturing (GB/T 28615-2012). Therefore, there are still some challenge to be addressed in future research for promoting components and machinery reuse.

4.5. Sustainable Strategy for Machining Process

There are other studies on machining process optimization to enhance MT use efficiency, which select four indexes, i.e., specific cutting energy, wear rate, surface roughness, and material removal rate [110,111]. The optimized objects of a sustainable machining process focus on cutting parameters of the condition of specific machine tools, such as spindle speed, cutting depth and feed rate for turning process. The existing literature mostly develops different machining strategy such as turning [112], milling [113] for different kinds of machine tools. Generally, production machines and machine peripherals are rarely included in the optimization of energy efficiency. A sustainable machining-related review has been fully developed involving cutting conditions, materials, optimal algorithm, costs, personal health and safety, and so on. The International Journal of Advanced Manufacturing Technology published more related literature about sustainable machining technology, like references [114] (reducing the environmental impacts), [115] (the optimum cutting
parameters), [116] (cryogenic machining), [117] (sustainable machining of round-shaped microgroove pattern), [118] (energy-efficient machining systems), [119] (process planning), [120] (multi objective for jobs scheduling), [121] (sustainable turning). In the sustainable-related technology for MT, there are also some other methods used. For instance, the energy prediction model of MT [122,123] uses the drilling process as study objective integrating feeding power and material drilling power into model. The average prediction accuracy could achieve 95.0% in case study. Additionally, the empirical modeling is used to promote the predict accuracy of energy consumption [124,125], which make it easier during physical parameters transition contributing sustainable manufacturing. Thus, this paper does not repeat this work in order to save time.

4.6. Other Technologies

With the development of high-speed networking and smart manufacturing technology, there are new requirements for machine tool design in real-time signal monitoring related to the machine state [126], real-time early warning system [127]. For instance, the 5G network not only assists the establishment of machine tool system wireless monitoring platform, but also promotes real-time signal characteristics capture related to energy efficiency increasing [128]. Big data analytics for kinds of machine tools could also support the future design improvement and innovation, which already has application in sustainable smart manufacturing [129]. In short, new network techniques will be inevitable for accelerating the realization of sustainable machine tools design in industry field.

The intelligent design of machine tools is mainly reflected in state monitoring, maintenance, and diagnostics through wireless method. Chen et al. [130] proposes the concept, characteristics, and systemic structure of the Intelligent Machine Tool, which presents detailed technology information. Figure 9 shows the integration process of intelligent technology and machine tools. Intelligent techniques could assist designers to extract the potential improvement information related to sustainable machine tool design, especially for CNC machine, which includes the big data monitoring from the control system such as applied widely Siemens series, FANUC Fanuc. The important step for achieving intelligence manufacturing is the how to obtain real-time monitoring data involving the data acquisition using standard communication interface, PLC (Programmable Logic Controller) and electrical circuit methods; data wrapping and transmission bus, operation and storage [131]. Nevertheless, the intelligence goal should be considered in the design process of the structure, control system, and sensor installation to enhance the function of machine tools. Smart sensor design for structural components of machine tools as a crucial step must be taken into account under the condition of keeping the reliability of data [132] and enhancing signal quality like capacitive displacement measurements [133]. Additionally, the process of integrating intelligence into machine tools design contributes to making decisions in the sustainable machining planning [134]. Chang et al. [135] reviewed the role of artificial intelligence algorithms on smart machine tools, which could be a reference for sustainable machine tools. Therefore, intelligence techniques will become the essential part of sustainable machine tool design for obtaining real-time monitoring data like energy consumption, cutting temperature, noise, tool wear and so on. They promote the application of sustainable machine tools in the field of sustainable manufacturing, smart manufacturing, intelligent manufacturing, and the smart factory. In all, the application of intelligent technology in sustainable machine tools should consider the following aspects: sensors selection with high reliability, data acquisition, wrapping and transmission bus, storage, and data handling with artificial intelligence algorithms. Meanwhile, the installation position of sensors must be determined due to the limitation of space.
In the other aspect, there are also techniques improving function reconfiguration, control systems with networks [136], stiffness, and high precision. The manufacturing process of key components also has a significant role in sustainable machine tool design and manufacturing, like the bearing manufacturing process [137]. The optimization of moving component like the guideway and spindle system could decrease energy consumption by reducing mass with new structure or material [138]. Technological innovation for MT design concentrating on increasing productivity is still an important research direction as a main driver. Meanwhile, high-precision design is also a research focus for satisfying micro work piece manufacturing requirements [139], as well as surface quality [140] through the analysis of machine stiffness and cutting tool design effect.

5. Conclusions and Future Research Directions

In this literature review, strategies and techniques are classified into partial design tools involving one or two sustainability aspects, and those covering three dimensions (environment, economy and society). The former is more mature and standard compared to the latter in the early design stage, due to uncertain elements of early design. Meanwhile, it takes into account whether or not the machine tools are to be designed and used. If the machine tools need to be designed or upgraded through an innovative approach, then it is the best opportunity to integrate the sustainability aspects, or else it should consider mainly the processing optimization method such as cutting parameters, tool path, and machining time after the machine tool service period. Additionally, we have examined influences on the three sustainability dimensions respectively for machine tools from the life cycle point of view. Strategies and technologies are identified from one part to components, then to product and system. The main conclusions are summarized as:

1. The partial design strategies such as light weight and modular design to integrated sustainable design method have three sustainability dimensions.

2. The sustainability assessment method for machine tools to support decision-making in the early design stage. The two categories, however, are faced with the issue of considering three sustainable design dimensions simultaneously in different life cycle stages.

3. Most research focuses on the environmental burden especially energy efficiency, while sustainable product design underscored the importance of three sustainability dimensions under the condition of functional attributes.

4. The key techniques are categorized into light weight, modular design, and cooling and lubricant system, which have benefits in sustainable machine tool design in different life cycle stages.

5. Furthermore, sustainability assessment used by machine tools are described as LCA (Life cycle assessment), LCC (Life cycle cost) and LCSA (Life cycle social assessment), which should be used conveniently and relate to design parameter in early design stage. Currently, the research focuses on one or two factors for achieving sustainable design and manufacturing for machine tools.

In future, machine tools manufacturers should not only consider the integrated design method for sustainability, but also evaluate sustainability performance through the whole life cycle. The development direction for sustainable machine tools techniques are shown as follows:
(1) The simulation technique contributes to design efficiency before manufacturing process, use and end-of-life.

(2) With the development of new types of sensor, wireless monitoring technology will be used to monitor the state of machine tool usage including energy consumption, failure diagnosis, coolant fluids and lubricant oil, and so on.

(3) The uniform standardization for the energy efficiency of machine tools should be developed based on standard components in order to make accurate judgments.

(4) The network environment will provide more opportunities for collecting existing MT data used to improve the next generation or new product designs.

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