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Sustainable performance oriented operational decision-making of single machine systems with deterministic product arrival time

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ABSTRACT

In order to achieve industrial sustainability and realize low carbon economy, various measures should be taken to reduce carbon dioxide emissions of production processes without compromising economic factors. In this paper, we study the operational decision-making problem incorporating both economic and environmental performance. We focus on single machine systems with deterministic product arrival time and the First Come First Served processing rule, and emphasize the processing time and consumed energy of the machine when it stays idle and is switched. We formulate a multi-objective optimization model with aims to minimize the total carbon dioxide emissions and the total completion time simultaneously. Considering the properties of our model, a non-dominated sorting genetic algorithm II (NSGA-II) is proposed to solve this problem. Several simulation examples and an industrial case are used to validate the feasibility and effectiveness of our proposed model and algorithm. Comparison with a previous algorithm confirms the better performance of our proposed algorithm.

1. Introduction

Global climate change greatly affects people's normal social and economic lives. The influences of greenhouse gas emissions on global climate change are gradually appearing and becoming more and more obvious. Greenhouse gas emissions have aroused widespread concern in international community. Reducing greenhouse gas emission has become a hot topic in controlling global climate change in the last several years. In order to fight environment degradation, various tougher legislations on reducing greenhouse gas emissions have been enacted. These legislations together with other driving force like public interest in environmental performance of companies steer the market towards more cleaner products and practices. Nowadays, the importance of environmental protection is increasingly emphasized (Dong et al., 2014) and more in-depth studies on reducing greenhouse gas emissions are being undertaken (Garetti and Taisch, 2012).

Energy generated from the consumption of renewable and nonrenewable resources sustains our normal lives. However, the process to generate energy significantly contributes to greenhouse gas emissions and global climate change. The manufacturing industry, the backbone of industrialized society, is one of the main energy consumers and greenhouse gas contributors in the past several decades (Jovane et al., 2008). The reduction of carbon emissions generated from energy consumption in production systems is necessary and meaningful. Minimizing the energy consumption in production processes is an essential consideration to reduce energy consumption in manufacturing industries (Rajemi et al., 2010). In reducing the energy consumption, more and more attention is also being given to minimize the products' embodied energy (Rahimifard et al., 2010).

In manufacturing industries, electricity consumption contributes to a significant portion of the total energy consumption. It is common knowledge that consuming electrical energy will produce carbon dioxide. So for manufacturing enterprises, they can reduce carbon dioxide emissions by saving electricity, and can indirectly improve the current situation of the global climate. Furthermore, it is known that machines staying idle would consume much electricity. Such consumption of electricity is different from that for processing in the production process. The latter is a reasonable and value-added energy consumption, while the former is a kind of energy waste. Therefore, the electricity consumption may be reduced by turning off the machines when they do not perform operations.

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In previous studies of production systems, most researchers only considered the economic performance in narrow or broad view, such as production cost and processing time. Little attention was given to the environmental performance of production systems. In the current context of increasingly stringent environmental concerns, a large number of theoretic research conclusions and production practices show that improving the enterprises' environmental performance is linked to long-term cost reduction, fulfilment of regulatory requirements, better ethical practices, natural resource preservation, enhanced public image, and competitive advantage. Following the realization of the importance of environmental protection, more and more researchers are beginning to emphasize not only the economic performance but also the environmental performance of production systems.

In this paper, we investigate the operational decision-making problem of single machine systems focusing on the minimization of total carbon dioxide emission and total completion time. The main contributions of this work are: (1) A multi-objective optimization model aiming to minimize the total carbon dioxide emission and the total completion time simultaneously is constructed. (2) A non-dominated sorting genetic algorithm II for solving the multi-objective optimization model is proposed. (3) The proposed approach is tested by two simulations and an industrial case. A comparison with the previous algorithm confirms the better performance of the proposed algorithm.

The organization of the rest paper is as follows. We present a brief literature review in Section 2. In Section 3, we describe our research problem in detail and then formulate a multi-objective model for it. Section 4 develops a non-dominated sorting genetic algorithm II to solve the proposed model. We investigate the computational performance of our proposed algorithm through several examples in Section 4. Section 5 draws conclusions and presents some related topics for future research.

2. Literature review

In the literature, many researchers have focused on turning off idle machines to reduce energy consumption. Swaminathan and Chakrabarty (2003) proposed a control system to reduce the energy consumption and meanwhile increase lifespan of the battery. They pointed out that a simple change on the state of the components (for example, on or off, etc.) can greatly reduce the energy consumption. Drake et al. (2006) found that a machine or a component in the start-up and idle mode consume large amounts of energy. They claimed that turning off the idle machine can save a lot of energy. Mouzon and Yildirim (2008) showed that in the production process, large amounts of energy is consumed when machines fail to be fully utilized. In order to avoid this kind of energy waste, in the case that products do not arrive at the same time, decision makers need to arrange the order of product arrivals and decide when to switch machines.

In recent several years, the measurement of carbon dioxide emissions has become an active topic of sustainability research. Cao et al. (2012) established three carbon efficiency functions to analyze the dynamic characteristics of varied emissions with independent variables of production volume, material removal volume, and economic return. Zhang et al. (2012) created a way to calculate carbon footprint of products by focusing on the connection characteristics between components. Huang et al. (2012) proposed an assessment framework for low carbon technology through both greenhouse gas emission reduction and sustainable development criteria. Güereca et al. (2013) calculated the carbon footprint by the following indicators: electric energy generation, vehicle fleet, purchased electricity, commuting, air travels, courier shipments, paper consumption and solid waste. Among these indicators, electric energy comes first.

Most previous researches on the reduction of energy consumption focused on how to bring in more efficient machines. More broad and holistic aspects to evaluate energy consumption have been provided recently. Jayal et al. (2010) presented an overview of some recent trends and new concepts that are emerging for evaluating the sustainability contents at the product, process, and system levels. Pusavec et al. (2010) proposed several methods to improve sustainability in manufacturing, and believed that reducing the energy consumption by machining processes should be one of the most effective strategies. Seow and Rahimifard (2011) adopted a novel approach to formulate energy flows within a manufacturing system based on a "product" viewpoint, and utilized the energy consumption data at "plant" and "process" levels to provide a breakdown of energy used during production. He et al. (2012) introduced a modeling method of task-oriented energy consumption for machining manufacturing system, which contributes to characterizing the energy consumption based on the task flow of production processes.

While many researchers have explored various approaches to reduce energy consumption, there are several studies showing the importance of operations management in reducing energy consumption. Gimenez et al. (2012) analyzed the effect of the environmental and social projects on the triple bottom line, and pointed out the necessity for sustainable research from the perspective of operation management. Hua et al. (2011) investigated how firms manage carbon footprints in inventory management under carbon emission trading mechanism. Benjaafar et al. (2011) illustrated how carbon emission concerns could be integrated into operational decision-making with regard to procurement, production, and inventory management using a series of relatively simple and widely used models.

Several researchers have conducted concrete investigations on operational decision-making by focusing on economic and environmental performances simultaneously. Oliveira and Antunes (2004) presented an economy-energy-environment multi-objective model based on the linear structure of inter-industry production linkages. It provides decision-makers with a comprehensive model which allows to assess environmental burdens with respect to changes in economic activities consistent with distinct policy measures. However, this proposed model includes sectors rather than simple processes and sectors may be too heterogeneous to correctly reflect particular processes. The results of their model are most accurate only when changes in the output structure are relatively small. Mouzon and Yildirim (2008) proposed a framework to solve a multi-objective optimization that minimizes total energy consumption and total tardiness. A greedy randomized adaptive search metaheuristic was developed to obtain an approximate Pareto front. However, many strict conditions, such as all products arrive at the same time, are assumed in their framework. Some important manufacturing factors like the waiting time of product are also not considered.

More recently, Rajemi et al. (2010) developed a model and a methodology for optimizing the energy footprint for a machined product. They explored and discussed the conflict and synergy between economic and environmental considerations as well as the effect of system boundaries in determining optimum machining conditions. In this work, they emphasized how to select the efficient machining operations based on energy and cost. The importance of minimizing the energy consumption of the production process from the perspective of operational management is not given attention. Fang et al. (2011) presented a general multi-objective mixed integer linear programming formulation to optimize the operating schedule of a flow shop that considers both productivity (i.e., makespan) and energy consumption (i.e., peak load and carbon footprint). They considered the operation speed as an independent variable which