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Dual-mode production planning for manufacturing with emission constraints

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ABSTRACT

We study a dual-mode production planning problem with emission constraints, where a manufacturer produces a single product with two optional technologies. The manufacturer is equipped with the regular and green technologies to comply with emission limitations, and either one or both can be adopted for production. We first investigate the problem under a mandatory emission-cap policy and then extend it to consider emission trading under an emission cap-and-trade scheme. Based on the structural properties of the problem and a multi-level decomposition approach, a polynomial dynamic programming algorithm is developed to solve the models optimally. Our analysis shows that the manufacturer should only use a mix of both technologies when the emission cap is a binding constraint. Numerical results show that the manufacturer's decisions and benefits are significantly affected by the emission cap under the mandatory emission-cap policy, especially when the cap is at a relatively low level. However, the carbon price may not remarkably affect the manufacturer's cost because its influence could be abated through the flexible technology switch under the emission cap-and-trade scheme.

1. Introduction

Environmental issues are a serious global concern because the climate change caused by increasing carbon and pollution emissions has adversely affected social and economic development worldwide (Barreto & Kypreos, 2004). Governments all over the world have been trying to reach a consensus on carbon emission reduction, and some are volunteering to implement emission-reduction policies. For example, in December 2009, the government of Canada committed to a national greenhouse gas reduction target of 17 percent below 2005 levels by 2020 (Canada-Gazette, 2011). The Chinese government also committed to cut its CO_2 emissions per unit of GDP by 40–45 percent by 2020 (Yi, Zou, Guo, Wang, & Wei, 2011). To achieve these reduction targets, a series of regulation policies are adopted by governments. For example, three major policies for carbon emission reduction, including mandatory emission cap, emission cap-and-trade scheme, and emission tax, were introduced by the Congressional Budget Office of Congress of the United States (CBO, 2008).

In this paper, we consider two types of emission regulation policies, namely, the mandatory emission-cap policy and the emission cap-and-trade scheme. The former is a regulatory instrument that regulates firm emissions through mandatory emission caps, whereas the latter is a market-based mechanism that enables firms to relax their emission limitations by trading emission permits. A mandatory emission-cap policy is favored by governments and has been widely applied for its simple design and ease of handling. For example, many local governments in China control the carbon emissions of their regions for adherence to the national goal of the central government and thus limit local firm emissions through mandatory emission permits. In the United States, many states employ similar regulatory instruments (Stavins, 1997). However, market-based emission cap-and-trade scheme is becoming increasingly popular. Two typical examples are the EU Emissions Trading Scheme (EU ETS) (European-Commission, 2012) and the Sulfur Dioxide (SO_2) emissions trading scheme in the United States (Rico, 1995). Moreover, some countries or regions adopt both instruments simultaneously. In China, aside from mandatory regulations, some cities and provinces such as Beijing, Shanghai, and Guangdong, initiated emission trading programs in early 2012 (Xinhuanet, 2013). In the United States, California built an emission trading system in 2012, and other western states have also been planning their emission trading schemes (Burtraw, McLaughlin, & Szambelan, 2012).

As the direct executors of emission reduction, regulations may have significant effects on firms with production that yields carbon

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emissions. Therefore, a credible emission control strategy is becoming an essential component of business success, especially for companies in industries that typically generate a large amount of pollution. These industries include the thermal power, petroleum, steel, and cement industries. In practice, an increasing number of companies are becoming conscious of the challenges placed on production and operations management under emission constraints. Such firms are now paying greater attention to how to plan production, how to arrange production technology, and how to manage inventory, among others. In other words, manufacturers should strike a good balance between emissions and costs to comply with emission constraints and to control costs by determining their production planning appropriately.

We focus on the manufacturer's dual-mode production planning problem with emission constraints, which corresponds to the emission-reduction policies imposed by the government. To comply with the constraints, the manufacturer is equipped with two production technologies, namely, a regular technology and a green technology. The green technology yields fewer emissions but costs more than the regular one. Some practical examples for the differences in the emissions and costs of regular and green technologies are provided by Gong and Zhou (2013). The manufacturer provides customers with a single product by adopting dual-mode production with two optional technologies. The manufacturer can adopt either one or both of these technologies for production. For each production run, a setup cost is required, as discussed in many production planning and lot sizing problems (Florian & Klein, 1971; Wagner & Whitin, 1958). Under a mandatory emission-cap policy, the manufacturer's production emissions are limited by a mandatory cap for a certain duration (e.g., a production period). Facing such an emission cap, the manufacturer has to adopt the green technology to comply with emission constraints because the use of regular technology alone can no longer adhere to the emission limitation. Under an emission cap-and-trade scheme, the manufacturer receives some tradable initial emission allowances. The manufacturer has to reduce emissions or purchase carbon credits when anticipating a shortage of emission allowances. It can, however, also sell or bank its allowances when anticipating a surplus. In this research, the manufacturer is assumed to be compelled to surrender sufficient allowances to cover all of its emissions for each production cycle and then sells off all spare allowances at the end of the planning horizon. Notice that, the "cap" in these two policies has different meanings. In the mandatory emission-cap policy, the cap represents the emission permit that limits the manufacturer's emissions. By contrast, in the emission cap-and-trade scheme, the cap represents the total initial emission allowances that could be used or traded in the market.

We first investigate the problem with a mandatory emission-cap policy. A mathematical model is formulated to provide optimal dual-mode production planning for a manufacturer, with an objective of minimal total cost over a finite horizon. We decompose the original problem into two subproblems, namely, the technology selection problem and the production planning problem. The technology selection problem is solved analytically, whereas the production planning problem is solved by some further decompositions. On the basis of the structural property of a subplan, we first decompose a production plan into a series of subplans and then further decompose a subplan into two smaller subintervals. Based on the multi-level decomposition, a dynamic programming algorithm is developed to solve the problem optimally in polynomial time. The problem is then extended to consider an emission cap-and-trade scheme. The extended problem is analyzed by the same approach and is proven to be polynomially solvable by the same algorithm developed for the model without emission trading. Numerical examples are employed to test the efficiency of our algorithm and to explore the impacts of emission constraints on the firm's operational decisions.

The application of the results of this work is extensive in practice, although it focuses on a deterministic problem. In the real world, manufactures usually use safety stock or rolling horizon to deal with stochastic problems. In a rolling horizon scenario, a real time and deterministic algorithm is required to obtain the optimal production planning, because the computation should be repeated many times. The polynomial algorithm developed in this paper can help firms to solve the problem efficiently.

The remainder of this paper is organized as follows. Section 2 reviews the literature related to our work. Section 3 studies the problem under a mandatory emission-cap policy and mathematically formulates such problem. Section 4 develops a polynomial dynamic programming algorithm to solve the problem. Section 5 extends the problem by considering the emission cap-and-trade scheme. Section 6 presents some numerical examples and investigate the impacts of emission constraints on the manufacturer's operational decisions. Section 7 concludes this paper.

2. Literature review

Two streams of research are closely related to our work. We review, on the one hand, the operations management problem with a focus on emission constraints. On the other hand, our work is related to capacitated single-item lot sizing problems. In what follows, we review studies relevant to each stream and highlight the differences between our work and existing research.

2.1. Operations management with emission constraints

The *first stream* of research is mainly focused on operational decision problems with emission constraints, such as lot sizing problem, inventory management, and transportation, among others. Many studies in this stream focus on single-period problems and contribute significantly to optimizing firm operational decisions and exploring the impacts of emission constraints on these decisions (Hua, Cheng, & Wang, 2011; Letmathe & Balakrishnan, 2005; Song & Leng, 2012; Zhang & Xu, 2013).

For multi-period problems, Benjaafar, Li, and Daskin (2012) propose a series of traditional lot sizing models to illustrate the impacts of carbon emission concerns on the operational decisions of procurement and production planning. Their results show that operational adjustments may result in a significant reduction in emissions without significant increases in costs. Hoen, Tan, Fransoo, and Van Houtum (2012) evaluate the effects of different emission constraints on the companies' transport mode selection strategies on the basis of trade-offs among inventory, transport, and emission costs. Their numerical results show that even though significant emission reduction can be achieved through transportation mode selection, the choice of the optimal emission reduction strategy depends on regulation policies. Rosič and Jammernegg (2013) formulate a dual-sourcing newsvendor model with consideration of the environmental effects of transport. They investigate two types of emission regulation policies and emphasize that an emission trade scheme is preferred to an emission tax policy for firms. Gong and Zhou (2013) investigate a production planning problem with emission trading, where two technologies can be adopted for production satisfying stochastic demands. They do not consider either the setup cost or the emission capacity, while both of which are involved in our study.

Some studies consider multiple modes in lot sizing problems. Absi, Dauzère-Pérès, Kedad-Sidhoum, Penz, and Rapine (2013) present a group of multi-mode lot sizing models considering four different types of emission constraints: periodic carbon emission constraint, cumulative carbon emission constraint, rolling carbon emission constraint, and global carbon emission constraint. A polynomial algorithm is developed for identifying optimal solutions for the model with periodic carbon emission constraint. Absi, Dauzère-Pérès, Kedad-Sidhoum, Penz, and Rapine (2015) extend their work