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An energy management approach for the mechanical manufacturing industry through developing a multi-objective energy benchmark

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ABSTRACT

Energy benchmark has been recognized as an effective analysis methodology and management tool of the energy usage. With wide distribution and large energy consumption in low efficiency, mechanical manufacturing industry possesses considerable energy-saving potential. However, there are few effective methods available for developing an energy benchmark in the mechanical manufacturing industry due to complexity and variety of energy-consumption processes resulting in the waste of massive energy. To achieve energy management and energy-efficient improvement in the mechanical manufacturing industry, this paper proposes a novel method for developing a multi-objective energy benchmark based on the energy consumption forecast and integrated assessment. Energy consumption databases, as an important part of the energy benchmark, are established to provide long-term use after establishment. Meanwhile, an energy consumption model of the whole production processes is built laying the foundation of the energy acquirement. The multi-objective energy benchmark could be determined through integrated assessment method of TOPSIS synthetically considering the real production requirements. In addition, the case study shows the practicability of the energy benchmark method for energy management and a potential energy saving of 21.3%.

1. Introduction

Industrial energy efficiency and potential are primarily analyzed through the application of energy indicators and energy benchmark [1]. Energy benchmark has been recognized as an effective analysis methodology and management tool of the energy usage [2]. Currently, a number of methods for developing the energy benchmark have been successfully applied to the steel industry [3], the chemical industry [4], the building industry [5], the environment industry [6], etc.

The study of energy benchmark has aroused extensive interest in recent years [7], especially in energy-intensive industries like the manufacturing industry [8]. The US Department of Energy set up special Industrial Assessment Centers to improve energy efficiency of the production process, and approximately 15,000 American businesses had implemented a number of projects such as developing energy benchmark and an energy audit [9]. China's Top Quality Control Official and the China National Standardization Management Committee jointly issued several national standards to provide policy support for establishing the energy benchmark [10]. Meanwhile, many researchers have also addressed some methods for developing the energy benchmark. Spiering proposed energy efficiency benchmark for injection molding processes, as well as the analysis and comparative evaluation of how the production factor energy as applied to manufacturing can be an impulse for parallel improvements regarding energy [11]. Wang developed an energy efficiency benchmark methodology and benchmark indicators making up for the absence of a system of energy efficiency indicators and a standard benchmark system [12].

The U.S. Energy Information Administration published an energy yearbook in 2012 showing that energy consumption in the mechanical manufacturing industry accounted for 74.7% of the total energy consumption in the manufacturing industry [13]. Numerous surveys indicated that the energy efficiency of the mechanical manufacturing process was very low, usually less than 30% [14]. With wide distribution and great energy consumption in low efficiency, the mechanical manufacturing process possesses considerable energy-saving potential [15]. Energy benchmark, as an important measure of energy management and energy saving, urgently needs to be developed in the mechanical manufacturing industry. Considering the energy benchmark in the mechanical

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Nomenclature

A, B, C	curve-fitting coefficient
b_1	load loss coefficient of mechanical drive system in the first drive link
B_i	number of pieces of transportation equipment
C_i	relative similarity degree
E_{Actu}	actual energy consumption
E_{cm}	cutting material energy consumption
E_{Fore}	forecast energy consumption
E_{ke}	kinetic energy of motor rotor
E_{km}	kinetic energy of mechanical main drive system
E_{id}	idling energy consumption
E_m	energy of coupled fields (electromagnetic field)
E_{Mach_k}	energy consumption of the machining process for one workpiece in the k^{th} mechanical manufacturing workshop
$E_{non\text{-}mach\_k}$	energy consumption of the non-machining process for one workpiece in the k^{th} mechanical manufacturing workshop
E_{sb}	standby energy consumption
E_{st}	starting energy consumption
F_i	number of pieces of packaging equipment
$g(n)$	function of starting energy consumption
H_j	entropy
I_i	number of pieces of inspection equipment
M_j	j^{th} number of machine tools
n	spindle speed
N_{Aux}, N_{Oil}, N_{Coat}, N_{Othe}	sharing number of workpieces in the sharing ECWAE, oiling, coating and other ECSs, respectively
N_{cm}	number of cutting material ECS
N_{id}	number of idling ECS
Nm	number of machine tools
N_{sb}	number of standby ECS
N_{st}	number of starting ECS
N_w	number of mechanical manufacturing workshops
P_a	additional load loss
P_{a0}	additional load loss of mechanical drive system
P_{Auxi}	sharing power of all workshop auxiliary equipment for a group of workpieces
P_c	cutting power of the tool
P_{cm}	cutting material power
P_{id}	idling power
P_{id0}	idling power of mechanical drive system
P_{Insp}	average operational power of the inspection equipment
P_{Le}	power loss of the main motor
P_{Pack}	average operational power of the packaging equipment
P_{sb}	standby power
P_{Shir}	sharing power of a group of workpieces during these process
P_{Tran}	average operational power of the transportation equipment
t_{cm}	cutting material time
t_{id}	idling time
t_{Insp}	inspection time of one workpiece
t_{Pack}	packaging time for one workpiece
t_{sb}	standby time
t_{st}	starting time
t_{Tran}	once transportation time
w_j	entropy weight
$\boldsymbol{Z}$	weighted fuzzy matrix
$\boldsymbol{Z}^{+}$	vector quantity of ideal solution
$\boldsymbol{Z}^{-}$	vector quantity of the negative ideal solution
α_0, α_1	load loss coefficient
κ	transferring coefficient
CPT	cost of processing technology
CRWs	completion rate of workpieces
E_{CO}	comprehensive optimal energy consumption
ECS	energy-consumption-step
ECWAE	energy consumption of workshop auxiliary equipment
EP	environmental performance
MP	manufacturing plan
MP_{CO}	comprehensive optimal MP
PT	production time
TOPSIS	Technique for Order Performance by Similarity to Ideal Solution

manufacturing industry, Cai proposed a new concept of fine energy consumption allowance (FECA) and a method for developing the FECA of the workpiece, which contributes to strengthening energy monitoring and management and improving energy efficiency [1]. Chen divided energy benchmark into technology benchmark and non-technology benchmark and briefly introduced the benchmark methods including computational analysis, actual measurement and statistical analysis [16]. Gong studied energy consumption prediction in the manufacturing process of large-scale mechanical products based on knowledge providing the important reference for energy benchmark study [17]. Liu proposed a method for dividing manufacturing products into a variety of general products and individual special products and presented the strategy for the product energy benchmark regarding to different product types, which laid a foundation for developing the energy benchmark considering different products [18]. Zhou proposed an energy-consumption model for establishing energy-consumption allowance of a workpiece in a machining system, and just introduced a modeling method [19]. Hoda addressed a methodology for energy use analysis and benchmarking of manufacturing lines, analyzed the energy use in manufacturing lines and introduced the concept of local energy benchmarking, but did not involve the specific benchmarking process [20]. In addition, most of the other studies are focusing on modeling energy consumption in the machining process. For example, Liu illustrated a method for forecasting the energy consumption of the main driving system in machining [21]. Gutowski presented the frame model of energy consumption for machine tools involving two aspects: the cutting energy and the auxiliary machining energy of machine tools contributing to the energy consumption classification of machine tools [22]. Li analyzed the constitution, measurement and saving approaches of the fixed energy consumption of machine tools (power demand of ensuring the operational readiness of a machine tool) [23]. To date, previous studies are significant for the energy benchmark study, but are far from sufficient to satisfy the demand for developing a reasonable energy benchmark in the mechanical manufacturing industry. Deficiencies of previous studies focus mainly on the following two aspects:

(1) The complexity and variety of the energy consumption processes result in difficulty of establishing the energy benchmark because of the lack of an effective method.
(2) It is necessary for energy benchmark to synthetically consider various production requirements or influence factors related to the energy benchmark, but existing studies only consider energy consumption of the production process using a single objective method without other significance factors such as time and cost.