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# A mixed integer programming model for long term capacity expansion planning: A case study from The Hunter Valley Coal Chain

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ABSTRACT

The Hunter Valley Coal Chain is the largest coal export operation in the world with a throughput in excess of 100 million tonnes per annum (Mtpa). Coal is delivered to the shipping terminal from 40 mines using 27 coal load points spread across the Hunter Valley region. This paper describes an MILP model for determining the capacity requirements, and the most cost effective capacity improvement initiatives, to meet demand while minimising the total cost of infrastructure and demurrage. We present results from computational experiments on the model's performance along with a comparison of the model's output with detailed analyses by the coal chain analysts and planners.



## 1. Introduction

The Hunter Valley Coal Chain is a joint venture between the mining, rail, terminal and port organisations that coordinate the export of coal from the area around the Australian town of Newcastle. Port Waratah Coal Services Limited (PWCS) operates the coal terminals at The Port of Newcastle, which is the world's largest coal handling operation with total coal exports exceeding 100 Mtpa. The coal chain comprises 40 coal mines owned by 13 individual coal producers. There are 27 mine loading points served by approximately 40 trains making around 16,000 trips per year. The system exports more than 80 different blended coal brands through five berths at three coal terminals which serve approximately 1200 vessels, with an average size of 90,000 tonnes, per year. There is a total stockpile capacity of 3.4 million tonnes at the port with approximately 1.8 million tonnes of workable stockpile space for port operations.

The coal chain operations are coordinated by the Hunter Valley Coal Chain Coordinator (HVCCC) group whose primary goal is to maximise coal export volumes on a daily basis, and to coordinate planning for the provision of future coal chain infrastructure. The HVCCC has developed a simulation model of the coal chain that considers mines, load points, rail operation and port operations, and uses this simulation model to support capacity planning decisions. This paper describes an advanced optimisation tool commissioned by the HVCCC and designed to complement and/or integrate with the current simulation tool. The research goal underlying the work described in the paper is to investigate whether optimisation modelling can be used to augment, and perhaps eventually replace, the highly detailed simulation models currently used for planning multi-million dollar investments in supply chain infrastructure.

## 2. Background

Much of the supply chain literature focusses on Supply Chain Management (SCM), the integration, coordination and management of the different key business processes, often operating within individual silos, that deliver products, services and information from suppliers to customers across the chain. This area of the literature provides a background to the current paper, in the sense that it deals with factors such as setting up, operating, and improving systems like coal supply chains. Romano (2003) provides an overview of developments in supply chain management noting that it has evolved from encompassing mainly logistics activities (inventory management, transportation, warehousing, and order processing) to include other processes such as customer relationship management, product development and commercialisation, and

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[1] www.csiro.au/org/CMIS.html.
[2] http://www.hvccc.com.au/Pages/welcome.aspx.
[3] http://www.riotintoironore.com.

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quality management. Complementary reviews of SCM and supply chain design are given by Grossmann (2004), Power (2005), Park (2005) , Meixell and Gargeya (2005), Petersen et al. (2005), Stadtler (2005), and Trkman et al. (2010).

There is an extensive literature relating to improving the efficiency of mining operations, which represent the first stage of a mineral supply chain. Newman et al. (2010) review the application of Operations Research methods applied to mine planning. Their focus is on the application of these methods to the later stages, relating to the extraction of material, of mining operations rather than on earlier stages such as exploration and development. They consider surface and underground mining separately and consider the various block sequencing models used to determine the optimal extraction patterns needed to minimise production costs while meeting quality requirements, possibly by blending different grades of material extracted from different areas of a mine. Mukherjee (1994), and then Mukherjee and Bera (1995), consider a multiple criteria integer linear programming approach to one of the earlier stages, mine development, as part of a case study from the Indian coal mining industry. The model is used for selecting mining projects from among a series of proposed developments subject to different selection criteria related to factors such as income, employment, environment and safety. Results from the model are given for case studies based on the requirements for mine projects planned by particular companies. Bernardo and Gillenwater (1991) describe a set of heuristics for determining the optimal sequencing of two machine types, miners for material extraction and roof bolters for stabilising the work areas, in underground coal mining while properly blending coal extracted from different mine sections. Pendharkar and Rodger (2000) describe a genetic search algorithm for production scheduling in coal mines. The non-linear model is used to determine an optimal production and blending sequence to maximise net profit while meeting production capacity and contractual quality specifications. The authors use the model to provide a solution to a small problem involving two mines, two processing facilities and two market buyers.

Various optimisation approaches are considered under the SCM umbrella. Melo et al. (2009) review facility location models in the context of supply chain management and in an earlier paper (Melo et al., 2005) propose a mathematical modelling framework for the strategic design of supply chain networks. Other authors who have considered the optimal design and configuration of deterministic and stochastic supply chains include Korpela et al. (2002), Gupta and Maranas (2003), Narasimhan and Mahapatra (2004), Guillena et al. (2005) and Santoso et al. (2005).

The focus in this paper is not the (optimal) design of a coal supply chain, nor optimal mine production planning, but rather a consideration of how we might maximise the throughput of products in such a supply chain by scheduling the use of specified sets of facilities and machines whose operations are constrained by capacities and operational rules relating to their use. In particular, we are interested in determining the optimal use of additional facilities and equipment proposed as part of a capacity expansion program for a supply chain, and to see whether the 'new' supply chain can provide the required increase in throughput. We expect that the application of SCM principles, or methodologies such as collaborative planning, forecasting and replenishment approaches to integrating supply chain members (Fliedner, 2003) would be used as part of the planning process to the expansion program.

With respect to supply chain scheduling, Hall and Potts (2003) noted that while there is an extensive supply chain literature, coordinated decision making in tactical supply chain scheduling models had not, at the time of their paper, been studied. They develop a job scheduling model for a tree structured supply chain in which a supplier makes deliveries to several customers who in turn make deliveries to customers, the benefit of cooperation between suppliers and customers is also considered. The objective is either to minimise the number of late jobs or to minimise the maximum lateness. They use a polynomial time dynamic programming based algorithm to solve a number of tractable problems within a set of supply chain examples. In a later paper, Chen and Hall (2007) extend these scheduling models to consider the effects of conflicts between suppliers and a manufacturer arising from the requirement that all parts needed for a job must be received before the manufacturing stage of the job can commence.

Peng et al. (2009) outline an optimisation model that considers raw coal production, washing and processing, transportation and sales for an integrated coal supply chain. The model includes logistics, capital flows, and information flows between process nodes. The objective is to maximise overall profit and customer satisfaction. The authors describe an application of the model to coal production at the Xuzhou coal mines in China. Conradie et al. (2008) address the problem of the operational scheduling of coal extraction, stacking and reclaiming processes across a coal supply chain. The authors consider a multiple objective system. The goals are to: maximize the sum total of all coal stacked on all the yards from all the mines in all time periods, to minimise the amount of excess tons produced, which is not moved to the stockpiles and for which there is no space at the mines, to distribute stacked coal evenly across the yards, and, to meet blend requirements relating to ash and fines content. The objective also considers uncertainty in the demand for coal products. The focus of the modelling is on operational scheduling and a simulated annealing method is used to provide good solutions to the resulting large scale problems in reasonable time.

With respect to rail scheduling, Dorfman and Medanic (2004) consider scheduling trains in a railway network using a local feedback-based travel advance strategy based on a discrete event model of trains moving along rail lines in the network. A greedy "travel advance strategy" heuristic is used to evaluate the times at which trains enter and leave nodes, representing stations, sidings and passing loops in the network. A capacity check algorithm is used to prevent deadlock and increase the computational efficiency of the method. Burdett and Kozan (2010) describe a hybrid job shop approach to representing and constructing train timetables. A constructive algorithm is used to implement the model together with simulated annealing and local search meta-heuristic improvement algorithms. The objective is to minimise the makespan, which is a proxy for railing throughput, of the system.

Ahmed and Sahinidis (2003) describe a stochastic integer programming method for capacity expansion planning. Their model is structured to determine future expansion times, sizes and locations to meet anticipated growth in demand. Specifically, the model addresses the problem of determining the timing and level of capacity expansions for a set of generalised production facilities, along with a policy for allocating available capacity to a set of products, while minimising expected investment and capacity allocation costs. Product demand, capacity expansion and capacity allocation costs are assumed to be stochastic. The model is constructed using a multistage stochastic programming formulation over a planning horizon of $n$ periods. The authors note that the resulting model is NP hard and, at a practical level, cannot be solved using standard integer programming techniques. A heuristic method based on relaxed linear program and decomposition methods is used to solve a number of test problems in substantially less time than required by the integer program models.

Huh et al. (2006) consider capacity planning under uncertainty using a network optimisation based heuristic to determine the sequence and timing for purchasing and retiring machines required to manufacture different products. The authors also consider variance reduction strategies that can be used with certain stochastic demand forecast distributions.