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Sustainability assessment of mechanical manufacturing systems in the industrial sector

Abstract:

Sustainability assessment is growingly recognized as an effective analytical methodology and management tool useful for managing and improving sustainability performance. In this study, a novel approach of sustainability benchmark assessment is presented to overcome the performance quantification and hierarchization deficiencies of current sustainability assessment methods. A conceptual model demonstrating how sustainability assessment of mechanical manufacturing systems in the industrial sector produces mutually beneficial energy, economy and environment outcomes that serve to reduce energy and cost demand and mitigate environmental challenges is illustrated. Through constructing the sustainability index system encompassing energy, economy and environment perspectives, the energy, economy and environment-oriented assessment models are presented. Furthermore, two concepts concerning sustainability benchmark and sustainability benchmark rating are proposed to benefit the sustainable performance quantification and hierarchization of mechanical manufacturing systems. This method based on sustainability benchmark assessment is applied to a small mechanical manufacturing enterprise in China through which users can visualize and identify sustainability performance for different mechanical manufacturing systems. Our approach can offer the negative feedback for users to enhance process management and technical improvement (process optimization) and to reconsider the energy, economic, and environment in new production cycle, enabling sustainability continuous cycle improvement. This study contributes a new theoretical insight for sustainability assessment by offering relational ties with technical and managerial aspects in support of industrial sustainability.

Key words: Sustainability assessment; Benchmark; Industrial sector; Mechanical manufacturing systems; Energy, economy and environment

Highlights:

- Propose a method for sustainability assessment of mechanical manufacturing systems
- Consider energy, economy, and environment of mechanical manufacturing systems
- A case study that demonstrates the practicability of the proposed method
- Facilitate the sustainable performance quantification and hierarchization
- Contributes a new theoretical insight for sustainability assessment

1 Introduction

1.1 Driving forces

In view of natural resource consumption and environmental degradation [1], where significant amounts of carbon emission are resulted, developing sustainability operations is an important part of the national strategy in China [2]. Numerous pathways and narratives have been developed to shed light on how the industrial sector could transform its production systems in line with the aspirational targets of the Paris Agreement and sustainable development goals [3]. Sustainability technologies, as a highly effective technical approach [4], are necessary for driving the production system transformation that is called for developing the industrial sustainability [5].

Industrial sector plays a pivotal role in the national economies of countries all around the world [6]. Yet, the industrial sector consumes a huge amount of natural resource and exert considerable pressure on the environment [7]. Sustainability has become an imperative responsibility for the industrial sector to survive in the contemporary society due to the lack of a sustainability focus of traditional manufacturing practices (i.e. product design, manufacturing/ remanufacturing, and life-cycle management) [8], and regulations imposed by stakeholders and policymakers [9].

Mechanical manufacturing system, as a typical manufacturing system, is a crucial part of product life cycle in industrial sector [10] and refers to the mechanical product manufacturing processes from acquiring resources to manufacturing products. The mechanical manufacturing processes consumes a lot of energy, materials and services at low efficiency [11], generating enormous environmental waste and carbon emission [12]. Therefore, how to efficiently promote sustainability of mechanical manufacturing systems with good economic benefits and services while protecting the environment and avoiding the increase of carbon emission has become an urgent problem [13].

The interest in sustainability in mechanical manufacturing is growing [14]. The sustainability assessment of mechanical manufacturing systems has been receiving remarkable attention as performance improvement actions [15]. Sustainability assessment, as a topical operations management approach, is recognized as an effective analytical methodology and management tool beneficial for sustainability performance [16]. Sustainability assessment is conducive to monitor sustainability indictors (i.e. energy usage, environmental effect, economy and others), understand sustainability levels of mechanical manufacturing systems, provide technology and policy supports for enhancing system sustainability, and hence promote the enterprise sustainable development [17]. For this direction, developing sustainability assessment methods is a promising approach for accelerating energy saving and emission reduction of mechanical manufacturing systems in the industrial sector [18].

1.2 Literature review

To promote sustainability performance of mechanical manufacturing in the industrial sector, sustainability assessment methods such as sustainability research dimensions [15], indictors [19], models and methods [20] have been carried out worldwide with remarkable results achieved. Nevertheless, these existing measures are deficient in evaluating and certifying sustainability performance for the application of specific constraints to energy use in mechanical manufacturing systems. This paper begins with summary and analyses of extant studies, followed by review of their deficiencies to evaluate the value of the sustainability assessment method.

The carbon tax is regarded as a sustainability approach for measuring and evaluating the environmental effects caused by the carbon emission. Plentiful research on carbon tax has been conducted to study the internal mechanism and macro impact on the enterprises [21], yet it is hard to reflect the microcosmic actives such as energy consumption flow and carbon footprint in mechanical manufacturing. European Commission proposed some eco-design and energy efficiency directive to improve the product sustainability [22]. However, this measure aims to offer the product performance results for stakeholders, lacking the ability to reflect the performance of intermediate links so that the measure is unsuitable for sustainability analysis and assessment of mechanical manufacturing systems. International Organisation for Standardization is developing a series of sustainability-oriented energy and environmental standards such as the ISO 14955 series in Tab.1, which deals with the standardization of energy and environmental evaluation and the improvement of machine tools and mechanical manufacturing systems [24]. The ISO 14955 series lacks a metric for evaluating the design of a machine tool considering the efficiency limit (e.g., the technically achievable efficiency) and the interaction of the components on a percentage scale [25].

Tab 1. ISO standards related to sustainability-oriented energy and environmental standards for mechanical manufacturing systems (reconstructed from Yoon et al. [23])

ISO standards	Descriptions
ISO/DIS 14955	Machine tools — Environmental evaluation of machine tools
ISO/DIS 20140	Automation systems and integration — evaluating energy efficiency and other factors of manufacturing systems that influence the environment
ISO/FDIS 22400	Automation systems and integration — key performance indicators (KPIs) for manufacturing operations management

For the sustainability assessment of mechanical manufacturing systems, a large number of scholars also have carried out relevant research and considered resource (i.e. energy, water), economic, environmental, and social performance across their entire product life cycle. For example, enterprises use life cycle assessment to centralize and compare alternatives during mechanical products manufacturing and development, document various performance influence to mechanical manufacturing systems, and provide sound basis for performance monitoring, management and optimization [26]. Energy issues in mechanical manufacturing industry have become a problem that desperately needs to be solved to promote energy-efficient production [27]. As for energy-oriented sustainability assessment, much of studies focus on energy performance assessment models, indicators and methods (as shown in Tab.2). Machine tools, as the major energy-consuming equipment of mechanical manufacturing systems, have multi-component energy features and uncertainty of energy loss per component, resulting in difficulty to evaluate the energy performance [23]. A sustainability assessment index is established for mechanical manufacturing systems which is envisaged to help manufacturers and users to objectively investigate the sustainability performance of machine tools, provide clear and effective information to decision makers, and support the transition towards greener machine tools [28]. A comparative experiment for the four test methods for evaluating machine tools' energy efficiency was carried out [29]. Assessment indicators of energy efficiency in manufacturing systems gradually develop into a system, and indicators are composed of the process energy efficiency indicator, workshop energy efficiency indicator, and other assessment indicator [30]. Energy-oriented sustainability assessment contains three levels step by step, that is, the energy consumption models, energy consumption assessment strategies, and energy consumption assessment index system. Energy consumption model is needed to assess manufacturing energy consumption. Some other factors (e.g., environment, cost and machine damage) which will influence the energy results are not included in the development of energy consumption model.

Tab. 2 Literature review on energy consumption models, indicators, and methods for mechanical manufacturing systems (Specific parameters for models are omitted, see specific literature for details)

Types	**Descriptions**	**Scholars**
Energy efficiency evaluation model based on machine tool components	$E_{total} = E_{spindle} + E_{feed} + E_{tool} + E_{cool} + E_{fix}$	He et al. [31]
	$P_M = P_S + \sum_{i}^{m} P_{x_i} + P_y + \sum_{j}^{n} P_{z_j}$	Jiang et al. [32]
	$\psi = \frac{\sum_{i=1}^{Q_m} \int_0^{t_{Mi}} \frac{-a_{1i} + \sqrt{a_{1i}^2 + 4a_{2i}(P_{in}(t) - P_{ui})}}{2a_{2i}} dt}{\int_0^{t_T} P_{in}(t) dt}$	Liu et al. [33]
Energy consumption model for material removal processes	$SEC = \frac{P_c}{60\mu MRR}$	Draganescu et al. [34]
	$SEC = C_0 + \frac{C_1}{MRR}$	Kara and Li et al. [35]
	$SEC = C_0 \cdot V_c^{\alpha} \cdot f^{\beta} \cdot a_p^{\gamma} \cdot D^{\varphi} + \frac{C_1}{V_c \cdot f \cdot a_P}$	Guo et al. [36]
	$SEC = k + k_1 \frac{n}{MRR} + k_2 \frac{1}{MRR}$	Li et al. [37]
Energy consumption model of mechanical manufacturing systems	$FEnergy = FMEnergy + FTEnergy + FAEnergy$	Tang et al. [38]
	$P_{total} = P_{SO} + P_L + P_{CFS} + P_{SR} + P_{XF} + P_{YF} + P_{ZF} + P_{TS} + P_{TC} + P_C$	Lv et al. [39]
	$E_S = \int_{T_0}^{T_q} P_S(t)$	Weinert et al. [40]
	$\eta_c = \frac{E_a}{E_\varphi} = \frac{\int_{t1}^{t2} P_a(t) dt}{\int_{t1}^{t2} P_\varphi(t) dt} = \frac{P_a(t)}{P_\varphi(t)}$	Zhou et al. [41]

Industrial sector is currently facing great pressure to reduce the overall manufacturing cost in order to sustain the position in hypercompetitive domestic and global market [42]. Economic efficiency is the key driver of mechanical manufacturing systems, and the enterprise regards profitability as the most important factor [43]. Economy-oriented sustainability assessment can identify and measure this standard of manufacturing cost. The life cycle cost (LCC) is an economic assessment method for the life cycle of products, which can estimate the cost of the entire life cycle of products and predict the cost of products [44]. A study attempts to illustrate the reduction of the manufacturing conversion cost by prioritizing and analyzing the cost factors and assessment method, resulting in cost saving, cleaner production, and more sustainable manufacturing processes [45]. Considering importance of economic assessment in flexible manufacturing systems to allow the creation of an optimized level of flexibility, a simulation-based framework for an assessment methodology was studied to promote target-oriented optimization and cost saving more effectively [46]. An assessment approach for energy centric selection of machining conditions based on minimum cost is proposed to investigate the sustainability and energy efficiency of their manufacturing processes [47]. A hybridized assessment framework studying six types of LCA and LCC integration is helpful to improve environmental and economic performance [48]. On basis of analyzing the remanufacturing machining and sustainability, a remanufacturing sustainability evaluation model and evaluation index system based on data collection and emergy is established [49]. An effective multi-criteria decision-making assessment model is presented which help facilitate and guide the selection of restoration technology [50]. The two possible storage strategies for two streams of returns in manufacturing and assessment of the differences between the two strategies in terms of manufacturing costs were performed, promoting the total profit maximization of each strategy [51].

In addition, environmental problems in mechanical manufacturing are topical for discussion with a series of methods and policies of environmental protection by environmental assessment developed. Environment-oriented sustainability assessment can be intuitively expressed and illustrated by quantitative environmental impact indicators, which are obtained by analyzing the data list of products or manufacturing systems with the ability to judge the degree of environmental impact [52]. Environmental assessment of manufacturing systems generally includes (i) fuel consumption, exhaust emission and noise, (ii) air and water pollution, (iii) recycle materials after the manufacturing of non-reusable parts, including solid wastes such as metal products and paper products to deal with, and (iv) producing carbon emission in manufacturing [53]. Additive manufacturing as an emerging technology with suggested potential to decrease environmental impacts in the manufacturing industry is important to assess potential environmental effects of implementation [54]. An adaptive sustainability assessment framework for evaluating cloud-based distributed mechanical manufacturing systems using an integrated sustainability indicator for environmental, economic, and social impacts provides a solution to assess the sustainability performance of cloud-based distributed manufacturing [55]. Considering three sustainability dimensions represented by social, economic, and environmental aspects, a new systematic and comprehensive framework for sustainability assessment of mechanical manufacturing processes that covers the three sustainability dimensions, contributing to the guidelines to select and quantify the relevant indicators, convert the quantified weighted indicators into dimensionless quantities, and rank the alternatives based on the aggregated scores [56].

Considering the impact of multiple factors on sustainability assessment in mechanical manufacturing systems, Zhang proposed a sustainability evaluation method integrating the energy, economic, and environment in remanufacturing systems [15]. This method requires the data of energy, economic and environment and lacks the quantification of sustainability for different systems. Besides, an energy benchmark approach based on TOPSIS method, considering the energy, economic and environment in mechanical manufacturing systems, is proposed to promote the sustainability of mechanical manufacturing [57]. However, this integrated assessment method is incompentent to quantify the sustainability, failing to show the sustainability grade and rating in the mechanical manufacturing systems. In sum, there is a serious lack of research on sustainability assessment of mechanical manufacturing systems from the energy, economic, and environmental perspectives [58]. Objects of sustainability assessment often independently consider the economy and environment, and neglect the energy potential, resulting in the lack of integrated analysis [44]. Mechanical manufacturing systems are an integrated system with various impacts on the nature, society, and environment. Further to the economic measures, the energy and environment aspects are gaining operational importance in mechanical manufacturing. Current methods of sustainability assessment focus on related indicators and models assessment like the simple or independent quantization by energy, economic, and environmental models, rather than synthetically considering the sustainability by some assessment methods or systems. Whether mechanical manufacturing systems satisfy the sustainability criterion is hard for performance quantification and hierarchization merely by corresponding indicators, causing difficulty in promoting sustainable development from energy, economic, and environmental perspectives [58]. Meanwhile, due to variety and variability of mechanical manufacturing performance, such as the complexity of energy-consumption and economic benefits and the multiformity of environmental implications [59], the sustainability assessment method should take a full consideration for these influences and circumstances.

Summarizing the literature review, there are several missing features in sustainability literature of mechanical manufacturing systems in the industrial sector that need to be addressed in combination to solve these problems and goals. Deficiencies of previous studies focus mainly on the following three aspects:

- integrated consideration of energy, economy and environment
- detailed sustainable index system, and
- sustainable performance quantification and hierarchization

1.3 Sustainability analysis from perspectives of energy, economy and environment

It is an important issue for industry development regarding how to reduce energy consumption and production cost and to improve the environmental performance for mechanical manufacturing systems under keeping the production quality. Sustainability analysis that mainly involves the energy, economic, and environmental performance is of significance to perform the sustainability assessment by establishing the sustainability indicators.

Energy performance focuses on the complexity of energy consumption sources, variability of energy consumption, and multi-levels of energy consumption in mechanical manufacturing systems in Fig.1. For the complexity of energy consumption sources, mechanical manufacturing processes involve various energy consumption equipment that include mechanical manufacturing equipment, logistics equipment, and auxiliary equipment, contributing to the complexity of energy-consumption sources [59]. Differences in energy consumption caused by different production plans are ubiquitous because of the variety of manufacturing approaches including the usage of manufacturing equipment (i.e. machine tools) and process parameters. Secondly, energy consumption in mechanical manufacturing processes is variational. Taking the machine tool (as a typical mechanical manufacturing equipment) an example, the power is variational whether for same or different processed object (product) in idling and material removal processes [60]. Variability of energy consumption in mechanical manufacturing processes is caused by the changing of energy consumption in each mechanical manufacturing procedure and the process of each equipment. Moreover, mechanical manufacturing systems is the main body of energy consumption. Manufacturing systems could be a machine tool, a production line, even a production workshop according to the different production tasks and requirements. Machine tool as a smallest mechanical manufacturing system, an independent machine tool can realize some manufacturing tasks for a product or part, which is regarded a machine tool level [28]. Energy consumption of machine tools account for much of the whole mechanical manufacturing systems. A production line comprises some machine tools, logistics equipment and other equipment, and their energy consumption is more complicated. Different production lines, auxiliary equipment (i.e. lighting and ventilation) and waste disposal equipment constitutes a workshop level. Therefore, energy consumption of different levels varies greatly.

Economic benefit in production processes is an important factor about the mechanical manufacturing operations. The smaller economic input, the better the economic benefit. Mechanical manufacturing cost is one of the main economic inputs except the cost of raw materials input. Manufacturing cost can reflect the level of productivity, raw materials, labors and equipment utilization, etc. Choosing a reasonable mechanical manufacturing technology not only improves product quality, but also improves economic and production efficiency. Effective workshop management can coordinate the production, which ensures the maximize benefits of their cost, safety, and other aspects. Besides, composition of manufacturing cost is complicated including the cost of workers, equipment, and auxiliary materials. Each cost could be divided into various and complex costs, rendering measurement of the economic input difficult to execute.

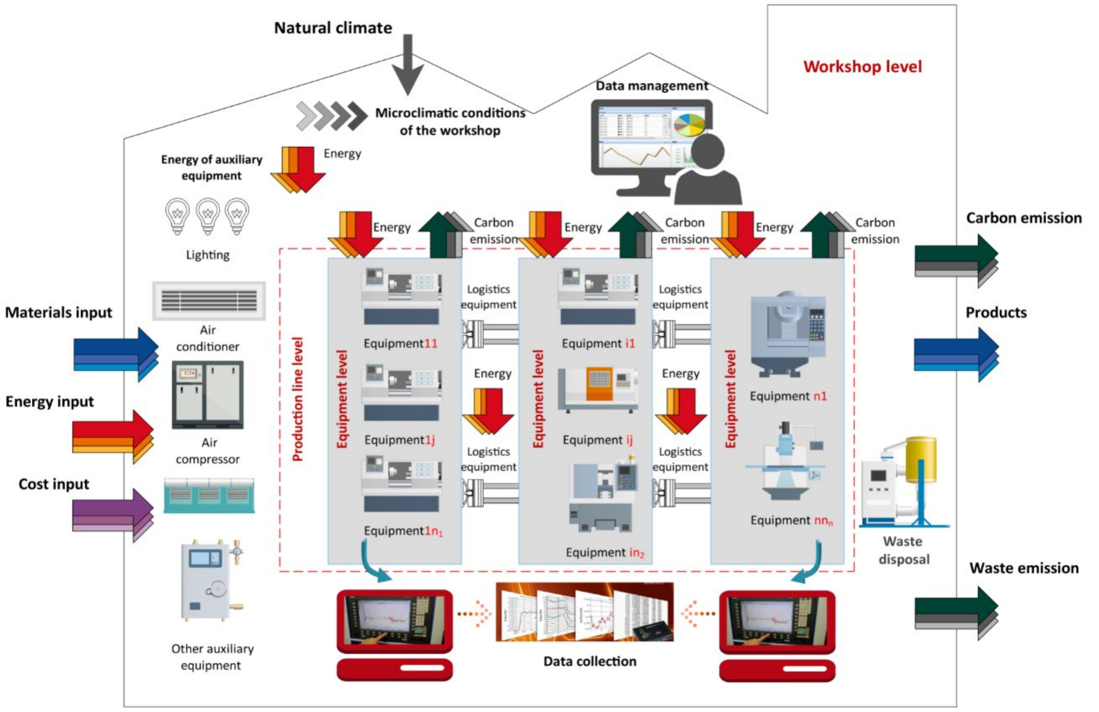

Fig.1 Constitutional complexity and performance of mechanical manufacturing systems from perspectives of energy, economy and environment

Environmental implication mainly focuses on carbon emissions, cutting fluids and waste in mechanical manufacturing processes. The carbon emissions are generated by the consumption of the electricity, the combustion of fuel, the consumption of cutting fluids, and the waste disposal. Most carbon emissions from mechanical manufacturing processes are indirect. For the minimum mechanical manufacturing unit, namely machine tools, the flow of carbon emissions is complicated and changeable. The wastewater produced in mechanical manufacturing processes comes from the cutting fluid. It is necessary to calculate the discharge of the cutting fluid. Destination of the cutting fluid has four whereabouts, some glued to the product, some glued to the chip, some evaporated in the form of gaseous gas after high temperature, the rest can be reused. Moreover, the waste of mechanical manufacturing systems can produce some waste including the broken tools, metal chips, the dust caused by the transmission, workshop broken parts, and the scrapped equipment, resulting in environmental implication to some extent.

1.4 Research gap and contributions

According to the literature review and sustainability analysis, although there are some studies on the sustainability assessment from the perspectives of energy, economy and environment, comprehensive research on energy, economy and environment for mechanical manufacturing systems is seriously lacking the efforts. Even if there are a small number of studies that considers the energy, economy, and environment in mechanical manufacturing systems, there is still a dearth of effective sustainable index systems as well as effective sustainability assessment methods in the form of integrating all indicators and quantifying and hierarchizing sustainability due to the complicated characteristic of mechanical manufacturing systems, as discussed above.

Therefore, in view of these limitations of current studies, an approach of sustainability benchmark assessment (SBA) is presented. This approach is based on sustainability benchmark to execute with the ability to perform sustainable performance quantification and rating by developing the sustainability benchmark system. The SBA, as a new approach for sustainability assessment, can overcome the difficulty in quantifying and delimiting a specific sustainability grade by corresponding performance indicators. This approach is easy to use and visualize the results, which can be adjusted immediately according to changes of mechanical manufacturing systems. The SBA practices conducted by enterprise managers can be helpful for them to enhance the processes management, control and optimization by the sustainability assessment information, which contributes to reducing energy and cost inputs and mitigating environmental pressures. By achieving the above objectives, this research will offer an important reference tool for sustainability or a preference object assessment in other fields.

2 Sustainability benchmark assessment

As mentioned above, current sustainability assessment methods of mechanical manufacturing systems in the industrial sector focus on indexation and model assessment. Whether mechanical manufacturing systems satisfy the sustainability criterion is hard for performance quantification and hierarchization merely by corresponding indicators, causing difficulty in offering technical and decision support of mechanical manufacturing systems. The proposed sustainability benchmark assessment (SBA) depends on the sustainability benchmark, and can perform sustainable performance quantification and hierarchization by developing the sustainability benchmark system.

Sustainable development of mechanical manufacturing enterprises has become a significant national sustainability strategy. Mechanical manufacturing systems, as an important part of the enterprise operations, are necessary for improving the sustainability to meet the government and market requirements and to enhance the competitiveness of enterprises. Considering that energy, economy, and environment for mechanical manufacturing systems can promote its sustainable development, processes management and optimization of such systems at these three aspects through the sustainability assessment in product manufacturing processes need more attention. Towards this direction, assessing the sustainable level of enterprises manufacturing systems by quantification and hierarchization and producing synergies of energy-economy-environment with the closed loop effect of the SBA can contribute to sustainability of the system in Fig.2. The proposed SBA not only offers an effective approach for assessing sustainability of mechanical manufacturing systems in the industrial sector but also serves in technical support for designing policies related to sustainability development of the industry.

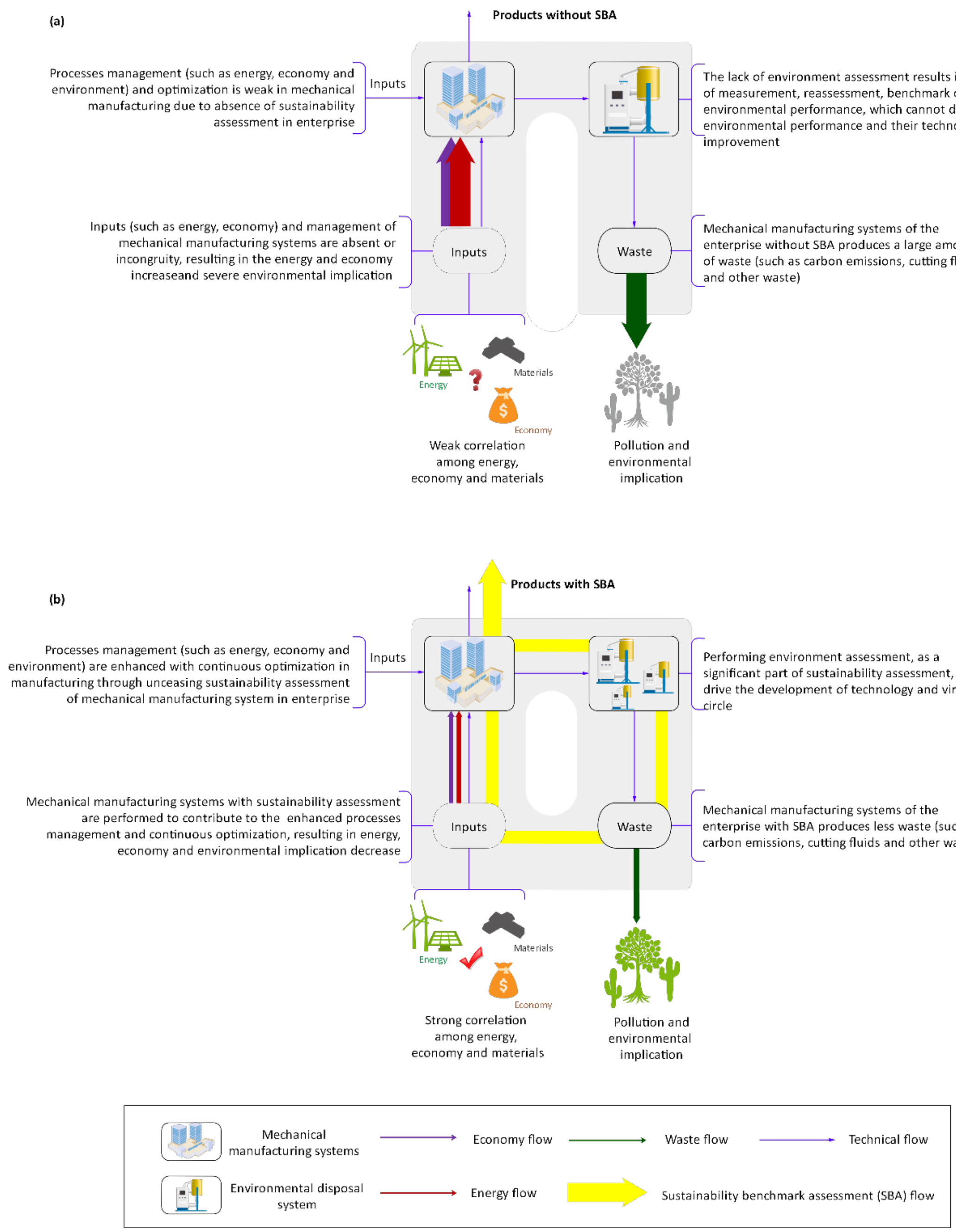

Fig.2 Conceptual model demonstrating how sustainability assessment (SBA) of mechanical manufacturing systems in the industrial sector produces mutually beneficial energy, economy, and environment outcomes that serve to reduce energy and cost demand and mitigate environmental challenges. **a**, Without SBA, products manufacturing life-cycle without complete consideration of energy-economy-environment synergies causes the weakness of processes management and control in mechanical manufacturing, resulting in the energy and cost increase and the environmental implication. **b**, By contrast, products manufacturing life-cycle with SBA could enhance processes management, control and optimization of mechanical manufacturing processes considering energy-economy-environment synergies, and produces mutually beneficial energy, economy and environment outcomes, which continuously promotes the sustainable development of the industrial sector.

3 Materials and methods

3.1 Scope and boundary

The goal of this study is to perform the sustainability assessment of mechanical manufacturing systems in the industrial sector. The functional unit (assessed object) considered is the mechanical manufacturing systems. The proposed sustainability assessment method is applicable to mechanical manufacturing system such as mechanical manufacturing workshop, production lines with multiple equipment (i.e. machine tools), even a single machine tool. About the system boundary, the sustainability assessment cycle is, in principle, a cradle-to-grave exercise [61]. For studied mechanical manufacturing systems, the approach can only be gate-to-gate, and the whole gate-to-gate process within the system boundary comprises all the mechanical manufacturing processes from the inputs (i.e. energy, materials) to the outputs (i.e. mechanical products). Therefore, for the sustainability assessment of mechanical manufacturing systems, the assessed period for the sustainability assessment of mechanical manufacturing systems could be a required production time cycle (i.e. one month, two months, half a year, or one year) and a required production task cycle that is a batch of products to be produced, and the production time cycle and production task cycle is abbreviated as the production cycle.

3.2 Sustainability indicators

To perform a quantitative analysis of the sustainability for mechanical manufacturing systems, a sustainability index framework is proposed involving three kinds of independent indicators (i.e. energy performance indicators, economic performance indicators, and environment performance indicators) and an integrated sustainability indicator. Each kind of independent indicators comprises multiple sub-indicators in Tab.3.

Tab.3 Sustainability indicators and actions

Classification	Performance indicators	Symbols	Descriptions and actions
Energy performance indicators	Energy consumption of unit product	E_{UP}	Involving energy consumption of the whole mechanical manufacturing processes in the workshop without containing energy consumption of the logistics system and workshop manufacturing environment system.
	Energy consumption of workshop logistics systems	E_{LS}	Involving energy consumption of all logistics systems within the production cycle.
	Energy consumption of workshop manufacturing environment	E_{ME}	Involving the energy consumption of air conditioner, fan, lighting equipment that provides necessary manufacturing services in the workshop manufacturing environment.
	Total energy consumption of production workshop	E_{PW}	Comprising the E_{UP}, $E_{LS}$and E_{ME} within the given production cycle, which can understand actual production requirements.
	Comprehensive energy consumption	E_{CEC}	Energy demand of unit output within the given production cycle.
Economic performance indicators	Total manufacturing cost of mechanical products	C_{TMC}	Manufacturing cost includes manufacturing equipment cost, worker cost, cost of auxiliary materials.
	Manufacturing cost of unit mechanical product	C_{UP}	
	Manufacturing cost of workshop logistics systems	C_{WLS}	The cost of energy consumption in operation is variational along with production task, therefore, the total cost of energy consumption in operation is regarded as the manufacturing cost of workshop logistics systems during the production cycle.
	Manufacturing cost of workshop manufacturing environment	C_{ME}	Standing for total cost of energy consumption for all workshop equipment in operation.
	Total manufacturing cost of production workshop	C_{PW}	The sum of the manufacturing cost of the product, workshop logistics systems and workshop manufacturing environment during the production cycle.
	Comprehensive manufacturing cost	C_{CMC}	An average cost for unit production cycle can estimate the economic input and analyzes the economic benefit.
Environment performance indicators	Cutting fluid emission of production workshop	CF	Usage of total cutting fluid emission in production workshop.
	Waste emission of production workshop	WA	Including the waste water, solid waste and scrap and their impact on environment.

Classification	Performance indicators	Symbols	Descriptions and actions
	Carbon emission of production workshop	CE	Caused by the energy consumption in mechanical manufacturing, the consumption of cutting fluid and reprocessing and waste processing directly or indirectly.
Integrated sustainability indicators	Integrated emergy	EM	An integrated sustainability indicator that considers the energy, economic and environment performance with the production cycle.

3.3 Data and models

Data and models that have energy, economy, and environment-oriented data and models are the basis of analyzing and evaluating the sustainability of mechanical manufacturing systems, and these data should be collected in advances. These sustainability performance indicators analyzed with data are characterized with some differences among different enterprises, even at different times of same enterprise according to their production task and demand.

3.3.1Energy-oriented data and models

Energy performance indicators include the energy consumption of unit product, energy consumption of workshop logistics systems, energy consumption of workshop manufacturing environment, total energy consumption of production workshop, and comprehensive energy consumption. Energy consumption of unit mechanical product involves energy consumption of the whole mechanical manufacturing processes in the workshop without containing energy consumption of the logistics and workshop manufacturing environment system. Energy consumption of unit mechanical product can reflect the actual energy demand for each kind of mechanical products, enabling the accounting of production energy. The data can be acquired by the energy monitoring or management system, as shown in Fig.1. Besides, energy consumption of unit product is also determined using the existing energy models based on production information [29].

$$E_{UP} = \sum_{i=1}^{n} K_i(\mathbf{y})$$

$$\mathbf{y} = F(\mathbf{x}) = U(\mathbf{x})$$

Where E_{UP} is energy consumption of unit product. n is number of manufacturing processes. $\mathbf{x} = (x_1, x_2, \dots, x_m)$ is m-dimensional real vectors, which influence the factors that represent the manufacturing process (e.g. types of the manufacturing equipment, number of manufacturing equipment, manufacturing parameters). $\mathbf{y} = (y, y_2, \dots, y_n)$ are n-dimensional real vectors that represent the energy consumption. $\mathbf{y} = F(\mathbf{x})$ is energy consumption model of manufacturing systems to be evaluated. $U(\mathbf{x}) = F(\mathbf{x})$ is the composite function. $K(.)$ is the function of calculated energy consumption.

The logistics system as an important component of workshop production systems consumes a great amount of energy (electricity). Energy consumption of workshop logistics system involves energy consumption of all logistics systems within the production cycle, and it is the sum of energy consumption of logistics systems E_{LS}. The data can be collected through information management of workshop logistics system. Energy consumption of workshop manufacturing environment involves the energy consumption of air conditioner, fan, lighting equipment that provides necessary manufacturing services. Similarly, E_{ME} is the sum of energy consumption of workshop manufacturing environment within the production cycle. Therefore, the total energy consumption of production workshop within the given production cycle in mechanical manufacturing could be calculated and analyzed:

$$E_{PW} = E_{UW} + E_{LS} + E_{ME}$$

Where, the E_{PW}, E_{UW}, E_{LS} and E_{ME} are total energy consumption of production workshop, energy consumption of unit product, energy consumption of workshop logistics systems, energy consumption of workshop manufacturing environment during the production cycle, respectively. The E_{UW} is energy consumption sum of all kinds of product manufactured during the production cycle.

The comprehensive energy consumption that is energy demand of unit output (unit mechanical product) could be acquired through above basic data, which can analyze and predict the energy consumption of the production workshop and evaluate the energy efficiency during the production cycle.

$$E_{CEC} = \frac{E_{PW}}{\gamma(t)}$$

Where, $\gamma(t)$ is the function of production time or production task during the production cycle

3.3.2 Economy-oriented data and models

Economic performance indexes include manufacturing cost of the product, manufacturing cost of workshop logistics systems, manufacturing cost of workshop manufacturing environment, total manufacturing cost of production workshop and comprehensive manufacturing cost.

Manufacturing cost includes manufacturing equipment cost, worker cost, cost of auxiliary materials. Usually, there are n kinds of mechanical product that need to be manufactured during the production cycle. Therefore, the manufacturingg cost of the mechanical product C_W is sum of all kinds of cost of the product. For manufacturing a batch of the same product during the production cycle, their data can be collected and counted from the enterprise information. Besides, the manufacturing cost of the product includes (i) the total manufacturing cost of the product C_{TMC} and manufacturing cost of unit product C_{UP}, which estimates the economic input and analyzes the economic benefit.

$$C_P = \sum_{i}^{N} C_{TMC\_i} = \sum_{i}^{N} \sum_{j}^{M} C_{UP\_i} \cdot Q_j$$

Where, C_P is the manufacturing cost of product during the production cycle; N, M and Q are the kind of mechanical products, number of same product and product number.

Constituting cost of logistics systems is complicated covering investment cost, cost of energy consumption in operations, and maintenance cost. To simplify the cost analyses of logistics systems, the investment cost as one-time input and maintenance cost that is small should be excluded for consideration in this study. The cost of energy consumption in operations is variational along with production task, therefore, the total cost of energy consumption in operations is regarded as the manufacturing cost of workshop logistics systems C_{WLS} during the production cycle. Similarly, the manufacturing cost of workshop manufacturing environment $C_{WME}$is mainly cost of energy consumption for all workshop equipment in operations. The cost can be calculated based on their energy consumption. Therefore, the total manufacturing cost of production workshop C_{PW} is the sum of the manufacturing cost of the mechanical product, workshop logistics systems, and workshop manufacturing environment during the production cycle. The comprehensive manufacturing cost C_{CMC} could be acquired through above basic data, which can analyze and predict the manufacturing cost of the production workshop during the production cycle.

$$C_{CMC} = \frac{C_{PW}}{\gamma(t)} = \frac{C_W + C_{LS} + C_{ME}}{\gamma(t)}$$

3.3.3 Environment-oriented data and models

Environment performance indexes include cutting fluid emission, waste emission, and carbon emission of production workshop. The data of collecting performance indexes is of great significance concerning how to reduce carbon emission, environmental pollution, and environment pressure and provide data support for enterprise sustainable development.

Reasonable use of cutting fluid can improve the quality of the mechanical product and prolong the tool life. According to the above analysis of cutting fluid flow, the cutting fluid except the part which circles back to the cutting fluid system is discharged into the environment causing environmental pollution. The cutting fluid emission could be calculated through the data of cutting fluid and emission factor υ during the production cycle.

$$CF = \upsilon Q_{total}$$

Where, CF is total cutting fluid emission of production workshop, Q_{total} is usage of cutting fluid.

The cutting fluid emission includes the waste water, solid waste and scrap, and their impact on environment. Waste emission is very complex, and these data could be collected according to enterprise's requirements.

Carbon emission, caused by the energy consumption in mechanical manufacturing, the consumption of cutting fluid and reprocessing and waste processing directly or indirectly, could be described according to basic data during the production cycle.

$$CE = \mu_1 E_{PW} + \mu_2 Q_{total} + \mu_3 WA_{total}$$

Where, CE is total carbon emission of production workshop, WA_{total} quantity of waste. μ_1, μ_2, μ_3 are respectively carbon emission factor of energy consumption, cutting fluid, and waste.

3.4 Sustainability assessment

3.4.1 Sustainability integrated model

Emergy theory is effective method to analyze the sustainability of the system with wide application. Emergy conversion rate is an important concept in the emergy theory, and emergy method can make different properties and different sources of energy and materials into a uniform standard to value, usually into solar emergy [58]. The basic expression is:

$$EM = \sum_{i=1}^{n} EM_i = \sum_{i=1}^{n} (T_i \times B_i)$$

EM is the solar emergy. T_i is the emergy conversion rate of different substances. B_i represents input stream of different units.

In view of the dimensions of the energy, economic, and environment of mechanical manufacturing in the industrial sector, a sustainability integrated model, as a unified measurement, was built on the basis of emergy theory to accurately measure the energy consumption, economic input, and environment emission. Establishing the sustainability integrated model lays a foundation for the sustainability assessment of the industrial sector. Therefore, the emergy of energy, economic, and environment in manufacturing can be calculated through above data during the production cycle.

$$EM_{energy} = T_E \cdot E_{PW}$$

$$EM_{economic} = T_C \cdot C_{PW}$$

$$EM_{environment} = T_{CF} \cdot CF + T_{WA} \cdot WA + T_{CE} \cdot CE$$

Where, EM_{energy}, $EM_{economic}$ and $EM_{environment}$ are emergy during the production cycle, respectively. T_E, T_C, T_{CF}, T_{WA} and T_{CE} are the emergy conversion rate of energy, cost, cutting fluid emission, waste emission, and carbon emission, respectively.

According to data of various emergy, the integrated emergy can be acquired.

$$EM_I = \omega_1 \cdot EM_{energy} + \omega_2 \cdot EM_{economic} + \omega_2 \cdot EM_{environment}$$

Where, EM_I is the integrated emergy, ω_1, ω_2 and ω_3 are sustainability assessment coefficient for the energy, economic, and environment. Generally, $\omega_1 = \omega_2 = \omega_3 = 1$, ω_i is different in particular circumstances. Differences in sustainability assessment coefficient represent the weight difference. Acquiring sustainability assessment coefficient (ω_1, ω_2 and ω_3) is simple but imprecise, and they are exceedingly dependent on the high expertise for decision-makers

3.4.2 Sustainability benchmark

Developing the sustainability benchmark is very significant to evaluate the sustainability of the mechanical manufacturing systems. At the same production cycle, given that there are n kinds of production scenarios, the integrated emergy are EM_{I_1}, EM_{I_2}, EM_{I_3}, $\cdots$, EM_{I_n}, respectively. Although the production condition that includes production object, production task, production environment have some differences and variations in same workshop at same production cycle, the production cycle (i.e. one month, quarter) is enough and could reflect the production energy consumption, economic input, and environment emission. Taking the EM_{I_1}, EM_{I_2}, EM_{I_3}, $\cdots$, EM_{I_n} as the sample, the alternative sustainability benchmarks are:

$$\overline{EM^{(b)}} = \frac{1}{n}\sum_{i=1}^{n} EM_{I\_i}$$

$$EM^{(b)}_{median} = g(EM_{I\_1}, EM_{I\_2}, \dots, EM_{I\_n})$$

$$EM^{(b)}_{60\%} = f_{60\%}(EM_{I\_1}, EM_{I\_2}, \dots, EM_{I\_n})$$

$$EM^{(b)}_{70\%} = f_{70\%}(EM_{I\_1}, EM_{I\_2}, \dots, EM_{I\_n})$$

$$EM^{(b)}_{mode} = h(EM_{I\_1}, EM_{I\_2}, \dots, EM_{I\_n})$$

$\overline{EM^{(b)}}$ is the average emergy benchmark of the sample. $EM^{(b)}_{median}$ is median emergy benchmark of the sample. $EM^{(b)}_{60\%}$ and $EM^{(b)}_{70\%}$ are emergy benchmark at 60% and 70% respectively of the sample in order from small to large. $EM^{(b)}_{mode}$ is mode emergy benchmark of the sample. The smaller this benchmark, the higher the production responsibility. In other words, the energy consumption, economic input, and environment emission are relatively small. Therefore, determining the sustainability benchmark needs to consider the enterprise and production level and popularity. The sustainability benchmark is:

$$EM^{(b)} \in \{\overline{EM^{(b)}},\ EM^{(b)}_{median},\ EM^{(b)}_{60\%}, EM^{(b)}_{70\%}, EM^{(b)}_{mode}, EM^{(b)}_{Other}\}$$

3.4.3 Sustainability benchmark rate

To establish a sustainability rating system, a new concept of sustainability benchmark rate (SBR) is proposed that can reflect their relationship between emergy of mechanical manufacturing systems and the emergy benchmark. The SBR identifies the actual emergy hierarchization of mechanical manufacturing systems during the production cycle. The SBR with different circumstances can be calculated using the following equation. For example, when the emergy of the mechanical manufacturing system is same in comparison with the sustainability benchmark, the SBR is calculated as 1.0. When the mechanical manufacturing system produces less emergy, the SBR is <1.0. When the mechanical manufacturing system produces more emergy, the SBR is >1.0.

$$\mathrm{SBR} = \frac{EM_x}{EM^{(b)}}$$

EM_x is the actual emergy of mechanical manufacturing systems at the production cycle. $EM^{(b)}$ is the sustainability benchmark of mechanical manufacturing systems.

3.4.4 Sustainability rating system

The SBR calculated by the sustainability benchmark of the mechanical manufacturing system is integrated to the sustainability rating system and represented by a grade. The sustainability rating system of mechanical manufacturing systems in the industrial sector employs several grades. Establishment of sustainability rating system includes determining the range of sustainability grade, modeling the sustainability grade and acquiring the sustainability grade.

Determining the range of sustainability grade depends on the SBR in various scenarios.

$$l = \frac{SBR_{max} - \overline{SBR_O}}{SBR_{max}} = \frac{EM_{max} - \overline{EM_O}}{EM_{max}}$$

Where, l is range of sustainability grade, SBR_{max} and $\overline{SBR_O}$ are maximal sustainability benchmark rate under the specific manufacturing system and average value of optimal sustainability benchmark rate under optimal mechanical manufacturing systems, respectively. EM_{max} and $\overline{EM_O}$ are the maximal emergy under specific mechanical manufacturing system and average value of optimal emergy under optimal mechanical manufacturing systems, respectively.

On basis of the range of sustainability grade, modeling the sustainability grade differ from the conventional grading that is equal distribution for grade. The method for grading is based on the sustainability grade and related parameters.

$$\Delta = \frac{l}{N-2}$$

$$l_0 = (1 - l)$$

$$R_1 \in (0, l_0)$$

$$R_2 \in [l_0, l_0 + \Delta)$$

$$R_3 \in [l_0 + \Delta, l_0 + 2\Delta)$$

$$\cdots$$

$$R_{N-1} \in [l_0 + (N-1)\Delta, 1)$$

$$R_N \in [1, \infty)$$

Δ is the range of unit grade. N is the number of sustainability levels. ，R_1、R_2、R_3、$R_{N-1}$and R_N are the range of different sustainability levels, in Fig.3. The R_1 level is optimal accordingly to establish the sustainability level. In this level, workshop always produces lowest emergy and have the best sustainability level. R_2 to R_N workshop’s emergy of the workshop increases in turn that the sustainability ability in turn reduce.

Through calculating the sustainable indicators and emergy indicators, sustainability of a new or required evaluated manufacturing system could be evaluated and given as a quantized grade based on determining the range of sustainability grade and modeling the sustainability grade.

4 Results

4.1 Case background

To perform a practice through the SBA method, a small mechanical manufacturing enterprise, as an object of analysis, is mainly engaged in the production of mechanical parts. In the studied small mechanical manufacturing enterprise, a gear manufacturing workshop as the application of sustainability assessment is selected. The gear manufacturing workshop comprises some hobbing machines including CNC gear hobbing machines (the studied type is YKS3120) and high-speed dry cutting CNC gear hobbing machines (the studied type is YE3120CNC7). Each hobbing machine could be viewed as a minimum cell manufacturing system. Each manufacturing system (hobbing machine: YKS3120 and YE3120CNC7) involves different technological parameters with different spindle speed (YKS3120: 130, 160, 200, 250 and 330rpm, and YE3120CNC7: 640, 680, 720, 760 and 800 rpm) under the same Feed (2.4 mm/r). For the gear production, a batch of gear in these hobbing machine as the study period is selected. For the convenience of performing a practice of the proposed SBA method, some production tasks need to be assumed. Given that each hobbing machine serves to same amount of the gear that the number is 100, therefore, sustainability of each manufacturing system (i.e. each hobbing machine) could be analyzed and quantized with the sustainability grade, and the manufacturing system is the most sustainable that can be highlighted in the gear workshop.

The YKS3120 is wet-cutting CNC hobbing machine with cutting fluid, however, the YE3120CNC7 is dry-cutting CNC hobbing machine which do not need to use cutting fluid. The manufactured gear is 45 steel with numbers of gear teeth (36), modulus (2 mm), pressure angle (20°), helix angle (20°), and full depth (4.5 mm).

4.2 Results

To simplify unnecessary computational steps for all mechanical manufacturing systems, a representative is introduced. For comprehensive energy consumption of the gear, gear manufacturing processes do not involve in the workshop logistics system, and the energy consumption of workshop manufacturing environment is small which can be ignored. Therefore, the comprehensive energy consumption of studied gears is mainly the manufacturing energy consumption. Taking YKS3120 for example, the comprehensive energy consumption per unit gear (E_{cec}) is determined via data collection and energy calculation. In this case, the energy is the electric energy, and its data depends on the energy calculation through processing information in terms of previous studies. Therefore, the E_{cec_YKS3120} is $0.3180\ \mathrm{kWh}$ under the process parameters of the spindle speed 130 (rpm) and feed 2.4 (mm/r).

Likewise, the cost of the workshop logistics system and workshop manufacturing environment is small and can be ignored because the gear is produced in a small batch. Therefore, manufacturing cost of unit gear could be counted. Investigations and analysis show that manufacturing cost of estimating the machine tool YKS3120 (C_{e_YKS3120}) and YE3120CNC7 ($C_{e\_\mathrm{YE3120CNC7}}$) is 200 and 250 CNY/h, respectively. According to the local wage standard and the comprehensive benefit of the enterprise, the labor cost of workshop workers (C_{labor}) is 16.2 CNY. Through collecting manufacturing time (T_m) in each hob machine in Tab.2, take YKS3120 which under the process parameters of spindle speed 130 (rpm) and feed 2.4 (mm/r) as an example, the equipment cost, labor cost and its total manufacturing cost per unit gear can be determined.

$$C_m = C_{e\_\mathrm{YKS3120}} \times T_m = 17.04\ \mathrm{CNY}$$

$$C_l = C_{labor} \times T_m = 1.38\ \mathrm{CNY}$$

$$C_{mc} = C_m + C_l = 18.42\ \mathrm{CNY}$$

Where, C_m is the equipment cost per gear, C_{e_YKS3120} is 200 CNY/h, T_m is manufacturing time, and C_{mc} is the total manufacturing cost per unit gear. Therefore, the comprehensive energy consumption per unit gear, equipment cost, labor cost and its total manufacturing cost per unit gear is acquired with the same method, as shown in Tab. 4.

Tab. 4 Energy consumption and cost under the different parameters

Machine tool	Spindle speed (r/min)	E_{CEC} (kWh)	T_m (s)	C_m (CNY)	C_l (CNY)	C_{mc} (CNY)
YKS3120	130	0.3180	306.8	17.04	1.38	18.42
	160	0.3070	243.7	13.54	1.10	14.64
	200	0.2539	199.9	11.11	0.90	12.01
	250	0.2265	175.8	9.77	0.79	10.56
	330	0.2007	152.5	8.47	0.69	9.16
YE3120CNC7	640	0.0450	25.9	1.80	0.12	1.92
	680	0.0433	24.3	1.69	0.11	1.80
	720	0.0406	22.1	1.53	0.10	1.63
	760	0.0402	21.3	1.48	0.10	1.58
	800	0.0401	20.5	1.42	0.09	1.51

For the environment aspect, the direct effect of cutting fluid can be neglected because of the small changes in the recycling process of the cutting fluid, very little cutting fluid discharged to the outside environment, and the less waste production. It is necessary to obtain the amount of cutting fluid used per unit gear because the calculation of the carbon emission depends on the electric energy consumed and the cutting fluid used. In this case, the amount of cutting fluid used can be calculated according to the flow rate per unit time in mechanical manufacturing. The flow rate of cutting fluid (q_0) is 5.44L/min for the YKS3120, However, the YE3120CNC7 belong to dry-cutting without usage of cutting fluid in this case. The amount of cutting fluid used has been counted in Tab.4. According to carbon emission factor of electric energy ($\mu_1 = 0.349\text{kgCO2/kWh}$) and the carbon emission factor of cutting fluid ($\mu_2 = 0.2\text{kgCO2/L}$), the carbon emission per gear is counted. Likewise, take YKS3120 which under the process parameters of spindle speed 130 (rpm) and feed 2.4 (mm/r) as an example, carbon emission per gear is as follows. Likewise, the amount of cutting fluid used and carbon emission per gear under different parameters can be obtained by using the same method, in Tab.5.

$$Q_{cf\_\text{YKS3120}} = q_0 \cdot T_m = 27.8\text{L}$$

$$CE_{\text{YKS3120}} = \mu_1 E_{CEC\_\text{YKS3120}} + \mu_2 Q_{cf\_\text{YKS3120}} = 5.67\text{kg}$$

Where, Q_{cf_YKS3120} is amount of cutting fluid used for YKS3120 under the process parameters of spindle speed 130 (rpm) and feed 2.4 (mm/r), and CE_{YKS3120} is carbon emission per gear.

Tab.5 Cutting fluid used and carbon emission under the different parameters

Machine tool	Spindle speed (r/min)	Amount of cutting fluid used (L)	Carbon emissions (kg)
YKS3120	130	27.8	5.67
	160	22.1	4.53
	200	18.1	3.71
	250	15.9	3.27
	330	13.8	2.84
YE3120CNC7	640	-	0.02
	680	-	0.02
	720	-	0.01
	760	-	0.01
	800	-	0.01

For comprehensive emergy per gear, cutting fluid has less effect on the sustainable development because it is recycling so that it is negligible. Therefore, the comprehensive emergy per gear (EM_{ce})in this case comprises the emergy of electric energy consumed in manufacturing, emergy of the manufacturing cost, and emergy of carbon emission generated. Through data acquisition of energy, economic and environment, the total emergy of a batch of gear in each manufacturing system (i.e. hob machine) could be determined. Take YKS3120 which under the process parameters of spindle speed 130 (rpm) and feed 2.4 (mm/r) as an example, the comprehensive emergy per gear EM_{ce} is as follows.

$$EM_{cec} = UEV_{EE} \times E_{cec} = 2.78 \times 10^5 \times 0.318 \times 3.6 \times 10^6 = 3.18 \times 10^{11}\text{sej}$$

$$EM_{cm} = UEV_{EL} \times C_{mc} = 8.61 \times 10^{11} \times 18.42 = 1.59 \times 10^{13}\text{sej}$$

$$EM_{CE} = UEV_{CE} \times CE = 7.24 \times 10^8 \times 5.67429 \times 10^3 = 4.11 \times 10^{12}\text{sej}$$

$$EM_{ce} = \omega_1 \cdot EM_{cec} + \omega_1 \cdot EM_{cm} + \omega_1 \cdot EM_{CE} = 2.03 \times 10^{13}\text{sej}$$

Where, EM_{cec} is emergy of electric energy consumed in manufacturing, namely comprehensive emergy per gear, UEV_{EE} is transformity of electric energy and 2.78×10^5 sej/J, EM_{cm} is the emergy of the manufacturing cost, UEV_{EL} is the transformity of services (i.e. the equipment and labor) and the transformity of the equipment and labor both are 8.61×10^{11}sej/CNY, EM_{CE} is emergy of the carbon emission generated, UEV_{CE} is transformity of the carbon emission and is 7.24×10^8 sej/g , EM_{ce} is comprehensive emergy per gear. ω_1, ω_2 and ω_3 are sustainability assessment coefficient for the energy, economic and environment. In this case, $\omega_1 = \omega_2 = \omega_3 = 1$, in term of the particular circumstances.

According the above analysis, the amount of the batch of gear is 100 for each hob machine, so the total emergy EM_{total} for the manufacturing system YKS3120 which under the process parameters of spindle speed 130 (rpm) and feed 2.4 (mm/r) can be determined as $EM_{total} = 2.03 \times 10^{15}$sej. In the same way, the total emergy of other manufacturing systems that are the YKS3120 and YE3120CNC7 under different process parameters can be determined as follows in Tab.6.

Tab.6 Emergy of mechanical manufacturing systems under the different parameters（unit: sej）

NO. of mechanical manufacturing systems	Object	Process parameters		EM_{total} (sej)
		Spindle speed (rpm)	feed (mm/r)	
1	YKS3120	130	2.4	2.03E+15
2		160		1.62E+15
3		200		1.33E+15
4		250		1.17E+15
5		330		1.01E+15
6	YE3120CNC7	640		1.71E+14
7		680		1.60E+14
8		720		1.46E+14
9		760		1.41E+14
10		800		1.36E+14

5 Discussion and implications

5.1 Discussion

To perform the sustainability assessment for each manufacturing process, it is necessary to establish a sustainability benchmark. On basis of determining the total emergy of each mechanical manufacturing system, the descriptive statistics results for alternatives of sustainability benchmark are in Tab.7. Alternatives at 60% and 70% of the sample in order from small to large, and for median and mode emergy benchmark are inapplicable due to the small sample size in the case. Therefore, the average emergy benchmark of the sample $\overline{EM^{(b)}}$ is regarded as sustainability benchmark for these mechanical manufacturing systems, and $\overline{EM^{(b)}}$ is $7.91\text{E} + 14$ sej . In the real application, the enlarging of sample size, the alternatives are more scientific and reasonable.

Tab.7 Descriptive statistics results for alternatives

Type	Number (sej)
Average	7.91E+14
Maximum	2.03E+15
Minimum	1.36E+14
Range	1.89E+15

On basis of determining the all alternatives, the SBR_{max} and $\overline{SBR_O}$ that are maximal sustainability benchmark rate under the specific mechanical manufacturing system and average value of optimal sustainability benchmark rate under optimal mechanical manufacturing systems, can be determined. In the case, the $\overline{EM_O}$ is 1.36E+14. Therefore, SBR_{max} and $\overline{SBR_O}$ are:

$$SBR_{max} = \frac{EM_{max}}{\overline{EM^{(b)}}} = \frac{2.03\text{E} + 15}{7.91\text{E} + 14} = 2.57$$

$$\overline{SBR_O} = \frac{\overline{EM_O}}{\overline{EM^{(b)}}} = \frac{1.36\text{E} + 14}{7.91\text{E} + 14} = 0.17$$

Moreover, to develop the sustainability rating system, the range of sustainability grade l depends on the SBR.

$$l = \frac{SBR_{max} - \overline{SBR_O}}{SBR_{max}} = \frac{2.57 - 0.17}{2.57} = 0.93$$

For the analyzed mechanical manufacturing systems in the industrial sector, a level-5 assessment system I established and the N is five. The grading is based on the sustainability grade using the equations in section 3.4.4. All parameters related to sustainability rating system are $\Delta = \frac{l}{N-2} = 0.31$, $l_0 = (1 - l) = 0.07$, $R_1 \in (0, 0.07)$, $R_2 \in [0.07{,}0.38)$, $R_3 \in [0.38{,}0.69)$, $R_4 \in [0.69{,}1.00)$ and $R_5 \in [1, \infty)$. Therefore, the sustainability rating system could be developed. Representation of the sustainability rating system is diverse, its basic information mainly includes the level and range, and the Fig. 3 is two kinds of typical representations.

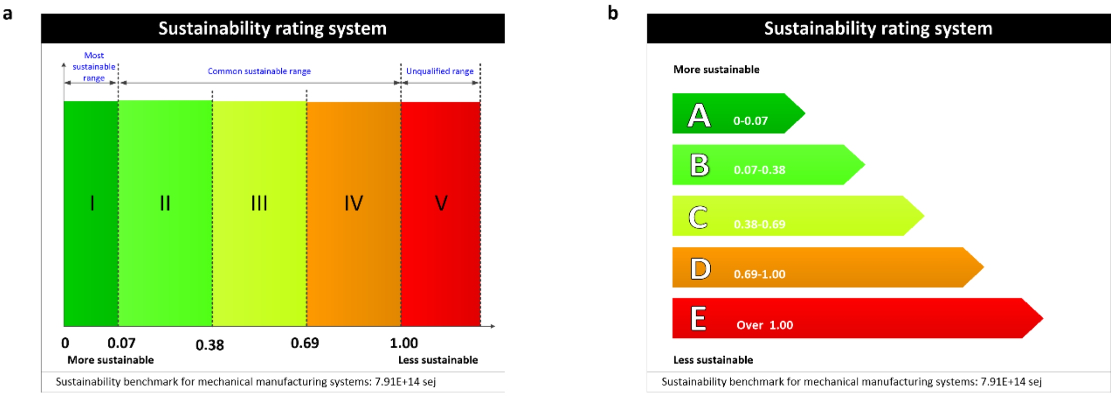

Fig.3 Two kinds of typical representations for the sustainability rating system

Through developing the above sustainability rating system, the sustainability of any mechanical manufacturing system can be assessed by calculating its sustainability benchmark rate. For example, two mechanical manufacturing systems that are NO. 4 and 7 mechanical manufacturing systems in Tab.7 can be assessed, and their sustainability benchmark rates are $SBR_4 = 1.48$ and $SBR_7 = 0.20$. Their sustainability using representations in Fig.3 (b) the are as shown in Fig.4. The Fig.4 indicates that the sustainability grade of the NO. 4 and 7 mechanical manufacturing systems are 'Leve B' and 'Level E', respectively. Differences of sustainability grades for the mechanical manufacturing systems are related to the hob machine and processes parameters. Therefore, the sustainability for using the high-speed dry cutting CNC gear hobbing machine (YE3120CNC7) is more excellent compared with CNC gear hobbing machines (YKS3120). Results of sustainability assessment are beneficial to the negative feedback of enhancing process management and technical improvement (process optimization), and to reconsider the energy, economic and environment in new production cycle, which makes sustainability continuous cycle improvement.

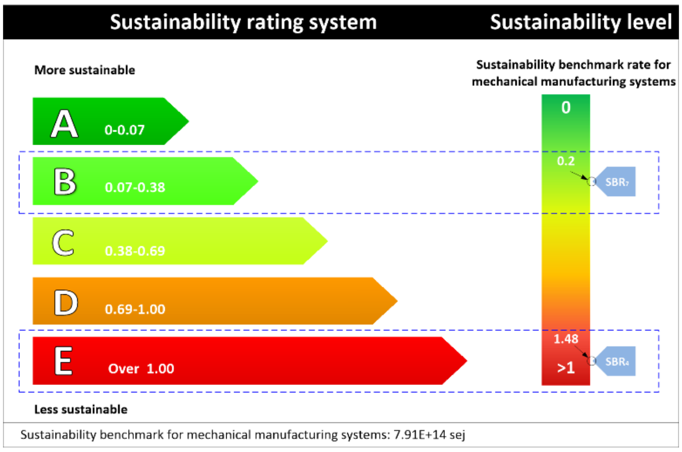

Fig.4 sustainability assessment for the NO. 4 and 7 mechanical manufacturing systems

Moreover, the proposed sustainability assessment method is the other mechanical manufacturing systems that are comprised of the production lines or manufacturing workshops. The assessed period for the sustainability assessment of manufacturing systems also could be a required production cycle (i.e. one month, two months, half a year or one year) and a required production task cycle that is a batch of products to be produced. This case is to illustrate the processes of the proposed method, but the data that includes the production task, mechanical manufacturing systems and involved other energy-economic-environment data makes sustainability benchmark highly discrete because of the limitation of the sample size in above application case. However, in real production, the assessment method is more stable during the extension of production time. Therefore, the production lines or manufacturing workshops could be graded by a stable sustainability rating system whether it is the production cycle or production task.

5.2 Practical implications analysis

Through the discussion, the proposed sustainability assessment method could perform performance quantification and hierarchization with sustainability benchmark system and visualization. Whether mechanical manufacturing systems satisfy the sustainability criterion? It is easy to do so through identifying their sustainability level by performance quantification and hierarchization and the assessment results will offer technical and decision support.

To improve the synergies of the energy-economic-environment and promote sustainability of enterprises, the following measures should be taken: (i) Institution of energy-economic-environment restraint and supervision should be seriously considered due to the massive energy consumption, economic input and environmental output for manufacturing systems, and a sustainability assessment benchmark, as an important measure, should be established. (ii) When the sustainability level of the manufacturing system is inferior to the benchmark, the workshop or enterprise should be subjected to financial and administrative penalty in terms of the extent beyond the benchmark. (iii) The sustainability awareness of all staff from perspectives of energy, economic and environment should be enhanced by regular examination training to avoid the needless energy and economic input and overmuch environmental implications. (iv) Incentive schemes should be implemented for enterprises that meet the sustainability benchmark to encourage them to reduce the energy conservation and emission reduction.

Moreover, there are also some challenges in the real applications including the data acquisition and sustainability updates. Data acquisition is difficult tackle due to the overwhelming quantity and variety of data. Improving the mechanical manufacturing technology, introducing advanced manufacturing equipment, and implementing excellent sustainability management approaches are useful ways to promote the sustainability level of the previous mechanical manufacturing systems. How to respond effectively to these measures in real time and auto update the sustainability level is an important challenge in real applications.

Therefore, in the next step, further studies will be explored from two aspects. On the one hand, data acquisition for establishing more fundamental energy, economic, and environment databases for mechanical manufacturing systems will be implemented continuously. On the other hand, the auto update method for sustainability level in random environment will be studied. Overcoming these challenges will be beneficial for the industry to save energy and reduce emissions of mechanical manufacturing systems and accelerate the industrial sustainable development.

6 Conclusions

Sustainability assessment, as a highly effective technical approach, are necessary for driving the mechanical manufacturing systems transformation that is called for the enterprise sustainability. In our work, to overcome the deficiencies of current sustainability assessment methods, an approach of Sustainability Benchmark Assessment (SBA) is presented, which contributes to not only providing an effective approach for improving the sustainability of mechanical manufacturing systems in the industrial sector but also to offering technical support for designing policies related to the sustainability.

Firstly, sustainability assessment methods related to mechanical manufacturing systems were analysed. An approach of sustainability benchmark assessment is presented, and this proposed SBA depends on the sustainability benchmark and can perform sustainable performance quantification and rating by developing the sustainability benchmark system. In this study, the sustainable level of mechanical manufacturing systems is quantified and graded, and producing synergies of energy-economic-environment with the closed loop effect of the SBA contributes to sustainability of the system.

Secondly, the sustainability performance of mechanical manufacturing systems in the industrial sector was analyzed from perspectives of energy, economic, and environment. The methodology of the proposed SBA considering energy, economic and environment for manufacturing systems was proposed. The proposed SBA comprised three steps: the construction of sustainable indicators, the acquisition of data and models, and the implement of sustainability assessment. Moreover, a sustainability integrated model that normalizes all sustainable indicators was presented. To quantify and to give a specific sustainability grade for manufacturing systems, the concept of the sustainability benchmark and sustainability benchmark rating were illustrated. The sustainability benchmark rating system was developed through its rating, which offers substantial help for the sustainability comparisons and demarcations.

Finally, the SBA was applied to a small mechanical manufacturing enterprise, China, indicating that the proposed SBA had the practicability of performing the sustainability assessment in manufacturing systems and can be beneficial to the negative feedback of enhancing process management and technical improvement (process optimization), and to reconsider the energy, economic, and environment in new production cycle, which makes sustainability continuous cycle improvement. This study contributes a new theoretical insight for sustainability assessment to offer relational ties with technical and managerial aspects in support of the industrial sustainability.

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