ARTICLE IN PRESS

International Journal of Mining Science and Technology xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

International Journal of Mining Science and Technology

journal homepage: www.elsevier.com/locate/ijmst

Simulation and optimization approach for uncertainty-based short-term planning in open pit mines

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ARTICLE INFO

Article history:
Received 25 December 2016
Received in revised form 6 January 2017
Accepted 3 February 2017
Available online xxxx

Keywords:
Scheduling
Simulation optimization
Short-term planning
Mine operational planning
Truck-shovel allocation

ABSTRACT

Accuracy in predictions leads to better planning with a minimum of opportunity lost. In open pit mining, the complexity of operations, coupled with a highly uncertain and dynamic production environment, limit the accuracy of predictions and force a reactive planning approach to mitigate deviations from original plans. A simulation optimization framework/tool is presented in this paper to account for uncertainties in mining operations for robust short-term production planning and proactive decision making. This framework/tool uses a discrete event simulation model of mine operations, which interacts with a goal-programming based mine operational optimization tool to develop an uncertainty based short-term schedule. Using scenario analysis, this framework allows the planner to make proactive decisions to achieve the mine's operational and long-term objectives. This paper details the development of simulation and optimization models and presents the implementation of the framework on an iron ore mine case study for verification through scenario analysis.

1. Introduction

Planning is a critical component of any successful operation. Accurate predictions of an outcome serve as the backbone of any planning activity. This paper aims to present an approach where discrete event simulation in conjunction with an optimization tool is used to generate robust near-optimal short-term mine production plans. This paper describes how a detailed mine operational discrete event simulation model can be developed, keeping it flexible enough for easy scenario analysis and re-usability over the course of mine life. The paper also presents the modeling techniques for truck haulage, the haulage road network, and interactions with external intelligent decision support systems for operational decision-making. The proposed simulation optimization framework uses a bottom-up approach; it simulates the operations to generate short-term plans within the constraints of the optimal long-term strategic plans. The external decision support system used is a mine operational optimization tool (MOOT) which provides shovel allocation decisions based on a strategic schedule, thus linking operations directly with the strategic schedule to generate uncertainty-based short-term plans.

Open pit mines usually have very large operations consisting of a number of equipment and years in mine life. Huge capital investments, bulk production demand and market dynamics have made it imperative for the mining industry to focus on the practices that will enable a mine to remain competitive over its lifetime. Selection and implementation of best practices require planning. The planning process is carried out in stages, as strategic plans, short-term plans and operational plans based on the planning time horizon. The main objectives of short-term plans are to achieve operational objectives of quality and quantity requirements of process plants and maximum utilization of equipment, and a high level of compliance with the strategic plans. The compliance of short-term plans during operations is essential for compliance with strategic plans to achieve economic objectives of the mine.

Optimal equipment planning is another important part of the process, and can only be realized with efficient utilization of all the assets involved. Optimal use of available equipment is also essential to realize the strategic economic objectives, as approximately 60% of total operating cost in open-pit mines is attributed to truck and shovel operations. The whole planning process to achieve organizational objectives may be moot if short-term and operational plans are inefficient. Short-term planning thus may be regarded as critical to achieve the mine's operational objectives and strategic targets.

Malhotra and List describe the various complexities and challenges faced by planners in the short-term planning process [1]. Most models in literature generally make assumptions to deal with these complexities which limit the practicality of the plans. Henderson and Turek stress that the plans must be practical; otherwise they can pose a limitation on their achievability and

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https://doi.org/10.1016/j.ijmst.2017.12.003
2095-2686/

Please cite this article in press as: Upadhyay SP, Askari-Nasab H. Simulation and optimization approach for uncertainty-based short-term planning in open pit mines. Int J Min Sci Technol (2017), https://doi.org/10.1016/j.ijmst.2017.12.003

the realization of operational objectives [2]. L'Heureux et al. proposed a detailed mathematical optimization model for short-term planning for a period of up to three months by incorporating operations in detail [3]. Gholamnejad proposed a binary integer programming model to solve the short term mine scheduling problem [4]. Similar models have been proposed by Eivazi and Askari-Nasab [5], Gurgur et al. [6], Kumral and Dowd [7] and others for short-term mine-planning accounting for various required details such as incorporating multiple destinations, precedence requirements and multiple competing objectives. Although some of the existing models incorporate various details of the operations, they do not account for uncertainties. Also, the fixed nature of production rates from shovels and the tonnage haulage capacity by trucks limits the achievability of the generated schedule, which depends greatly on the haulage profile, available number of trucks in the system, and the truck-dispatching efficiency. Practical applicability or achievability of the schedules is a major limitation observed in most models. A practical short-term plan would be one that accounts for the shovel movement times and production lost during such movements between faces, equipment failures, equipment availability, real-time grade blending and fluctuations, and changing rates of production from shovels based on their locations, available trucks, haul-road gradients and truck-dispatching efficiency.

Simulation models also find a large scope in the mining industry and are used for prediction-based decision-making for specific problems. Sturgul reviewed the application of simulation in mining in the United States and creditsRist for the first published application of computer simulation in mining [8,9]. Kolonja and Mutmansky, Ataeepour and Baafi and many others have used simulation to prove the positive impact of truck-dispatching strategies in mining [10,11]. Mena et al. used system productivity simulation and optimization framework for truck allocations to maximize the productivity of the fleet in a truck-shovel system of an open pit mine [12]. Awuah-Offei et al. and Upadhyay et al. used simulation to determine the optimal number of truck-and-shovel requirements in open pit mines [13,14]. Similarly, Tarshizi et al. used discrete event simulation to improve the efficiency of truck-shovel operations and Yuriy and Vayenas applied simulation with a reliability assessment model to predict the impact of failures on production, availability and utilization of equipment [15,16]. Most of the simulation models in mining, published in literature, focus on specific problems and do not detail the development of the models as such. Also the models are limited in scope and are designed to tackle specific problems.

Modeling accurate truck haulage systems is crucial to modeling a realistic simulation of mine operations. Most simulation models, as noted by Jaoua et al. [17], model the transportation system as a macroscopic process, which does not account for platoon formations and the interaction of trucks on haul roads leading to decreased travel speeds. But at the same time, incorporating a real-time control in a microscopic process to model truck movements may be resource intensive. In most cases a faster truck slows down to the speed of a leading slower truck and travels in a platoon if overtaking is not allowed, which is the case in most mining systems. Thus, inhibiting the overtaking, forcing the faster truck to move at the same speed as the leading slower truck may be considered sufficient to model the truck haulage system for the scale and objectives of the simulation model presented in this paper. It is also important to model the truck speeds based on haul road characteristics, as trucks don't travel with constant speed throughout the road network. The main parameters affecting the speed of trucks include driver behavior, rimpull curve characteristics of trucks, haul road gradient and rolling resistances, and certain other factors related to safety such as visibility (day and night). The driver behavior is a critical factor which requires a thorough study before modeling it into the simulation. It was considered sufficient to model the behavior of an average driver for all trucks based on historical dispatch data. The truck speeds, thus, are modeled based on rimpull curve characteristics of trucks and haul road characteristics in this paper.

Simulation optimization is a fairly new approach in the mining industry. Fioroni et al. used simulation in conjunction with a mixed integer linear programming model to reduce mining costs by optimal production planning [18]. Jaoua et al. used a simulation optimization approach to develop a simulation-based real-time control tool for truck dispatching [19]. Simulation optimization approach has not yet been used widely in the mining industry, but it shows a great potential for developing robust tools for decision-making purposes.

Conventional planning processes in literature do not provide a direct link between short-term plans and operational executions. It is usually taken care of by the planners. This also leads operational executions to deviate from short-term plans, requiring regular updates of short-term plans in a reactive planning approach. Also, the inherent uncertainties of mining operations and the regular updates of short-term plans instill poor confidence in the plans, hindering confident proactive decision making. Not incorporating trucks and the available haulage capacity is another major drawback in the conventional planning process, which may lead to overestimating production. Also, predicting the time-based fluctuations in head grade and tonnage feed to plants is not possible using the conventional deterministic models.

Most research in the area of short-term and operational planning has been limited to mathematical programming based optimization techniques. But L'Heureux et al. observes that modeling a mining operation in detail by incorporating multiple periods, faces, shovel movements, truck allocations and plants limits solvability because the models are so big [3]. Even state-of-the-art hardware and software will be unable to handle their complexity and size [20]. A simulation optimization approach provides a better alternative to handle this problem: a smaller number of periods can be considered in the mathematical optimization model, and more details can be incorporated within simulation models, providing an opportunity to incorporate all the operational details into the planning process. Also, the proposed approach generates the short-term schedule based on the simulated operations, and thus remains practical and achievable, while providing an opportunity for proactive planning through scenario analysis. This approach also captures the available haulage capacity and truck-dispatching system in place to account for all details of operational executions, along with predictions of the fluctuations in head grade and tonnage feed to process plants.

This paper presents a goal programming based tool, MOOT, for optimal operational decision making and details the development of a discrete event simulation model in Arena which is flexible and reusable over time [21]. The emphasis is on modeling techniques for haul road networks, truck travel and an interaction mechanism to communicate with an external decision support system (MOOT) for optimal shovel and truck allocation decision making. The rest of the paper is structured as follows: the simulation optimization framework is presented first and describes the overall approach, followed by a description of MOOT and a detailed development of the simulation model. The implementation of the simulation optimization model is then presented in a case study, followed by discussion and conclusions.

2. Simulation optimization framework

The overall framework of this research is presented in Fig. 1, which shows the application of an intelligent operational decision-making tool (MOOT) for short-term mine planning and