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# The green capacitated multi-item lot sizing problem with parallel machines☆

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ABSTRACT

Carbon emissions related to energy consumptions from the manufacturing industry have become a substantial part of environmental burdens. To reduce carbon emissions, we introduce carbon emission constraints into the capacitated multi-item lot sizing problem with nonidentical parallel machines. The problem aims to satisfy customer demand for various items over the planning horizon, with an objective to minimize total costs without violating the capacity and carbon emission constraints. We formulate the problem with a mixed integer programming model and propose Lagrangian relaxation and column generation methods to improve lower bounds over the linear programming relaxation. Furthermore, we apply a heuristic named progressive selection to solve the problem and compare the heuristic with other state-of-the-art approaches in the literature. Computational results indicate that the progressive selection heuristic is computationally tractable and can obtain superior results under the same computational resources.

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## 1. Introduction

There is a consensus that carbon emissions are associated with global warming. Reducing carbon emissions is on the top of global agenda to control the warming impacts. As a result, legislations have been evolving to enforce the control of the carbon emissions, such as the Kyoto Protocol (Protocol, 1997) and the European Union Emissions Trading System. However, the carbon emissions are still a long-lasting global issue. As stated by Peters et al. (2012), the global carbon emissions from the fossil-fuel combustion and cement production grew 5.9% in 2010, surpassed nine petagrams of carbon for the first time, and more than offset the 1.4% decrease in 2009. The impact of the 2008–2009 global financial crisis on emissions has been short-lived owing to the high emission growth in the emerging economies, a return to emission growth in the developed economies, and an increase in the fossil-fuel intensity of the world economy.

As carbon emissions are directly related to the energy consumptions during production processes, manufacturing companies are responsible for finding environmental-friendly techniques to reduce energy consumptions and carbon emissions. Industrial practitioners and researchers have been researching to support the manufacturing industry in this critical field. For example, He et al. (2015, 2012) presented methods to estimate and optimize the energy consumption of manufacturing processes that help manufacturing companies make decisions on selecting machine tools to reduce energy consumptions and carbon emissions. In addition to the reduction of energy consumptions and carbon emissions, minimizing production costs is as well an essential metric when making production decisions. It is of the utmost importance to have an ideal trade-off between production costs and carbon emissions. Herein, this paper introduces a green capacitated multi-item lot sizing problem with nonidentical parallel machines (GLS-NM).

The goal of the GLS-NM problem is to find a production plan that minimizes total costs without violations of capacity and carbon emission constraints. The problem considers multiple items

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that have pre-given demand varied over a horizon of finite periods. All demand must be satisfied on time either through carried-inventories from previous periods or through production in the current period. There are different machines capable of producing an item, subjecting to different associated costs, time, and carbon emissions. However, among all alternative machines, only one of them can be assigned to produce the item in a period. Such restriction is placed on the problem because high setup costs often hinder splitting the production into different machines in various industries, such as pharmaceutical and painting ones. Each lot of production is associated with time-independent setup costs regardless of the number of production units. Also, inventory-holding costs are required to carry inventories from period to period. The output of this problem consists of machine purchasing and selection, setup periods, time-phased production, and inventory carryover for all items over the planning horizon.

We formulate the GLS-NM problem with a mixed integer programming (MIP) model, which is a complicated NP-hard problem because even the capacitated single-item lot sizing problem was shown to be NP-hard by Florian et al. (1980). Our computational experiments show that the general branch-and-bound method cannot achieve desirable solutions for the regular-size GLS-NM problem. Herein, we propose a heuristic named progressive selection (PS) to obtain better feasible solutions for the problem. The PS heuristic was initially proposed by Wu et al. (2017) for the integrated lot sizing and cutting stock problem. The heuristic first generates an initial population of bounding solutions using the linear programming (LP) relaxation and heuristics and then utilizes domain knowledge derived from these solutions to create restricted subproblems. These restricted subproblems have some setup variables fixed and can be efficiently solved. The goal of the PS approach is that, by solving these restricted subproblems, the objective values of the original problem can be iteratively improved and eventually converge to a solution of good quality. Our computational test shows that the PS heuristic can obtain competitive results while being computationally tractable. Additionally, we propose Lagrangian relaxation and column generation methods to significantly improve lower bounds over the LP relaxation, as shown in the computational results.

We organize the remainder of this paper as follows. Literature review is given in Section 2. In Section 3, we propose a mathematical formulation for the GLS-NM problem, for which we propose Lagrangian relaxation and column generation methods to achieve lower bounds in Section 4. Section 5 describes the application of the PS heuristic for the GLS-NM problem. Section 6 presents computational results and comparisons among the PS heuristic and other state-of-the-art methods. Finally, we conclude with future research directions in Section 7.

## 2. Literature review

Since the seminal paper of Wagner and Whitin (1958) addressing the uncapacitated single-item lot sizing problem, research has been intensively performed for various types of lot sizing problems. Recently, Fragkos et al. (2016) proposed a horizon Dantzig–Wolfe decomposition for the capacitated lot sizing problem with setup times. Akartunalı et al. (2016) proposed two-period convex hull closures for the multi-item lot sizing problems. For lot sizing problems with parallel machines, Fiorotto and de Araujo (2014) and Fiorotto et al. (2015) developed Lagrangian-based heuristics to obtain feasible solutions, followed by de Araujo et al. (2015) who developed a heuristic hybridizing Lagrangian relaxation and Dantzig–Wolfe decomposition and Wu et al. (2018) who proposed an analytics branching and selection method. We refer interested readers to Brahimi et al. (2017) for recent surveys on the classical lot sizing problems.

Some research has introduced carbon emission constraints into lot sizing models. Heck and Schmidt (2010) proposed a non-linear cost function that addresses ecological considerations for lot sizing. This research proposed eco-enhanced approaches to reduce overall production costs and environmental impacts simultaneously. Furthermore, Benjaafar et al. (2013) illustrated how to integrate carbon emissions into operational decision-making concerning production and inventory management. Absi et al. (2013) introduced four types of carbon emission constraints into the single-item uncapacitated lot sizing problem. Velázquez-Martínez et al. (2014) proposed an estimation method for carbon emissions of transportation in a dynamic lot sizing model. Yu et al. (2013) proposed a classical dynamic lot sizing model with carbon emissions under multi-mode production and developed a polynomial dynamic programming algorithm to solve the model optimally. In addition, Akbalik and Rapine (2014) and Absi et al. (2016) studied the single-item lot sizing problem with carbon emission constraints. Helmrich et al. (2015) generalized a lot sizing problem by considering carbon emission constraints and proposed several heuristics. Some other papers consider carbon emissions for the economic order quantity problems, such as Hua et al. (2011), Bouchery et al. (2012), Chen et al. (2013), Konur and Schaefer (2014), and Toptal et al. (2014).

In Absi et al. (2013), the periodic carbon emission constraint enforces the average amount of carbon emission at any period to be lower than or equal to the maximum unitary environmental impact allowed. The cumulative carbon emission constraint allows that the amount of unused carbon emission of a given period can be used in future periods without exceeding the cumulative capacities. The global carbon emission constraint enforces that the unitary carbon emission over the whole horizon cannot be larger than the maximum unitary environmental impact allowed. The rolling carbon emission constraint assumes that only a rolling horizon of few periods can be used to compensate carbon emissions between periods, different from the cumulative constraint assuming, at each period $t$, that the horizon from 1 to $t$ can be used to compensate the carbon emissions. Absi et al. (2016) extended the periodic carbon emission constraint, assuming that a fixed carbon emission is incurred at each period when a product mode is selected. All these constraints impose a maximum value on the average carbon emission per product, different from this paper that imposes a maximum value on the total periodic carbon emission.

Helmrich et al. (2015) proposed a mathematical model with a global carbon emission constraint, imposing a maximum value of carbon emission over the planning horizon. For the model, the carbon emission constraint is enforced through analyzing the trade-off of carbon emissions generated in production, setup, and inventory-holding operations. Benjaafar et al. (2013) and Akbalik and Rapine (2014) proposed similar models with the cap-and-trade policy. Benjaafar et al. (2013) also analyzed the effect of different emission regulations, including strict emission caps, taxes on emissions, and cap-and-offset. For the model proposed by Velázquez-Martínez et al. (2014), the global carbon emission constraint is enforced through analyzing the trade-off of carbon emissions generated in purchasing orders and product transportation. However, neither production mode nor machine selection decisions are considered in these models. Also, the shortcoming of the global carbon emission constraint lies in that producers can create large carbon emissions by producing large quantities at the beginning of the planning horizon and balance the total carbon emission by producing little at the end of the planning horizon, which may violate the carbon emission limits commonly enforced in each separate period.

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