An Agent-Based System Framework for Dynamic Mine Scheduling

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ABSTRACT

Decisions in the current and future mining environment are increasingly tied to reducing operating costs. Improving 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. Traditional systems currently in use today, operate in an iterative mode constantly switching between scheduling and execution. Techniques from Artificial Intelligence 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 have brought new and interesting possibilities. This paper presents an agent-based system framework for mine planning and scheduling problems with focus on real time fleet management, plant and equipment performance monitoring, downtime and delay reporting, stockpile management, personnel and equipment tracking and product distribution and transportation.

INTRODUCTION

Mine Production and Information Requirements

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 utilisation of the mobile fleet for optimal productivity. 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-utilised. 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.

A key component of any process improvement program is the accurate and timely collection of data relevant to each business unit on the site. Customising the information for effective decision-making ensures that managers, supervisors and engineers are focused towards improving the quality and productivity of each unit as well as profitability of the entire operation. From an efficiency and productivity perspective, personnel must be able to access what the equipment is doing at all times. Real time information will assess whether the equipment is in its optimal utilisation or not. From an information standpoint, personnel such as mine managers, mining engineers, planning managers, MIS managers, production foremen, mechanical and electrical engineers as well as equipment operators can make use of information derived from the real time data to improve the mines overall productivity. It is crucial they are provided the data with which to make informed day to day decisions as well as use suitable key performance indicators in the formulation of long term plans.

Current Systems for Mine Scheduling

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 manufacturing scenario described above is no different to the haulage scenario that every mine is faced with. Market factors constantly change causing different priorities to exist at different times. Some of them that are to be managed include production targets, equipment productivity, production costs (including capital equipment costs, fuel costs, etc), and blend ratios or product quality.

The mine is similar to a factory. The two major inputs - capital and labour - 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 tonnes, the amount of waste and the attributes of the ore (quality or grade). In the long-term planning process, capital and labour should be optimised 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 address these factors through a number of automated or semi-automated tools for mine scheduling and optimisation. 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.

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. The assignments also affect the optimality of a schedule with respect to criteria such as cost, tardiness, or throughput. In summary, scheduling is an optimisation process where limited resources are allocated over time among both parallel and sequential activities.

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 [6] developed a market-based distributed production control system based on learning and cooperative agents. Goh et al [9] 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 [6, 7].

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. Types of schedules include life of mine plan (long term), 5 year plan (long term), annual plan (medium to short term), and weekly and/or monthly schedules (short term).

The objectives of mine scheduling may include [11]:

- providing a steady and balanced ore feed to the mill or a steady blended product such as iron ore for direct shipping;
- maximising the Net Present Value (NPV) of the project by accessing higher grades early and always filling the mill with the best available feed;
- providing a steady, balanced work load for the ore and waste mining equipment fleets;
- deferring the mining of waste as long as possible to minimise the Present Value of the stripping cost;

- defining pushback campaigns to maximise waste mining efficiencies and/or minimise contract mining costs;
- bench widths so that equipment can operate efficiently and safely, and to avoid the need for costly "dozing down" to a lower bench;
- maintaining haul road access to working benches and maintaining an effective sump;
- providing sufficient face length for the design production rate;
- providing time in the mining cycle for grade control and for opening up a box cut on a new bench;
- optimising the blend of production from two or more pits while managing active and low-grade stockpiles.

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.

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. The choice of equipment or groups of equipment and other resources that should be represented in the mine schedule - though not an easy one - can follow a certain logical procedure as described in a schematic form in Figure 1. Process types are broad classifications of processes.

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 of the following types:

- In-Pit Locations – These are the locations where ore is found within the earth.

- Stockpiles – Used for the storage of mined material.
- Dumps – Locations where waste is deposited.

Again, as in the case of processes, the choice of locations depends on the actual structure of the site and various reporting and monitoring requirements. From a scheduling point of view, a decision process like the one presented in Figure 2 can be followed in choosing locations.

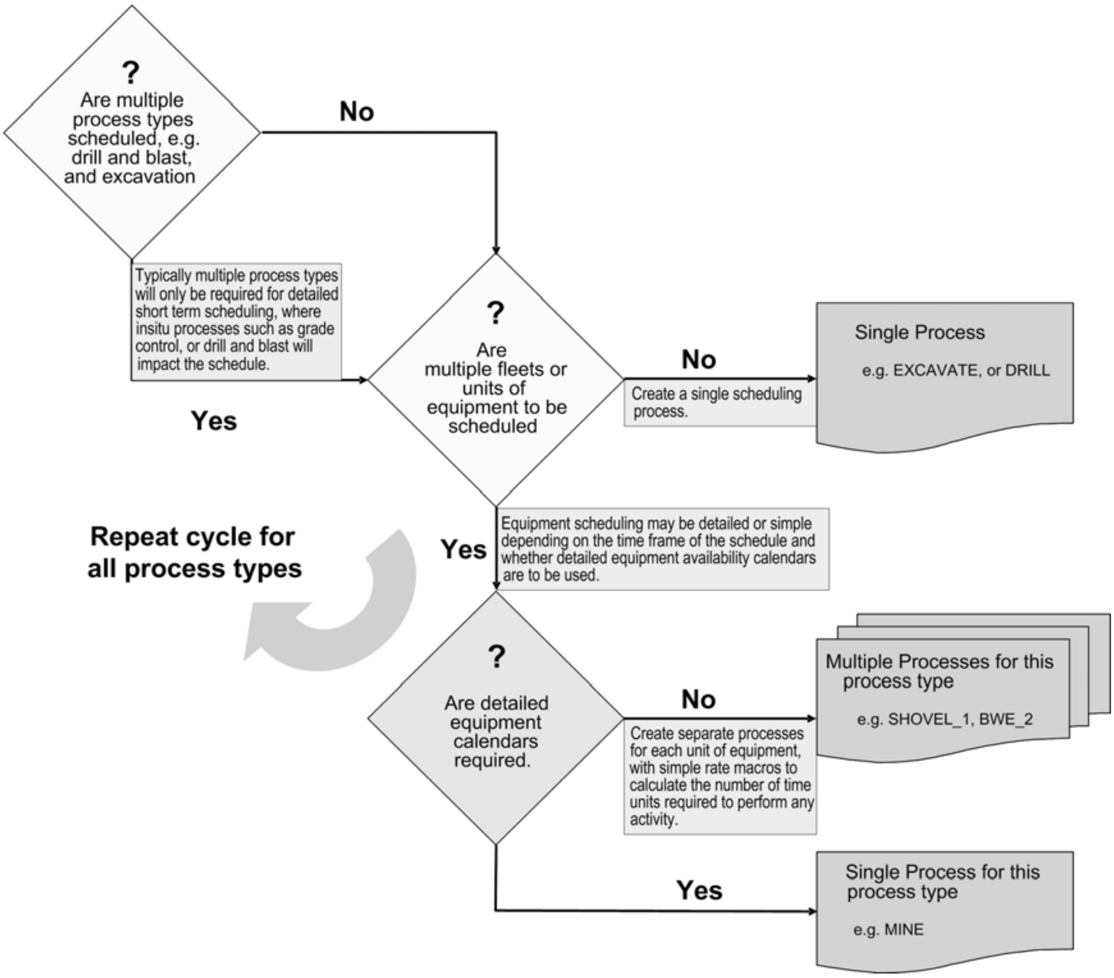

Figure 1: Decision tree for the representation of equipment and human resources as processes in a mine scheduling information structure.

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. Many of these will be of interest to the site as they are a resource from which material is taken out or accumulated in, and it may be necessary to maintain statistics on them. Material can change location within a mine using one of the three routes shown in Figure 3.

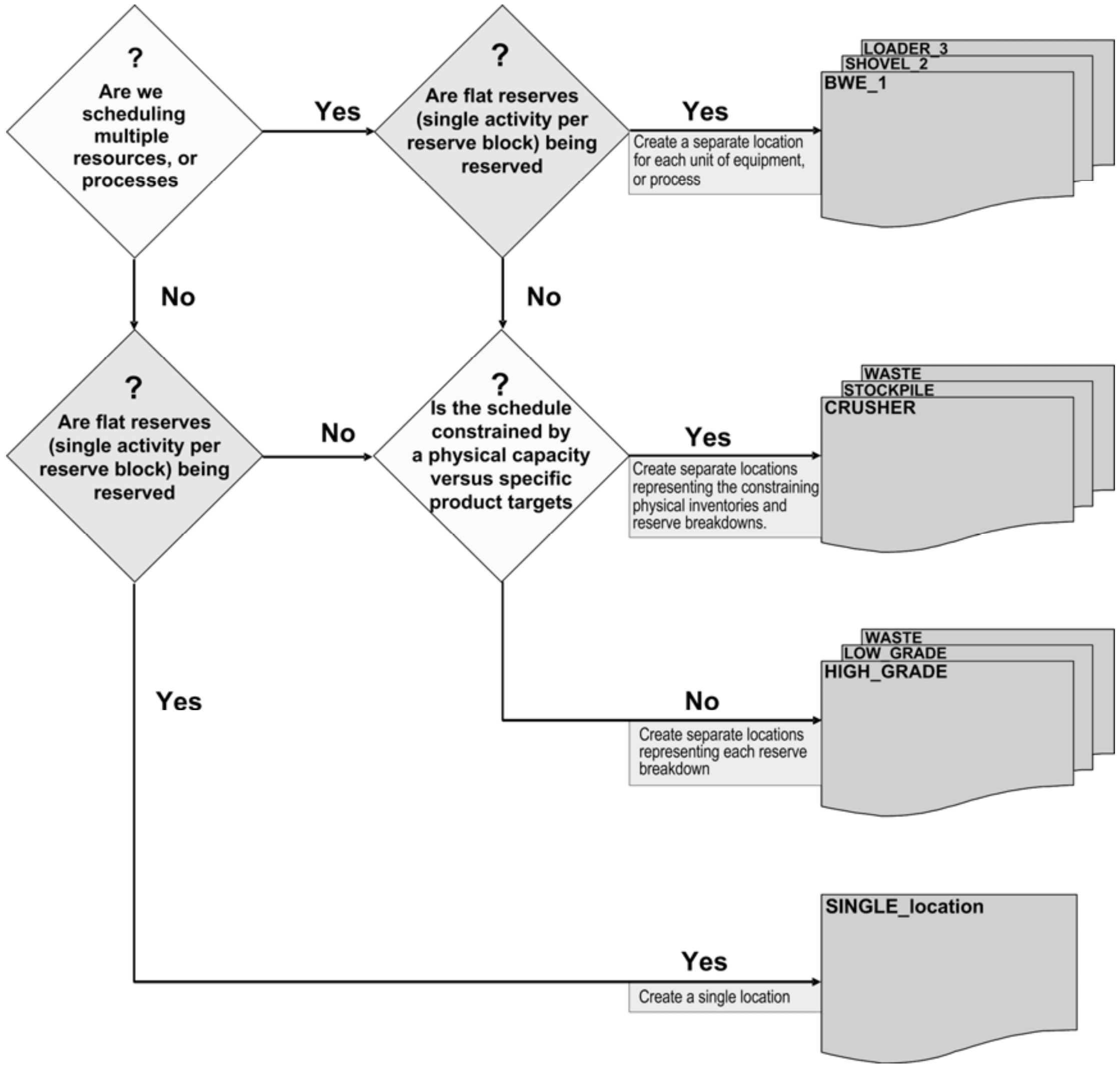

Figure 2: Decision tree for the representation of locations in a mine scheduling information structure.

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.

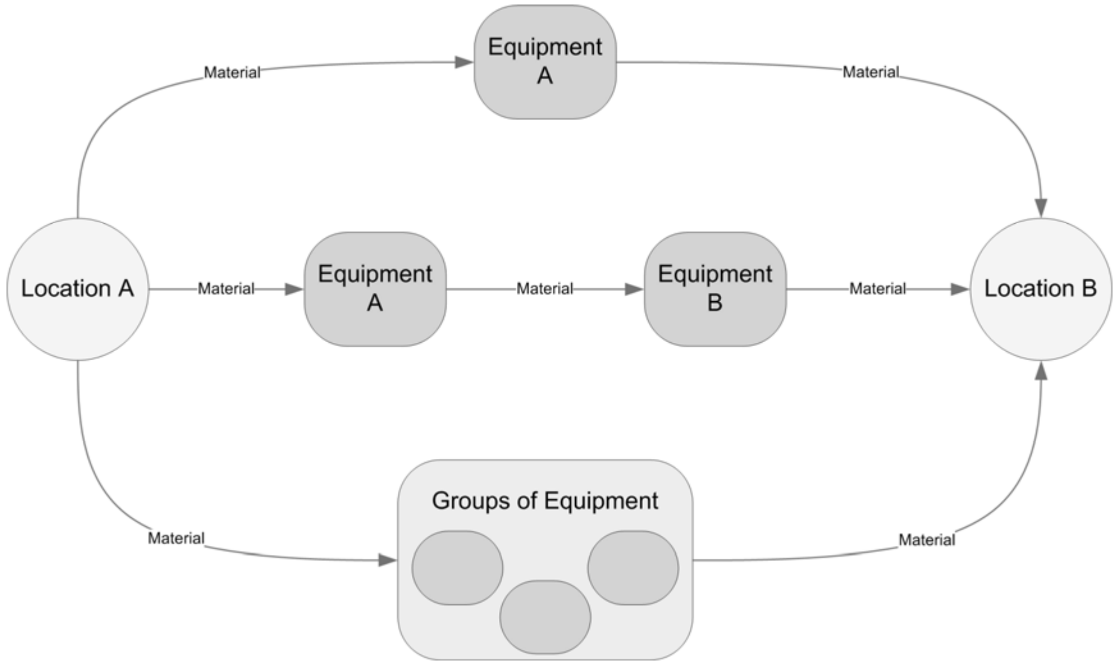

Figure 3: Possible routes of material movement between locations in a mine.

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.

AGENT BASED SYSTEM FRAMEWORK FOR MINE SCHEDULING

In this section we discuss the various components of the agent based system framework for mine scheduling as well as the position of the system in the enterprise information structure. Figure 4 presents in a simplified form the information structure of a mining enterprise. The level of information is increasing going up the structure, while the level of control is increasing going down. The proposed agent based system would be placed between the strategic planning level (top) and the control and data acquisition level. From the perspective of running the mine on a shift by shift basis Levels 1 and 2 are extremely important. From the point of view of planning and making strategic decisions to improve the overall productivity and profitability of the mine, Level 3 is essential.

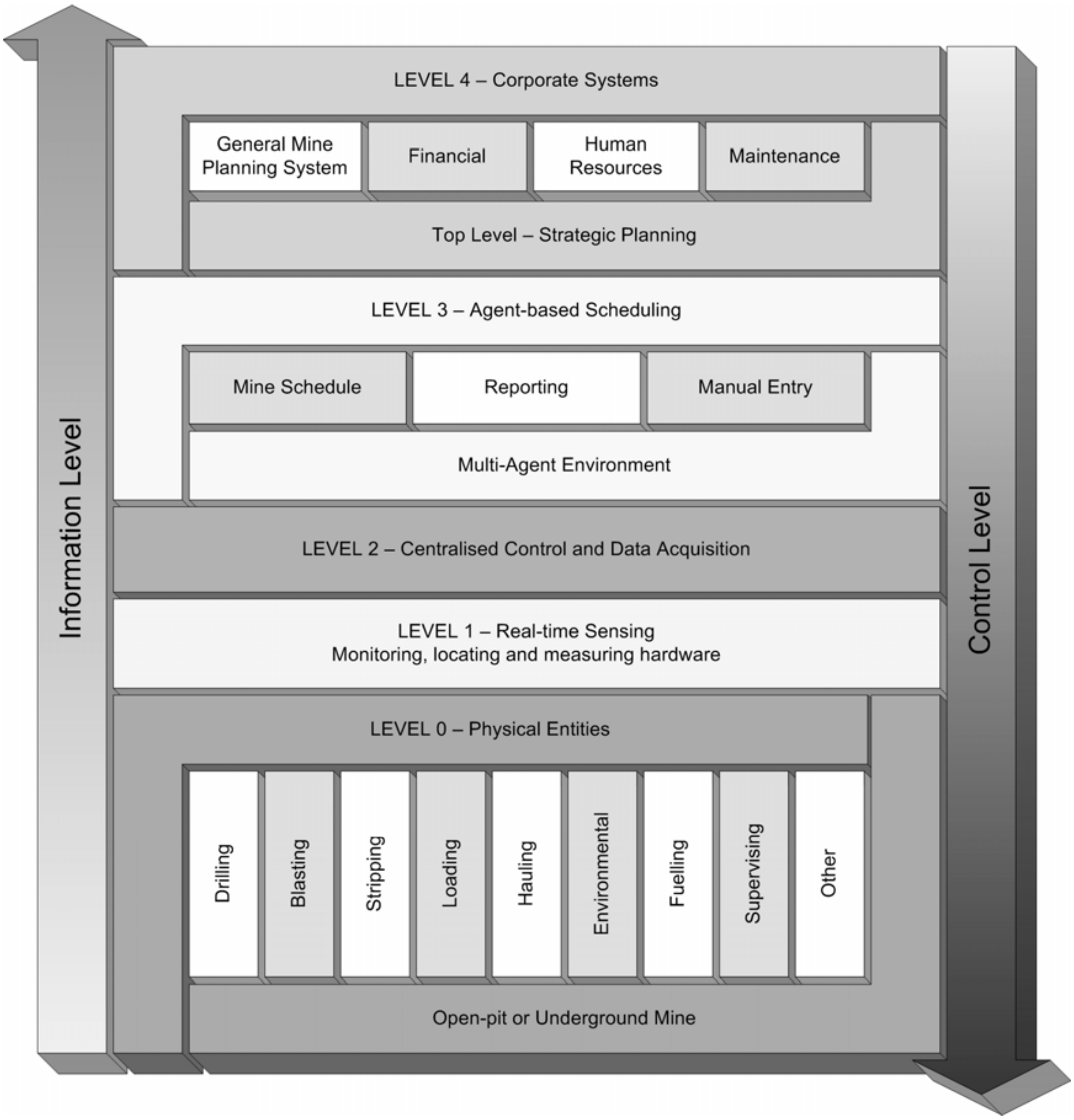

Figure 4: Simplified diagram of information and control level structure in an agent based mine planning and scheduling system.

The agent based system consists of the following types of agents:

- agents for material state alteration devices (static agents)
- agents for material loading devices (loading agents).
- agents for material hauling devices (hauling agents).
- agents for devices that provide service to static, loading and hauling agents (service agents).
- agents for devices that perform a function not directly related to the production process (auxiliary agents).

- a system manager agent that receives the required schedule and generates appropriate orders.
- order co-ordinator agents for each order from the system manager agent.

Table 1 shows the various categories of plant and equipment that are typically used within an open cast mine and the corresponding agent types.

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 1: Typical equipment used in open pit mining and respective agent types.

Real Time Information Requirements and Sources

One of the key factors to the success of an 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 should be able to acquire data in real time from a variety of devices on board mobile and fixed equipment (Figure 5). Currently there are quite a few companies that design and develop electronic devices and software for interfacing with a variety of devices. Typical functionality performed by such devices includes:

- Graphic touch screen for operator information and interaction.
- GPS or tagging systems to allow the positioning of field equipment.
- Payload monitoring systems to allow the recording of actual production quantities.
- Engine management to assist with interrogation of breakdowns, cycle information and record maintenance information.
- Programmable Logic Controllers (PLC's) to get crusher rates, power management, maintenance and control information etc.
- Dust monitors and weather stations for environmental monitoring.

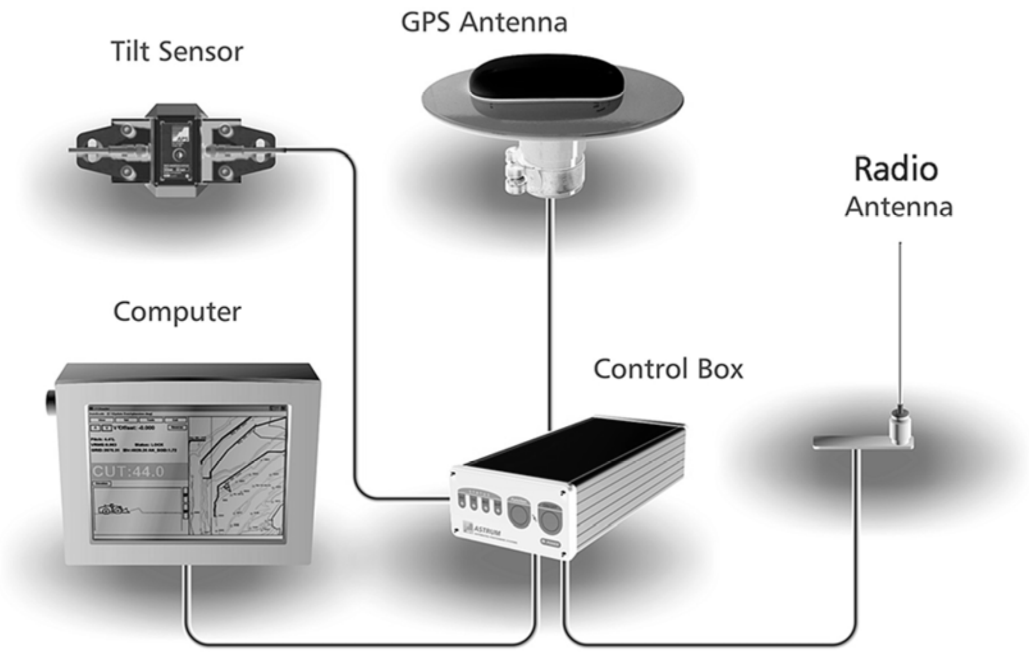

Figure 5: Schematic diagram of hardware on mobile equipment.

Agent Interaction Protocol

The Contract Net protocol is suggested 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 [10]. 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 [12, 5]. It is the protocol in use by an existing agent-based dispatching system for the mineral extraction industry, MineSuiteTM from Advanced Systems Integration Pty. Ltd. [2, 3, 4]. MineSuiteTM uses agents for the control of haulage operations in a mine. 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 possible 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.

If there are no bidders for the tender then the loading agent withdraws the tender and floats the next tender for a short time later. This process continues till the end of the planning horizon. 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.

When no Tenders are currently active, an internal market is initiated for hauling agents to trade orders. An order co-ordinator agent exists for every valid order within the system that is not already being serviced or completed. An order co-ordinator agent makes the details of its order publicly available. Hauling agents iterate through the list of all orders. For each order, a hauling agent uses a bid feasibility computation procedure to determine if it is able to service the order. If this is the case, it communicates an offer to the order co-ordinator agent. When the order co-ordinator agent receives an offer for an order, it passes it in turn to the system manager which uses its usual process to compute if the new bidder is more suited to executing the contract. If the system manager feels that the new hauling device is better suited to servicing the order using its configured methodology of determining the best bid, it notifies the loading agent. The loading agent then notifies the hauling agent which lost the contract and suitably amends the contract. Each transaction initiated by an offer being made to an order co-ordinator agent is treated as atomic, i.e. no other offers are concurrently dealt with during the processing of the transaction.

Agents of the other categories (auxiliary and static) that do not interact using the Contract Net protocol can communicate through a Blackboard system where real time data and requests for actions are placed or a coordination protocol.

Tender Prioritisation

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 uses the following procedure to select the tender that is announced first:

- If a loading agent exists (in the set of loading agents concurrently initiating tenders) whose priority level is higher than that of all other loading agents initiating tenders at that time, the tender initiated by the higher priority agent is announced and processed first.
- 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.

SUMMARY AND FUTURE WORK

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. The agent based system framework 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.

Future work will include the development of a prototype system using agent development tools and its application on 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 work is also required in the development of the secondary protocol for coordination outside of Contract Net. While Contract Net seems a natural choice for the interaction protocol between hauling and loading agents, further system development will be necessary for the coordination of auxiliary, static and service agents.

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 prototype system becomes available and operational, 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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