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Emergy-based evaluation and improvement for sustainable manufacturing systems considering resource efficiency and environment performance

Conghu Liu[a,c], Wei Cai[b,*], Shun Jia[d], Mingyu Zhang[a], Huanyin Guo[a], Luoke Hu[e], Zhigang Jiang[f]

[a] School of Mechanical and Electronic Engineering, Suzhou University, Suzhou 234000, China
[b] College of Engineering and Technology, Southwest University, Chongqing 400715, China
[c] Antai College of Economics and Management, Shanghai Jiao Tong University, Shanghai 200030, China
[d] Department of Industrial Engineering, Shandong University of Science and Technology, Qingdao 266590, China
[e] Institute of Industrial Engineering, School of Mechanical Engineering, Zhejiang University, Hangzhou 310027, China
[f] Hubei Key Laboratory of Mechanical Transmission and Manufacturing Engineering, Wuhan University of Science & Technology, Wuhan 430081, China

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ABSTRACT

Sustainable manufacturing, regarded as resource efficient, environment-friendly and customer satisfaction production, is major driving force for sustainable development. With growing demand for decoupling between resources and world economic development, accelerating sustainable manufacturing has become an important strategy. Therefore, a novel method based on emergy theory is proposed to perform the comprehensive evaluation and improvement of manufacturing systems. Firstly, drivers and challenges are analyzed, and the boundary and connotation of manufacturing systems are defined. Then, an emergy-based calculation model of the energy, material, service and waste is presented considering the variety and dimension of the input and output of manufacturing systems. The model expresses the mechanism of the transfer, coupling and conversion of the emergy for manufacturing systems. Besides, some indicator systems are established including functional emergy indicators, structural emergy indicators, eco-efficiency emergy indicators and sustainability indicators of manufacturing systems. The inner link between the economic, environment and social benefits of manufacturing systems is revealed through these indicators. On this basis, an improvement benchmarking card is developed to achieve the excellent quality, high efficiency, energy reduction, resource saving and environmental protection of manufacturing systems. Finally, a case study illustrates the practicability of the proposed method, and results show that the proposed method provides theoretical support for evaluating and improving the sustainability of manufacturing systems to coordinate the resources and development of the manufacturing industry.

1. Introduction

Manufacturing is a pillar industry for creating human wealth and important embodiment of the national economy and overall national strength of a country [1]. However, the manufacturing industry creates products and services for human demands in the transformation of manufacturing resource for the production process [2]. The manufacturing industry consumes a lot of limited energy, materials and services in low energy efficiency and resource conversion rate [3], which results in a lot of waste and causes serious damage to the environment [4]. Therefore, promoting the energy, resources and service efficiency and improving the environmental performance as much as possible are a major problem to be solved [5], contributing to realizing the sustainable development of the manufacturing industry [6]. At present, manufacturing planning in a number of countries, such as US "Advanced Manufacturing National Program (AMNP)", German "Industrie 4.0" plan, French plan "la nouvelle France industrielle" and the UK Foresight publications on the "Future of Manufacturing", and "Made in China 2025", are steadily implementing [7]. The rapid realization of the transformation of the sustainable manufacturing paradigm has been the common choice for many countries to seize the commanding strategic point in the international manufacturing competition [8]. As a result, the research of sustainable manufacturing has aroused extensive interest, which is becoming a hot field of interdisciplinary research [9].

Many research institutions in the world have been set up for sustainable manufacturing, for example: Consortium on Green Design and Manufacturing (CGDM) in University of California at Berkeley [10], design and manufacturing Collège International pour la Recherche en Productique (CIRP) [11], Environmentally Conscious Design & Manufacturing (ECDM) in University of Windsor [12], Center for industrial

* Corresponding author.
E-mail address: weicai@swu.edu.cn (W. Cai).

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Nomenclature

Em	the value of solar energy
UEV_i	the emergy transformity of different substances
N	the input stream of different units (including quality, energy, money, etc.)
Em_{en}	the energy-emergy of the manufacturing systems
$Em_{en}{}^{j}$	energy-emergy of the j-th subsystem of the manufacturing systems
$\overline{En}_{\overline{p}}^{j}$	the $\overline{p}$-th renewable energy of the j-th subsystem
$UEV(\overline{En}_{\overline{p}})$	the emergy transformity of $\overline{En}_{\overline{p}}$
En_{p}^{j}	the p-th no-renewable energy of the j-th subsystem
$UEV(En_{p}^{j})$	the emergy transformity of En_{p}^{j}
Em_{ma}	the material-emergy of the manufacturing systems
$Em_{ma}{}^{j}$	the material-emergy of the j-th subsystem of the manufacturing systems
$\overline{Ma}_{\overline{q}}^{j}$	the $\overline{q}$-th renewable material of the j-th subsystem
$UEV(\overline{Ma}_{\overline{q}})$	the emergy transformity of $\overline{Ma}_{\overline{q}}$
Em_{se}	the service-emergy of the manufacturing systems
$Em_{se}{}^{j}$	the service-emergy of the j-th subsystem of the manufacturing systems
Se_{u}^{j}	the u-th service of the j-th subsystem emergy transformity of Se_{u}^{j}
Em_{iw}	the waste-emergy of the manufacturing systems
$Em_{iw}{}^{j}$	waste-emergy of the j-th subsystem of the manufacturing systems
Iw_{w}^{j}	the w-th waste of the j-th subsystem
$UEV(Iw_{w}^{j})$	emergy transformity of Iw_{w}^{j}
Em_{pr}	the profit income emergy of the manufacturing systems
U_{pr}	the monetary benefit value obtained by the system
UEV_c	the emergy/money ratio
Ma_{q}^{j}	theq-th no-renewable material of the j-th subsystem
$UEV(Ma_{q}^{j})$	the emergy transformity of Ma_{q}^{j}

ecology in Yale University [13], Research team on sustainable manufacturing in the manufacturing center of University of Cambridge [14]. These studies have made great progresses in the green design [15], clean technology [16], green recycling, remanufacturing [17] and the knowledge management of sustainable production [18].

Studies on sustainable manufacturing have been widely carried out in recent years. The sustainable manufacturing technology is a rapidly developing field. There is evidence of sustainable work in product design, supply chain, production technology and avoiding waste activities [19]. Green technology (from process and tooling to the entire enterprise) is a way to ensure the sustainable development of the future manufacturing system [20]. Tools and options for building new solutions of sustainable manufacturing concept were provided by Marco-Garetti [21]. A world-class sustainable manufacturing framework was developed by structured questionnaire and multiple regression analysis [22]. A tactics library that provides a link between the general sustainability concept and more specific examples of the operation practice for factory resource efficiency was introduced [23]. The steps towards sustainable manufacturing through modelling material, energy and waste flows were proposed by Smith [24]. The key green engineering research areas of sustainable manufacturing was presented in the perspective of pharmaceutical and fine chemicals manufacturers by Jiménezgonzález [25]. Steps from economic growth to sustainable development were illustrated for competitive sustainable manufacturing by Jovane [26].

Design for sustainable manufacturing enterprise is considered to be a new guide regarding survival of manufacturing enterprise. Some concepts of sustainability were presented to guide manufacturing enterprises analysis and design with the most effective aspects for analyzing sustainability [27]. A system approach for TOU based electricity demand response for sustainable manufacturing systems under the production target constraint was proposed by Wang [28]. A process-oriented Information Model (PIM) was built to integrate the relevant information regarding the sustainable manufacturing with the product design information [29]. Comprehensive sustainability framework for manufacturing domain was proposed to strengthen the enablers and mitigate barriers based on the responses of researchers and industry professionals [30]. A lean and cleaner production benchmarking method for sustainability assessment in a manufacturing company of Brazil was analyzed by Ramos [31]. From Chinese auto-parts suppliers' perspective, composite sustainable manufacturing practice and performance framework was established [32]. A new match-up technique for determining the rescheduling zone and a feasible reschedule in job-shop problems for sustainable manufacturing systems were developed by Salido [33]. The utilization of CHP in electricity load management for sustainable manufacturing systems was proposed by Sun to examine the benefits regarding cost savings for manufacturers [34]. An integrated simulation tool helping to maximize production efficiency and balance environmental constraints already in the system design phase for sustainable manufacturing systems was proposed by Wang [35]. A tool "Energy Cards" merging energy data and enabling the transfer of energy data, information and knowledge in a structured and clear manner was presented by Hopf [36]. On the energy mining in the production process of machining systems, the energy benchmarking was proposed by Cai to improve the efficiency and performance of the energy utilization in machining systems [37]. An investigation into methods for predicting material removal energy consumption in turning was proposed by Lv to support energy consumption reduction [38]. Minimising the machining energy consumption of a machine tool by sequencing the features of a part was studied by Hu [39]. These researches focus on energy efficiency, while the research on resource efficiency, service and waste efficiency is relatively few in the manufacturing system. Obviously, the research of sustainable manufacturing technology should be further studied.

On the evaluation of sustainable manufacturing, an open, inclusive and neutral set of indicators was presented by Che to measure sustainability of manufactured products and manufacturing processes in five dimensions of sustainability: environmental stewardship, economic growth, social well-being, technological advancement, and performance management [40]. The facilitate decision considering sustainable manufacturing assessment was introduced to develop an understanding of the complex interplay of factors from the operational (micro) scale through the enterprise (macro) scale [41]. The evaluation and modeling of environmental impacts in additive manufacturing for sustainable manufacturing was proposed by Bourhis [42]. An integrating approach is developed to assess broader sustainability impacts by conducting economic assessment, environmental impact assessment, and social impact assessment at the work cell level by Zhang and Haapala [43]. The strategy selection for sustainable manufacturing with a hierarchal multi-criteria decision-making method was addressed by Singh [44]. The LCA Integrated ANP Framework for Selection of sustainable manufacturing processes was presented by Kek [45]. A novel emergy based evaluation method for remanufacturing machining systems was proposed by Liu [46]. The potential capability estimation for real time electricity demand response of sustainable manufacturing systems using markov decision process was presented by Sun [47].

To sum up, sustainable manufacturing has become the focal point of the common concern of the academia, the industry and the business community [48], which is the only way for industrial transformation and upgrading, and the important content of the construction of ecological performance [49]. These studies have actively promoted the optimal operating strategies for the development of sustainable