Data-driven sustainability evaluation of machining system: a case study

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Abstract
Improving resource efficiency and reducing waste discharge are the inevitable trends of the development of sustainable machining system. Therefore, a data-driven sustainability evaluation method of machining system is proposed. The input (energy, materials, equipment, R&D, and services) and output (wastes and products) data of machining system are collected. These dimensional data are processed by emergy. The emergy flow calculation model of the machining process is established for data modeling, and the sustainability evaluation index of machining system is constructed for data analysis. Finally, an engine base machining process is taken as a case study for innovative practice, and the targeted process optimization is adopted based on its sustainability evaluation for innovative practice. The feasibility and effectiveness of the method are verified. This study provides theoretical and methodological support for promoting the sustainability of the manufacturing industry.

Keywords Data-driven · Machining process · Sustainability · Evaluation

1 Introduction
Machinery manufacturing is one of the pillars of human wealth creation. However, its manufacturing process consumes a large amount of resources and generates a lot of waste, which is one of the main causes of the current serious global environmental [1]. The machining system is a volumetric manufacturing system, and globally the energy consumed by machine tools in machining accounts for up to 75% of the energy consumption of the manufacturing industry [2], but the energy efficiency of the machining process is low, with an average energy efficiency of less than 30% [3]. Resource consumption and environmental issues in the manufacturing industry have attracted widespread attention [4]. How to improve the sustainability as much as possible is an urgent problem for the current manufacturing industry [5, 6]. Sustainable machining has attracted the interest of many experts and scholars. Various measures and methods are adopted to improve the sustainability of machining system. For example, sustainable application possibilities for process optimization in machining using vegetable oil-based nanofluids are highlighted by Wickramasinghe [7]. A novel intelligent reasoning system to estimate energy consumption and optimize cutting parameters toward sustainable machining is presented by Xu [8]. Adaptability of AlTiN-based coated tools with green cutting technologies in sustainable machining is studied by Lai [9]. In grinding operation, sustainable application of grinding wheel waste as abrasive for abrasive water jet machining process is studied by Sabarinathan [10]. In the unconventional machining processes, sustainability considering impact factors and reduction methods of energy consumption is analyzed by Zheng [11]. The Environmental Performance Index reveals a strong possibility of the industrial application of nanofluids in machining with the sustainability-based performance evaluation [12]. Regarding sustainable green cutting technology, clean cutting of titanium alloy is implemented by nano additive-assisted minimum quantity lubrication technique [13]. Machinability under different processing conditions in sustainable manufacturing is studied and compared by Venkatesan [14]. A micro electrochemical machining sustainability assessment framework based on five dimensions of sustainability is established to justify its use and initial investment.
cost [15]. Energy-efficient machining is an effective way of sustainable production in current manufacturing industry [16]. Sustainable machining also has a development in unconventional machining systems [17]. Modeling and optimization of temperature and surface roughness in the milling of AISI D2 steel is studied for sustainable machining [18]. A novel energy model of machine-operator systems to assess the energy efficiency of machining processes is established for sustainable machining [19]. A method to improve the productivity and precision of titanium alloy parts is proposed for promoting sustainable ultra-precision manufacturing [20]. Economical and environmentally friendly methods to improve the machinability of titanium and its alloys have been proposed by Gupta [21]. These studies show that process, cost, and environmental benefits of sustainable machining are the focus of attention [22, 23]. They have promoted the development and application of sustainable machining and achieved good results.

The resource consumption of machining manufacturing system is huge, which has great potential to be further explored. The research on the evaluation of machining system oriented to sustainability is of great significance. Machining process is a complex system, involving energy, logistics, research and development (R&D), services, equipment, and waste. It is necessary to evaluate the sustainability of the whole machining system based on the unified measurement of these factors. The application of energy theory in manufacturing enterprises [24, 25] and production systems [26] has been used for reference, and good results have been achieved. A method to evaluate the machining system is proposed and applied to the engine base machining workshop. The innovation of this study is that the relationship among energy flow, logistics, and service in the system is directly displayed through energy calculation, and the evaluation index system constructed can more accurately and truly reflect the problems existing in the machining system, which makes the optimization of sustainability targeted and feasible. It provides theoretical and methodological support for the green transformation and upgrading of machining system.

In order to reach the research objectives of this paper, the research framework is as follows. Section 2 is the method, which mainly introduces framework, energy measurement model, and sustainability evaluation indexes of the machining system. Section 3 is a case study on the engine base machining system to verify the validity and feasibility of the method, and Section 4 is the conclusion.

2 Method

2.1 Framework

This paper builds a data-driven method to measure and evaluate the sustainability of machining system. Its framework is as follows:

(i) Data collection is mainly the input and output of the machining system; data processing uses energy to measure energy, materials, equipment, R&D, services, wastes, and products.
(ii) Data modeling is to establish an energy flow calculation model of the machining process.
(iii) Data analysis is based on the sustainability evaluation index of machining system.
(iv) Innovative practice puts forward a targeted process optimization based on its sustainability evaluation.

The method can provide support for the evaluation and optimization of sustainability for machining system, as well as support for the sustainable development of enterprises. The method framework is as follows (Fig 1):

2.2 Data collection

The input of industrial production system involves energy, materials, equipment, R&D, and services, and the output includes waste (waste water, waste gas, waste liquid, and solid waste) and products.

According to the energy processing requirements and the input-output classification of machining system, data collection is implemented by the accounting and statistical standards. In order to facilitate calculation and evaluation, it collects the data of machining system on an annual basis. In order to reduce the uncertainty of the system, we average these data to every working day. Collection measures mainly include literature review, collection and sorting of production data, production log, dispatch list, sample collection and analysis, consultation and questionnaire of skilled workers, and data benchmarking of the same industry.

2.3 Emergy measure model

The emergy theory was first created in the 1980s by Odum [27], a famous American ecologist. It is a new ecological economic value theory and systems analysis method. The emergy is the amount of some effective energy that is used directly and indirectly in the production of a product or service. It is basically expressed by converting all the different forms of energy in the biosphere into a solar value using a uniform scale [28]. Since different resources, products, or services have different energy values, the emergy conversion rate is used to express the energy value of different categories of energy in an energy hierarchy.

The basic expression of energy analysis is as follows:

\[ EM = UEV_j \times N \]
EM is emergy. UEV is the emergy conversion of different substances. N is different units of matter.

Emergy is able to quantitatively measure many types of resources, energy, products, waste, and money into a single unit. It can be calculated to obtain the emergy of different inputs and outputs of machining system, so that the same unit of emergy is used to compare and evaluate.

Based on the investigation and analysis of the machining system, the energy, production materials, services, and waste data of the machining processes are collected, and the emergy measure model of the machining system is constructed.

(1) Emergy of production energy

The main energy source of machining system is electric, some of which are coal (heating), diesel (power), hydrogen (cutting), and so on.

\[ E_n = \sum_{i=1}^{n} [N_i \times UEV(N_i)] \]

\( E_n \) is the emergy of production energy in machining system. \( N_i \) is the \( i \)-th energy used in machining system. \( n \) is the total number of types of energy used in the machining system.

(2) Emergy of production materials

Production materials of machining system mainly include steel, alloys, cutting fluids, cleaning oil, and water.

\[ E_m = \sum_{j=1}^{m} [M_i \times UEV(M_i)] \]

\( E_m \) is the emergy of production materials in machining system. \( M_i \) is the \( i \)-th material used in machining system. \( m \) is the total number of types of materials.

(3) Emergy of equipment

It mainly includes equipment, fixture, depreciation cost, repair and maintenance cost, and other equipments required by the system.

\[ E_e = \sum_{i=1}^{e} [E_i \times UEV(E_i)] \]

\( E_e \) is the emergy of equipment in machining system. \( E_i \) is the \( i \)-th equipment used in machining system. \( e \) is the total number of types of equipment.

(4) Emergy of R&D (Research and Development)

R&D mainly includes resources used for process development and improvement.

\[ E_r = \sum_{i=1}^{r} [R_i \times UEV(R_i)] \]

\( E_r \) is the emergy of R&D in machining system. \( R_i \) is the \( i \)-th resources used for process development and improvement in machining system. \( r \) is the total number of types of resources used for R&D.

(5) Emergy of production services
Production services mainly include human resources, production management, plant infrastructure, and technology in machining system, which are consumed by all services to maintain the operation of machining system.

\[ E_s = \sum_{i=1}^{s} [S_i \times \text{UEV}(S_i)] \]

\( E_s \) is the emergy of production services in machining system. \( S_i \) is the \( i \)-th resources used for production services in machining system. \( s \) is the total number of types of resources used for production services.

(6) Emergy of waste

The wastes are mainly waste water, waste gas, and waste residue produced in machining system.

\[ E_w = \sum_{i=1}^{w} [W_i \times \text{UEV}(W_i)] \]

\( E_w \) is the emergy of waste. \( W_i \) is the \( i \)-th waste in machining system. \( w \) is the total number of types of waste.

The emergy measurement model of machining system transforms various types of energy, materials, equipment, R & D, services, and waste into emergy quantitative measurement, which provides theoretical support for the evaluation and optimization of the sustainability of machining manufacturing system.

### 2.4 Sustainability evaluation indexes of machining system

It needs to clarify the emergy flow relationship of machining manufacturing system before building the emergy index of machining system. The internal structure of machining system mainly includes equipment, R & D, and service, while energy and materials are the input to the system. Some of them are renewable resources and some are non-renewable resources.

(1) Net emergy yield ratio (NEYR)

Net emergy yield ratio (NEYR) is the ratio between the emergy consumed in the operation of machining system and the economic feedback emergy. Its formula is as follows:

\[ \text{NEYR} = \frac{(E_y - E_w)}{(E_n + E_m + E_h + E_m + E_e + E_r)} \]

NEYR is used to measure the production efficiency of a machining system. It can measure the net contribution of the machining system to economic activities and the energy utilization efficiency. When a certain economic emergy is obtained, the higher the value of the output emergy produced, the higher the production efficiency of the system. The competitiveness of the economic activity of a system with a high NEYR value is the basic condition for sustainable development of the machining system.

(2) Emergy yield ratio (EYR)

EYR refers to the ratio of the emergy of system output to the emergy of input. The higher its value indicates the higher productivity of the system. The more favorable it is for the development of the system. In the case of a machining system, which is different from an ecosystem, the emergy of the output of the system consists mainly of products and waste, while the emergy of input includes energy and materials. EYR of the machining system is as follows:

\[ \text{EYR} = \frac{(E_y - E_w)}{(E_n + E_m)} \]

\( E_y \) is the product emergy of the machining system.

EYR is used to measure the emergy production and utilization efficiency of the machining system. The contribution of the system to the whole social and economic production activities and the utilization rate of resources can also be well measured and reflected through this indicator. This index can measure the competitiveness of system economic activities and the sustainable development index of products. The higher the value is, the stronger the competitiveness of system economic activities and the higher the sustainable development index is, which is suitable for long-term sustainable development, and vice versa.

(3) Environmental load rate (ELR)

ELR is the ratio of non-renewable resources input to renewable resources input to reflect the comparison between environmental pressure brought by the system and local environmental carrying capacity. In consideration of the discharge of some wastes in machining system, these wastes will inevitably cause pressure on the surrounding environment. The calculation formula of ELR is obtained as follows:

\[ \text{ELR} = \frac{(N + F + E_w)}{R} \]

\( R \) is the input of local renewable resources, \( N \) is the input of local nonrenewable resources, and \( F \) is the input of purchased resources.

The higher the ELR, the greater the pressure of the system on the surrounding environment. This indicator is the most direct indicator of the relationship between the system and the natural environment.

(4) Emergy index of sustainability (ESI)

SEI of the system is the ratio of emergy output rate and system environmental load rate. Calculation formula is as follows:

\[ \text{SEI} = \]
ESI = EYR/ELR

This indicator combines social, economic, and ecological aspects to obtain a high-performance composite evaluation indicator. The higher the value of the system’s sustainability index, the more sustainable the system is.

3 Case study

3.1 Engine base machining system

The engine base machining system in a certain enterprise is taken as the research object in this paper. This engine base belongs to mass production. The personnel, equipment, materials, methods, and environment of the machining process are stable and standardized. It includes the casting, normalizing, rough processing, finishing, inspection, and warehousing of rough castings. The specific steps are as follows (Fig. 2):

The machining process of the engine base is a typical system, which is representative and exemplary. We use its machining system for emergy calculation, sustainability evaluation, and process optimization, and provide a new theory and method for the sustainable improvement of the mechanical manufacturing system.

3.2 Emergy accounting of machining system

The emergy calculation of the machining system of engine base mainly includes energy, materials, services, equipment, and waste. The emergy system diagram is shown in Figure 3:

The data of machining workshop of engine base is collected with the help of enterprise managers and front-line employees. The emergy flow in the machining system is shown in Tables 1 and 2.

3.3 Sustainability evaluation of machining system

The emergy flow of machining system includes energy, material, R&D, equipment, service, and waste. Energy is transmitted in the form of energy flow. Materials and subsidiary materials flow are transmitted in the form of material flow. R&D, equipment, and services flow are transmitted in the form of money flows. Waste flows into and interacts with the ecological environment. According to Table 1, the emergy flow in the machining system of the machine base is shown in Table 3.
According to the above emergy calculation data, the calculation results of emergy evaluation index of engine base machining system are shown in Table 4.

The production efficiency of engine base machining system is very low from the perspective of NEYR, and its economic competitiveness is weak. NEYR is only 1.12. Generally speaking, the production efficiency of this machining system needs to be improved. From the perspective of energy flow, production materials and services account for a large proportion, indicating that the system is high input and low return. Its technology and R&D investment are low. It does not belong to the high-tech system.

If EYR is less than 2, it indicates that the system operation is not a sustainable production and development process, and the emergy of products is not increased due to production activities, but a process of consumption or transformation. The EYR of this machining system is 2.42. This shows that the capacity of sustainable development is weak and needs to be improved.

Table 1  Emergy data collection table of engine base machining system

| Collection object | Unit     | Emergy conversion rate (sej/unit) | Reference | Collection date | Emergy (sej) |
|-------------------|----------|-----------------------------------|-----------|----------------|--------------|
| Renewable resources |          |                                   |           |                |              |
| 1. Solar energy   | J        | 1                                 | [27]      | 1.68E+05       | 1.68E+05     |
| 2. Wind energy    | J        | 1.90E+03                          | [27]      | 9.34E+01       | 1.77E+05     |
| 3. Rainwater potential energy | J | 3.54E+04                          | [27]      | 3.87E+01       | 1.37E+06     |
| 4. Rainwater chemical energy | J | 2.31E+04                          | [27]      | 8.60E+00       | 1.99E+05     |
| 5. Geothermal energy | J       | 4.37E+04                          | [27]      | 3.97E+01       | 1.73E+06     |
| 6. Water          | g        | 2.18E+04                          | [27]      | 6.96E+06       | 1.52E+11     |
| Purchasing emergy (F) |          |                                   |           |                |              |
| 7. Sand mixing machine | CNY   | 8.61E+11                          | [25]      | 1.13E+03       | 9.74E+14     |
| 8. Spade          | CNY      | 8.61E+11                          | [25]      | 1.17E+01       | 1.01E+13     |
| 9. Metal mold     | CNY      | 8.61E+11                          | [25]      | 2.48E+01       | 2.13E+13     |
| 10. Coated sand   | CNY      | 8.61E+11                          | [25]      | 5.21E+00       | 4.49E+12     |
| 11. Molding machine | CNY   | 8.61E+11                          | [25]      | 6.89E+02       | 5.93E+14     |
| 12. Sandbox       | CNY      | 8.61E+11                          | [25]      | 3.31E+02       | 2.85E+14     |
| 13. Electric furnace | CNY | 8.61E+11                          | [24]      | 1.45E+02       | 1.25E+14     |
| 14. Iron          | g        | 2.00E+10                          | [24]      | 6.21E+05       | 1.24E+16     |
| 15. Aluminum      | g        | 5.40E+09                          | [24]      | 3.19E+05       | 1.73E+15     |
| 16. Steel scrap   | g        | 1.96E+10                          | [24]      | 4.48E+03       | 8.79E+13     |
| 17. Sandblasting machine | CNY | 8.61E+11                          | [24]      | 3.06E+02       | 2.64E+14     |
| 18. Grinding wheel | CNY     | 8.61E+11                          | [24]      | 5.87E+01       | 5.05E+13     |
| 19. Cutter        | CNY      | 8.61E+11                          | [24]      | 1.04E+03       | 8.96E+14     |
| Normalizing process |          |                                   |           |                |              |
| 20. Normalizing furnace | CNY   | 8.61E+11                          | [25]      | 5.29E+02       | 4.55E+14     |
| 21. Smelting furnace | CNY   | 8.61E+11                          | [25]      | 4.41E+02       | 3.80E+14     |
| Roughing and finishing process |          |                                   |           |                |              |
| 22. CK6140 CNC lathe | CNY | 8.61E+11                          | [24]      | 4.98E+02       | 4.29E+14     |
| 23. Special machine tool | CNY | 8.61E+11                          | [24]      | 2.19E+02       | 1.88E+14     |
| 24. Z3050 radial drilling machine | CNY | 8.61E+11                          | [24]      | 4.30E+02       | 3.70E+14     |
| 25. Coolant       | CNY      | 8.61E+11                          | [24]      | 1.43E+01       | 1.23E+13     |
| 26. Cutting fluid | CNY      | 8.61E+11                          | [24]      | 2.28E+01       | 1.96E+13     |
| 27. Cleaning fluid | CNY     | 8.61E+11                          | [24]      | 1.14E+01       | 9.81E+12     |
| 28. Clamps        | CNY      | 8.61E+11                          | [25]      | 1.77E+01       | 1.52E+13     |
| Inspection process |          |                                   |           |                |              |
| 29. CCD detector  | CNY      | 8.61E+11                          | [25]      | 5.00E+01       | 4.31E+13     |
| 30. Quality inspection machine | CNY | 8.61E+11                          | [25]      | 2.30E+01       | 1.98E+13     |
ELR of this machining system is 1.59E+05, which shows that a large number of nonrenewable resources are consumed in local areas (machining workshops), and the environmental pressure of this machining system is very large.

ESI of this machining system is 1.52E-05, which indicates that the machining system is not sustainable and must be improved by new processes and methods.

Based on the above evaluation, the sustainability of the engine base machining system is very weak, the environmental pressure is large, and the production efficiency is low. In the long run, this kind of processing technology needs to be improved or replaced, and clean production and green lean manufacturing need to be strengthened.

### 3.4 Targeted process optimization

Process optimization of engine base machining system for sustainability is determined by the above emergy evaluation indexes. In order to improve the sustainable development capability of this machining system, the following process optimization measures are taken.

1. **Optimization of casting process**

   Because the original process used closed pouring, it resulted in the unstable filling of molten steel and the problem that the waste liquid could not be recycled. When the closed pouring is changed to the open pouring, the flow of molten steel becomes more stable. The whole stamping process is...
much simpler than before, and the defect rate is greatly reduced. The liquid steel is filled from several different positions at the bottom of the casting. It greatly reduces the punching time and avoids the influence of oxide generated in a long time on the quality. For the ecological environment, the molten steel can be recycled by flow under the pouring mode. This greatly reduces the emission of waste, especially waste liquid in the casting process, which is both economic and environmental protection. After optimization, the yield is increased by 6.1%, the riser cost of single casting is reduced by 3 CNY, the coating cost of single casting is reduced by 40 CNY, the amount of waste liquid is reduced by 3000 g/d, and the production efficiency is increased by 8.7%.

(2) Optimization of finishing process

We can find that the emergy of the waste in the machining system is 3.03e + 15 in Table 1, which is 5.5% of the product benefit. This has a great impact on NEYR and EYR of the machining system, and directly reduces the system’s ESI.

The main reason is that the proportion of cutting waste liquid and cooling waste liquid in the total waste liquid is relatively large, which leads to the increase of emergy waste rate of the system.

In order to further improve the ecological benefits, the waste discharge is needed to improve. Through the introduction of two new processing technologies, dry processing and low-temperature-balanced cold air precision cutting, zero discharge of cutting and cooling waste liquid is realized. This optimization measure is worth taking from the perspective of emergy value, which saves emergy of 1.02e+15/d.

(3) Reduced waste emissions

The waste gas from machining is collected by pipes and collecting covers. The waste gas is introduced into the low temperature plasma waste gas treatment equipment. The exhaust gas is ionized into various electrons and ions under the action of high voltage in the equipment, which has high energy and is easy to react with surrounding oxygen to generate water and carbon dioxide. At this time, the emission of waste gas is obviously controlled, and the emergy of waste is effectively reduced by 9.90E+14/d.

We have taken a series of optimization measures. NEYR increased from 1.12 to 1.65. EYR increased from 2.42 to 2.67. The production efficiency of engine base machining system is increased by 13.40%. This shows that the utilization efficiency of the input emergy of the machining system is greatly improved. After optimization, the economic benefits are obviously improved. In the aspect of environment, it optimizes the material emergy of casting process and the emergy of processing process, and reduces the amount of waste. ELR decreased from 1.59e + 05 to 1.53E + 05, and the pressure of engine base machining system on the environment decreased significantly. In the aspect of sustainable development, with the increase of EYR and the decrease of ELR, ESI increased from 1.52e-05 to 1.74e-05, and its increase range is 14.2%. After optimization, the sustainable development index has a significant increase (Fig 4).

3.5 Discussion

Some similar literature [17, 21, 29] were compared. We find that the research has the following advantages:

The data-driven sustainability evaluation of sustainable machining system can clearly represent the flow characteristics of machining system by data-driven. It analyzes the internal characteristics of machining system from the energy perspective,
which is different from the economic perspective. It can provide new decision-making ideas of manager from data-driven.

Secondly, the sustainability evaluation index system of machining system comprehensively considers the economic, social, and environmental benefits. It reveals the internal mechanism of the sustainability of machining manufacturing system. This provides a clear path for the sustainable development of machining system.

Thirdly, sustainable manufacturing system is the inevitable trend of future development. It is an urgent need to measure, evaluate, and optimize the machining system from the perspective of sustainable development in the process of green transformation and upgrading of manufacturing industry.

It is an urgent need for improving the ecological benefits of manufacturing enterprises to win the market and customers [30], avoid administrative punishment from the government, and improve the positive image of enterprises. This is the key to enhance the sustainability of the manufacturing system. This kind of optimization decision is exactly what the manufacturing enterprises are trying to find.

4 Conclusion

Sustainable manufacturing system is to integrate environmental values and social responsibility into the enterprise value system, which is the embodiment of sustainable development of human society in the modern manufacturing industry.

Data-driven is applied to evaluate sustainability of machining system in this paper. Its main innovations are as follows: based on the data collection of the input and output of machining system, the energy, production materials, services, and waste of the machining system are analyzed by the perspective of emergy, which solves the problem of different units of measurement. The evaluation index system is established for data modeling, which includes NEYR, EYR, ELR, and ESI. Through data analysis and evaluation of the machining system of engine base, the optimization measure of casting process, optimization of finishing process, and reducing waste emissions are taken. Its effect is obvious, waste discharge is reduced, production efficiency is improved, environmental load rate is reduced, and sustainable development capacity is enhanced.

This study has a good reference for the green transformation and upgrading of manufacturing enterprises, and can provide effective solutions for decision makers. The data-driven based on emergy evaluation theory to the whole process of mechanical production will further be applied. This is significant for the development of sustainable manufacturing.

Author contribution Cuixia Zhang and Cui Wang contributed to the conception of the study; Conghu Liu and Guang Zhu performed the experiment; Conghu Liu and Wenyi Li contributed significantly to the analysis and manuscript preparation; Cuixia Zhang and Cui Wang performed the data analyses and wrote the manuscript; Mengdi Gao and Wenyi Li helped perform the analysis with constructive discussions.
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Data availability All data generated or analyzed during this study are included in this published article.

Declarations

Consent to participate Written informed consent for publication was obtained from all participants.

Consent for publication All the authors agree to publish this paper in The International Journal of Advanced Manufacturing Technology.

Conflict of interest The authors declare no competing interests.

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