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Life cycle oriented low carbon manufacturing of mechanical equipment: method and application

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Abstract
Mechanical equipment is a significant contributor to carbon emissions. By analyzing the life cycle carbon emissions of mechanical equipment, it can be obtained that the consumption of materials and energy are the key factors. Focusing on decreasing material and energy consumption in the life cycle of mechanical equipment, a series of low carbon design strategies are proposed, including material selection, lightweight design, and design for disassembly and recycling; specifically, in this paper, low carbon operation strategies on the machine and workshop levels are discussed. Operations including power matching, energy recovery, and transmission chain shortening can be performed at the machine level, as well as scheduling and production optimization at the workshop level. The proposed method is applied to a piece of typical equipment, a hydraulic forming press, and results show that the proposed low carbon manufacturing methods have significant carbon emission reduction potential. Combined with current research hotspots, the integration of design methods and tools and the carbon emission reduction techniques enabled by intelligent manufacturing are future directions.

Keywords: Low carbon manufacturing, carbon emissions, energy saving, forming, lifecycle

INTRODUCTION

Climate change is one of the most urgent crises in our time[1]. Carbon emission, which is a major contributor to climate change, must be reduced[2,3]. Especially in China, which is the world's factory and the world's largest carbon emitter, contributed 33% to global emissions in 2021, and remains the main driver of the growth of global carbon emissions[4]. Manufacturing, as one of the most dynamic industries in the world, accounts for approximately one-third of total global CO_2 emissions[5], which reminds us to reduce and reverse climate change from the manufacturing industrial aspect[1]. As the world's manufacturing center, China's manufacturing industry currently accounts for more than 50% of the national total carbon emissions[6]. Mechanical equipment, as the core component in the manufacturing industry, is in urgent need of carbon emission reduction, of which low carbon manufacturing is an excellent solution[7].

Low carbon manufacturing, which refers to the manufacturing process that produces low carbon emissions intensity and uses energy and resources efficiently and effectively[8], has brought about widespread concerns among governments, corporations, and individuals worldwide and is widely used in efforts to reduce carbon emissions from mechanical equipment. Existing efforts aim to reduce carbon emissions from different stages of mechanical equipment and can be categorized as low carbon design (at the design stage)[9], low carbon processing (at the product manufacturing stage)[10], and low carbon production management (at the using stage)[11].

low carbon design

Low carbon design means decreasing the weight as much as possible, decreasing or replacing scarce materials, and extending life without harming performance[12]. The existing effort has indicated that 80% of the environmental impact is determined by the design stage[9]. It is crucial to consider reducing the carbon emissions of mechanical equipment in the design stage.

Carbon emissions vary greatly due to the large variability in the carbon emissions during the life cycle stages of raw material acquisition, production, use, and end-of-life (EOL) disposal[13]. For instance, aluminum alloy requires to consume much more energy than steel under the same mass in the material acquisition stage. And the product made of aluminum alloy is much harder to machine than the product made of steel. However, aluminum alloy is a lightweight material, resulting in the product made of aluminum alloy becoming lighter and saving a large amount of energy in the using stage when meeting the same mechanical performance[14]. For this reason, more and more structural components are being made from lightweight materials. Gagliardi *et al.* analyzed the impact of the manufacturing and use of car body components of different materials on carbon emissions[15]. Results show that the glass-fiber reinforced thermoset (3kg CO_2eq) and the carbon-fiber reinforced thermoplastic (4kg CO_2eq) own the lowest carbon emissions. Xiang *et al.* developed a digital twin model of material manufacture, processing, and use to obtain the carbon emissions of different materials to support low carbon material selection[16].

The structural design is also important for carbon emissions reduction, as it can further reduce the use of materials. Existing efforts on the structural design have focused on large-weight manufacturing equipment's components (e.g., mold and sliders of press) and structural parts of transport (e.g., automotive chassis and aircraft body) aiming for high fuel economy and safety. Li *et al.* proposed a hydraulic press slider topology optimization method for carbon emissions reduction, which considers the influence of the slider structure design on its welding process[17]. Liu *et al.* further proposed a topology optimization method considering carbon emissions of the slider casting process[18]. To ensure the durability of the mold, manufacturers usually design the mold thick and heavy, which leads to an increase in carbon emissions during the manufacture and use of the mold. Wang *et al.* proposed a mold structure optimization design method for carbon emissions reduction as well as ensuring the durability of the mold[19]. Considering the high frequency of use of transport, some efforts have been focused on optimizing the structure of automotive chassis[20] and seats[21] to reduce the carbon emissions from fuel consumption.

Existing efforts on low carbon design usually do not consider the interaction between material selection and structural design and it may lead to increased carbon emissions. For instance, aluminum alloy is much more difficult to machine than steel; failure to consider the processing characteristics of aluminum alloy in the structure design stage may increase the processing difficulty in the processing stage and even lead to failure of processing and waste of material.

Low carbon processing

Low carbon processing, which refers to minimizing the use of resources and energy during processing[22,23], has focused on both the machine level and the process level.

Existing efforts on low carbon processing at the machine level can be categorized into energy flows analysis, energy consumption modeling, and equipment structural improvements. U. Götze *et al.* analyzed the energy efficiency and cost of a machine tool[24]. Then an energy flow model was built for comprehensive evaluation of energy efficiency and cost of the machine tool. Zhang *et al.* developed a bond graph-based energy consumption model for machine tool spindle systems according to the structure and energy flow characteristics of machine tool spindle systems[25]. Yoon *et al.* investigated the power characteristics of a five-axis machine and developed a machine-based power consumption model to support energy consumption reduction[26]. Shang *et al.* analyzed and concluded five power consumption characteristics of heavy-duty machine tools and developed a generic power consumption model[27]. According to these analyses of the energy consumption characteristics of machine tools, Liu *et al.* developed a bond graph-based energy consumption model for machine tools[28]. Zhao *et al.* investigated the energy flow of a large and medium-sized hydraulic press and indicated that the main reason for low energy efficiency is the mismatch between load characteristics and drive modes[29]. Some efforts have focused on improving energy efficiency by improving the equipment structure to achieve energy matching. Gao et al proposed a novel energy-efficient system that conjoined two hydraulic press actuators to use the gravitational potential energy of one actuator for another actuator going up[30]. Jin *et al.* developed a novel drive system that can simultaneously adjust the speed and torque of the system to increase the matching degree between its output power and the demanded power of the load[31].

At the process level, existing efforts have focused on process energy modeling and process parameters optimization based on intelligent algorithms. Cai *et al.* developed an energy consumption model for the forward-and-reverse multidirectional turning process according to its characteristics to improve the turning process's energy efficiency[32]. Balogun *et al.* developed a process energy model for machining processes based on the analysis of the energy demand of the different modules of the machine tool[33]. Based on the stress-strain analysis of blank deformation, Li *et al.* proposed a process energy model for the stamping process to support process optimization[34]. Based on these models, various algorithms are applied to optimize the process to improve energy efficiency. Han *et al.* optimized the milling process through the Linear Decreasing Particle Swarm Algorithm to achieve the balance between cutting power and material removal rate[35]. A multi-objective grey wolf optimization algorithm was applied to optimize the machining process to achieve a balance between energy consumption and production time[36].

The current research gap lies in that mechanical equipment is an organic whole, and it may lead to the effects of carbon emission reduction falling into a local optimum if energy efficiency improvements at the machine and process levels are not considered in concert. For instance, different structures of a piece of equipment have different energy flow characteristics and the optimization at the process level for the original equipment may fail when optimizing the structure of equipment to improve the energy efficiency at the machine level.

Low carbon production management

Since mechanical equipment consumes a lot of energy in the workshop, there is a need for low carbon production management. New algorithms, novel scheduling methods, and integrated optimization methods are used to plan production and reduce carbon emissions in the manufacturing phase.

In new algorithms exploration, Lin *et al.* developed a teaching-based multi-objective optimization algorithm to achieve maximum makespan and minimum carbon footprint for turning production[37]. May *et al.* proposed a green genetic algorithm to evaluate multi-objective problems related to job shop sustainability[38]. The study found that worthless energy consumption can be significantly reduced by adopting composite energy-saving machine behavior strategies. Lu *et al.* proposed a hybrid multi-objective backtracking search algorithm to solve the scheduling problem of the permutation flow shop[39].

As for novel scheduling methods studies, Zhang *et al.* proposed a factory energy-saving production scheduling method considering real-time electricity prices. Considering different periods in the microgrid (i.e., morning shift, mid-day shift, and night shift), the results showed that electricity costs can be reduced by 6.2%, 12.3%, and 21.5%, respectively[40]. Baykasoglu *et al.* proposed the online and dynamic scheduling method of a manufacturing enterprise, which reduced the energy consumption of the enterprise and increased the annual income[41]. Considering the emergencies (e.g., equipment breakdown) in the production process, Yu *et al.* formulated the corrective maintenance scheduling problem as an online task assignment problem for energy-efficient mechanical equipment[42]. Li *et al.* proposed an optimization method that updates the status of jobs and machine schedules when dynamic events occur to enable energy-efficient production in flexible job shops[43].

In exploring integrated optimization methods, Wang *et al.* proposed an innovative and systematic approach to milling process planning and scheduling optimization for sustainable machining. Several intelligent algorithms are applied and benchmarked to determine the best scenario[44]. Yan *et al.* proposed a multi-level optimization method, namely cutting parameter optimization (machine level) and optimal scheduling (workshop level). The method differs from common scheduling methods in that the machining time for each job at each stage is a fixed value in the model[45]. Koltsaklis *et al.* proposed a general optimization framework to solve the optimal design and operation scheduling problems of energy microgrids. The proposed model highlighted the potential risks associated with key energy projects undertaken by investors and/or policymakers[46]. Zhang *et al.* proposed a Digital Twin (DT)-driven carbon emission prediction and low-carbon control smart manufacturing workshop, including the establishment of the workshop DT model, the DT data interaction and fusion method, and the DT-driven carbon emission prediction and low-carbon control method[47].

Currently, these studies tend to focus on a single stage while ignoring a more systematic view of the "life cycle", leading to a local optimum of carbon emission, energy consumption, and efficiency. The systematic life cycle view requires manufacturers to consider energy saving and carbon emissions reduction holistically from all stages including raw-material acquisition, manufacturing, use, and EOL disposal[12,48]. For instance, in the design stage, the structural design and material selection should consider the impact of that structure and material on the emissions and energy consumption during the processing stage[49].

The research presented in this paper explores methods for low carbon manufacturing oriented to the life cycle of mechanical equipment, aiming at providing organized thinking to reduce material and energy consumption as well as the carbon footprint of the equipment. The methods contain producing low carbon emissions intensity and using energy and resources efficiently during the lifecycle of equipment.

The rest of the paper is organized as follows: firstly, introduces the approaches for carbon emissions analysis, low carbon design, and low carbon operation of mechanical equipment. Secondly, novel applications about life cycle oriented low carbon manufacturing on forming are discussed. Thirdly, proposes perspectives for future research, combining the concepts of "integration" and "intelligence". Finally, the paper is concluded.

METHODOLOGY

Mechanical equipment is a wide variety of devices that can relieve human labor, powered by electricity or fossil fuel energy (e.g., agricultural machinery, heavy mining machinery, engineering machinery, machine tools, *etc.*). It is widely used in all types of manufacturing and has become an increasingly important element in any production system. With the development of manufacturing technology, more and more types of mechanical equipment with different functions are developed and put into production, but the problem of high carbon emissions in their life cycle still exists. A framework that clarifies the life cycle-oriented low carbon manufacturing methods of mechanical equipment is constructed, as shown in Figure 1.

Low carbon manufacturing mainly concentrates on the life cycle energy and resource efficiency of mechanical equipment. Carbon footprint calculation based on the life cycle is the foundation, and the concept of "low carbon" for different stages needs to be performed. A number of design and optimization approaches are also essential.

Life cycle carbon emissions

Since low carbon design and manufacturing will not be achieved without a comprehensive model of carbon emissions, the cradle-to-grave lifecycle of mechanical equipment includes raw material and energy acquisition, manufacture, assembly, transportation, use, and recycling and disposal.

The carbon emission in a life cycle derived from the consumption of energy and material in each stage is shown in Figure 2. The total carbon emission (G_T) can be obtained as:

$$G_{\mathrm{T}} = G_{\mathrm{A}} + G_{\mathrm{M}} + G_{\mathrm{P}} + G_{\mathrm{D}} + G_{\mathrm{U}} + G_{\mathrm{R}}, \tag{1}$$

where G_A, G_M, G_P, G_D, G_U, and G_R are the carbon emissions in corresponding stages, as shown in Figure 2.

The carbon emission of the raw materials and energy acquisition stage (G_A) can be calculated by:

$$G_{\mathrm{A}} = \sum_i m_{\mathrm{rm}\_i} \times k_{\mathrm{rm}\_i} + \sum_j e_{\mathrm{e}\_j} \times k_{\mathrm{e}\_j}, \tag{2}$$

where m_{rm_i} is the mass of the raw material i, $k_{rm\text{-}i}$ is the carbon emission factor of manufacturing the raw material i, E_{e_j} is the primary energy j in the stage, and k_{e_j} is the carbon emission factor of producing energy j.

The manufacturing stage is one of the main contributors to carbon emissions. To quantify the carbon emissions in this stage, a life cycle assessment (LCA) needs to be performed. By analyzing the life cycle manufacturing process of the mechanical equipment, the carbon emission of the manufacturing stage (G_M) can be calculated by accumulating the carbon emissions of all components' all processes, which can be expressed as:

$$G_{\mathrm{M}} = \sum_{n}\sum_{nj}\left(\sum_{ni}\left(m_{n-nj}^{ni} \times k_{n-nj}^{ni}\right) + E_{\mathrm{M}\_n-nj} \times k_{\mathrm{E}}\right) + m_{\mathrm{CO_2}} + E_{stress} \times k_{\mathrm{E}}, \tag{3}$$

where m_{n-nj}^{ni} and k_{n-nj}^{ni} are the mass and the carbon emission factor of the consumed material *ni* in the processing *nj* of the component *n*, respectively; $E_{\mathrm{M}\_n\text{-}nj}$ is the consumed electric energy in the processing *nj* of the component *n*; k_{E} is the carbon emission factor of producing electric power; $m_{\mathrm{CO_2}}$ is the direct carbon emissions in the manufacturing stage; E_{stress} is the electric energy consumption of stress relieving.

After all components are manufactured, they are assembled into mechanical equipment. The carbon emission of the assembly stage (G_{P}) is derived from the electric energy consumption (E_{P}), which can be expressed as:

$$G_{\mathrm{P}} = E_{\mathrm{P}} \times k_{\mathrm{E}}. \tag{4}$$

The carbon emission of the transportation stage (G_{D}) is subject to the mass of the assembled mechanical equipment (m_{MS}) and the transportation distance (s), which can be expressed as:

$$G_{\mathrm{D}} = m_{\mathrm{MS}} \times s \times k_{\mathrm{truck}} + m_{\mathrm{MS}} \times s \times v_{\mathrm{diesel}} \times k_{\mathrm{diesel}}, \tag{5}$$

where k_{truck} is the carbon emission factor of truck transportation, v_{diesel} is the diesel consumption factor, and k_{diesel} is the carbon emission factor of diesel production.

During the use of the mechanical equipment, electrical energy (E_{U}) and materials (m_{U}) are consumed to process the parts, and the carbon emissions in this stage (G_{U}) can be calculated by:

$$G_{\mathrm{U}} = \sum\left(E_{\mathrm{U}} \times k_{\mathrm{E}} + m_{\mathrm{U}} \times k_{m_{\mathrm{U}}}\right), \tag{6}$$

where $k_{m_{\mathrm{U}}}$ is the carbon emission factor of material m_{U}.

Understanding and identifying the energy dissipation characteristics of mechanical equipment are necessary preconditions for building the energy consumption model. The working procedure of mechanical equipment under a single operating condition can be expressed as a state transformation that the original energy changes into required energy through serial media characteristic states by using a group of units (i.e., the drive units, the transmission units, and the execution units). The mechanical equipment's energy consumption can be calculated by accumulating the amount of all unit's dissipation and the required energy, which can be expressed as:

$$E_{\mathrm{U}} = \sum_{j1}^{Z}\left(\sum_{j2} E_{j1-j2-\mathrm{DU}} + \sum_{j3} E_{j2-j3-\mathrm{TU}} + \sum_{j4} E_{j3-j4-\mathrm{EU}}\right) + E_{\mathrm{required}}, \tag{7}$$

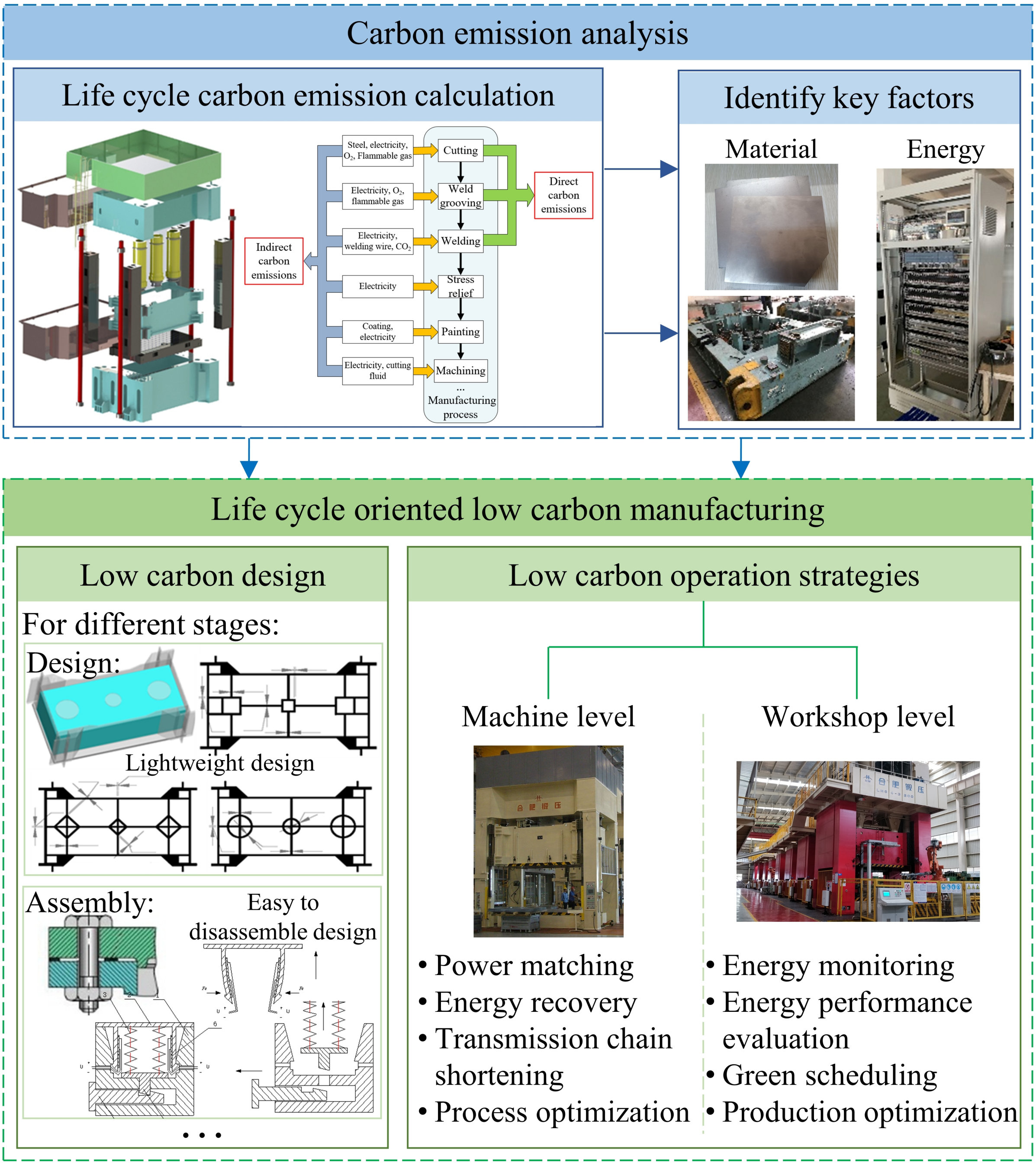

Figure 1. Framework of the life cycle-oriented low carbon manufacturing of mechanical equipment.

where $E_{j1\text{-}j2\text{-DU}}$, $E_{j2\text{-}j3\text{-TU}}$, $E_{j3\text{-}j4\text{-EU}}$ are the energy losses in operation process j_1 of drive units j_2, transmission units j_3, and execution units j_4, respectively; E_{required} is the required energy; Z is the number of process stages.

In the stage of recycling and disposal, energy (E_R) and additional materials (m_R) will be consumed, and some raw materials and components will be obtained and subsequently used to manufacture the new mechanical equipment. The carbon emission of the recycling and disposal stage (G_R) can be calculated by:

$$G_{\mathrm{R}} = E_{\mathrm{R}} \times k_{\mathrm{E}} + m_{\mathrm{R}} \times k_{m_{\mathrm{R}}} - G_{\mathrm{A}}^{'} - G_{\mathrm{M}}^{'} - G_{\mathrm{P}}^{'}, \tag{8}$$

where $k_{m_{\mathrm{R}}}$ is the carbon emission factor of material m_{R}; G'_{A}, G'_{M}, G'_{P} are the carbon emission of the recycled raw materials, individual parts, and assembled components, respectively.

Life cycle oriented low carbon manufacturing

According to the life cycle carbon emissions analysis of mechanical equipment, it can be seen that materials and energy consumption are critical contributors to carbon emissions. Therefore, focusing on decreasing the consumption of material and energy in the life cycle, a series of low carbon design methods and operation strategies are proposed.

Low carbon design

Low carbon design is an effective way to solve carbon emission problems from the beginning, by considering the function, quality, cost, and other related factors of the mechanical equipment to reduce the material and energy consumption in all stages of its life cycle. The framework of low carbon design is shown in Figure 3.

Following the life-cycle based carbon emission assessment, a low carbon design for different stages is required. Some approaches may be necessary for the low carbon design, such as energy-saving, material-saving, and service life-improving.

The first part of low carbon design is material selection. It aims at selecting suitable engineering materials and executing lifecycle embodied energy estimation methods based on the online material database. The principle of material selection is to use materials that are harmless, degradable, reused, recycled, and less expensive to process.

The second part of the design stage is lightweight design. It can realize low carbon emissions by achieving weight and material reduction of a part/component. A lightweight design has three specific components: size, shape, and topology optimization. In size optimization, some design requirements (e.g., stress, mass, displacement, *etc.*) are achieved by changing the properties of the structural elements (e.g., shell element thickness, beam element cross-section properties, *etc.*). In shape optimization, to determine the structure of the border shape, it is necessary to investigate how to determine the shape of the boundary or internal geometry to improve the structural characteristics. In topology optimization, the material distribution is optimized, and the best distribution scheme is found in the design space of the uniformly distributed material.

Low carbon design for manufacturing is to design a manufacturing process with low energy and material consumption without sacrificing product quality, cost, reliability, and functionality. For example, the use of dry cutting processes, 3D printing processes, vacuum heat treatment processes, *etc.*

Analyzing the carbon footprint in the assembly process and identifying the factors of carbon emissions during assembly is also necessary. Modularity and ease-to-disassembly are regarded as the design goals so that the structure of mechanical equipment is not only convenient for assembly, disassembly, and recycling but also for manufacturing. The main factors to be considered are the connection type, the material of the joint, the assembly environment, the assembly inspection process, the degree of dependence on the auxiliary process, and the carbon emission factor of energy.

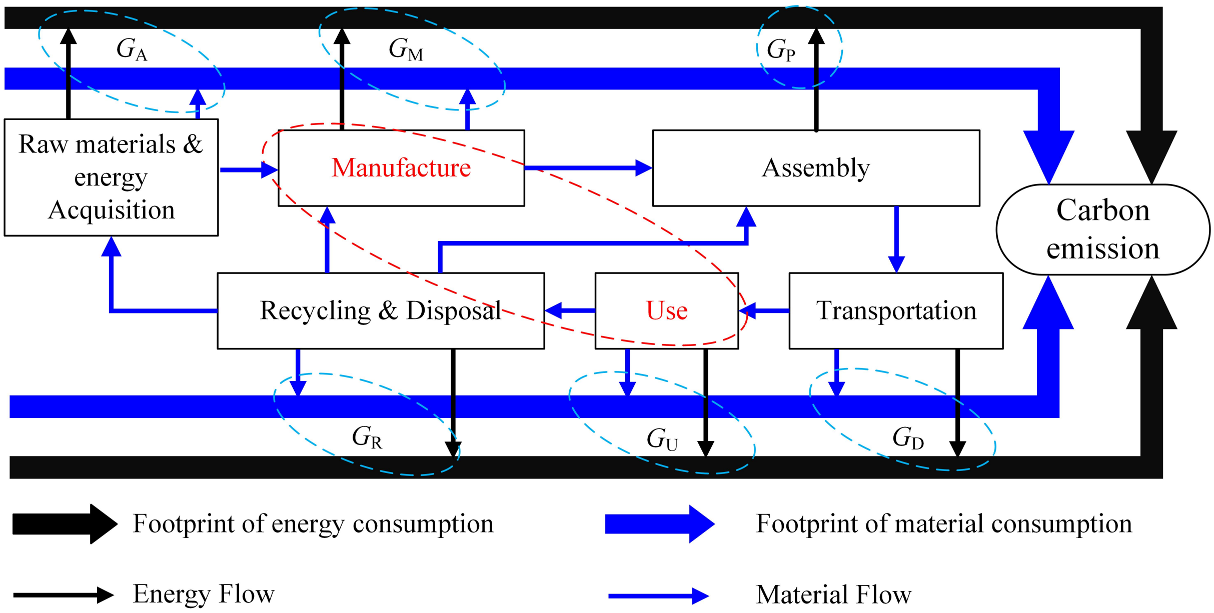

Figure 2. The carbon footprint of mechanical equipment in its life cycle.

In the use stage, multi-level design is necessary, which means reducing carbon emissions by promoting energy efficiency in equipment, process, and workshop. This multi-level design method can achieve carbon emissions reduction from a systematical perspective.

At last, at the end-of-life stage, recovery and recycling reduce low carbon emissions, mainly benefiting from material saving. The methods include artificial intelligence systems for component recycling, advanced crushing technologies, comprehensive evaluation technologies for recovery systems, and separation and classification of materials. Especially in remanufacturing, using remanufactured components can reduce carbon emissions by rebuilding a component to the specifications of the original manufactured product using a combination of reused, repaired, and new parts. Remanufactured components are of significant advantages in terms of cost, energy consumption, material, and carbon emission in contrast with prototype new components.

Low carbon operation strategies

After finishing design and manufacturing, the mechanical equipment will be in service in the enterprise for a long time, generally lasting for years to decades, which will produce a large number of carbon emissions. Nowadays, with the development of carbon neutrality targets worldwide, creating a low-carbon environment during operation has become the demand of enterprises. Therefore, low carbon operation strategies of mechanical equipment from different perspectives, respectively, on the machine level and workshop level, are discussed in this section.

(1) Machine level

The machine is the basic manufacturing unit, which is mechanically, electrically, or electronically operated for performing a task. Creating a "low carbon" machine during its operation processes can be achieved by the operations of power matching, energy recovery, transmission chain shortening, and process optimization, as shown in Figure 4.

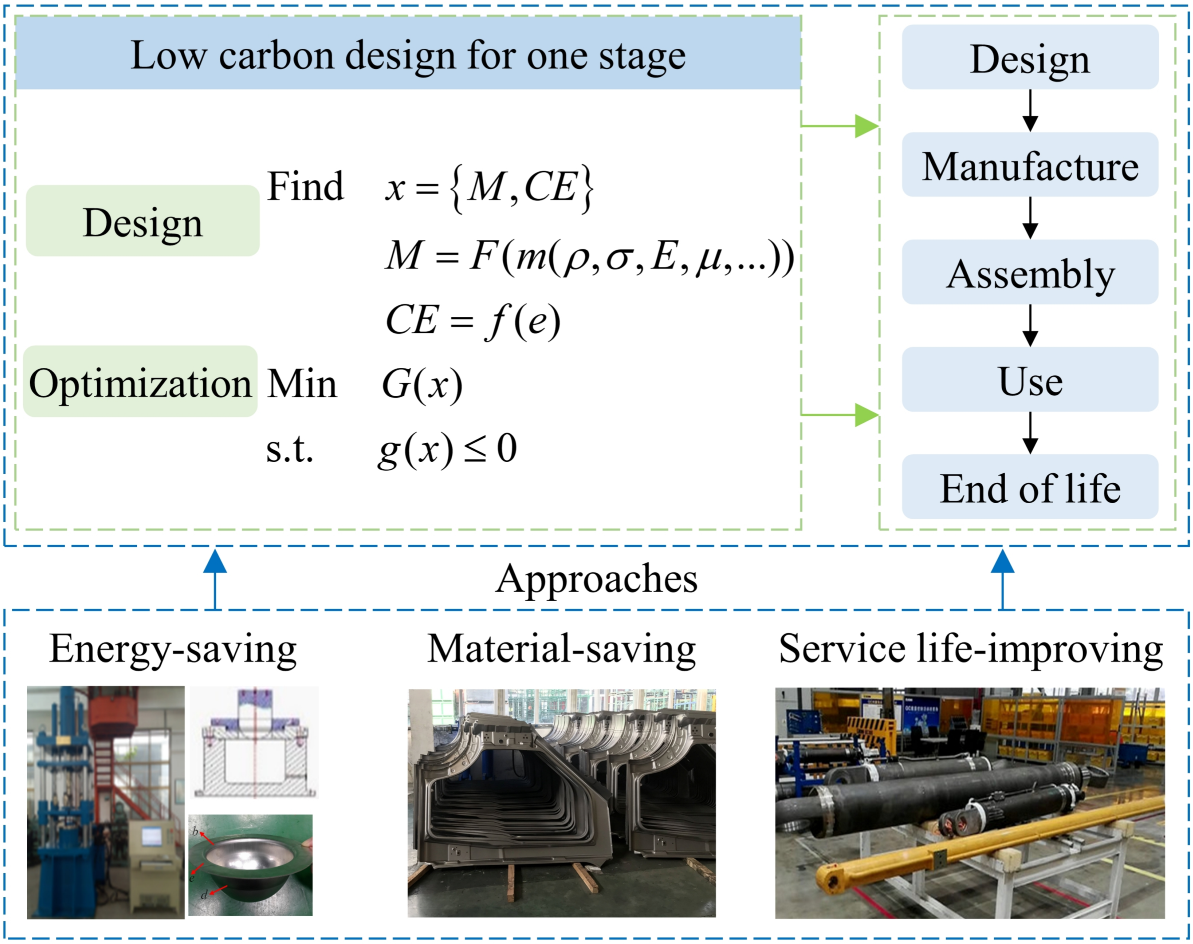

Figure 3. The framework of low carbon design. (x is a variable related to mass (M) and energy consumption (CE); every mass M has its corresponding attributes, which are density ρ, material strength σ, the elastic modulus E, and Poisson's ratio μ, etc.; CE is related to energy consumption factor e; $G(x)$ is the carbon emission and the objective function; $g(x)$ is the constraint function).

The main components on a machine, such as the drive units, usually cannot match the power requirements of load, resulting in the long-term low load and low energy efficiency operation of the machine. The power matching optimization for the machine helps solve the problem. The objects are to improve the matching degree between the installed and demanded power and to reduce the degree of mismatch caused by significant power demanded in different operations of the machine. Variable speed drive units and optimized design of drive units to meet the demanded power can be considered for power matching operation. Moreover, an overall power matching control method, including central energy supply and time-sharing, is valid for improving the energy-saving effect of the machine.

In some auxiliary actions, a large amount of energy is not involved in the processing but is converted into thermal energy and dissipated in the air, so that energy recovery is required. In energy recovery, the energy storage element stores the potential energy when the mechanical equipment performs auxiliary actions and releases the stored energy during processing. Further, by creating a link between the execution units of two pieces of mechanical equipment, the gravitational potential energy of the execution unit of one mechanical equipment can be used to provide energy directly to the other equipment. There would be no energy conversion and the potential energy will be used more efficiently.

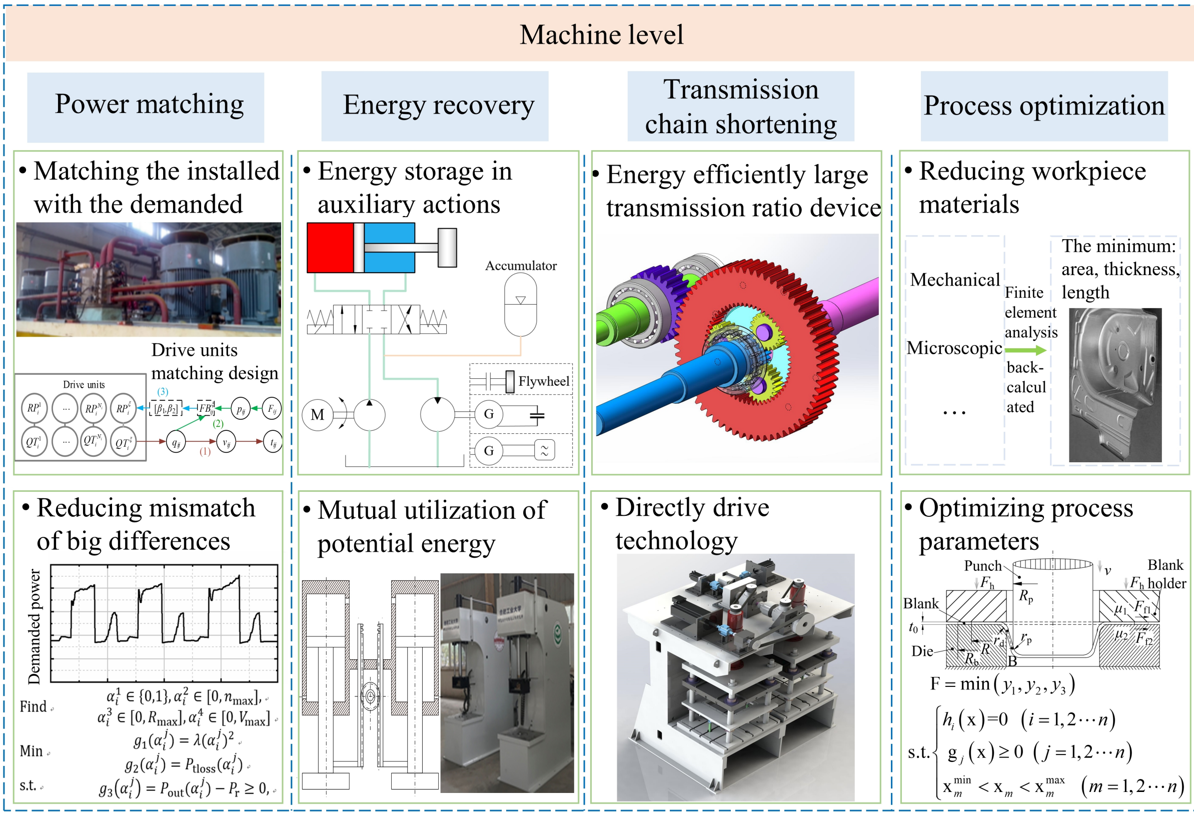

Figure 4. Low carbon operation strategies on the machine level.

Energy is consumed during the transmission process, and energy consumption increases with the growth of the transmission chain. The length of the transmission chain should be reduced. The shorter the drive chain used, not only the higher the energy efficiency, but also the higher the drive efficiency, the faster the response time, and the higher the drive accuracy. Operations, including replacing multi-stage drives with larger ratios, and driving actuators directly by drive units, can be considered.

In the manufacturing process, it is crucial to reduce the carbon emission under the premise of processing quality including mechanical performance, surface quality, and microscopic performance. It can be implemented by redesigning the workpiece and optimizing the process parameters.

According to the process performance requirements, the size and thickness of the blank are back-calculated by combining the process parameters with mechanical and microscopic properties. Then, through finite element analysis, the minimum size and thickness of the workpiece blank can be obtained and the workpiece material is reduced.

The products have different energy consumption and quality under different process parameters (e.g., speed, force, friction coefficient, die radius, *etc.*). During the machining process, if the process parameters are not selected properly, it may lead to defects such as cracks along with a large amount of energy consumption. These problems can be solved by adjusting the process parameters to reduce energy consumption while meeting the process quality requirements. First, low carbon evaluation indicators should be established, including carbon footprint indicators, performance, and quality evaluation indicators. These evaluation indicators should be used as the objective function in the optimization method. Then, the optimized process parameters and constraints should be determined according to the performance and processing requirements. The sample points of the design variables in the value space should be determined before building the model, and the corresponding experimental design should be performed. After obtaining the evaluation index values of each sample point, the response model between the process parameters and the low carbon evaluation index is established. The corresponding process parameters are optimized through mathematical algorithms and the optimization results are obtained.

(2) Workshop level

An integrated framework to support low carbon and energy-efficient manufacturing on the workshop level is depicted in Figure 5. The framework is built on two layers, data acquisition and operation management. Operation management comprises three procedures, energy analysis, energy performance evaluation, and production optimization. Data acquisition provides valuable information for the next layer. The information is based on crucial production and energy-related data monitored during the manufacturing process. Next, operation management is performed to propose suggestions for energy and material saving and production efficiency improvement.

Energy analysis is used to establish energy models from the perspective of the manufacturing process and the part embodied energy, respectively. Modeling of the former is to facilitate the identification of energy consumption at each stage and to provide targeted energy conservation recommendations for each step. And modeling from the latter perspective is to recognize the consumed energy in manufacturing different parts and to provide the basis for the optimal scheme selection of the subsequent production scheduling. Then, based on the established energy models, energy performance evaluation enables the identification of energy distribution, energy-intensive processes, and bottlenecks during production. To achieve these goals, discrete event simulation (DES) is a common and effective tool. Finally, production optimization is performed to find tradeoffs between material, energy, and production efficiency.

Moreover, the operations of production line layout optimization and product multi-process optimization can also be taken into consideration. The former is to adjust the position of each element in the production line to minimize the intermediate transfer path to reduce energy consumption. The latter is to redesign the processes and procedures for workpieces to match the machining capacity of the production line and reduce the material removed during processing.

APPLICATION ON FORMING

The hydraulic press is one of the most important mechanical equipment using hydraulic cylinders to generate a compressive force acting on the workpiece. The press is widely used in many manufacturing fields (e.g., blanking, punching, deep drawing, and metal forming) owing to its ability to deliver high forming pressures with heavy dead weight. Unfortunately, they are also large energy consumers. By 2021, China had produced about 3.5 million hydraulic presses. If the average power demand of a press is 40 kWh, more than 490 billion kWh will be consumed per year, which is comparable to the total energy consumed by South Africa in 2021[50]. And the energy consumption of the equipment manufacturing industry accounted for 1.882% of China's total energy consumption in 2019[51].

Therefore, low carbon manufacturing for hydraulic presses would achieve large-scale carbon emission reduction. This calls for hydraulic press designers to increase their understanding of energy and material use throughout the life cycle of a hydraulic press.

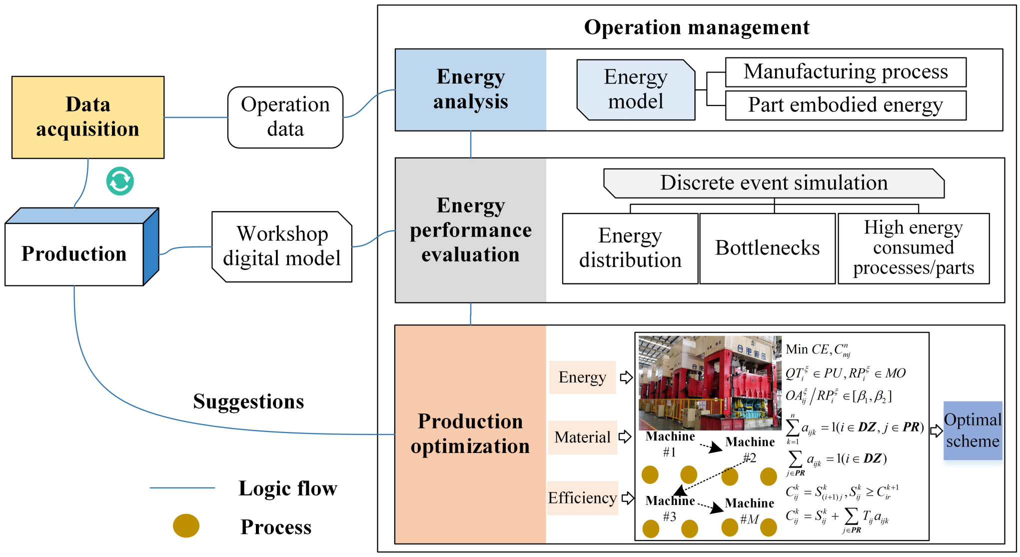

Figure 5. An integrated framework to support low carbon manufacturing on the workshop level.

A 2000-ton rapid sheet tension hydraulic press with an installed power of 510 kW and a structure of three beams and four pillars is investigated, as shown in Figure 6. The working cylinders are fixed in the cylinder hole of the upper beam, the pistons are arranged in the working cylinder. The lower end of the pistons is connected to the slider, and the slider moves up and down along the pillar guide. The life cycle oriented low carbon manufacturing technology route of a hydraulic press is shown in Figure 6. In the life cycle of a hydraulic press, the carbon emission in the manufacture and use stage is the critical contributor. Therefore, carbon emissions from these two stages will be analyzed.

Carbon emission analysis

Carbon emissions in the manufacture

The main processes related to carbon emissions of the components during the hydraulic press manufacture stage are raw material acquisition, steel sheet cutting, weld grooving, welding, and stress relieving. In the simplified LCA process, the system boundary is defined as shown in Figure 7, in which the factors not directly related to the manufacturing processes (i.e., transportation, storage, and some aided processes) are omitted.

According to the manufacturing process, the cradle-to-gate LCA inventory data of carbon emission evaluation of the three beams and four pillars, including raw materials, electrical energy, and direct carbon emission, are shown in Table 1.

The carbon emission factors used in the paper are shown in Table 2. The carbon emissions from the manufacturing process of three beams and four pillars of the hydraulic press can be calculated, as shown in Table 3, and the carbon emission distribution is shown in Figure 8.

The results indicate that the use of raw materials is the most significant contributor (i.e., 95.89%) to the carbon emissions in the manufacturing stage of a press. Welding is the second most important contributor, and groove shape is the most critical factor for welding wire consumption.

Table 1. Life cycle inventory data of the hydraulic press

Structures	Raw materials (kg)		Electrical energy (kWh)	Direct carbon emission ($kgCO_2$)
	Steel sheet	Welding wire		
Slider	27011.00	393.08	2025.66	1053.12
Upper beam	56947.00	828.73	4270.69	2220.28
Lower beam	89441.00	1301.60	6707.54	3487.17
Pillars	28249.00	411.10	2118.51	1101.38

Table 2. Carbon emission factors used in this paper

Parameters	Amount	Unit
The carbon emission factor of East China Power Grid	0.8367	$kgCO_2eq/kWh$
The carbon emission factor of Chinese steel sheet manufacturing	2.3367	$kgCO_2eq/kg$
The carbon emission factor of welding wire manufacturing	2.4390	$kgCO_2eq/kg$

Table 3. Carbon emission in manufacturing of the hydraulic press (Unit: $kgCO_2eq$)

Structures	G_{M-R}	G_{M-E}	G_{M-M}	Carbon emission	Total carbon emission
Slider	64075.33	1694.87	1053.12	66823.32	498863.02
Upper beam	135089.33	3573.29	2220.28	140882.89	
Lower beam	212171.39	5612.20	3487.17	221270.76	
Pillars	67012.11	1772.56	1101.38	69886.05	

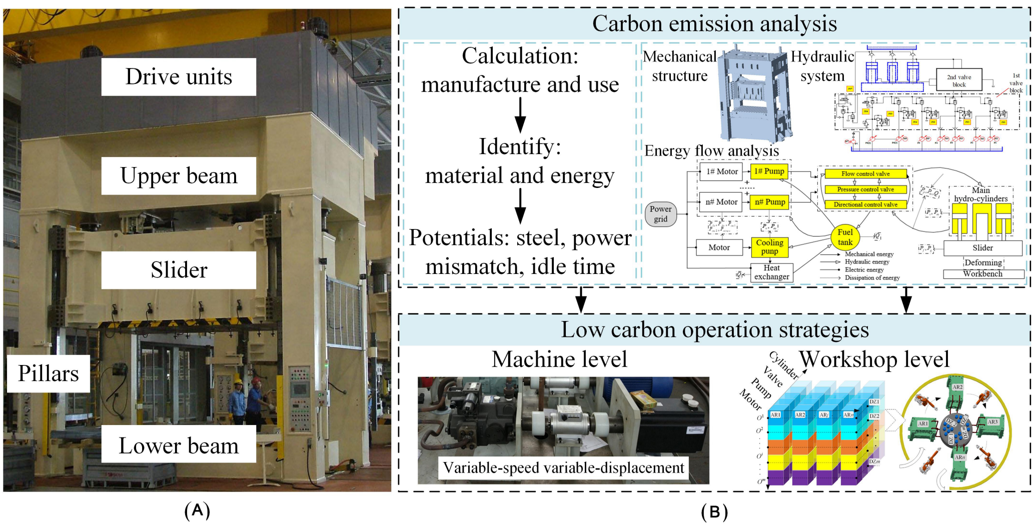

Figure 6. (A) A 2000-ton rapid sheet tension hydraulic press and (B) life cycle oriented low carbon manufacturing technology route of the hydraulic press.

Carbon emissions in use

In order to obtain a simplified energy dissipation model of the hydraulic press system, a relatively small proportion of energy consumption can be simplified. For a series of intermediate energy conversions in the working processes, the hydraulic press system can be divided into five units according to the characteristics of energy conversion of each component. They are E-M, M-H, H-H, H-M, and M-F, which are performed by the elements of motors, pumps, pipes, valves, and cylinders, respectively, as shown in Figure 9. Different units have their energy dissipation characteristics. It is impossible to implement real-time monitoring of

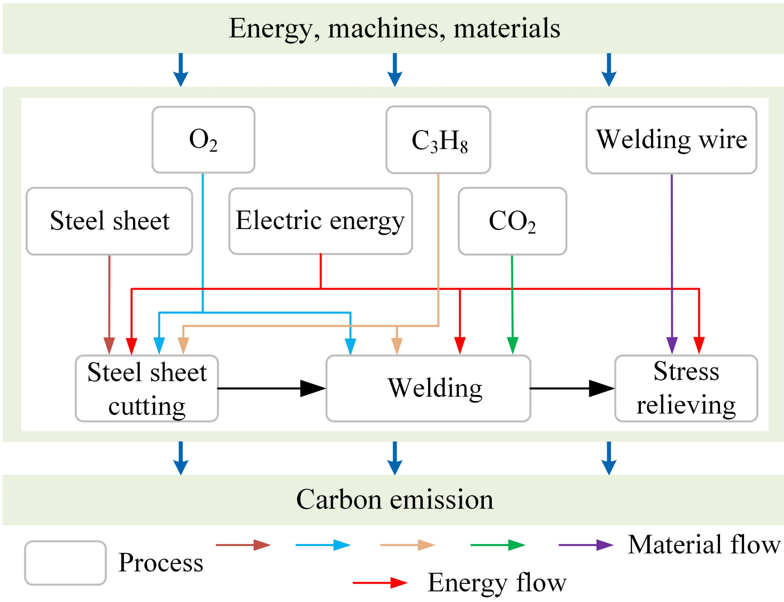

Figure 7. System boundary of carbon emissions in the manufacturing process of the hydraulic press[52].

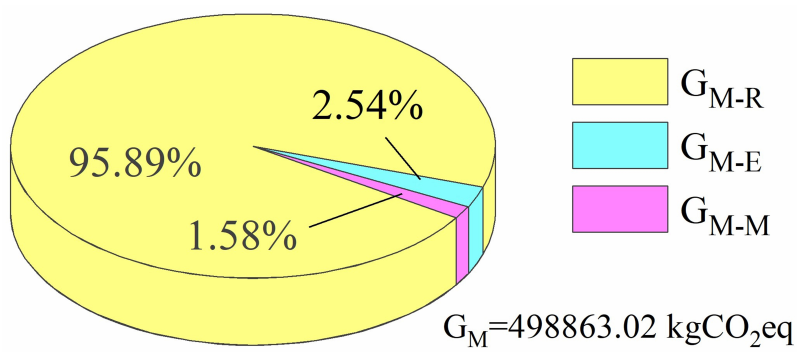

Figure 8. Distribution of carbon emissions in the manufacturing stage of the hydraulic press. (G_M is the carbon emissions of raw materials, G_{M-E} is the carbon emissions derived from energy consumption during manufacturing processes, and G_{M-M} is the direct carbon emissions in the processes).

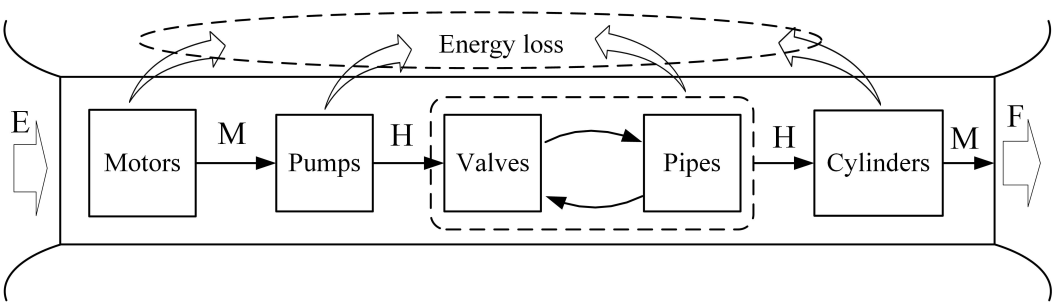

Figure 9. The basic energy flow of the hydraulic press system in use[53] (E is for electrical energy, M is for mechanical energy, H is for hydraulic energy, and F is for forming energy).

each unit's output and input in the production conditions. Based on the law of energy conservation, the energy dissipation model of the system can be simplified.

Generally, the hydraulic press works 8 hours a day, 250 days per year, and has 20 years of service life during its life cycle. The energy consumption of the hydraulic press in a working process is shown in Table 4 (the duration of a working process is 24 seconds). The carbon emissions from the use of the hydraulic press throughout its life cycle can be calculated as shown in Table 4.

As a result, the percentages of carbon emissions during use are 29.92%, 44.42%, 16.94%, and 1.64% for E-M, M-H, H-H, and H-M units, respectively, as shown in Figure 10, while only 7% of the energy is used for deformation (i.e., M-F).

Carbon reduction potentials

In the manufacturing stage, lowering the use of the primary raw material (i.e., steel sheets) is critical to reducing the total carbon emissions of a hydraulic press manufacturing stage. This result also implies that lightweight design should be implemented to achieve the goal of low carbon in the design and manufacturing stages.

The low energy efficiency in use is the main contributor to carbon emissions, which is caused by the low matching degree between the power requirement of the actuators and the output power of the drive units, as shown in Figure 11. The output power of the drive system cannot be aligned with the power required in various forming stages. Therefore, reducing the mismatching degree would be an efficient way to reduce carbon emissions in use. At the same time, the long idling time of the drive units in the hydraulic press is another contributor to carbon emissions, so decreasing the idling time without affecting the press operations is essential to reduce carbon emissions in use.

Low carbon operation strategies

Based on the obtained carbon emission reduction potentials of the hydraulic press, low carbon operation strategies can be developed at the machine and workshop level, as shown in Figure 12. For a single hydraulic press, energy matching is an important way to reduce energy consumption. The forming process parameters are essential for the forming quality and also affect the energy consumption; therefore, process parameters optimization is a critical way to reduce energy consumption. Meanwhile, more than one forming process is usually needed in metal forming, and several hydraulic presses can be equipped in a production line to perform the forming tasks. Under this circumstance, improving the matching degree between the output power with the load from the perspective of the whole system is another meaningful strategy at the workshop level.

Energy matching for the drive unit

A hydraulic drive unit, including a motor and a pump, is widely used to convert electrical energy into hydraulic energy. As the traditional drive units (i.e., variable motor speed or variable pump displacement) cannot take into account the energy efficiency of the motor and the pump at the same time, a control method that simultaneously adjusts the motor speed and the pump displacement was proposed to meet the flow demand of the load. In the proposed system, a variable asynchronous motor driving a variable displacement piston pump is employed in the drive unit. Different load conditions require different flow rates, and the given flow can be achieved by adjusting the motor speed or the pump displacement. Since the drive unit has different energy efficiencies under various combinations of speed and displacement, the one with the maximum energy efficiency can be selected by analyzing the energy efficiencies of the motor and pump, as shown in Figure 13.

Table 4. Energy consumption in a working process and carbon emission from the use of the hydraulic press

Process	Energy consumption (kJ)	Total energy consumption (kJ)	Carbon emission in use (kgCO_2eq)
E-M	1489.80	4979.19	6943605.96
M-H	2211.70		
H-H	843.63		
H-M	81.90		
M-F	352.16		

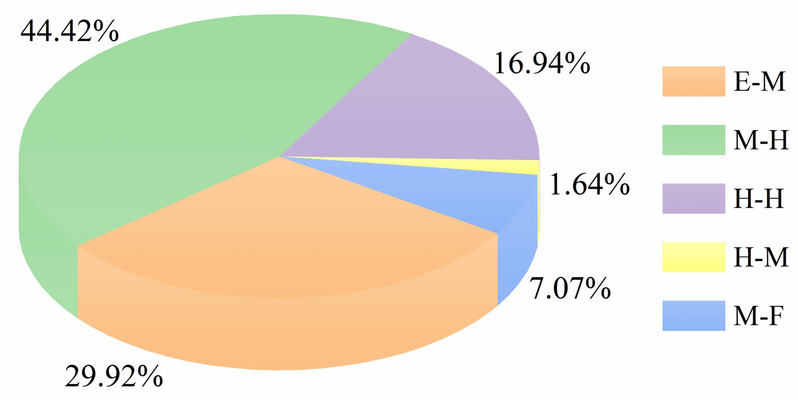

Figure 10. Distribution of carbon emissions in the use stage of the hydraulic press[30].

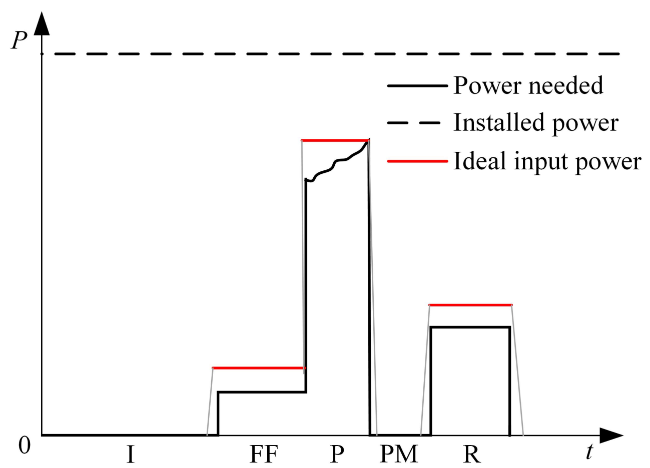

Figure 11. Demanded power of all stages in a forming process[29]. I: Idle; FF: fast falling; P: press; PM: pressure maintaining; and R: returning.

The energy efficiency of the motor (η_m) and pump (η_p) varies with the load rate (ratio of output power to rated power) and the system pressure, respectively. The output power of the pump is equal to the product of the system pressure and the flow rate, which is associated with the motor speed. Thus, the overall energy efficiency of the drive unit (product of η_m and η_p) can be expressed by the motor speed n, which can be further optimized to obtain the maximum overall energy efficiency, as shown in Figure 14.

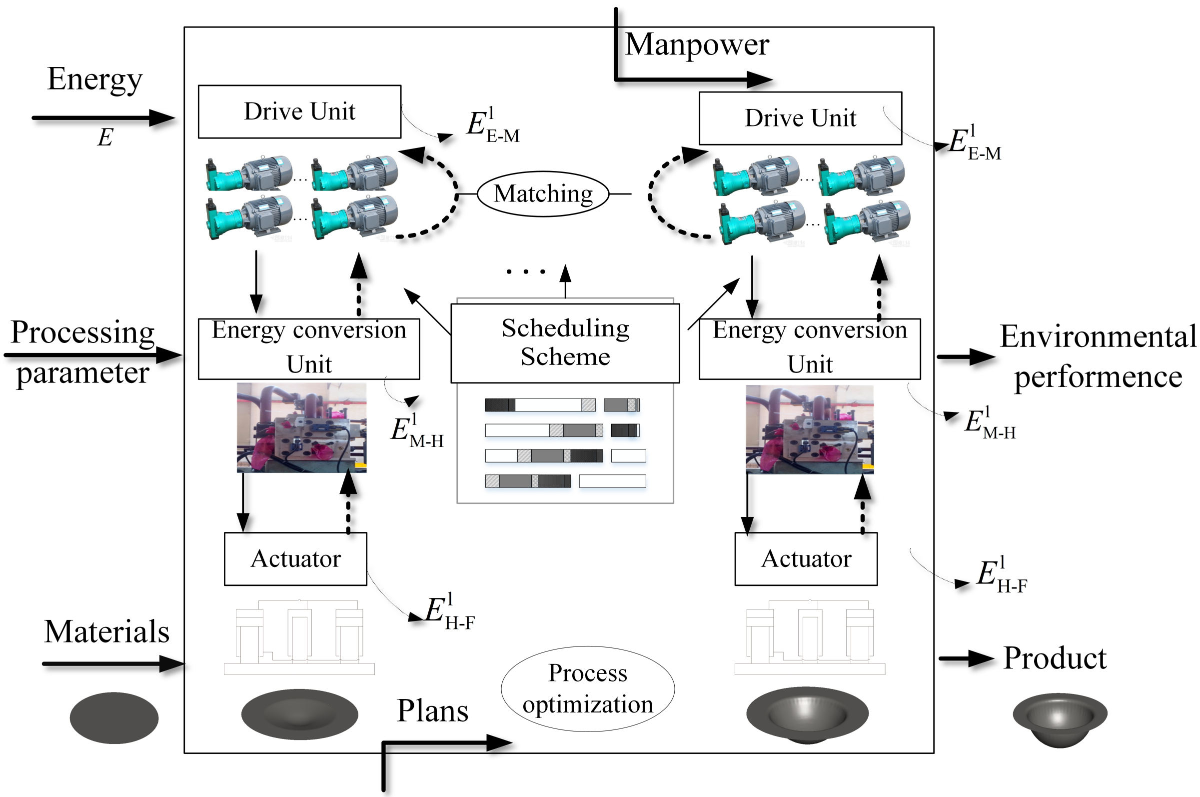

Figure 12. Low carbon operation strategies in a hydraulic press production line.

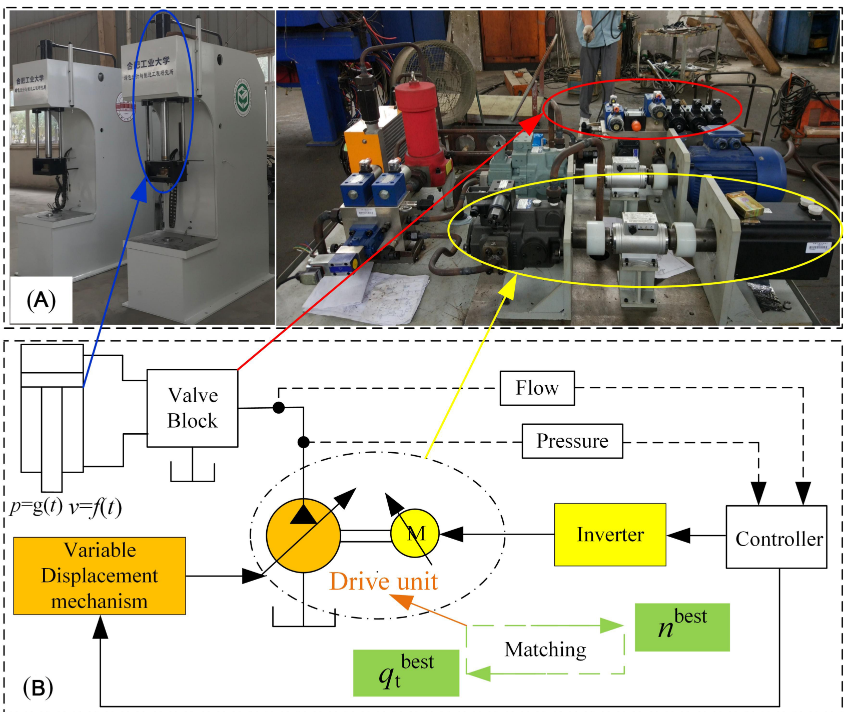

Figure 13. (A) Experimental platform and (B) control schematic diagram for the drive unit of variable displacement and variable speed[54] (q_t^{best} is the displacement of the pump and n^{best} is the speed of the motor in combination with maximum energy efficiency).

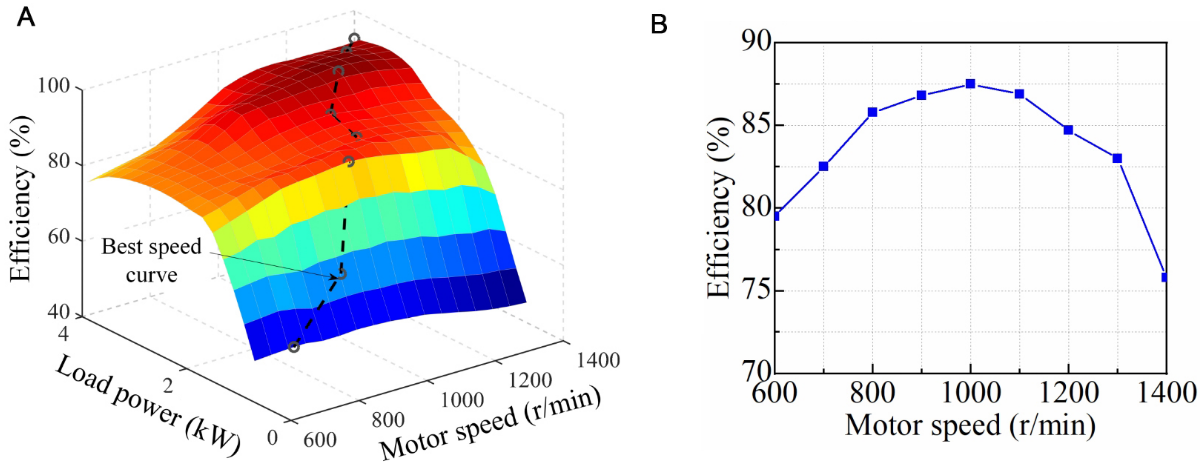

Figure 14. Energy efficiency of drive unit changing with motor speed under (A) variable load power, and (B) given load power at 2 kW[54].

It can be seen from Figure 14 that the optimum speed and the maximum energy efficiency vary with the load power. Under the condition of light load, the overall efficiency of the drive unit decreases with the increase in motor speed. When the load power is greater than a specific value, the overall efficiency increases first and then decreases, which means the overall efficiency has a maximum value. Therefore, for a given load, the motor speed can be adjusted, along with the pump displacement, to improve the overall energy efficiency and achieve the purpose of energy saving. Experiments show that the energy efficiency of the drive unit employing a variable motor variable displacement pump is increased by 8% compared to the drive unit with a variable displacement pump[54].

Multi-press sharing drive system

To solve the problems of mismatch and long idling time, an energy matching method for a single hydraulic press was proposed[55-57]. The drive system of the hydraulic press is partitioned into several drive zones with different installed power to match the demanded power of the corresponding working stages, as shown in Figure 15.

When the hydraulic press runs in working stage 1#, the corresponding drive zone 1# in the drive system will be activated and supply energy to the press. When working stage 1# is finished, drive zone 1# will be deactivated, and drive zone 2# will be activated to serve the hydraulic press when it is in working stage 2#. Each drive zone only works when the hydraulics are in the corresponding working stage and stays unloading for the rest of the whole cycle. When working stage N# ends, the drive zone N# will be deactivated, and the entire drive system will prepare for the next forming cycle. In this method, each working stage would be driven by the corresponding drive zone with matching output power.

However, for the drive system in this configuration, each drive zone only supplies energy in the corresponding working stage and stays idle in other stages, which consume more energy than the traditional way. This problem can be solved by grouping hydraulic presses, as shown in Figure 16.

A group of five 2000-ton rapid sheet tension hydraulic presses (HP1, HP2, HP3, HP4, and HP5), were selected as the research object to validate the proposed energy-saving method. The forming process for each hydraulic press in a group with similar power requirements and load characteristics was partitioned into five working stages. Furthermore, the drive system was divided into five drive zones, with the power

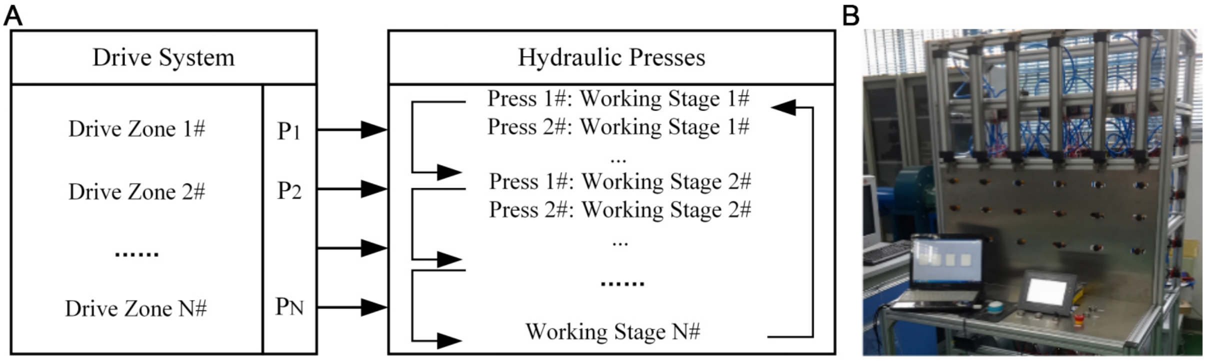

Figure 15. (A) Physical architecture of the energy matching method[55] and (B) pneumatic experimental prototype. (In the figure, the drive system is divided into *N* drive zones according to the number of working stages of the hydraulic press in a forming process; and the output power *Pi* of each drive zone matches the required power of the hydraulic press working in the corresponding working stage).

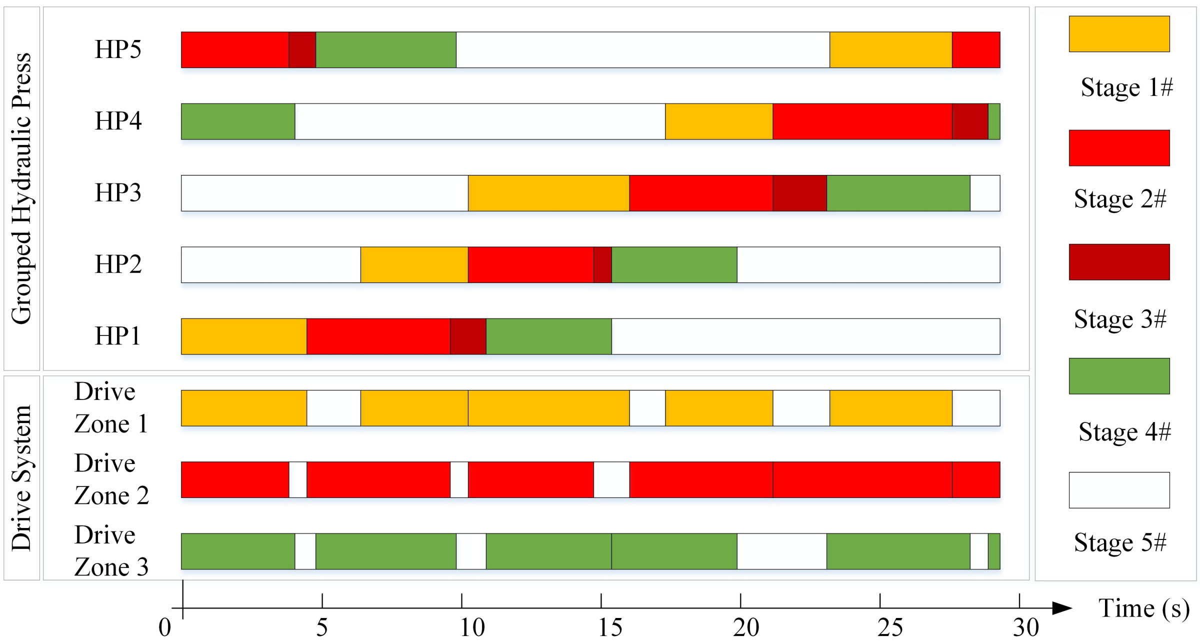

Figure 16. Working status of the drive system for grouped hydraulic press[56]. (in the figure, Stage 1#: FF; Stage 2#: P; Stage 3#: PM; Stage 4#: R; and Stage 5#: I).

matching to the corresponding working stage. As the needed power for stage 3# and stage 5# was zero, no motor pumps were assigned to these drive zones.

As can be seen from Figure 16, these three drive zones were shared by the five hydraulic presses, and the times drive zones stayed in idling status significantly decreased than the traditional hydraulic system.

Based on the above energy consumption model presented, the energy consumption in a working cycle can be calculated according to the proposed scheme, as shown in Table 5 and Figure 17. The results show that the average energy consumption of one hydraulic press (OP) in the group is much less than that of a single hydraulic press (AP) and the energy efficiency is much higher. It can be seen that the energy consumption in the forming stage has not been significantly changed, while the energy consumption of hydraulic presses working in an idling state has been reduced or even eliminated.

Table 5. Energy consumption of one hydraulic press in the group (OP) and a single press (AP) (unit: kJ)[57]

	Stage 1#	Stage 2#	Stage 3#	Stage 4#	Stage 5#	Total
OP	236.76	1333.69	0	946.20	0	2516.65
AP	330.04	1333.69	409.54	946.20	1638.15	4657.62

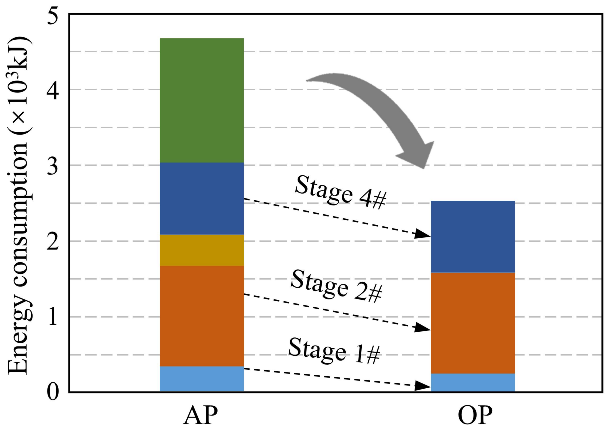

Figure 17. Energy consumption for a single press (AP) and one hydraulic press (OP) in the group[57].

Discussions

Aiming at lowering carbon emissions, operation strategies including energy matching for the drive unit and multi-press sharing system were investigated based on LCA results of the manufacturing process and energy analysis in use. Compared with existing research efforts, more work was performed to search the opportunities for energy management at different levels, and significant potentials for low carbon manufacturing of hydraulic press were presented.

According to the results of the carbon emissions analysis in the manufacturing process of a hydraulic press, it is noticeable that the use of raw materials is the most significant contributor to carbon emissions. Therefore, a lightweight design for the physical structure of the hydraulic press (especially for the three beams) can significantly reduce carbon emissions in the whole manufacturing stage. In this background, topology optimization may be a powerful tool for low-carbon design applications.

Furthermore, integration of these low carbon strategies under the perspective of a hierarchy from the equipment and forming processes to the workshop can be developed, as shown in Figure 18, where energy management and control are implemented at the systematic level. Thus, the low carbon manufacturing and operation of the hydraulic press can be further realized.

PERSPECTIVES

Integration of design methods and tools

In tools development, the concept of "integration" is more and more popular nowadays, so the integration of different design tools and methods must be a new trend in low carbon manufacturing, as shown in Figure 19. It can realize the reuse and parameterization design of the model, the process route planning, the simulation assembly and disassembly of the product, the product life cycle evaluation, and so on in the

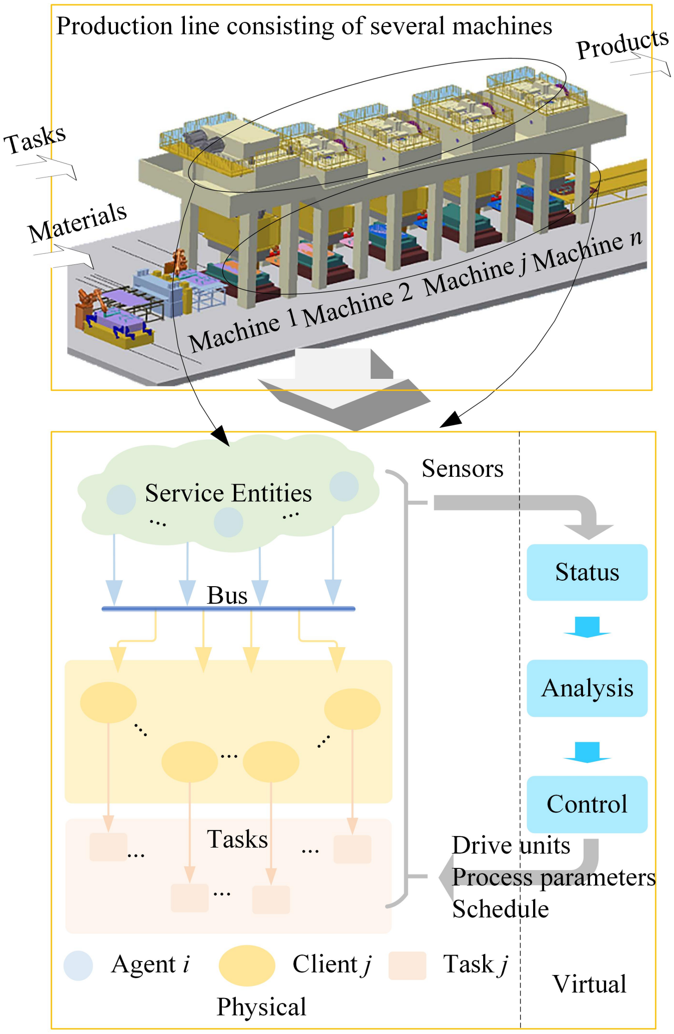

Figure 18. Integration of low carbon manufacturing strategies under the perspective of a hierarchy from the equipment, forming processes to the workshop.

design stage. The product design and development cycle will be significantly shortened, the development costs will be reduced, and the product's environmental performance will be improved systematically.

The functional architecture of the tool and software that integrates resource restoring, analyzing, and application is illustrated in Figure 20. The software provides dynamic predictive analysis and production scheduling functions for efficient operation modeling and optimization, for example, in a stamping workshop. Furthermore, it meets the exact, precise, and real-time requirements for energy consumption and operation efficiency, predictive analysis, and production schedule. It can provide information such as power and duration when the machine processes different parts, make more accurate predictions on the energy consumption and makespan of the workshop, and more accurately optimize the production scheduling scheme, to control the efficient operation of the workshop.

Carbon emission reduction enabled by smart manufacturing

At present, intelligent manufacturing is a research hotspot, and mechanical equipment tends to be more intelligent. The energy-saving and emission-reduction technology enabled and assisted by smart

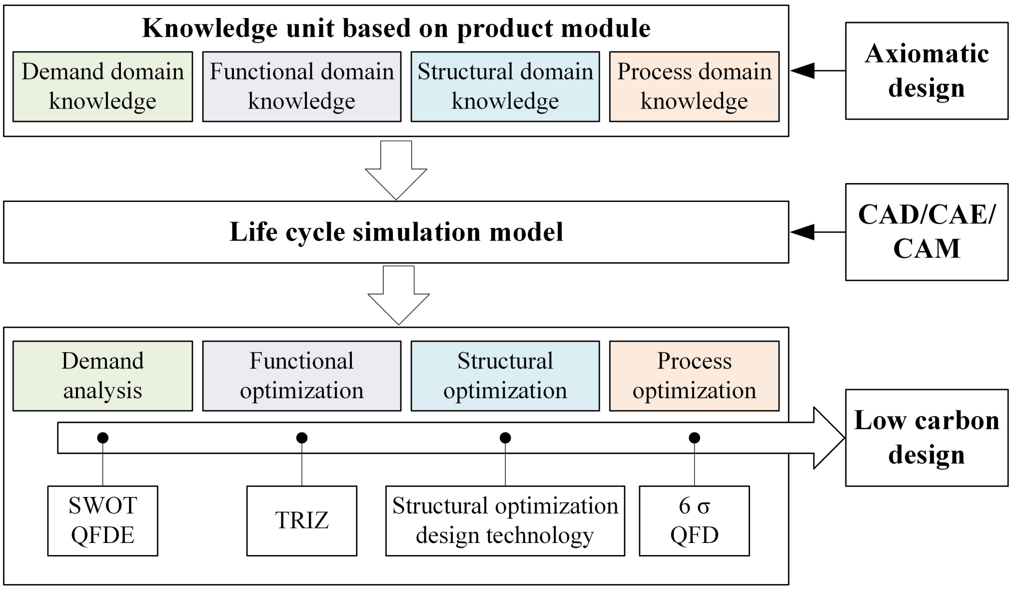

Figure 19. Tools and method integration in life cycle oriented low carbon manufacturing.

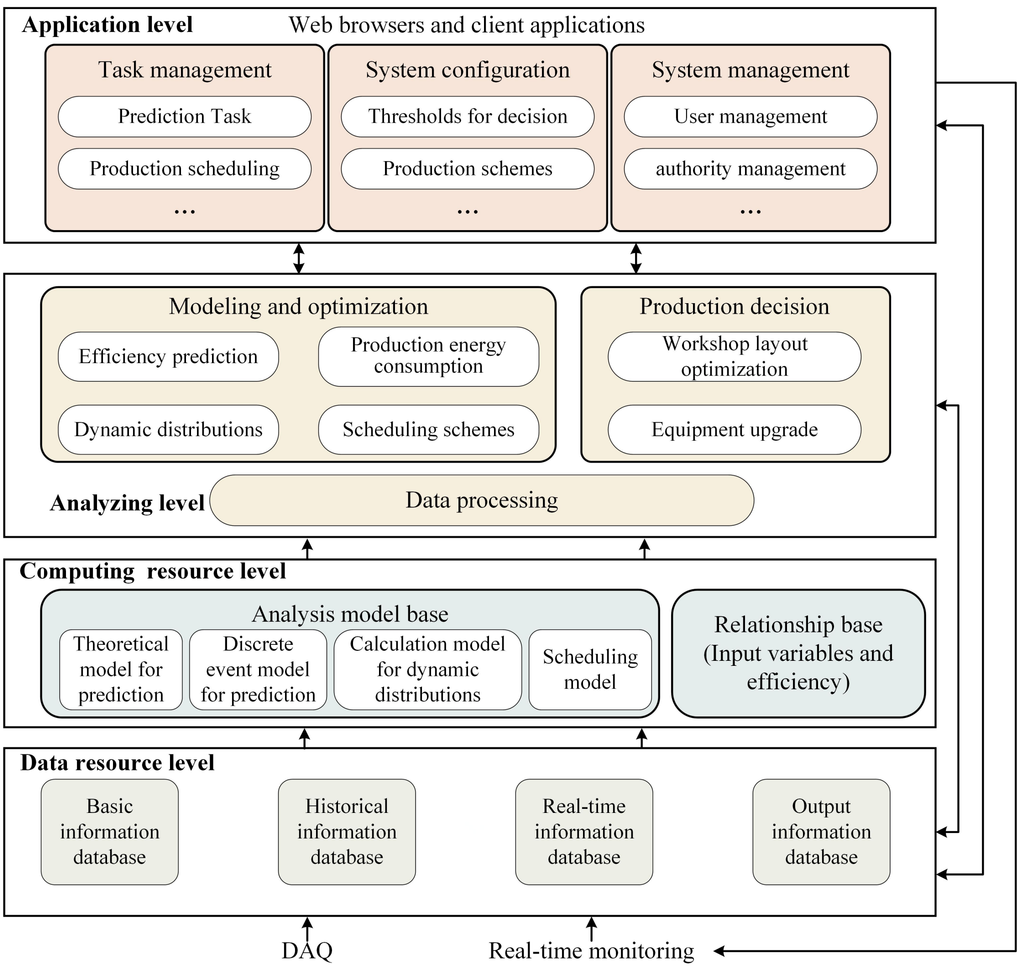

Figure 20. Functional architecture of the software.

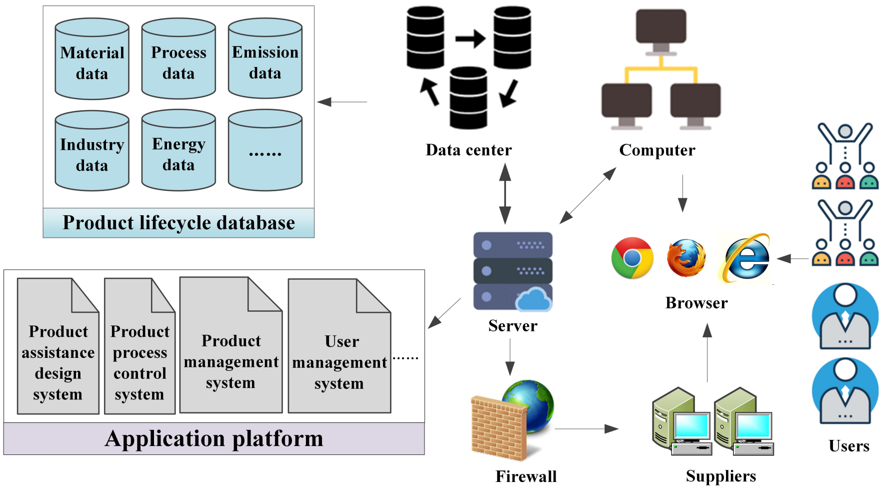

Figure 21. Dynamic and distributed design based on big data and the Internet.

manufacturing will also be a hot research direction in the future. Intelligent methods and technologies will be applied in low carbon manufacturing oriented to the life cycle, such as big data, IoT, and digital twins. Take big data as an example, a dynamic and distributed design based on big data and the Internet is shown in Figure 21. Based on the product lifecycle database, users can realize process control, product assistance design, *etc.*, through the network to reduce product material and energy consumption. This research direction will improve decision quality more effectively, reduce decision-making costs remarkably, and identify objectives more clearly.

SUMMARY AND CONCLUSIONS

A life cycle oriented low carbon manufacturing method is proposed and applied on typical mechanical equipment, a forming press, and some conclusions can be made:

(1) The life cycle carbon emissions of the mechanical equipment were analyzed and it was concluded that material and energy consumption are essential contributors. To reduce material and energy consumption, a series of low-carbon design and operation strategies are proposed.

(2) The design methods include lightweight design, modular design, and design for easy disassembly. The operations such as power matching, energy recovery, and transmission chain shortening on the machine level, as well as scheduling and production optimization on the workshop level, can be conducted.

(3) A hydraulic press was taken as a case to verify the proposed method, and the results showed effective carbon emission reduction.

(4) Combined with the current research, the integration of design methods and tools as well as carbon reduction assisted by intelligent manufacturing will be the hot research directions for low carbon manufacturing in the future.

The next step of the research is to combine digital twin technology for full lifecycle management and control of hydroforming equipment for low carbon manufacturing. Meanwhile, the method proposed in this paper will be extended and applied to more mechanical equipment to promote reducing carbon emissions. With the development of the manufacturing industry, more and more mechanical equipment is being phased out, so that more efficient and energy-saving strategies for equipment end-of-life disposal will be studied and proposed in the future.

DECLARATIONS

Authors' contributions

Conceptualization: Huang H
Formal analysis: Xiong W, Gan L
Methodology: Huang H
Validation: Zou X, Li L
Discussion: Li L
Writing-original draft: Huang H, Zou X
Writing-review & editing: Huang H, Zou X, Li L
Visualization: Zou X, Xiong W
Supervision: Huang H, Liu Z
Funding acquisition: Huang H, Li L

Availability of data and materials

Not applicable.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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