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A carbon efficiency evaluation method for manufacturing process chain decision-making

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ABSTRACT

Low carbon manufacturing (LCM) is increasingly being regarded as the direction for technological innovation and implementation in industry. The manufacturing process chain plays a critical role in LCM to consider and define the whole production process, thus the analysis and evaluation method for its decision-making is urgently needed. Although interest in addressing carbon emission reduction in manufacturing is rising, the study of incorporating carbon emission reduction and economic improvement into the process chain is still considerably deficient. This work proposes a novel method to identify a process chain with the optimal carbon efficiency, where the carbon efficiency of process chain (CEpc) regarded as an effective indicator is evaluated by manufacturing value and carbon emissions defined based on eco-efficiency. In addition, the estimation models of manufacturing value and carbon emission are proposed, based on which, a decision-making model is established to solve the process chain decision-making issues with objective to maximize CEpc. An illustrative example of the sleeve part manufacturing process is conducted to demonstrate the effectiveness of this method. And the outcome can help decision makers to select the process chain with optimal carbon efficiency based on the dynamic change of production and different processing conditions. Furthermore, sensitivity analysis on material utilization rate, recycling rate as well as processing efficiency is presented to reveal the impacts of relevant improvement measures in CEpc for manufacturers.

1. Introduction

Manufacturing is mainstay of the fortune creating, which transforms raw materials and information into products for satisfying human demands (Wang et al., 2013). However, convert materials into industrial parts is the main source of energy consumptions and carbon emissions (Jeswiet and Nava, 2009). With the tremendous development in world economy and manufacturing technology, the consumer demand on manufactured products become more diversified and personalized, and the update speed as well as consumption of goods is on a continuous growth, leading to a faster usage on natural resources and energy (Sabharwal and Garg, 2013; Tian et al., 2012). In 2013 the global CO_2 emissions were 32.3 billion tons, while China's emissions reached 9.5 billion tons (around 29% of world's CO_2 emissions), the per capita carbon emissions in China overtaking Europe for the first time (NBS, 2015). Therefore, protection of resources, reducing energy and curbing carbon emission has become an emerging topic in the sustainable manufacturing (Cao and Li, 2014; Tian et al., 2014).

In the past years, current hotspots of international research have been focused on promoting the utilization of energy and nature resource from process cell level up to system level (Marius et al., 2014). In a manufacturing system, one process chain is a set of disparate production processes, various processing equipments, handing system and the operators. All these manufacturing variables influence the required resource and energy consumptions during manufacturing. Namely, manufacturing process chain plays an essential role in the implementation of cost savings and carbon emission reduction connected with production system. However, the manufacturing process optimization on low-carbon is often considered inadequate (Shi and Meier, 2012).

In modern industrial enterprises, several different process chains can be employed in the same product manufacturing, and fully satisfied the technical requirement specified in the drawing. For the purpose of identifying the process chain with the optimal

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Nomenclature

b^e	price of electrical energy consumption per unit production [*Yuan*]
b_i^s	product retail price of *ith* process chain [*Yuan*]
b_i^p	unit purchase price of raw materials of *ith* process chain [*Yuan*]
b_i^r	disposal cost of single part of *ith* process chain [*Yuan*]
b_h	price of h^{th} primary energy per unit [*Yuan*]
b_k	price of k^{th} secondary energy secondary energy or energy-consumed medium per unit [*Yuan*]
$b_{i,l}^{tool}$	price of cutting tools in process step *l* of *ith* process chain [*Yuan*]
$CEpc_i$	carbon efficiency of *ith* process chain [$Yuan/kgco_2$]
CE	coefficient of carbon dioxide equivalent of per standard coal [$kgco_2/kgce$]
Cpc_i	carbon emissions of *ith* process chain [$kgco_2$]
d_r	raw materials' carbon emission factor [$kgco_2/kg$]
d^{tool}	cutting tools' carbon emission factor [$kgco_2/kg$]
$E_{i,}$	original value of the machine in process step *l* of *ith* process chain [*Yuan*]
EE_k	standard coal equivalent coefficient of k^{th} secondary energy or energy-consumed medium [$kgce/kg$]
EE_e	standard coal equivalent coefficient of electricity [$kgce/kg$]
EE_h	standard coal equivalent coefficient of h^{th} primary energy [$kgce/kg$]
$f_{i,l}$	unit average labor cost in process step *l* of *ith* process chain [$Yuan/s$]
$G_{i,l}$	service life of the machine in process step *l* of *ith* process chain
g_i^m	the mass of removed raw materials of single part of *ith* process chain [*kg*]
H_i	the production volume of *ith* process chain
j	the accrual month of depreciation
$m_{i,l}^{tool}$	the mass of cutting tools in process step *l* of *ith* process chain [*kg*]
$n_{i,l}$	the amount of the machine in process step *l* of *ith* process chain
$P_{i,l}^u$	load power in process step *l* of *ith* process chain [*kw*]
$P_{i,l}^a$	idle power in process step *l* of *ith* process chain [*kw*]
$P_{i,l}^o$	allowance power in process step *l* of *ith* process chain [*kw*]
$Q_{i,l,h}$	the amount of *hth* primary energy consumption in process step *l* of *ith* process chain
$S_{i,l}$	expected net salvage value of the machine in process step *l* of *ith* process chain [*Yuan*]
T_i	total processing time of one part of *ith* process chain [*s*]
$T_{i,l}^w$	monthly working duration in process step *l* of *ith* process chain [*s*]
$T_{i,l}$	total processing time of one part in process step *l* of *ith* process chain [*s*]
$t_{i,l}^{load}$	load time of one part in process step *l* of *ith* process chain [*s*]
$t_{i,l}^{idle}$	idle time of one part in process step *l* of *ith* process chain [*s*]
$t_{i,l}^{allow}$	allowance time of one part in process step *l* of *ith* process chain [*s*]
$T_{i,l}^{tool}$	service life of cutting tool in process step *l* of *ith* process chain [*s*]
V_i^{ar}	auxiliary resource consumption cost of *ith* process chain [*Yuan*]
V_i^{elec}	electrical energy consumption cost of *ith* process chain [*Yuan*]
V_i^{md}	machines depreciation cost of *ith* process chain [*Yuan*]
Vpc_i	the manufacturing value of *ith* process chain [*Yuan*]
$W_{i,l,k}$	the *kth* secondary energy or energy-consumed medium consumption in process step *l* of *ith* process chain [*kg*]
$z_{i,l}$	manufacturing completed time in process step *l* of *ith* process chain [month]
β_i	processing scrap rate of *ith* process chain

comprehensive performance, decision makers need to analyze and evaluate the significant differences among various process chains on material consumption, energy consumption, pollutant emission, process time and cost-effective strategy. For instance, one type of shaft sleeve parts can be produced either by the metal cutting process, or formed by using the powder metallurgy process; In the process of gear manufacturing, adopting the high-speed dry gear milling process or wet gear hobbing process has huge differences on production cost and environmental impact. Thus, process chain adaptations through implementing process alternatives are estimated to reduce the resource consumption and carbon emission significantly (Denkena et al., 2013). Although the decision-making for LCM has been extensively studied, most existing research are concerned at process parameter level and process step level, for example, process parameter optimization (Jiang et al., 2015; Yi et al., 2015) and process step sequencing (Shao et al., 2009; He et al., 2015). The decision-making research for LCM on process chain level is relatively less. Furthermore, due to the diversity of decision factors and feasible process chains, and the uncertainty of dynamic production conditions, the process chain low-carbon decision-making problem is still lack of ideal solution.

The paper presents our work on manufacturing process chain decision-making by taken into account environmental and economic dimensions. A carbon efficiency evaluation method is presented to identify the process chain with the optimal carbon efficiency for decision-makers. In this method, the carbon efficiency of process chain (CEpc) regarded as an effective indicator to combine multiple decision criteria into a single indicator is evaluated by manufacturing value and carbon emissions defined based on eco-efficiency. Additionally, the estimation model of manufacturing value and carbon emissions of process chains are proposed, through which the carbon emissions and manufacturing value can be estimated. Furthermore, the decision-making model is proposed with objectives to maximize the CEpc and select the optimal process chain for decision maker based on dynamic change of production and different processing conditions. Thereby, the study on carbon emission reduction and economic benefit enhancing of manufacturing process chain will be a significant step forward towards LCM.

This paper is organized as follows. Section 2 provides a brief review on related researches, and the novelties of this work are summarized. With the section 3 outlining the idea for the