Mine Schedule Implementation Using a Multi-Agent Based System

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Abstract. Mining is a very capital-intensive business where new ventures or expansion are often based on forecasts for long term profitability. Performance is dependent on how cost effective the mine equipment is from day one. The costs of owning and maintaining capital equipment require effective utilization of the mobile fleet for optimal productivity. The core competency of a mining company is the ability to create the greatest efficiency and lowest cost in meeting production goals. This makes decisions about matching the selection of mine sites, assignment of people and equipment with output rates that satisfy customer demand critical for the success of the business. Sophisticated scheduling that addresses a multitude of constraints and variables for infrastructure, geotechnology and market conditions is required. Traditional systems currently in use today, operate in an iterative mode constantly switching between scheduling and execution. Techniques from Artificial Intelligence (AI) have already been used in Intelligent Manufacturing for more than twenty years. However, the recent developments in multi-agent systems in the new domain of Distributed Artificial Intelligence (DAI) have brought new and interesting possibilities. Agent based computing has been hailed as the most significant breakthrough in software development and the new revolution in software. The agent based system described in this paper can be used to develop mine scheduling solutions that are fully customizable to a number of mining scenarios and provide a much more dynamic scheduling environment than current mine scheduling applications.

Keywords. mine scheduling, agent-based systems, optimization, Contract Net.

1. INTRODUCTION

Decisions in a mining environment nowadays are increasingly tied to reducing operating costs. Improving production, performance, productivity and profitability is crucial. Production, ancillary, plant and shipping equipment need to be monitored and controlled by online systems delivering production statistics and real-time information to everyone involved, including equipment operators. In order to achieve this level of monitoring, information needs to be made available in real time. Sometimes trucks can be queuing at one loader whilst loaders at another location are idle waiting on trucks to arrive. In this situation both the loaders and trucks are being under-utilized. In other scenarios, shovels underloading trucks results in production decreases and if overloaded, may cause damage or premature wear and tear resulting in costly repair bills and excessive down times. If this is allowed to occur on a regular basis without check, the mine may be incurring unnecessary additions to its operating costs without knowing it, costs that could be subtracting millions of dollars from profits.

Traditional systems constantly switch between scheduling and execution modes. Commonly, a mine develops a schedule (using Linear Programming methods) for its haulage operations using prototypical gathered data. However, the real world tends to change in ways that invalidate advance schedules. The weather changes, a truck or loading device breaks down, the digging is particularly hard, a bin gets full because of problems with a down stream conveyor; these are all real problems affecting every single operation on a daily basis. The design plans and targets that have then been set are now invalidated as the system attempts to cope, quite unsuccessfully of course, with the design goal. Natural systems do not simply plan in advance, but adjust their operations on a time scale comparable to that in which their environment changes.

The mine is similar to a factory. The two major inputs - capital and labor - are the same. These are however, combined with a third resource; the geology and geography of the deposit. Nature provides to the mine or mining company, a deposit with certain attributes. Typically these attributes are the number of tones, the amount of waste and the attributes of the ore (quality or grade). In the long-term planning process, capital and labor should be optimized to the geological resource. Once the long-term plan is set, then on a daily basis planning needs to ensure the goal is achieved. Like a factory this involves daily planning, maintenance and resource allocation. Unfortunately however the geology and geography make this daily work complex.

Scheduling software packages available to mining companies nowadays generally cope with these factors and address them through a number of automated or semi-automated tools for mine scheduling and optimization. The output of such systems comes in the form of a sequence of mining related events or activities that can be serial or parallel in their timing.

2. AGENT BASED SYSTEMS IN PRODUCTION PLANNING AND SCHEDULING

Planning is the process of selecting and sequencing activities such that they achieve one or more goals and satisfy a set of domain constraints. Scheduling is the process of selecting among alternative plans and assigning resources and times to the set of activities in the plan. These assignments must obey a set of rules or constraints that reflect the temporal relationships between activities and the capacity limitations of a set of shared resources (Figure 1). The assignments also affect the optimality of a schedule with respect to criteria such as cost, tardiness, or throughput. In summary, scheduling is an optimization process where limited resources are allocated over time among both parallel and sequential activities.

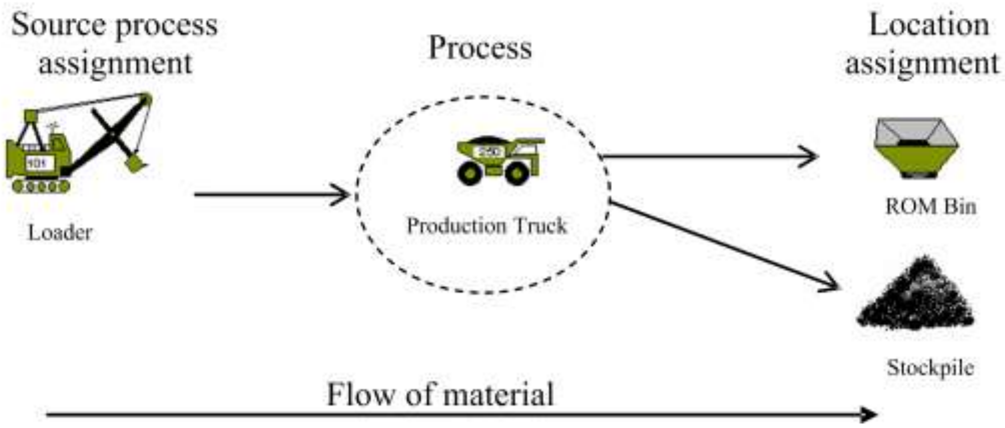

Figure 1. Example of assignment constraints from a mining situation - processes of type 'Production Truck' might be permitted only to receive material from processes of type 'Loader', and dump material to locations of types 'Stockpile' and 'ROM Bin'.

Production scheduling is a difficult problem, particularly when it takes place in an open, dynamic environment such as a mine. In such environments, rarely do things go as expected. The set of things to do is generally dynamic. The system may be asked to do additional tasks that were not anticipated, and sometimes is allowed to omit certain tasks. The resources available to perform tasks are subject to change. Certain resources can become unavailable, and additional resources introduced. The beginning time and the processing time of a task are also subject to variation. A task can take more time or less time than anticipated, and tasks can arrive early or late. Because of its highly combinatorial aspects, its dynamic nature and its practical interest for manufacturing systems, the scheduling problem has been widely studied in the literature by various methods: heuristics, constraint propagation techniques, constraint satisfaction problem formalism, simulated annealing, Taboo search, genetic algorithms, neural networks, etc.

Agent technology has recently been used in attempts to resolve production scheduling problems. Atkins et al. [1] presented an architecture that combines planning and resource allocation algorithms to produce a set of plans which execute in hard real-time on a multi-resource platform and exhibit tolerance to a user-specified set of internal system faults. Frankovic et al [3] developed a market-based distributed production control system based on learning and cooperative agents. Goh et al [6] proposed a manufacturing optimization and configuration approach that integrates a multi-agent bidding mechanism and Monte Carlo optimization methodology. Agent technology has been applied to resource exploration and other mining related fields [4, 5].

3. MINE SCHEDULING

Scheduling is required for the development and production activities in underground and open pit mines. Mine schedules commonly consist of mining block entities with assigned processes. These schedule entities or activities are located in time by a start date and duration or end date. The process assigned to each activity has particular equipment and / or human resources associated with. The objectives of mine scheduling may include maximizing the Net Present Value of the project, providing a balanced work load for the equipment fleets, maintaining required production rates and optimizing the blend of production from two or more pits [8].

Mining is divided into multiple phases including exploration, material extraction (drill and blast, excavation, etc.), hauling the product and waste materials (trucks, conveyor belts, etc.), beneficiation of the product (crushing, leaching, etc.), and shipping the product to the client.

3.1 Processes

These phases can be broken down to smaller more distinct processes. A process is a representation of an entity that performs production-oriented tasks in the real world. The process concept is central to the information model of the mine. Because the processes are the productive or working entities of the mine, the rate or amount of mine production is measured in terms of the work the processes have done. Technically, there are no restrictions on the mine entities that can be set up as processes. Typically, though, the various types of machinery of the mine constitute processes. A process is usually a single piece of equipment or a logical group of equipment that is a part of the productivity or daily operations of the mine. Process types are broad classifications of processes. Table 1 lists examples of process types that might be defined for typical mine operations. Figure 2 also shows a decision tree for selecting processes to be represented in the information structure of a mine.

3.2 Locations

Products and other materials are mined from, hauled to, and stored in various locations within the mine. A location is a representation of a point on the mine map, usually one that is a source or a store of material. These may be in-pit locations where ore is found within the earth, stockpiles used for the storage of mined material, and dumps where waste is deposited. The choice of locations depends on the actual structure of the site and various reporting and monitoring requirements (Figure 3). Typically, locations are in-pits where material is mined from, stockpiles at which material is stacked, bins which are filled and subsequently emptied, dump sites at which overburden is dumped, fuel tanks from where fuel is dispensed, etc (Table 2). Material can change location within a mine using one of the three routes shown in Figure 4.

Open Cut or Underground Metal Mine	**Underground Coal Mine**	**Processing or Beneficiation Plant**
Truck, LHDs, Loader, Shovel, Dragline, Water Truck, Grader, Dozer, Fuel Truck, Fuel Station, Water Truck, Drill Rigs, Bolters, Pump, Crusher, Conveyor	AFC, Hydraulic Power Pack, Belt, Bin, Longwall, Development, U/G Coal, Clearance System, Shearer, Bradford Breaker, Crusher, Stage Loader, Feeder Breaker, Syntron, Continuous Miner, Shuttle Car, Roof Supports, Boot End, Monorail, Personnel Carrier, Surface Coal Clearance System, Fan	Coal Preparation, Raw Coal Transportation, Product Coal Transportation, Reagent, Air Supply, Air Systems, Bins / Hoppers, Boxes, Breaker, Centrifuge, Chute, Classifier, Controls/Instruments, Conveyor, Cyclone, Distributor, Electrical Distribution, External, Feeders, Filter, Flotation Machine, Launders, Lube Systems, Magnet, Magnetic Separators, Piping, Pump, Reclaimer, Samplers, Screens, Sieve Bends, Spiral Loops, Stacker, Sump, Tank, Thickener, Thrower, Ventilation, Water Supply

Table 1. Examples of process types from typical mining operations.

Open Cut Mine	**Underground Mines**	**Processing Plant**
Inpit, Dump, ROM Bin, ROM Stockpile, Inpit Stockpile, Expit Stockpile	Block, Panel, Underground Bin, Ore pass, Stope	ROM Stockpile, Product Stockpile, Circular Stockpile, Rectangular Stockpile, Reject Stockpile, Feed Bin

Table 2. Examples of locations that might be defined for typical mine operations.

The interaction between locations and processes is the key to storing location production information. The movement of material between two locations is logged via the production of one or more intervening processes. Location production information consists of the quantity and quality of material removed from and/or added to each location. For each location it is calculated based on the cumulative production of processes where the location is involved, either as a source or a destination of the process. In a more generalised context, locations can also represent different states of material with no change in their actual position within the mine. For example, in-situ material can be ‘relocated’ to drill and blasted material via a drill and blast process.

As schedules get more short term they also become more dynamic in nature with increasing requirements for close to real time data and input. As the planning time frame becomes shorter, more emphasis must be placed on scheduling downstream operations to ensure production targets are achieved. For many large scale mining operations, key logistical issues ultimately result in short term management nightmares. Agent based systems can provide the link between short-term scheduling and the implementation of constantly updated schedules in the mine using current information from the actual situation in the mine. This is the main aim of the system described in this paper.

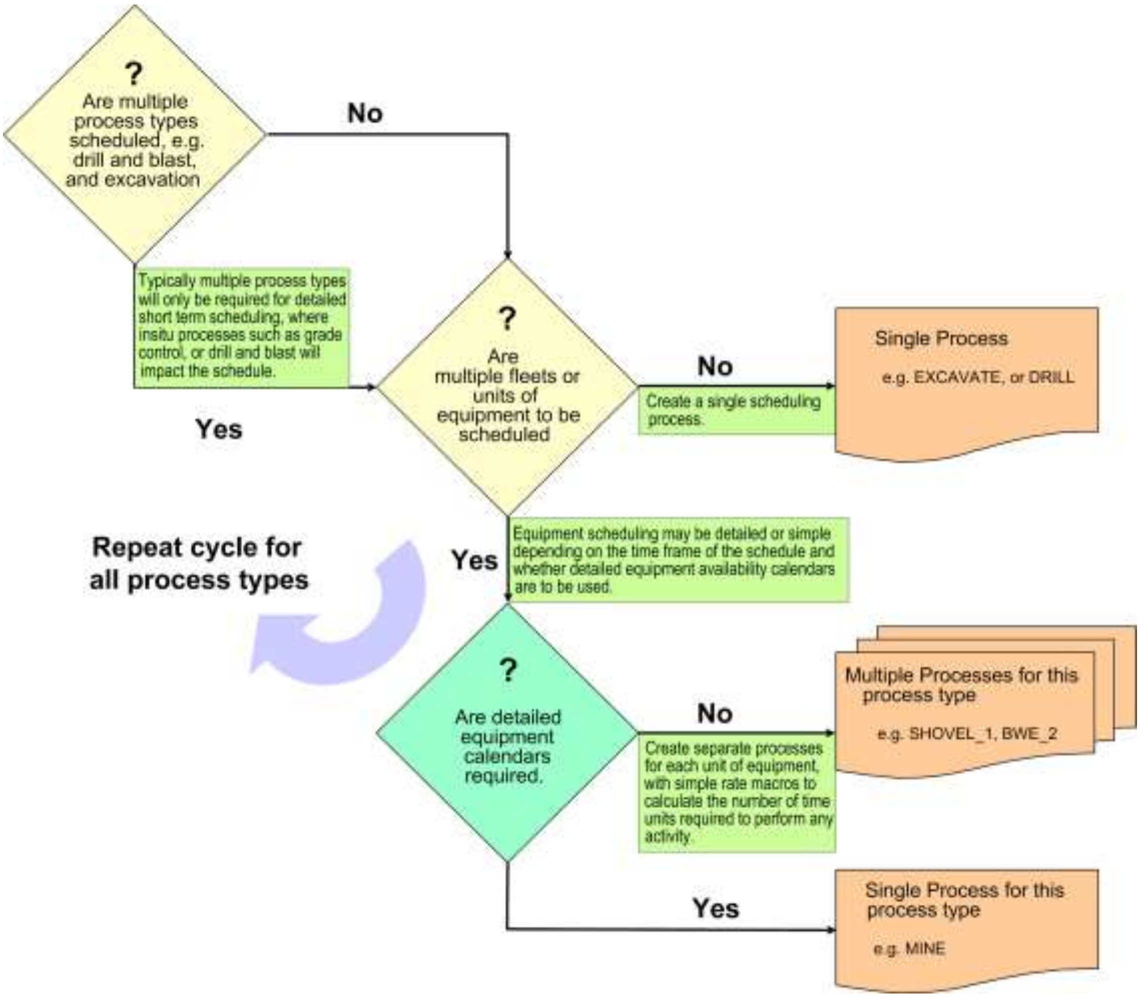

Figure 2. Decision tree for the representation of equipment and human resources as processes in a mine scheduling information structure.

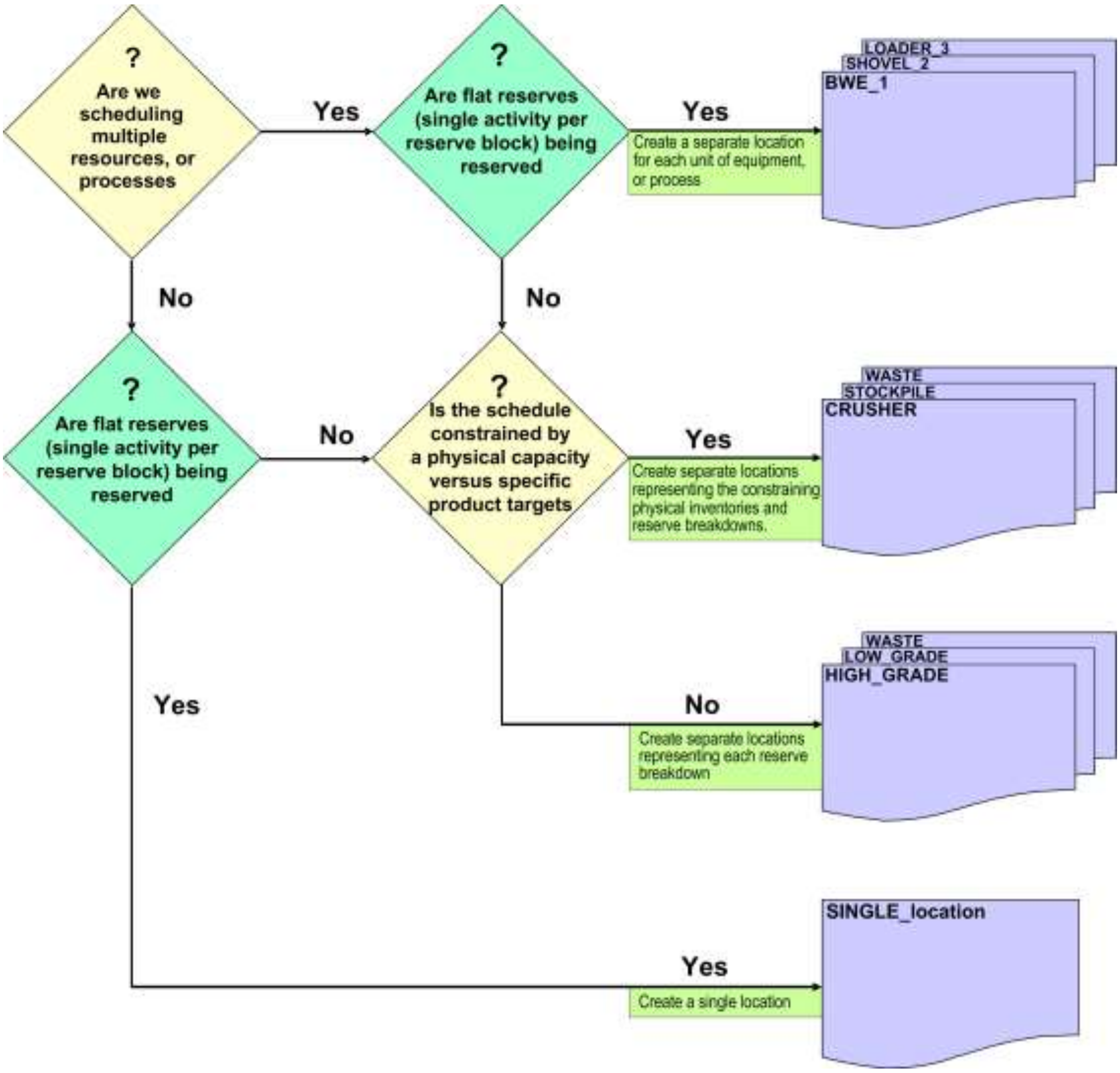

Figure 3. Decision tree for the representation of locations in a mine scheduling information structure.

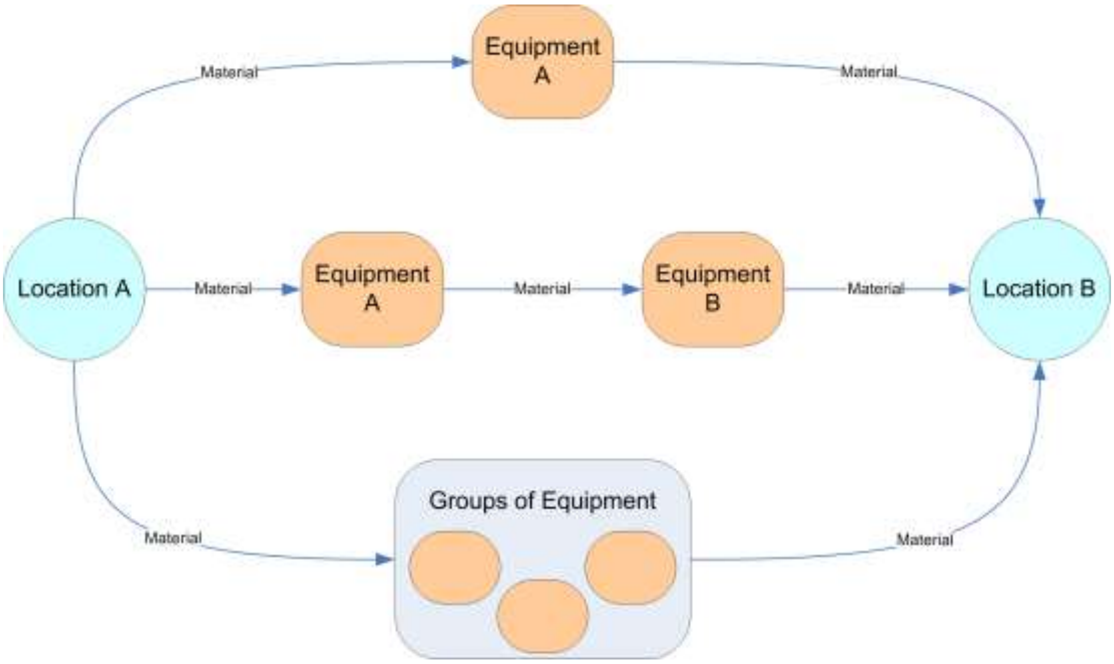

Figure 4. Possible routes of material movement between locations in a mine.

4. AGENT BASED SYSTEM FOR MINE SCHEDULING

In this section we discuss the various components of the agent based system for mine scheduling. The system is currently under development in the Department of Geotechnology and Environment of the Technological Education Institute of Western Macedonia. It consists of the following agents:

a. Static agents for each material state alteration device.
b. Loading agents for each material loading device.
c. Hauling agents for each material hauling device.
d. Service agents for each device that provides service to static, loading and hauling agents.
e. Auxiliary agents for devices performing a function outside of the production process.
f. A system manager agent that receives the required schedule and generates orders.
g. An order co-ordinator agent for each order from the system manager agent.

IBM's Agent Building and Learning Environment (ABLE), a Java framework and component library for building intelligent agents that uses machine learning and reasoning, is used for the development of the various agents (Figure 5). The ABLE framework provides a library of AbleBeans that uses the JavaBeans design. These beans give a wide variety of capabilities, ranging from data import and data transformation to inferencing and machine learning. They can be used for classification, predication, categorization, configuration, performance tuning, problem determination, event correlation, resource allocation, and planning. Their design allows them to be used synchronously or asynchronously (on a separate thread), as well as distributed across different Java virtual machines on the same or different physical computers. AbleBeans can also be extended to add custom functionality, allowing users to create intelligent components with arbitrary complexity. Table 3 shows the various categories of plant and equipment that are typically used within an open cast mine and the corresponding agent types.

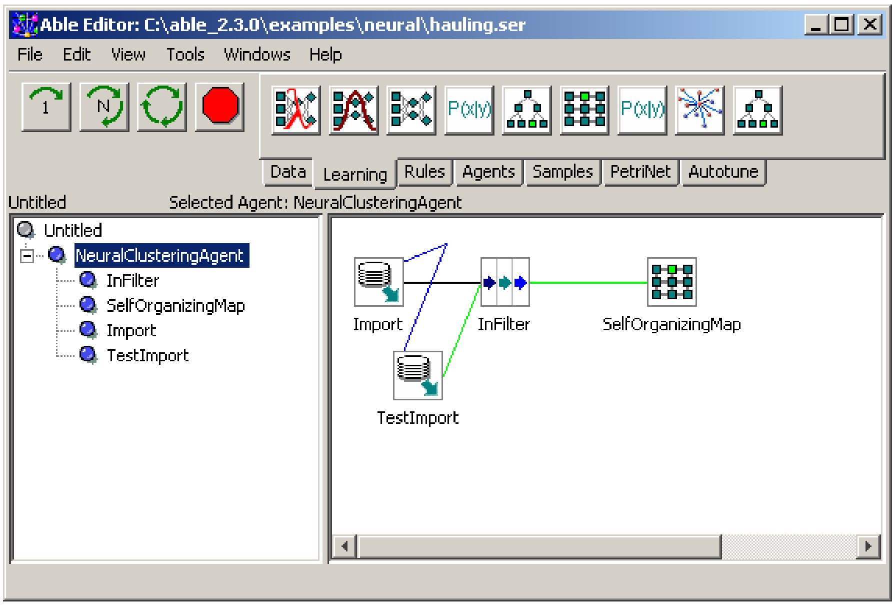

Figure 5. Screenshot from IBM's ABLE agent development environment.

Equipment	**Function**	**Agent Type**
Drill Rigs	To perform the drilling of holes within which explosives are placed	Auxiliary
Drag Lines	Used to move overburden in order to get to the underlying ore	Hauling
Shovels and Loaders	Used to dig and load waste materials or products into trucks	Loading
Trucks	Used to haul material from the pit to stockpiles, hoppers, or dump sites	Hauling
Dozers	To rip and push material into piles	Hauling
Graders	For levelling roads for the transport of material	Auxiliary
Fuel Trucks	To fuel production equipment used within the mine	Service
Fuel Stations	To fuel mobile production equipment and other ancillary equipment such as 4WDs, personnel vehicles, etc.	Service
Water Trucks	For dust control	Auxiliary
Environmental Monitoring Stations	To monitor dust, wind velocity, humidity, etc. to assist with determining when to blast, etc.	Static
Crushers	Used for sizing products appropriately	Static
Pumps	Often used for dewatering operations	Static
Power Substations	For provision of stable power to the enterprise	Static
Conveyors	For moving material within fixed locations	Hauling
Stackers	For placing products on stockpiles	Loading
Reclaimers	For removing materials from stockpiles	Loading

Table 3. Typical equipment used in open pit mining and respective agent types.

4.1 Real Time Information Requirements

One of the key factors to the success of the agent based mine scheduling system is its ability to receive information in real time. This real time capability allows personnel to take corrective measures the moment they are aware of a change in situation rather than being made aware of the problem after the shift when productivity has already been affected. The system, when used in a real world scenario, should be able to acquire data in real time from a variety of devices on board mobile and fixed equipment. Currently there are quite a few companies that design and develop electronic devices and software for interfacing with a variety of devices. For system development purposes, simulated data are used that approach a mine's daily operation, including events such as changing weather conditions, equipment failures and accidents.

4.2 Agent Interaction Protocol

The Contract Net protocol is used for the interaction between the various service, loading and hauling agents, the order co-ordinator agent and the system manager. It is an interaction protocol for cooperative problem solving among agents [7]. It is based on the contracting mechanism used by business to control the exchange of goods and services. The contract net protocol is appropriate for connection problems where we search for appropriate agents to work on a given task [9, 2]. The following actions can be performed by agents interacting with this protocol:

Tenders are initiated by loading agents and announced by the system manager agent. Possibly many Tenders may be announced to generate a complete plan for a planning horizon of duration T at the start of the shift. Additional tenders may subsequently be announced as time progresses to maintain the planning horizon. Tenders for servicing can also be announced by all fuel powered equipment represented in the agent based system.

A ***bid*** is a response to a tender. In this system hauling agents respond to loading tenders with bids. Service agents can also bid for servicing tenders.

A ***contract*** is a commitment to provide a service. In this system, contracts tie the loading device that lets the tender with the successful bidder (hauling device) or a fuel truck or station to a fuel powered device. Hauling agents receive contracts corresponding to specific tenders from the system manager agent. Hauling agents may trade contracts amongst themselves.

An ***offer*** is a proposal from a hauling agent to execute a contract that another hauling agent has committed to executing. In this system, an offer is communicated by one hauling agent to another.

The following is an outline of the system operation. At the start of a shift, each loading agent initiates a tender by creating a tender specification and passing it to the system manager agent. Both at the start of a shift and at points during the course of a shift when multiple tenders are initiated (by multiple loading agents) at the same time, the system manager agent uses the tender priority (defined below) to select the tender to be announced first. The system manager agent announces the bid by making its terms of reference available to every hauling agent. Each hauling agent first determines if it is feasible to bid for this tender (using the bid feasibility computation procedure defined below). If a hauling agent determines that it is feasible to bid for a tender, it communicates its bid to the system manager agent. From the set of bids received, the system manager agent identifies the best bid as the winning bid. The hauling agent making the winning bid is awarded an order, while the remaining bidding agents are told that their bids were rejected. The system manager also informs the loading agent that let the tender of the outcome of the bidding process (i.e., details of the winning bid). Based on the capacity of the hauling device mentioned in the winning bid, the loading rate of the loading device, the start time announced in the tender and the arrive time of the hauling device, the loading agent computes the end time when the loading device would finish loading. If this is less than the current planning horizon of the loader, the loading agent initiates a new bid with a new start time equal to the end time. The process iterates until a plan covering the entire planning horizon is generated.

Agents of the other categories (auxiliary and static) that do not interact using the Contract Net protocol communicate through a Blackboard system where real time data and requests for actions are placed. The role of each type of agent and its operation is analyzed in the following paragraphs.

4.2.1 Loading Agent

The loading agents are generated against loading equipment ready to serve hauling equipment or can simply be issued for all operational loading equipment. Initially, loading equipment not part of the truck dispatch circuit will not have a loading agent announcing contracts. Primary functionality of the agent includes:

- Acting upon orders from the system manager based on mine schedule activities.
- Initiating tenders.
- Maintaining a current plan for the corresponding loading device. The current plan consists of a temporal sequence of contracts issued to hauling agents for servicing the loading device (including orders that have not been successful in attracting a bidder)
- Cancelling contracts in the event of loading device breakdown or slowdown in operations
- Removing completed contracts from the list
- Creating new tenders in the event of better than expected contract execution and there being a sufficient time slot in between to enable an additional load.
- Placing requests for refueling by a service agent.

While no tenders are being floated, the loading agent goes through its period up to the planning horizon, and once again floats tenders for the periods in between when it has blank spots in its loading schedule.

4.2.2 Hauling Agent

The primary functionality of the hauling agent is:

- Maintaining a current plan for the corresponding hauling device. A current plan consists of a temporal sequence of contracts.
- Making bids for announced tenders. If a truck has a locked assignment then it bids only on tenders for the loader it is locked to. In these situations the contract manager agent will realize that this truck should be the preferred bidder.
- Making offers for orders in the internal market.
- Dealing with deviations from the current plan.
- Placing requests for refueling by a service or auxiliary agent.

The following are utilized by the hauling agent to determine if it is feasible to bid in response to a tender or make an offer for an order in the internal marketplace. First the following set of rules must be met:

- Configured assignment restrictions must not prevent the hauling device from being loaded by the loading device.
- The hauling device can arrive at the loading device before the start time of the tender.

4.2.3 Static Agent

This agent is generated against stationary equipment that needs to be monitored. Examples are environmental monitoring stations, dewatering pumps and crushers. Such equipment is crucial for maintaining appropriate working conditions in the mine or for ensuring a continuous production. Static agents can act as sources of real time information or request actions to be taken by agents of the next category (auxiliary agents). For example, a station monitoring dust levels along the haul road can request the dispatch of a water truck.

4.2.4 Auxiliary Agent

Auxiliary agents are generated against mobile equipment such as drill rigs and water trucks. They act upon requests from the system manager that are linked with the production process. Requests to auxiliary agents can also be generated by static agents for environmental control in the mine.

4.2.5 Service Agent

A service agent is generated against equipment, mobile or stationary, that is used to keep loading and hauling devices in operation, such as Fuel Trucks. They are indirectly linked to the production process and for this reason they do not necessarily need to be part of the contract based negotiations. However, if their number is sufficiently high to require better control of their assignments, special service contracts can be generated for them. They receive orders from the System Manager agent following requests by loading and hauling agents for servicing. They also keep track and report on a number of parameters such as operator, status, number of equipment filled/served, and quantities of fuel and other materials dispensed.

4.2.6 System Manager Agent

The primary functionality of this agent includes:

- Converting mine schedule activities to appropriate orders to loading and auxiliary agents.
- Selecting a tender to announce (when multiple tenders are simultaneously initiated).
- Broadcasting tender announcements to all hauling agents.
- Receiving bids in response to a tender.
- Identifying the best bidder.
- Informing hauling and loading agents of the outcome of bids.
- Controlling and acting upon information placed on the blackboard (coordination outside Contract Net) by auxiliary, static and other agents.

4.2.7 Contract and Tender Coordinator Agent

The primary functionality of this agent includes:

- Maintaining the outstanding contracts within the market place (including tenders that have not had successful bidders)

- Receiving and processing offers in conjunction with the System Manager Agent for the order in the internal market.
- Determining the outcome of an offer and re-assigning the contract to a different hauling agent.

4.3 Tender Prioritization

Loading devices are assigned priorities in the system (e.g., a shovel may have priority over a loader). The ordering is partial, i.e. more than one loading device may be assigned to the same priority level (thus making them incomparable under the priority ordering). Priority orderings are represented by integer values assigned to loading devices, with a lower value denoting a higher priority. If more than one loading agent initiates a tender at the same time, the system manager agent selects the tender initiated by the loading agent with the higher priority. If all loading agents in the set of loading agents concurrently initiating tenders are at the same priority level, the tender initiated by the loading agent with the highest difference between target and actual loading rates (if target loading rate is less than actual loading rate) is selected for processing first. If a tie is detected under this criterion, it is resolved with a random choice. These criteria will ensure a degree of load-balancing between loading devices at the same priority level.

5. SUMMARY AND FUTURE WORK

An agent based system is described in this paper that can be used to provide the link between scheduling and the actual production situation in an operational mine using real-time information. This system can help to implement a developed mine schedule by representing equipment resources using agents and converting mine schedule activities to appropriate orders directed to its various agent components.

Future work will include further development of the prototype system using simulated mine schedules and site operation data. The development of such schedules and data is in itself a time consuming aspect of the work as it is very hard to collect appropriate information from existing mining sites. This is the case even in mines with installed dispatch and telemetry systems. Further development is also required of the secondary protocol for coordination outside of Contract Net. The application of the prototype system to mine simulation for equipment selection and mine feasibility study purposes is also one of the main aims for future research. Once the development of the prototype system is complete, it will be possible to test the feasibility of a proposed mine schedule and the sufficiency of selected equipment resources by simulating the mine's daily operation.

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