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A resource constrained scheduling problem with multiple independent producers and a single linking constraint: A coal supply chain example

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ABSTRACT

This paper examines a resource constrained production planning and scheduling problem motivated by the coal supply chain. In this problem, multiple independent producers are connected with a resource availability (or, *linking*) constraint. A general description of such problems is provided, before decomposing the problem into two *levels*. In the first level, we deal with production planning and in the second level, we deal with tactical resource scheduling. A real-world coal supply chain example is presented to anchor the approach. The overall problem can be formulated as an integrated mixed integer programming model which, in several cases, struggles to find even a feasible solution in reasonable amount of time. This paper discusses a distributed decision making approach based on column generation (CG). Computational experiments show that, the CG scheme has significant advantages over the integrated model and a Lagrangian relaxation scheme proposed by Thomas et al. (2013). This paper concludes with detailed discussions on the results and future research directions.

1. Introduction

In this paper, we consider a resource constrained planning and scheduling problem in a supply chain in which many independent *producers* (or service providers) coordinate with a *resource manager* who provides resources such as trucks, trains or infrastructure, to transport products to their destinations. In such supply chains, producers independently make planning decisions and the resource manager (an independent decision maker) makes scheduling decisions that collectively affect the efficiency of the supply chain. The supply chain's objective is to ensure a feasible allocation of resources that minimises total system cost.

There are several real-life supply chains of this sort. In coal supply chains, multiple independent mines (producers) are often connected to a shipping terminal via a shared rail network. A single rail operator (resource manager) often coordinates rail schedules with the mines, to schedule trains (or, trips) between the mines and the shipping terminal in order to meet shipping orders (or, demand) of each mine (see, for example, Singh et al., 2012 and Thomas et al., 2013). A similar problem is also observed in wine supply chains (see Singh et al., 2005) in which, each *grower* has contracts with many wineries. Each winery needs certain varieties of grapes based on their production requirements. These need to be delivered to them in a preferred sequence. The winery needs to coordinate harvesting and transport of grapes to minimise wastage and waiting time (reducing perishability) and to maximise resource utilisation (of crushers, fermenters). See Singh et al. (2005) for a detailed analysis of coordinated scheduling problems wine supply chains in Australia.

In a general problem, each independent producer receives a set of orders from their customers. These orders can be satisfied with different combinations of shared/common resources. The resources are often be grouped into classes based on their properties. The resource manager has a finite number of resources in each class. Therefore, there will be a conflict if the producers' requests exceed the availability of these resources. At the production planning level, producers are not concerned about resource availability in each class. For producers, fulfilment of orders of all customers is of far greater importance. An optimal allocation and scheduling of resources is subsequently necessary to improve the overall performance, which can be achieved via either a cost minimisation, profit maximisation or a makespan or tardiness objective.

It is possible to formulate (and maybe solve) the above supply chain problem in an integrated manner. In such a model, we could consider a single decision-making problem that includes all producers and the resource manager. Such an integrated model is likely to be large and complex. Most scheduling problems are *NP-hard* (see Brucker and Knust, 2006; Lenstra et al., 1977). The

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integrated scheduling problem adds to this complexity because the producers and the resource manager are independent decision making entities who are often reluctant to coordinate fully and transparently, to share their competitive information.

In this paper, we develop an approach, using a customised column generation (CG) scheme, to solve resource allocation and resource scheduling problems. In the production planning stage, each producer defines a possible allocation of resources. This means that resource allocation and its scheduling can be carried out sequentially. Thus, the original problem is decomposed into smaller solvable sub-problems. Essentially, we develop a *distributed decision making* framework which is solved using a *decomposition approach*. Even though we explain the proposed solution approaches in the context of a coal supply chain, our method can be extended to other similar supply chains too. Section 2 provides a summary of related work. Section 3 describes the problem and its features. Section 4 explains the production planning problem for each producer. In Sections 5 and 6 we present a CG algorithm and its improvements, respectively. Section 7 gives an overview of the datasets and performance measures. Section 8 summarises detailed results and comparisons of the different modelling approaches.

2. Related work

Integrated models are often solved using decomposition techniques such as Lagrangian relaxation, column generation and Benders decomposition. The vast literature available in this topic highlights its advantages and practical applications. For example, decomposition approaches are able to handle the complexity of planning and scheduling problems (see Wang et al., 2008). Given the inherent complexity of distributed decision making problems, decomposition methods can be employed for solving these problems. Bracken and McGill (1973) introduced hierarchical optimisation as a generalisation of mathematical programming, where a series of optimisation problems are solved in a predetermined sequence. In this, independent decision makers are considered separately, thereby reducing the problem size and complexity of the integrated model. Decomposed optimisation techniques have been extended to job-shop scheduling problems (see Brandimarte and Calderini, 1995; Zribi et al., 2007), resource constrained scheduling problems (RCSP) (see Hans et al., 2007; Kelly and Zyngier, 2008), manufacturing problems (see Wu and Ierapetritou, 2007; Ebadian et al., 2009; Timm and Blecken, 2011). Pochet and Wolsey (2006) discuss different production planning models and mixed integer programming formulations. They suggest many practical reformulation techniques and polyhedral results to strengthen the model and solve it effectively.

Dantzig and Wolfe (1960) introduced an efficient decomposition algorithm for a special class of problems. Today, Dantzig–Wolfe decomposition (DWD) is a widely applied solution approach for solving large optimisation problems. Column generation (CG) methods have been incorporated along with the DWD to successfully solve many problems such as the cutting-stock problem, vehicle routing problem, crew scheduling problem, *p*-median problem, and graph colouring problem (see Borndorfer et al., 2005; Lubbecke and Desrosiers, 2005; Vanderbeck and Wolsey, 2010). Read Desrosiers and Lubbecke (2005) for an introduction to CG and its key features. Choi and Tcha (2007) proposed a CG approach to address a heterogeneous-fleet vehicle routing problem. Capone et al. (2010) compare two variants of CG schemes developed for a resource allocation problem in wireless mesh networks. All of these show that the CG scheme is effective for solving large problems. Wentges (1997) introduced a weighted DWD and presented some results on the convergence of this scheme under certain conditions. Pessoa et al. (2010) discuss a stronger convergence of this algorithm. The major issues concerned with DWD are slow convergence and stabilisation of dual prices. Ben Amor et al. (2009) and Vanderbeck and Wolsey (2010) analyse some of the latest (dual price) stabilisation techniques.

Thomas et al. (2013) propose a decomposition algorithm based on the Lagrangian relaxation (LR) to solve a similar problem. The main contributions of Thomas et al. (2013) are: (i) the mathematical models for production planning; (ii) distributed algorithm based on the LR and improvements with the Volume algorithm and the Wedelin algorithm; (iii) heuristics to compute the upper bound; and (iv) extensive computational experiments. The authors highlight the advantages of a distributed decision making approach over an integrated approach. Even though the LR algorithm performed better than the integrated model, it was time consuming for larger problems. Hence CG algorithms are explored to solve the integrated problem. A combination of multiple stabilisation methods are explored to improve the performance of the CG algorithm. Rather than directly applying the CG algorithm, we discuss and customise a few techniques that improve the computational efficiency.

3. Problem description

Consider a model where a set of independent producers are connected with a single shared resource constraint. The constraints of each producer have some influence on the utilisation of the shared resource, which, in reality, is the independent decision of the resource manager. Since the resources are finite, these independent producers have to coordinate (implicitly) through the resource manager to achieve a better decision outcome for themselves. There are multiple ways to model and solve this problem. The first option is to model and solve this as a single large mixed integer programming problem. This model has to include all the constraints from the producers and the resource manager. Since this model integrates all the independent decision makers, we refer to it as *the integrated model*. Practical instances of such problems tend to be very large-sized. The integrated model has many solvable production planning sub-problems, and one resource scheduling problem linking the single resource manager and the (many) producers. Thus, we decompose the problem into two parts:

- *Production planning:* Each producer plans its production based on its priorities and objective, and places a set of requests to the resource manager for a certain number of resources. In other words, each producer defines a set of requests (jobs) to meet its orders.
- *Resource scheduling:* After receiving the requests (jobs) from the producers, the resource manager prepares a schedule based on resource availability. This problem is equivalent to a job scheduling problem.

As a result of this decomposition, decisions are separated and distributed across the many independent partners in the system. Therefore, in such distributed models, it is not necessary to share too much information between the independent partners; while this is, of course, necessary in the integrated model. To understand the formulation and solution approaches better, we explain the problem with the help of an example from a coal supply chain.

3.1. A coal supply chain example

In a coal supply chain, many mines produce/mine coal based on the market demand and use a single rail operator to transport the coal to a shipping terminal. The coal supply chain has multiple