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Capacity planning in supply chains of mineral resources

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ABSTRACT

The paper addresses the existing gap in the literature on the optimisation in capacity planning for mineral supply chains. The presented optimisation procedure aims at minimising the cost of infrastructure expansion for any given scenario of future demand. The optimisation procedure is designed as a matheuristic – a hybridisation of mixed integer linear programming (MILP), and a simulated annealing based scheduler. The optimisation procedure is iterative in nature and has the following distinctive features. Each iteration starts with generating a MILP model and finding a minimal cost infrastructure expansion for this model. Then, the scheduler analyses the MILP solution by constructing a schedule. In constructing this schedule, the scheduler reduces its search space using the MILP solution. The scheduler identifies bottlenecks in the infrastructure, which are used for generating a new MILP model at the next iteration. The MILP and the scheduler use different levels of data aggregation and their interaction mechanism is designed as a solution process of a bi-criteria optimisation problem. The computational experiments on data, originating from the world's largest coal exporter, shows the ability of the developed matheuristic to solve industrial-scaled instances of the problem.

1. Introduction

Coal, iron and other mineral resources have a vital role in the world economy. For example, in 2012 coal provided 29.9% of the global primary energy needs and generated 41% of the world's electricity.[1] One of the difficult managerial problems in supply chains of mineral resources is *capacity planning*, which aims at finding a cost effective expansion of the infrastructure in order to satisfy a forecasted increase in demand. The difficulty of the problem is due to the complexity of this type of supply chains which involve mines that produce the commodity; trains which transport the commodity to the sea terminals through a railway network; train-loading facilities at the mines; building stockpiles on the limited strips of land at the sea terminals, with each stockpile having a pre-determined composition of shipments from different mines; as well as groups of equipment at the sea terminals used to unload trains, to build stockpiles and to load the ships. Capacity planning is crucial for supply chains of mineral resources due to the multi-million dollar cost associated with capacity expansion, the long lead-time for building the additional infrastructure and the difficulty of withdrawing from building projects and purchasing commitments.

In the considered class of supply chains, the demand is generated by pre-specified arrival and departure times of ships and their cargo requirements. The cargo requirement of a ship is the set of stockpiles to be loaded onto the ship. One of the approaches to capacity planning is to base the decision making process on a set of scenarios of ships' arrivals, departures,

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1 http://www.worldcoal.org/bin/pdf/original_pdf_file/coal_facts_2013(11_09_2013).pdf.

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0020-0255/

and their cargoes. According to the scenario-based approach, for each scenario, it is necessary to minimise the cost of expansion of the supply chain infrastructure in order to meet the scenario requirements. In this paper, we present an optimisation procedure which, for a given scenario, optimises the cost of infrastructure expansion. In practice, the capacity planning is an extremely complex process that involves different methods and analysis from different viewpoints. The cost minimisation problem considered in this paper is the core of this planning process.

The contribution of this paper is twofold. Firstly, the paper fills the gap in the literature on optimisation in capacity planning for supply chains of mineral resources, since very little has been published on this very challenging problem. Secondly, the paper contributes a new optimisation procedure with the design motivated by the necessity to consider the entire supply chain and a long planning horizon, and at the same time to account for the impact of queues and congestions.

The optimisation procedure, presented in this paper, is based on the hybridisation of two optimisation engines: mixed integer linear programming (MILP) and a metaheuristic based scheduler. The hybridisation of a mathematical program and a metaheuristic is commonly referred to as a matheuristic [22,5]. As far as the field of hybrid optimisation algorithms is concerned, the paper contributes an optimisation procedure with the following distinct features:

- the engines use different levels of data aggregation and their interaction is designed as an iterative optimisation of the constraints in the MILP;
- the MILP, which determines the infrastructure expansion at each iteration, is specifically designed for this type of supply chains and, to the authors' best knowledge, has not been previously reported in the literature;
- the simulated annealing based scheduler uses the flows of commodity specified by the MILP in order to reduce the search space in the process of analysing the infrastructure expansion;
- the scheduler identifies bottlenecks in the supply chain, and therefore what constraints in the MILP to be modified at the next iteration in order to make the MILP model more accurate.

The above features of our optimisation procedure can be viewed as a framework which leads to different algorithms depending on the choice of MILP model and/or scheduler. Various implementations of this framework and their comparison is one of the directions of future research. The presented implementation of this framework has been justified by means of computational experiments with real world data provided by the Hunter Valley Coal Chain,[2] which is the world's largest exporter of coal. To the authors' knowledge, this is the only attempt of modelling with such level of accuracy whilst enabling the solution of industrial-scaled instances of the problem. Also, even though the optimisation procedure was tested using data from coal supply chains, our procedure is equally applicable to supply chains of other mineral resources, like iron ore.

The remainder of the paper is organised as follows. Section 2 provides a motivation and a comparison with the existing literature. Section 3 provides more details on the supply chains of the considered type. Section 4 gives an overview of the optimisation procedure. Section 5 presents the mixed integer linear program and Section 6 describes the scheduler. Section 7 contains the results of computational experiments. The conclusions can be found in Section 8.

2. Motivation and comparison with the existing literature

Two factors have motivated this research. The first is the lack of publications on the very challenging optimisation aspect of the capacity planning in supply chains of mineral resources, which partly can be attributed to the complexity of these supply chains. For example, in regards to the Hunter Valley Coal Chain, [4] acknowledges that "To the best of our knowledge, there are only a few papers in the literature on the use of optimisation models in bulk goods supply chains of this complexity". The complexity of the cost minimisation problem, considered in our paper, stems from the following requirements. The capacity planning as a long-term planning problem needs data aggregation (see for example [30,7]). However, this aggregation should not diminish the significance of the multi-stage nature of supply chains of mineral resources. It is well known (see for example [32]) that neglecting the scheduling can distort capacity estimates so far as to make the results of capacity planning invalid. This leads to a difficult trade-off – aggregation versus the necessity to take care of queues and congestions.

The gap in the literature which has motivated our research is not compensated by the vast body of knowledge on the related topics such as capacity planning in manufacturing or supply chain network design. The majority of these publications are not relevant to the optimisation of capacity planning for supply chains of mineral resources since they do not address to the required extent the necessity of considering the long-term strategic decisions in conjunction with the impact of possible queues and congestions. Thus, an obvious related area is manufacturing with its multi-stage production processes. However, these publications either do not take into account enough details of transportation which, in supply chains of mineral resources, involves trains and a railway network, or are concerned with cyclical production (see for example the survey [10]). Also, the common practice in capacity planning in manufacturing settings is to replace a sequence of operations by a set of operations or even to aggregate sequences of operations into a single operation. This approach ignores the order of operations and hence congestion (see for example [12,6,33]).

Another closely related area is capacity investment and supply chain network design. However, the rich literature in this area focuses on highly aggregated models, which ignores the impact of queues and congestions, hence rendering these publications inapplicable for the problem considered in our paper. For example, in [28,13], the models do not go below

[2] http://www.hvccc.com.au.