Journal of Cleaner Production 91 (2015) 145–157

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Life cycle oriented low-carbon operation models of machinery manufacturing industry

Yanbin Du [a, b, *], Qian Yi [c, d], Congbo Li [c], Lan Liao [a]

[a] Chongqing Key Laboratory of Manufacturing Equipment Mechanism Design and Control, Chongqing Technology and Business University, Chongqing, PR China
[b] Research Center of Energy Management and Low Carbon Development, Chongqing Technology and Business University, Chongqing, PR China
[c] State Key Laboratory of Mechanical Transmission, Chongqing University, Chongqing, PR China
[d] College of Information Sciences and Technology, Pennsylvania State University, Pennsylvania, USA

ARTICLE INFO

Article history:
Received 3 June 2013
Received in revised form
6 December 2014
Accepted 7 December 2014
Available online 13 December 2014

Keywords:
Low-carbon
Life cycle
Machinery manufacturing industry

ABSTRACT

It is urgent for machinery manufacturing industry to implement low-carbon manufacturing to solve the problems of high-energy consumption and high-carbon emissions. Combining the theory of product life cycle, a system framework of low-carbon operation models in machinery manufacturing industry is established, which consists of an objective layer, a strategy layer, a process layer and a supporting layer. In addition, four typical low-carbon operation models of machinery manufacturing industry are proposed from the perspectives of low-carbon product design, source control, process control and EOL (end-of-life) product disposal respectively. Finally, the proposed models are illustrated in a case of implementing low-carbon manufacturing by a machine tool manufacturer.

1. Introduction

Machinery manufacturing industry, which provides lots of production materials and products for the society, has become a pillar industry of national economy. However, it is a traditional industry of high energy consumption, serious environmental contamination and high carbon emissions. Nowadays, global warming has become the most talked-about environmental issue and carbon dioxide (CO_2) emissions are the most important cause of global warming. The increasing pressure on material availability, energy prices and emerging environmental legislation are driving manufacturers to take various measures to reduce their material and energy consumption as well as their carbon footprint (Ball et al., 2009). Low-carbon manufacturing has aroused a widespread concern among governments, corporations, and individuals around the world. For example, the UK government has set out a transition plan which aims at cutting emissions and protecting the vulnerable environment on the premise of maintaining secure energy supplies and maximizing economic opportunities to promote the UK to become a low-carbon country(UK Government, 2009). Moreover, Government of China has proposed an ambitious goal to reduce the intensity of carbon dioxide emissions per unit of GDP in 2020 by 40%–45% compared with that in 2005, which has been integrated into its long-term economic and social development plans as an obligatory object (State Council of China, 2009).

So far, manufacturing companies have implemented a variety of strategies to reduce their carbon footprints. Moreover, scholars in universities and institutes have done a lot of researches on the definition and theories of low-carbon manufacturing. Tridech and Cheng (2011) discussed concepts of LCM (Low-carbon manufacturing) and explored theoretical models, characterization and implementation perspectives associated with LCM. Also, Ball et al. (2009) analyzed and integrated the material flow, energy flow and waste flow through a manufacturing facility and thus developed a systematic model to establish the correlation between input and output of carbon flow. Gutowski (2007) divided energy consumption of manufacturing process into two types: energy consumption of material fabrication and energy consumption of manufacturing process, and further proposed four strategies to reduce carbon footprint. Moreover, Pohlman et al. (2012) presented an economic framework for the integration of energy efficiency and renewable energy in manufacturing plants that can achieve net-

* Corresponding author. Chongqing Key Laboratory of Manufacturing Equipment Mechanism Design and Control, Chongqing Technology and Business University, Chongqing, PR China. Tel./fax: +86 23 62768400.
E-mail address: duzi2009@163.com (Y. Du).

http://dx.doi.org/10.1016/j.jclepro.2014.12.028
0959-6526/

zero carbon emissions at net-zero costs. Lane and Potter (2007) reviewed the evidence of consumer attitudes to low carbon cars and identified key 'hotspot' factors that influence consumers' adoption of low-carbon products. Trappey et al. (2012) used an economic input–output life cycle assessment approach to evaluate the carbon emissions of new products and determine problematic carbon emissions within the supply chain. Sutherland et al. (2003) pointed out that operation of environmentally responsible manufacturing should consider two levels, i.e. enterprise level operations and factory level operations (cover process monitor, material control, recycle and reuse, waste and energy management). Recently, Wang et al. (2013) presented an integrated method to evaluate energy efficiency in machining workshop, which has significances to energy saving and carbon emissions reduction. Zhang et al. (2012) proposed a novel identification method of connection units with high GHG emissions to find the factors related to the carbon footprint from the aspect of product structure.

Low-carbon manufacturing (LCM) refers to the creation of low-carbon products through sustainable manufacturing processes that minimize carbon emissions and energy consumption. It is different from sustainable manufacturing which emphasizes not only the minimization of negative environmental impacts, but also reduction of resource consumption (Wiedmann and Minx, 2008). It can be summarized from the literature reviews that operation of low-carbon manufacturing is a systematic, comprehensive and practical process involving various factors including product design, management model, manufacturing process, production equipment and personal quality. As Smith et al. (2013) put it, the higher energy requirements and shorter economic timeframes make it much more difficult for manufacturing industry to achieve net-zero energy. Furthermore, due to the complexity of low-carbon manufacturing and the uniqueness of machinery products, it is difficult for the machinery manufacturing industry to implement low-carbon manufacturing successfully.

Although the previous researches about operation models of low-carbon manufacturing have provided some insights into the definition of low-carbon manufacturing, it still remains ill-defined for the operation of low-carbon manufacturing in machinery manufacturing industry, such as determination of operation objectives, selection of operation strategies, operation procedure and supporting systems design. Aiming at these problems, this manuscript intends to investigate the operation model of low-carbon manufacturing to provide some reference and guidance for machinery manufacturing industry. Compared to existing literature, the actual contribution of this paper is to clarify the definition of LCM, integrate the relevant factors of LCM and provide the implementation procedure and framework of LCM.

2. Materials and methods

2.1. System framework of low-carbon operation models in machinery manufacturing industry

The machinery manufacturing industry, which create end products that apply mechanical force, is part of the manufacturing sector. It typically employs multiple metal forming processes in manufacturing the various parts of the machine, including forging, stamping, welding, forming, machining and assembling (Jessica, 2014). Manufacturing includes energy-intensive industries and less energy-intensive industries. As a discrete manufacturing system, machinery manufacturing industry belongs to less energy-intensive industries and its major source of energy is electricity (Gutowski et al., 2006). Based on the experiences and research findings during the process of low-carbon manufacturing development, a four-layer system framework of low-carbon operation models in machinery manufacturing industry has been established, as shown in Fig. 1. It can be concluded from the proposed operation models that low-carbon manufacturing focuses on improving energy utilization ratio and resources utilization ratio through low-carbon product design, low-carbon energy structure, low-carbon manufacturing process and EOL product disposal.

- First layer-objective system. In the first layer, the objective system of low-carbon manufacturing is established for machinery manufacturing industry. Low-carbon manufacturing emphasizes the coordination maximization of economic benefits (including low cost, high profit and high productivity) and social benefits (involving high energy efficiency, low carbon emissions, high resource efficiency and less waste). Hence, coordination maximization refers to the balance of economic benefits and social or environmental benefits. More specifically, the objective function is composed of various indexes from the perspectives of economic or social benefits. Finally, a sustainable development paradigm involving resource and energy consumption as well as carbon emissions comprehensively can be established.
- Second layer-low-carbon operation strategies. There are four aspects of operation strategies presented to reduce carbon emissions for machinery manufacturing industry, including low-carbon product design, source control, process control and EOL product disposal. Low-carbon product design means to provide products of high energy efficiency and resource efficiency. Source control refers to selecting low-carbon energy supply and raw materials of lower carbon footprint instead of the traditional energy and materials. Process control refers to full controls on production process from the aspects of energy saving and material saving to reduce carbon emissions. EOL product disposal refers to reusing, remanufacturing or recycling the used parts or products.
- Third layer-life cycle process. Product life cycle stages include raw-material acquisition, manufacturing, use of product and EOL product disposal. Machinery products are different from chemical products and metallurgical products. The energy consumption of machinery products in use stage may be more than that in the manufacturing process. Therefore, low-carbon manufacturing should not only involve the manufacturing process, but also incorporate the use stage of machinery product. Low-carbon manufacturing for machinery manufacturing industry can be achieved only when carbon reduction can be realized in all individual stages of product life cycle.
- Fourth layer-supporting system. The supported operating systems and platform of low-carbon manufacturing are established for machinery manufacturing industry, which mainly include low-carbon design system, gathering system of energy information, operation supporting system of energy optimization, monitoring and control system of carbon emissions, and information system of low-carbon management (Kuo, 2013; Song and Lee, 2010).

The four layers, which are closely related to each other, constitute an organic system of low-carbon operation models in machinery manufacturing industry. The primary process of implementing low-carbon manufacturing is to determine the strategic objectives and motive forces of low-carbon manufacturing. Therefore, the first layer that represents the objective system of low-carbon manufacturing is the ultimate goal of machinery manufacturing industry. The second layer is the principal part in the system framework of low-carbon operation models, which presents operation strategies and further demonstrates how to implement low-carbon manufacturing in aspect of