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Data-driven modeling and simulation framework for material handling systems in coal mines

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ABSTRACT

In coal mining industry, discrete-event simulation has been widely used to support decisions in material handling system (MHS) to achieve premiums on revenues. However, the conventional simulation modeling approach requires extensive expertise of simulation during the modeling phase and lacks flexibility when the MHS structure changes. In this paper, a data-driven modeling and simulation framework is developed for MHS of coal mines to automatically generate a discrete-event simulation model based on current MHS structural and operational data. To this end, a formal information model based on Unified Modeling Language (UML) is first developed to provide MHS structural information for simulation model generation, production information for simulation execution, and output requirement information for defining simulation outputs. Then, Petri net-based model generation procedures are designed and used to automatically generate a simulation model in Arena® based on the simulation inputs conforming to the constructed information model. The proposed framework is demonstrated for one of the largest open-pit coal mines in the USA, and it has been demonstrated that the framework can be used to effectively generate the simulation models that precisely represent MHS of coal mines, and then be used to support various decisions in coal mining such as equipment scheduling.

1. Introduction

Coal production has significantly increased over the past sixty years in the USA, where the amount of coal produced in 2010 exceeded 1085.3 million tons. In electricity generation industry, coal is still the largest power source as over 1400 coal-fired electricity generation units are distributed in the USA and 45% of electricity was generated using coal in 2010 (U.S. Energy Information Administration, 2011). The relatively low price of using coal together with other fossil fuels such as natural gas and petroleum enables the USA industries to be competitive in the worldwide market. Therefore, in many respects coal-mining is the backbone of the USA economy (The Truth about Surface Mining).

In a coal mine, ore is routed from pit or stope to the customer via MHS which consists of several processing and transportation equipment. As shown in statistics, about 40–70% of total production cost for coal mines is constituted by material handling processes (Feng & Zhao, 2010). Therefore, the overall mine production performance highly depends on decisions made for the MHS. More specifically, various decisions are made (e.g. hauler schedule, conveyor connections, blending recipe) in each shift to route coal in a way to satisfy the quality requirements of the coal from customers as well as to maximize productivity in tonnage. However, finding the "optimal" or even good decision variable settings for complex MHS is very challenging. Especially in large mines, there are nearly one hundred decision variables that need to be set. Commercial software such as DISPATCH™ is already available to handle such complex decision problems in mining. DISPATCH™ is based on linear programming and heuristic methods and used to dispatch trucks and shovels to satisfy customer requirements that are indicated through performance metrics such as desired dump rate and blend quality at dumping location (Alarie & Gamache, 2002). But a formal methodology is necessary for suggesting verified decisions including truck locks and conveyor flow routes before they are implemented in software like DISPATCH™. These suggested decisions should be based on high level production goals such as quality delivered to customer trains and total trains filled in each shift. Other than above-mentioned commercial software, mathematical programming-based methods and discrete-event simulation can serve as suggestion methodologies. However, those mathematical programming-based methods cannot capture the detailed randomness within the system or guarantee the accuracy of results since approximations are made in the formulation and solution search procedures for complex MHS. Discrete-event simulation is a powerful decision support tool as it is proven to be effective for capturing high degree of complexity and uncertainty inherent in MHS for

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carrying out what-if analysis (Hunt, 1994). As there is no formal suggestion mechanism available to the industry users currently, the use of simulation for what-if analyses is a much-needed support to their decision making.

Typical simulation modeling and analysis involves various activities such as model development, debugging, verification, validation, and analysis (Law, 2006). Those activities are usually very time-consuming even for a simulation expert (Son, Jones, & Wysk, 2003a). For MHS of coal mines, the above-mentioned, time-consuming activities need to be repeated for modeling different systems (e.g. two different mines) with very similar structures. This is due to the lack of generic information models and libraries of different components of coal mines. In addition, whenever system structure changes such as changing the layout of conveyor belts or shifting crushers in the same mine, it is necessary to update, test, and re-validate the corresponding simulation model. Thus, there is a need for a generic approach for automatically building simulation models of different MHS with similar structures. To address above-mentioned issues, a data-driven modeling and simulation framework is proposed in this paper to address above-mentioned issues.

The data-driven simulation model is defined in Pidd (1992) as the one that is designed to be applicable to systems with similar structures. Compared with typical modeling approach, data-driven modeling approach guarantees low development cost and time since use and maintenance of software are independent of model development (Franz, 1989). In this framework, a formal information model is designed in UML class diagrams as the basis of simulation model generation procedures and input/output data table design. In order to model the MHS in a formal way such that the framework can be reused by different developers, Petri net is selected in this paper as the formalism of modeling MHS. Petri net is a directed bipartite graph which has two types of nodes called places and transitions (Proth & Xie, 1996). As it possesses advantages (e.g. mathematical definition of execution semantics) in modeling and analysis of systems (see Peterson, 1981; Girault & Valk, 2003), model generation procedures are designed based on Petri net model to code automatic model generator (AMG) for automatically generating a simulation model for what-if analysis. The proposed framework is then demonstrated for one of the largest open-pit coal mines in the USA. The framework applies to most surface/underground coal mines around the world. Besides, other types of mines (e.g. metal mines) with the similar material handling processes as specified in Fig. 2 can employ the framework as well.

The reminder of the paper is structured as follows. In Section 2, related works in the literature are summarized on data-driven simulation of MHS in manufacturing. In Section 3, structure of MHS of coal mines and material handling processes are specified, and a formal information model corresponding to the specifications is designed. Then, Petri net-based simulation model generation procedures are designed for coding AMG. The proposed framework is then demonstrated in Section 4 for one of the largest open-pit coal mines in the USA. In addition, solutions to improve simulation speed are also discussed based on the modeling experience of the authors for the considered case study. In Section 5, conclusions and directions for future extensions to the proposed framework are discussed.

2. Literature review

The MHS in manufacturing and mining systems are similar in that they contain material processing, transportation and inventories operations. In the past 20 years, applications of data-driven simulation mainly have focused on MHS in manufacturing. Various commercial simulation packages were employed to implement the models. To name a few, a *model based generic simulation model generator* for manufacturing systems is described in Ozdemirel and Mackulak (1993). The generator is designed using group technology classification scheme to create different model components as modules. A conceptual framework for modeling a manufacturing system and the implementation of model in WITNESS® is discussed in Lee, Cho, and Jung (2000). In that paper, machine-centered part routing graph and transport-tending part routing graph are converted from process plan to generate simulation model. Formal and reusable information model for automatic generation of shop floor control system is proposed by Son and Wysk (2001) and Son et al. (2003a). A systematic framework for the generation of simulation-based shop floor control system is then proposed in Son, Wysk, and Jones (2003b). In that paper, an *Automatic Execution Model Generator* and *Automatic Simulation Model Generator* are developed to generate Message-based Part State Graph-based shop level execution model and Arena simulation model. Various manufacturing systems such as Air Force Wing operation system (Brown & Powers, 2000), home manufacturing system (Nasereddin, Mullens, & Cope, 2002), generic machine shop system (McLean, Jones, & Riddick, 2002) and automotive general assembly system (Wang, Qing, Xiao, Wang, & Li, 2011) have been studied using data-driven simulation. To extend automatic generation approach to system design stage, Computer-Aided Design (CAD) is integrated into manufacturing system simulation model generation by Kim et al. (2009) and Wy and et al. (2011). At the supply chain level, a data-driven simulation method in the design and performance improvement of aerospace sector supply chain, by using company data warehouse to generate and validate Arena simulation model, is implemented in Tannock, Cao, Farr, and Byrne (2007).

Different from the methods used in above reviewed literatures, combination of the following features incorporated in the proposed framework make it unique: (1) comprehensive formal information model is first designed for MHS of both surface/underground coal mines; (2) the simulation outputs are defined in the format that is used in mine data warehouse instead of default statistics outputs from simulation software; (3) users are given flexibility in changing the MHS decision variables during simulation run; (4) the framework has been validated against real historical data from one of the largest open-pit coal mines in the USA and can be used in mine equipment scheduling.

3. Data-driven modeling and simulation

3.1. Overview of data-driven modeling and simulation framework

The data-driven modeling and simulation framework proposed in this paper contains four main stages for its realization: (1) *Develop information model*; (2) *Code AMG*; (3) *Generate generic simulation model automatically*; and (4) *Perform what-if analysis* as shown in Fig. 1.

In the first stage (Section 3.3), information model is developed to describe the information requirements for construction/execution of simulation model and data format for constructing simulation input/output data tables. This modeling procedure depends on the simulation objectives (e.g. detail level of modeling the activities in the system and output data requirements), MHS structure and material handling processes (Section 3.2) described in system specification file. The developed information model needs to be validated and proved generic for the target MHS structure. In the second stage (Section 3.4), simulation model generation procedures are designed and coded in AMG for automatic model generation based on the information model and connections among material handling processes described in system