



# Optimization of an autonomous vehicle dispatch system in an underground mine

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## Synopsis

The mining industry has much potential for automation. A great deal of work has been done on this subject and is still ongoing. With automation comes the possibility for optimization, because more information is available and actions can be repeated with more accuracy. This paper looks at possible solutions to the problem of optimizing the autonomous vehicle dispatch system in an underground mine. Possible optimization strategies are evaluated using a simulated environment. The majority of the results indicate that improvements on current methods are possible.

**Keywords:** mining automation, simulation, vehicles, dispatching strategy, optimization.

## Introduction

Automation in the mining environment is a field that enjoys considerable attention. Because of the hazardous environment, a strong drive exists to have as little human presence underground as possible. Many factors make automation underground a challenging prospect. These factors include difficulty in collecting and distributing data. Mining automation in general and the challenges accompanying it are described in Pukkila and Särkkä (2000). This paper focuses on a block cave mining scenario where vehicles such as load haul dumpers (LHD) and trucks are used to collect and transport ore underground. A typical LHD can be seen in Figure 1.

LHDs are used to load and transport ore from the areas where it is fragmented by blasting (or caving in the case of a block cave mine) to transfer points, from where it is either processed or transported further.

The problem of mathematically modelling the motion (including slip) of an LHD, is addressed in Yavin (2004) and Dragt *et al.* (2004), where comprehensive mathematical models are proposed and simulated. More information on the automation of LHDs can be found in Steele *et al.* (1993) and Scheding *et al.* (1999).

As a result of the automation process, the availability of data (from local sensors on vehicles and global sensors) increases and a

central point of control and monitoring can be established. The next step must be to find ways of using this data to optimize the control algorithms to ensure higher productivity. The increase in productivity must be high enough to justify the cost of establishing and running the various automation systems. In this paper it is assumed that the vehicles are fully automated and a central point of control and data collection exists. The aim is to outline work done on the optimization of the vehicle dispatch system in an underground mine. Therefore, there will be no further discussion concerning automation, but it must be kept in mind that it is needed as a foundation for optimization of the dispatch system.

A great deal of work has been done regarding scheduling and optimization in a vehicle dispatch system. The publications related to this subject that were found are predominantly from the fields of manufacturing and automated road traffic. Examples of this can be found in Evers and Koppers (1996) and Smith and Sarin (1992). The application of these techniques to the underground mining environment is, however, limited. Most research is still done on the automation of vehicles, and the dispatching currently relies mostly on human discretion and experience. Mines are increasingly being automated as technology develops. This will lead to an increase in the need for optimal use of the available information and control possibilities. With the existing infrastructure it will then be very cost-effective to implement some strategy to make optimal decisions possible. The work described in this paper will therefore become more applicable as automation in mines develops, but it can also provide benefits, in terms of decision making, in any mine where some sensing capabilities are available, even if the vehicles are manually operated.

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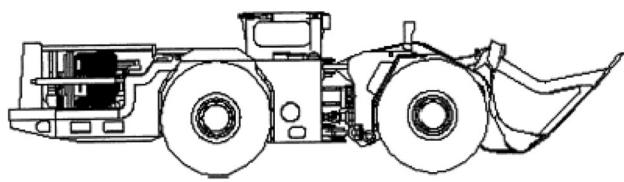


Figure 1—A typical LHD (side view)

## System modelling

A system of vehicles in an underground mine can be described as a hybrid system. A hybrid system is a dynamic system composed of discrete and continuous states. A more complete and generic definition of hybrid systems can be found in Tomlin *et al.* (2000). Autonomous vehicles can be in one of a number of discrete modes (states). In each of these modes the behaviour of the autonomous vehicle is governed by continuous dynamics. Examples of states that are typically found in a mining environment are: loading, off-loading, refuelling, etc. Another state is when the vehicle is in transit. In this state it is obvious that the movement is governed by continuous dynamics. In a state like loading there is limited movement of the vehicle as a whole, but the continuous dynamics can be found in the movements associated with the scooping up of ore (by LHD) or the tilting of a bucket (by truck). In Bemporad *et al.* (2000) a simple temperature control system is used as an example of a hybrid system.

The graphical representation of the temperature control system is called a hybrid automaton. The hybrid automaton representing the dispatch system of the vehicles in an underground mine, can be seen in Figure 2 and Figure 3. These figures serve only to give a better understanding of the operation of the system. The simulations that will be discussed later are built on hybrid system principles, but not based on a specific mathematical model.

## Simulations

The simulations discussed in this paper are done in Matlab<sup>\*</sup>.

### Description of environment

The simulated environment is based on the layout of a diamond mine implementing a block cave mining technique. The specific details of the type of the mining technique are not important for the scope of this research. The principles used in the dispatching of vehicles will be very similar for many different types of mines and mining techniques. The results discussed in this paper are therefore not limited to this specific mining scenario.

A graphical representation of the simulation environment is shown in Figure 4. It can be seen that the movement of the vehicles is confined to tunnels. The possible routes between different points are therefore fixed. The simulation environment has 7 tunnels that are in production with 15 drawpoints between each pair of tunnels. These numbers closely reflect real-life mining environments.

The basic operation of the simulated mine is as follows: Ore collects at the drawpoints because of blasting and caving. The ore is loaded by LHDs and transported to the transfer points. At the transfer points an LHD dumps its load into a truck. After the truck has received enough loads to fill its bucket, it transports the ore to the crusher. The load is dumped into the crusher, from where the ore is crushed and processed further. The simulation is only concerned with everything from the point where the ore is available at the drawpoint until it is dumped into the crusher. The main objective is to test different dispatching strategies to determine if the movements of the vehicles can be optimized. With optimization is meant that the strategies improve on the current dispatching scheme in terms of specific evaluation criteria. These criteria are discussed below.

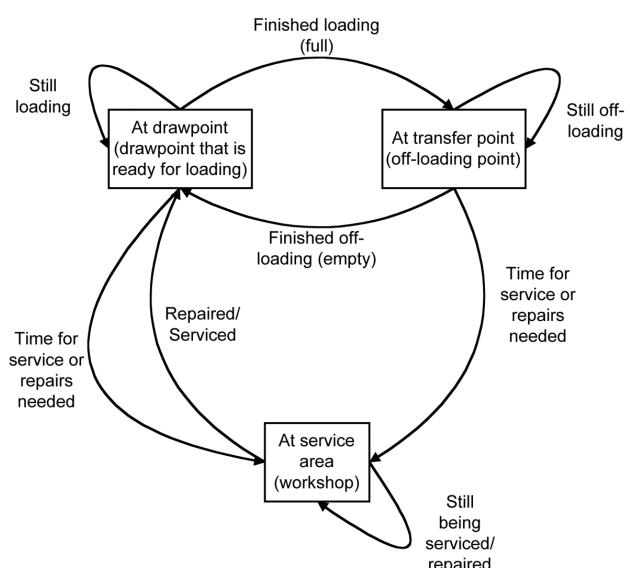


Figure 2—Automation for LHD dispatching: the Figure shows a simple representation of the different states of each LHD in the underground mine environment as well as the transition between states, and the requirements for each transition are given beside the arrow

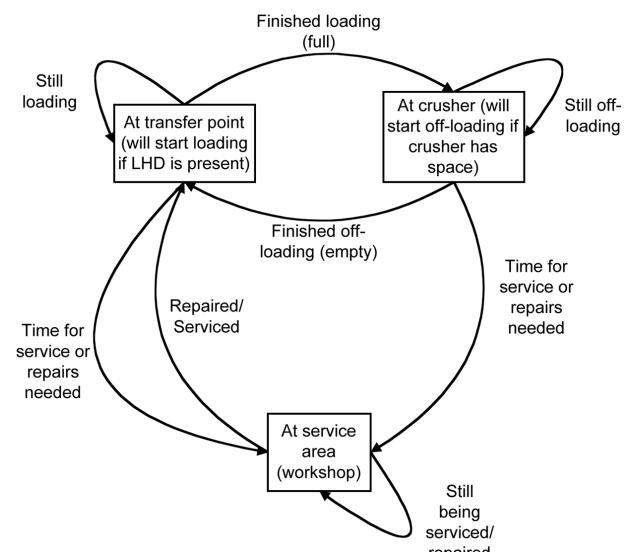
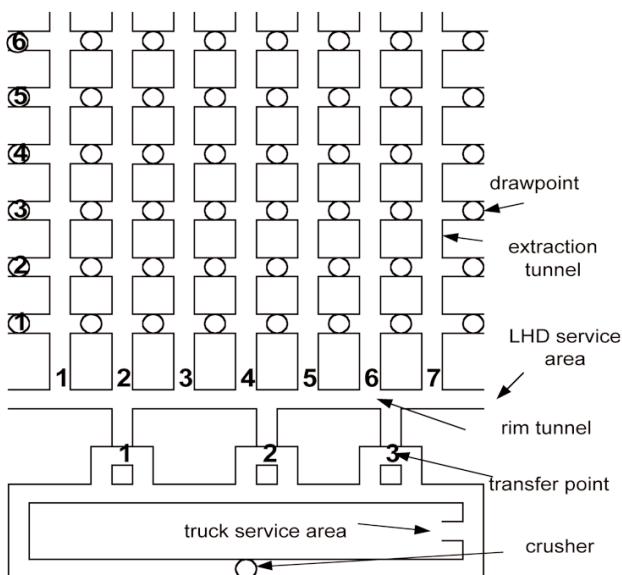


Figure 3—Automation for truck dispatching: the Figure shows a simple representation of the different states of each truck in the underground mine environment as well as the transition between states, and the requirements for each transition are given beside the arrow

\*Matlab: A technical computing language. The MathWorks, Inc.

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**Figure 4—Simulation environment:** the tunnel outlines can be seen and the circles represent drawpoints. The circle at the bottom represents the crusher, and the loop at the bottom is the tunnel connecting the transfer points with the crusher (this is not drawn according to scale)

## Collision avoidance

The assumption was made that the tunnels in the simulation are too narrow for vehicles to pass each other. Vehicles moving in the same direction, with not too much of a difference in velocity, can be in the same tunnel at the same time, but in other scenarios some form of collision avoidance is needed. It is also important to note that only one LHD is allowed in a specific extraction tunnel (Figure 4) at one time. This is because the back-end of an LHD protrudes into the extraction tunnel while it is loading, and therefore another LHD cannot pass. This means that the majority of the collision avoidance is done in the rim tunnel (Figure 4) and where an extraction tunnel intersects the rim tunnel. Figure 5 illustrates the scenarios where the collision avoidance principles are implemented in the simulation. The collision avoidance is implemented identically for all the dispatching strategies discussed later. It will not be explicitly mentioned again, but nevertheless it is a crucial part of most of the vehicle movements. An example of a collision avoidance strategy for an automated guided vehicle (AGV) system can be found in Ho (2000).

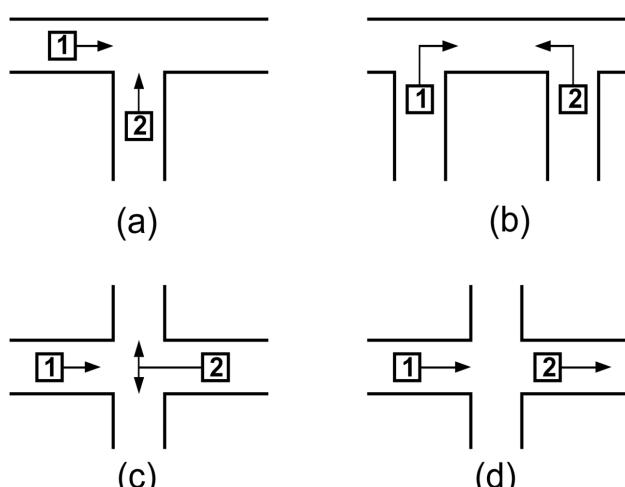
Closely related to collision avoidance is obstacle avoidance. In the simulation the assumption was also made that the tunnels are clear of any stationary obstacles. In a real mine it might happen that stationary obstacles exist (temporarily or permanent). A good example is a vehicle that breaks down. However, it was assumed that when a vehicle breaks down it could move to the service area immediately in some or other way. Therefore obstacle avoidance is not taken into account, but only collision avoidance between moving vehicles. In Xu *et al.* (2003) the problem of obstacle avoidance in underground navigation is addressed. It must, however, be said that all the vehicles must avoid the tunnel walls, which can be regarded as obstacles.

The scenarios shown in Figure 5 will now be discussed shortly:

- (a) Vehicle 1 is moving in the rim tunnel and vehicle 2 wants to enter the rim tunnel from an extraction tunnel. To avoid a collision, vehicle 2 must wait until vehicle 1 has passed the intersection before it can enter the rim tunnel
- (b) Vehicle 1 and 2 want to enter the rim tunnel at the same time, and their intended directions will cause a collision. To avoid a collision one of the vehicles, in this case vehicle 2 (the one with the higher number), must wait until vehicle 1 has passed the intersection where vehicle 2 is situated
- (c) Vehicle 1 and 2 are in the rim tunnel and moving towards each other. The positions of the vehicles ensure that a collision is inevitable if neither of them takes evasive action. To avoid a collision the following possibilities exist: If both of them can stop before they pass the destination intersection (intersection where the vehicle must turn) of the other vehicle, then vehicle 2 stops and waits until vehicle 1 has turned out of the rim tunnel. If one of them has already passed the destination intersection of the other vehicle, then it will just carry on while the other vehicle stops before the intersection until the rim tunnel is clear. If both are past the other vehicle's respective destination intersection, then one of the vehicles must reverse so that the other can reach the intersection, and wait until the rim tunnel is clear
- (d) Both vehicles are moving in the rim tunnel in the same direction. To avoid a collision, a safe distance must be defined that has to be present between the vehicles. This is achieved by just controlling the speed of the following vehicle (vehicle 1 in Figure 5).

## Generating initial conditions

To obtain relevant results, the simulation conditions must be as realistic as possible. Included in the simulation is the random occurrence of hang-ups. A hang-up occurs when a



**Figure 5—Collision avoidance:** the Figure indicates the position of the vehicle in relation to an intersection, as well as the direction of movement of each vehicle. This Figure is intended to illustrate the concept of collision avoidance and not to accurately reflect the layout of the mine

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rock is too big and gets stuck in the funnel above a drawpoint. This requires additional drilling and blasting before a drawpoint can be active again. In the simulation random hang-ups are generated according to a probability distribution based on historical data from a physical mine.

The servicing and repairs of the vehicles are not included in the simulation. This is not that unrealistic because the simulation is run for only one week of production. Vehicles can easily run for a week without a breakdown, or being serviced. The fuel consumption and refuelling of the vehicles are, however, included in the simulation.

Realistic initial conditions for further simulations were obtained by running the simulation for a week of production. A week of production stretches over 5 days, 24 hours a day. This was done from a zero state, i.e. the crusher level was at its minimum and the total loaded from each drawpoint was zero. Random hang-ups were generated. The rules for dispatching of the vehicles closely followed that which is currently found in physical mines. The LHDs are each assigned to a specific tunnel, and visits the active drawpoints, in that tunnel, sequentially. After each drawpoint an LHD visits a transfer point to off-load before moving on to the next drawpoint. The trucks move in only one direction around the loop (seen in Figure 4). A truck stays at a transfer point until it has received enough loads to fill it up, and then moves to the crusher. If all transfer points are occupied then the trucks that finished dumping into the crusher must wait.

The values of all the relevant variables were saved and used as initial conditions for further simulations.

## Performance evaluation criteria

The major objective of most businesses is to maximize profit. A mine is no exception. Therefore one of the most important evaluation criteria for the dispatch system simulation is the production achieved, as there is usually a strong link between maximum production and profit. This is measured in terms of the total tons of ore drawn, or equivalently the total tons dumped into the crusher. The main objective of the different dispatching strategies is therefore to maximize the total tons produced.

Another important objective specific to a block cave mine, is to keep the ore level above the drawpoints as even as possible. To achieve this, the visits to active drawpoints must be scheduled so that the ore level is evenly drawn, and hang-ups must be cleared as soon as possible. The effectiveness of the different simulated strategies is therefore also evaluated according to the variation in the ore level over the active mining area. A lower variation increases the possibility of maximum future production.

A crusher shutdown occurs when the crusher runs empty for a predetermined time. The last objective is to have as few crusher shutdowns as possible. To achieve this, the arrival of the trucks at the crusher must be spaced evenly with long enough intervals so that the trucks don't have to wait, but also short enough so that the crusher does not run empty. Therefore the last objective of the simulated dispatching strategies is to minimize the number of crusher shutdowns.

## Dispatching strategies

The generated initial conditions were used as a starting point for the simulation of each of the strategies discussed below. All the drawpoints were made active at the start, i.e. all hang-ups were assumed to be cleared. All the simulations were run for the equivalent of one week of production.

### Strategy 1

This strategy is the same as the one used to generate the initial conditions. The results obtained with this strategy are used as the base case against which the rest of the results can be evaluated. Figure 6 illustrates the LHD movements of this strategy, and Figure 7 the truck movements.

### Strategy 2

This strategy is exactly the same as the first one, but the order in which the LHDs visit the drawpoints is reversed for every other tunnel. In other words, an LHD will start from the nearest drawpoint and the LHD in the next tunnel will start from the furthest drawpoint. The LHD movements of Strategy 2 are illustrated in Figure 8. This strategy is aimed at keeping the ore level above the drawpoints more even, while still obtaining maximum production.

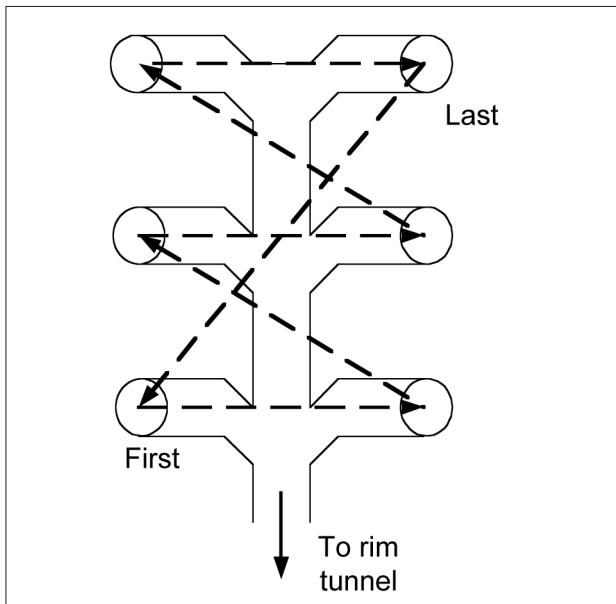


Figure 6—LHD movements of Strategy 1

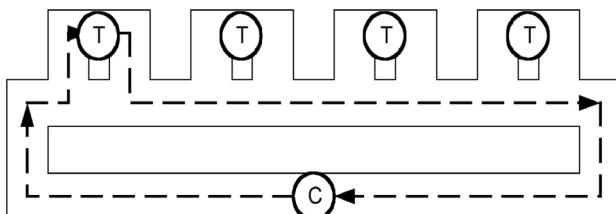


Figure 7—Truck movements of Strategy 1

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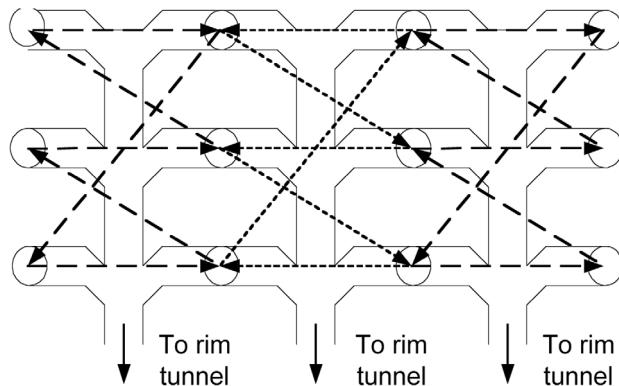


Figure 8—LHD movements of Strategy 2

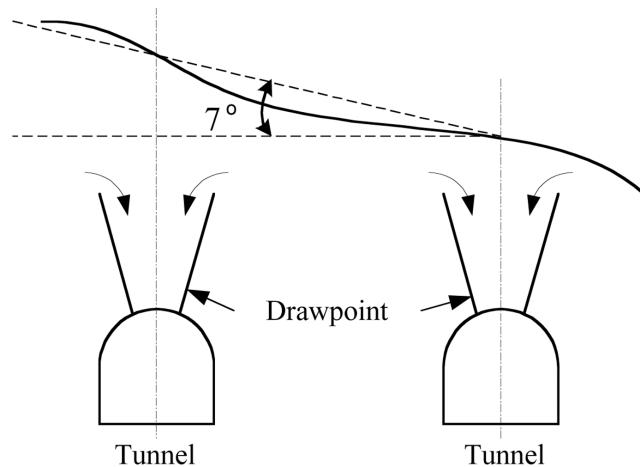


Figure 9—A side view of a cross-cut through the centre of two drawpoints. The maximum allowable difference in ore level above adjacent drawpoints is shown graphically

### Strategy 3

The focus of this strategy is to keep the difference in the ore levels above adjacent drawpoints as low as possible. The LHDs are still assigned to specific tunnels, but the order in which the drawpoints are visited, is determined dynamically. A cost function is used to determine the most appropriate drawpoint to visit. The value of the cost function is computed for every possible drawpoint, and the drawpoint that gives the lowest value is chosen as destination. The cost function contains a term describing the difference in levels between the drawpoint and adjacent drawpoints, as well as a term describing the tons drawn from the specific drawpoint.

The distance between the drawpoint and LHD was considered as another term, but because the distances to the different drawpoints are fixed, only the nearest points will benefit from this term. It was therefore not implemented because an important specification is that the ore level must be drawn evenly over the whole mine area. The terms of the cost function look as follow:

$$T_1 = \frac{\text{ton drawn today}}{\text{quota per day}} \quad [1]$$

$$T_2 = \frac{\text{adjacent level difference}}{\text{max level difference}} \quad [2]$$

Term 2 will be included four times in the cost function, because from Figure 4 it can be seen that each drawpoint has 4 adjacent drawpoints. The maximum level difference between adjacent drawpoints was computed as 1 449 tons for points in the same tunnel, and 2 898 tons for points in adjacent tunnels. This was obtained from the fact that the maximum angular difference between the levels directly above the drawpoints must be 7° as shown in Figure 9. The terms are normalized as can be seen in Equations [1] and [2], so that it can be added together. The cost function then looks as follows:

$$J_k = T_1 + T_{2,1} + T_{2,2} + T_{2,3} + T_{2,4} \quad [3]$$

The subscript  $k$  denotes the specific drawpoint for which the cost function is computed. When an LHD is finished off-loading, the cost function is evaluated for each drawpoint in the tunnel associated with the LHD. The drawpoint that produces the lowest value of  $J$  is set as the new destination for the LHD.

The movements of the trucks correspond to that of Strategy 1 and 2.

### Strategy 4

This strategy involves only the truck movements. The movements of the LHDs correspond to that of Strategy 1. The aim of this strategy is to space the arrivals of the trucks at

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the crusher more evenly. This should result in less crusher shutdowns, and the time that trucks have to wait when the crusher is full should also be reduced.

The trucks still move in one direction around the truck loop, but they do not have to obtain their entire load from one transfer point, as was the case in all the previous strategies. A truck should, however, be fully loaded before it moves to the crusher. Because the trucks move only in one direction around the loop, a truck can move only from one transfer point to another until it reaches the last one in the loop. In the case of the simulation described in this paper, the last transfer point would be number 3, because only 7 tunnels are active (Figure 4). A truck can move only to a transfer point with a higher number if that point is not occupied by another truck, or no other truck is already on its way to that point. When a truck reaches the last transfer point it must stay there until it is fully loaded.

## Strategy 5

This strategy again focuses on the movements of the LHDs. The truck movements correspond to that found in Strategy 1. Strategy 5 is basically the same as Strategy 3 but in this case each LHD is not assigned to a specific tunnel. The cost function is computed for all the active drawpoints in all the available tunnels. The drawpoint resulting in the lowest value for the cost function is chosen as the new destination of the LHD. An available tunnel is one in which no LHD is present, and to which no LHD is currently on its way. It is also not closed for secondary breaking. The number of LHDs is equal to the number of active tunnels. For each tunnel that is closed for secondary breaking, one LHD must go to the service area and wait for that tunnel to become active again. This strategy will obviously place a lot of strain on the collision avoidance algorithms. For this reason it was decided to keep the transfer points assigned to specific tunnels as in all the other strategies.

Table I

## Crusher results

Strategy	Crusher total (tons)*	Crusher stops†
1	157 200	24
2	160 800	6
3	158 640	13
4	151 080	4
5	842 40	17
2 + 4	143 280	4
3 + 4	152 160	3

Table II

## Drawpoint results

Strategy	Drawpoint average (tons)	Standard deviation (tons)
1	1 310	563
2	1 340	548
3	1 322	464
4	1 259	522
5	702	403
2 + 4	1 194	541
3 + 4	1 268	468

Combining different strategies creates more possibilities. It is clear that Strategy 1 to 3 all have the same dispatching strategy for the trucks, and that Strategy 4 uses the LHD dispatching of Strategy 1. Therefore some combinations of strategies are already implemented automatically. This is because the problem consists of two distinct dispatching systems (for LHDs and trucks), which interact only at the transfer points. The only other possibilities for combinations of strategies are Strategy 2 with 4, and Strategy 3 with 4. These combinations were also simulated.

## Results

The results given in this section focus on the evaluation criteria discussed earlier. Table I and II contain some of the relevant results obtained after one week of simulated production with each different dispatching strategy, as well as certain strategy combinations. These results will be discussed in more detail in the following section. (See Tables I and II.)

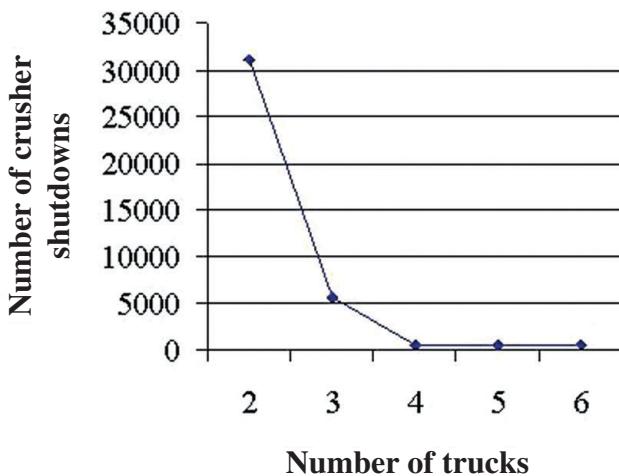


Figure 10—Number of crusher shutdowns for different numbers of trucks using Strategy 4

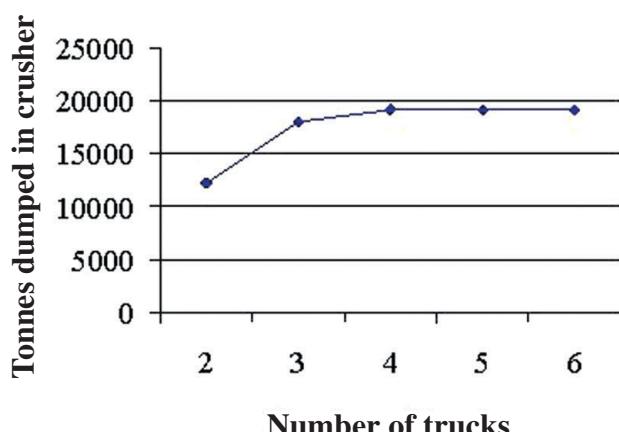


Figure 11—The total tons dumped into the crusher for different numbers of trucks using Strategy 4

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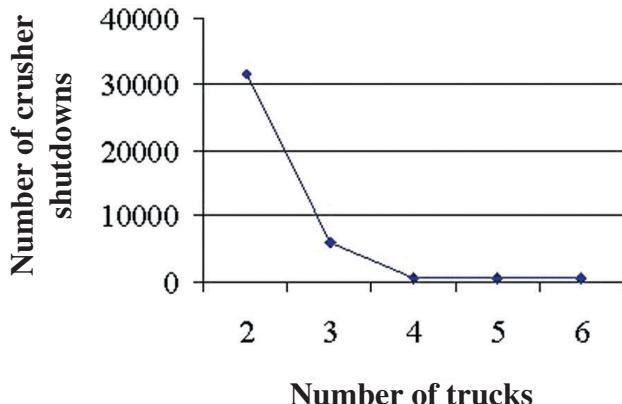


Figure 12—Number of crusher shutdowns for different numbers of trucks using a combination of Strategy 2 and 4

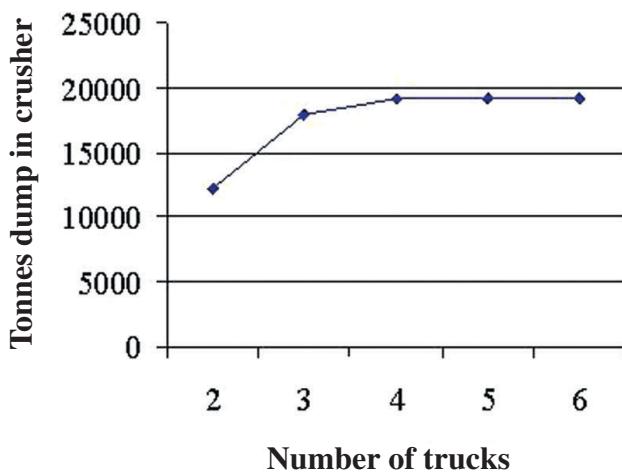


Figure 13—The total tons dumped into the crusher for different numbers of trucks using the combination of Strategy 2 and 4

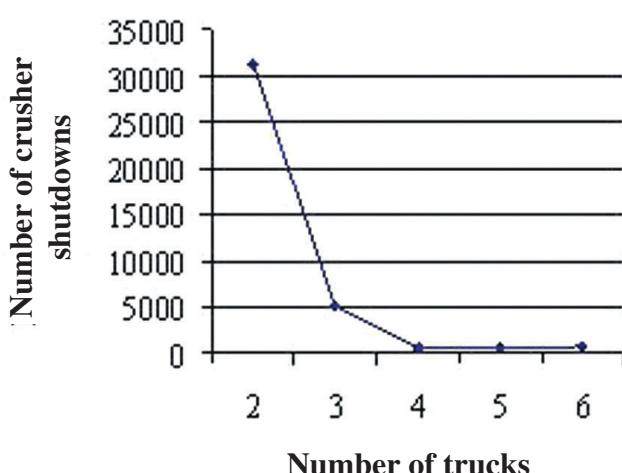


Figure 14—Number of crusher shutdowns for different numbers of trucks using a combination of Strategy 3 and 4

## Optimal number of trucks

The number of vehicles is a parameter that can easily be controlled in a dispatch system. In a mining environment the purchasing cost and running cost of a vehicle can be very high. It is therefore very important to have the correct number of vehicles to achieve optimal productivity, but also to limit the costs associated with the vehicles. The constraint that only one LHD is allowed in a tunnel at a time means that the number of LHDs is fixed by the layout of the mine.

The number of trucks, however, is not a fixed parameter and therefore Strategy 4 and the combinations containing Strategy 4 were simulated with different numbers of trucks. Only these specific strategies were used for this particular experiment because Strategy 4 is specifically aimed at the movements of the trucks. These simulations were run for the equivalent of one day of production, therefore the total tons produced will be significantly less than the amounts found in Table I. The influence of the number of trucks on the crusher results can be seen in Figures 10 to 15. In the simulation only three transfer points were active. The maximum number of trucks used was 6. This ensures that even if all three transfer points become available at once, there would be a truck waiting to occupy it. Any more trucks would therefore not make a difference in production. The number of trucks used in the above mentioned simulation runs is two, three, four, five, and six.

The simulation records a crusher shutdown when the crusher level stays at its minimum value for a period of 12 minutes (in terms of real time and not simulation time). This criterion was changed to 1 second to illustrate the effect of the number of trucks on the number of crusher shutdowns more clearly. This means that the results indicate the time in seconds that the crusher level was at its minimum level (under 30 tons). In the following figures this is called crusher downtime.

## Ore surface profiles

Figures 16 to 22 give graphical representations of the ore surface above the drawpoints. The surface profiles indicate the tons drawn, and therefore it is actually an inverted view

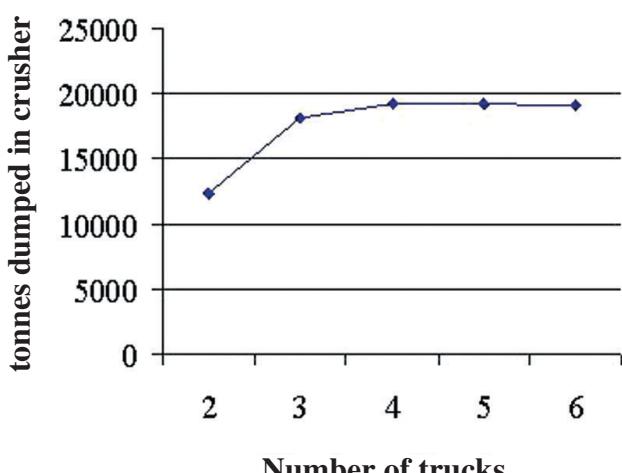


Figure 15—The total tons dumped into the crusher for different numbers of trucks using a combination of Strategy 3 and 4

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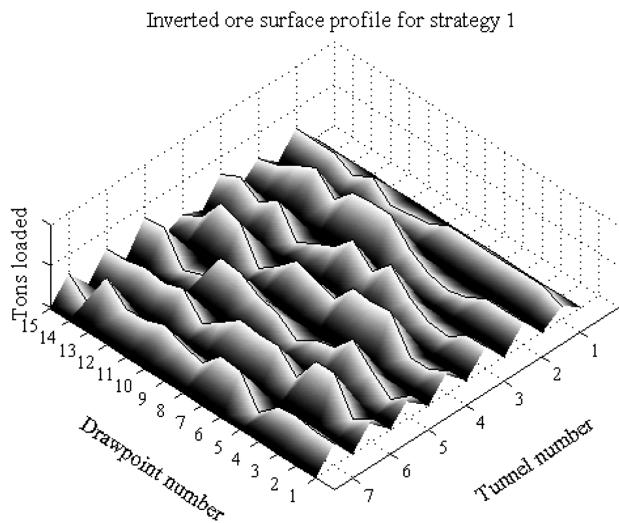


Figure 16—The figure shows the inverted profile of the ore level above the drawpoints for one week of simulated production with Strategy 1

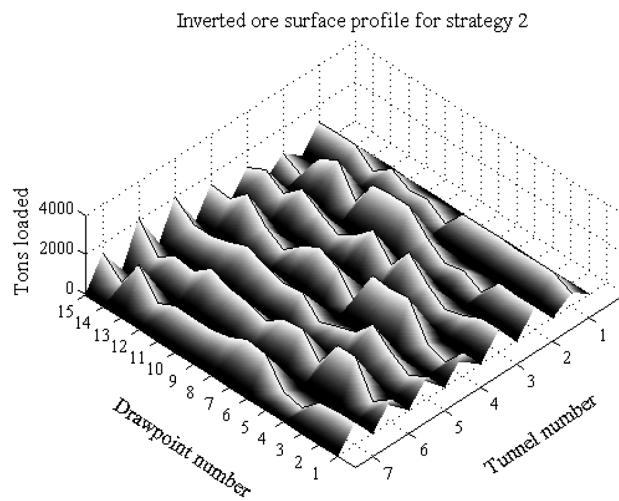


Figure 17—The figure shows the inverted profile of the ore level above the drawpoints for one week of simulated production with Strategy 2

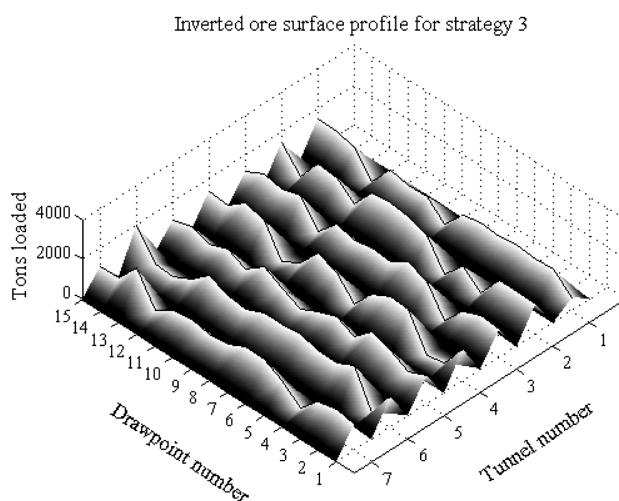


Figure 18—The figure shows the inverted profile of the ore level above the drawpoints for one week of simulated production with Strategy 3

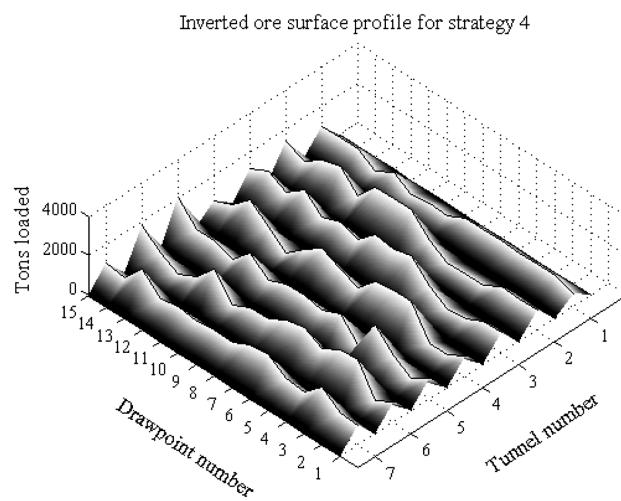


Figure 19—The figure shows the inverted profile of the ore level above the drawpoints for one week of simulated production with Strategy 4

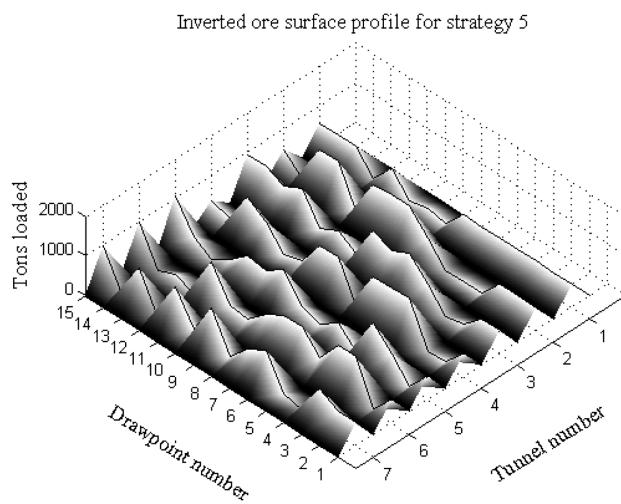


Figure 20—The figure shows the inverted profile of the ore level above the drawpoints for one week of simulated production with Strategy 5

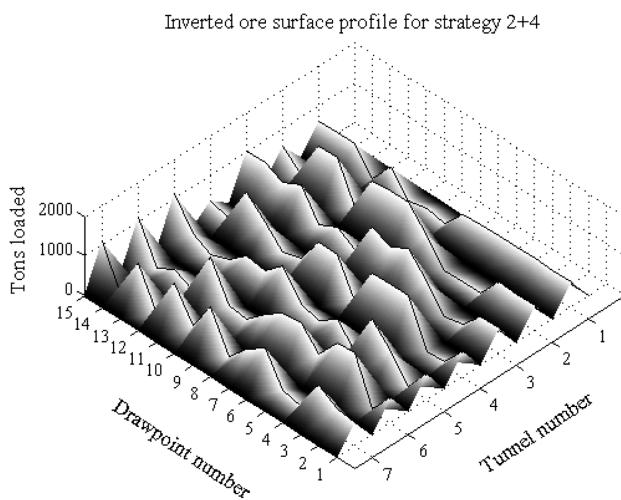
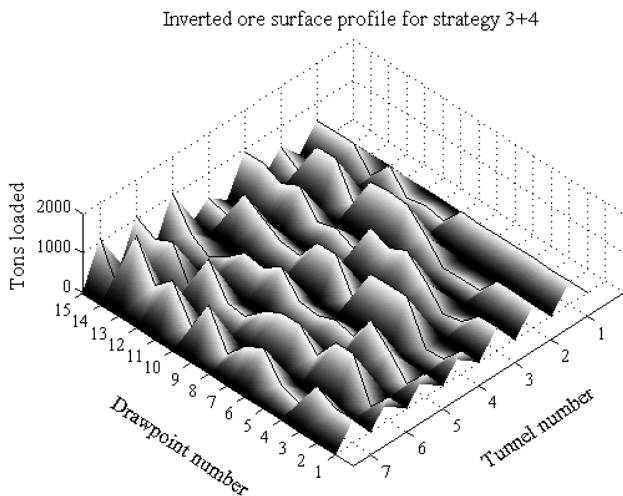


Figure 21—The figure shows the inverted profile of the ore level above the drawpoints for one week of simulated production with the combination of Strategy 2 and 4

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**Figure 22**—The figure shows the inverted profile of the ore level above the drawpoints for one week of simulated production with the combination of Strategy 3 and 4

of the ore surface. A higher quantity of ore drawn from a drawpoint will cause a lower ore level above that drawpoint, but the surface plots show the inverse of this. The reason for including these plots is to show the measure of success of each strategy to keep the ore level above the drawpoints even. One of the main goals stated for the dispatching strategies is to keep the ore level above the drawpoints as even as possible. Spaces have been put between each tunnel in the ore surface figures, so that it can be interpreted more easily. The evenness of the surface can therefore be judged more easily for each tunnel individually.

## Discussion

### Crusher results

From the results in Table I it is clear that Strategy 2 performed the best in terms of total tons produced, and Strategy 2+4 the worst. Strategy 2 also produced one of the lowest number of crusher shutdowns. In terms of the crusher results, Strategy 2 is by far the most effective. Strategies 1 and 3 produce more crusher stoppages. This is to be expected because Strategy 3 is aimed at maximizing the tons drawn from the drawpoints and to keep the ore level as even as possible. It does not attempt to evenly space the arrivals of LHDs at transfer points and therefore also not to evenly space the arrival of trucks at the crusher. In Strategy 1 the LHDs progressively move to further drawpoints and this means that the travelling distances for the individual LHDs are almost the same at any time. The LHDs therefore tend to arrive at the transfer points at the same time, and in between very little off-loading takes place. This causes the trucks to receive many loads in a short time, and at other times to wait long for loads. The arrival of the trucks at the crusher is therefore not evenly spaced, and the crusher runs empty more often and has to switch off more. This problem is addressed by Strategy 2 because the travelling distance is different for adjacent LHDs most of the time.

Strategy 4 and the combinations containing Strategy 4 produced low values for the total tons dumped in the crusher, but on the other hand they produced the least number of crusher stoppages. This is because Strategy 4 is aimed at spreading the arrivals of the trucks at the crusher evenly by reducing the travelling distances to the crusher if the truck is full, as well as to the nearest transfer point when the truck is empty. The lower total tons produced could be due to the fact that the different strategies combined to obtain these results were developed in isolation, with different goals in mind. It could therefore be expected that the strategies will not necessarily complement each other.

The expectation was that Strategy 5 would not perform very well. This is because of the increased collision avoidance, travelling times, and travelling distances of the LHDs. The results obtained with Strategy 5 confirm this prediction, and it shows that the performance of this strategy is very poor compared to all the other strategies. The number of crusher shutdowns obtained with Strategy 5 is not significantly higher than that obtained with the other strategies. It is important to keep in mind the time that the crusher is off before a new truckload arrives. This means that a lower number of crusher shutdowns does not necessarily imply better performance, and it must be evaluated in conjunction with the total produced tons. The low number of tons produced with Strategy 5 (Table I) clearly indicates that the crusher downtime was much higher compared to that of the other strategies.

The effects of the number of trucks on the results related to the crusher can be seen in Figures 13 to 18. These results reveal nothing surprising. As one would expect, the total tons dumped into the crusher increases as the number of trucks increases. However, the total tons produced reaches a limit, and it stays more or less constant for further increases in truck numbers. This limit occurs because the production of the trucks depends on the production of the LHDs, and the production of the LHDs is limited. The factors that limit the LHD production include the following:

- Only one LHD can off-load at a transfer point at a time
- An LHD can only off-load at its assigned transfer point
- Only one LHD is allowed in a tunnel at a time, and the number of LHDs equals the number of active tunnels
- Each drawpoint in a tunnel must be serviced to keep the ore level even. This means that the travelling distances of the LHDs are not fixed. The travelling time is therefore also a limiting factor.

Other limiting factors for the trucks are:

- The capacity of a truck is limited
- A truck must be full before it goes to the crusher. It must therefore wait for five LHD loads before it can off-load
- Only one truck can off-load into the crusher at a time
- Only one truck can occupy a transfer point at a time.

In Figures 10 to 15 it can also be seen that the number of crusher shutdowns decrease as the number of trucks increases. This number again reaches a limit that stays more or less constant as the number of trucks increases further. The reasons for this crusher shutdown limit are basically the same as those given above for the crusher total limit. The

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limits in production and crusher shutdowns are first reached with four trucks. It can be concluded that the optimal number of trucks is four, because a further increase in the number of trucks yields no further improvement.

## Drawpoint results

Before the drawpoint results are discussed, it must be kept in mind that some drawpoints became inactive due to hang-ups that occurred. The standard deviation values in Table II will therefore not reflect the true potential of the strategies because large level differences between inactive and active drawpoints are inevitable. The results are, however, sufficient to compare the performance of the different strategies with each other.

From the results in Table II it can be seen that the tons loaded from the drawpoints reflect the values of the crusher totals in Table I. This makes sense because all the ore loaded from the drawpoints must go to the crusher.

The values of the standard deviations indicate that Strategy 3 improves on Strategy 1. Strategy 3 therefore succeeds in keeping the ore level more even, while still maintaining a high level of productivity. The standard deviation results for last four strategies cannot really be compared to those of the first three due to the lower production values. The lower deviations therefore do not carry any weight and they will not be discussed further. It is, however, worthy to note that the combination of Strategy 3 and 4 produces the second lowest deviation and Strategy 5 the lowest deviation (Table II). These results could be expected because Strategy 3 and Strategy 5 are explicitly aimed at keeping the ore level even.

The ore surface profiles in Figures 16 to 22 give a more complete picture of the effectiveness of each strategy in terms of keeping the ore level even. The cause of some of the deep dips in the profiles can be attributed to drawpoints that became inactive due to hang-ups.

## Conclusions

Different dispatching strategies were developed with specific objectives in mind. These strategies were tested using a simulated environment. Results were recorded for each dispatching strategy, and these results were evaluated according to the evaluation criteria listed earlier. The objective of the above-mentioned work was to determine if more efficient dispatching strategies, compared to current dispatching, could be implemented in an underground mine. It could also offer a useful base for future development of dispatching strategies in automated mines. The results that were obtained are briefly summarized below.

All the strategies were successful to some degree in terms of their specific objectives. The only strategy that can be classified as a failure is Strategy 5, but this was expected. Strategies 2 and 3 delivered high quantities of ore, and Strategy 3 produced one of the lowest standard deviations in terms of the ore level above the drawpoints. Strategy 4 and the combinations containing Strategy 4 produced the lowest number of crusher shutdowns. The combinations of strategies, however, did not produce quantities of ore as high

as Strategies 2 and 3. This can be attributed to the separated nature of the systems of vehicles in the mine. These strategies were also simulated with different numbers of trucks, and the optimal number of trucks was found to be four. The strategy that performed the best overall, according to the results presented earlier, is Strategy 3. The best solution will, however, depend on the specific application. These strategies are good starting points from which more refined solutions can be developed for real life situations.

The success of these dispatching strategies in a practical implementation will depend heavily on the available infrastructure, and the quantity and quality of the information that is available. If the objectives are too ambitious it might seem that the cost of implementing a dispatching system is not worth it. However, in most situations it will offer great advantages in terms of safety and productivity.

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