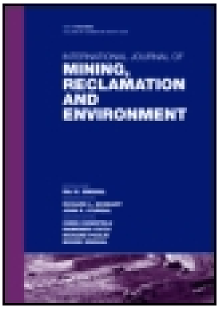

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Overview of Solution Strategies Used in Truck Dispatching Systems for Open Pit Mines

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ABSTRACT

This paper deals with dispatching systems in open-pit mines. It illustrates the different strategies that exist for solving the dispatching problem and analyses the advantages and disadvantages of these strategies. Moreover, the most important elements that should be part of the dispatching system in the future are highlighted.

KEYWORDS: dispatching, open-pit mine, optimization.

1 INTRODUCTION

Material transportation is one of the most important aspects of open-pit mine operation. In the literature, many authors agree that material transportation represents 50% of operating costs. Some authors estimate that for some mines it can reach 60%. Reducing these costs by a few percent will result in significant savings. These potential savings have led to the development of transportation management systems, including dispatching systems. Two goals were targeted in solving dispatching problems: improve productivity and reduce operating costs.

This paper deals with dispatching systems in open-pit mines. It illustrates the different strategies that exist for solving the dispatching problem and analyses the advantages and disadvantages of these strategies. First, the paper gives a description of different dispatching problems found outside mining industry. The second section classifies the dispatching problems encountered in the mining industry and describes the mining specific peculiarities compared to those described in the first section. Each of the following three sections presents one of the dispatching strategies that have been used until now in the mining industry. The last section highlights the most

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important elements that should be part of the dispatching system in the future. The analysis of the ideal system is based on the potential offered by the recent improvement in technologies, communication, operations research and computer sciences.

2 OVERVIEW OF VEHICLES DISPATCHING PROBLEMS OUTSIDE THE MINING INDUSTRY

Truck dispatching problems do not occur only in the mining industry. In fact, dispatching problems are present in any industry having to manage a fleet of vehicles or a group of people such as in the shipping, taxi and the package delivery industries. Many authors have written on these problems. We review here only few papers, more precisely those dealing with the general aspects of the dispatching problems. The goal is to present a classification of the different problems and also the difficulties encountered with their solution.

Ronen [1] presents general considerations about the characteristics of truck dispatching situations. This author reports that this kind of problem has often soft constraints, that is, constraints that can be violated at some cost if it is globally profitable to do so. He also describes two important aspects of the problem: the variability of the demand (the demand changes from one period of time to the other) and the multiple objectives (fleet managers make their decisions by optimizing different aspects of the problem at the same time). Ronen mentions that most of the difficulties encountered in truck dispatching problems are chiefly due to the variability of the demand. This author notes that the efficient use of a truck fleet is also related to the primary problem of determining the size of the fleet, which is difficult to estimate because of the variability of the demand. Finally, Ronen reports that real-world problems are often too complicated to be solved in practice by exact methods and only heuristic solutions are, therefore, practicable.

Heuristics methods are procedures which are not mathematically proven but which are based upon practical or logical operating procedures. Some heuristic methods often give good results, but there is no mathematical proof that these results are the optimal ones or that they can be reproduced every time. However, heuristic methods have been quite popular in the literature related to dispatching problems, because they are easy to implement and do not require much computation when making dispatching decisions, which is important when decisions have to be taken in real-time.

Powell [2] presents the *dynamic vehicle allocation problem* in the shipping industry, which is a subclass of problems considered by Ronen [1]. This problem basically consists of alternately answering the two following questions for each truck to dispatch.

- When a shipper calls a carrier, the fleet manager must decide which truck will be sent to the shipper for the loading and make the next delivery.

- After a delivery completion, if no loading is already scheduled for the related truck, the fleet manager must decide where that truck should be repositioned in anticipation of future loading demands.

Powell mentions that the complexity of this problem depends mostly on the knowledge of incoming demands that may be known or forecasted. Different solution approaches are possible depending on the state of the knowledge of the future demands. Powell reports four main approaches: deterministic transshipment networks, stochastic networks, Markov decision processes and stochastic programming. In addition to the general characteristics given by Ronen [1], the dynamic vehicle allocation problem also requires real-time solutions for most of the real-world applications. Hence, heuristic methods using a rolling time horizon have been implemented in most of the cases.

Gendreau and Potvin [3] describe four highly dynamic problems, which are a generalization of the dynamic vehicle allocation problem described by Powell [2] since they include vehicle routing problems. They are *dial-a-ride*, *repair service*, *courier service* and *express mail delivery problems*. Among these problems, the authors argue that the dial-a-ride problem is the most dynamic one because it contains for each transported item different pickup and delivery locations, some capacity restrictions and soft time window constraints. An illustration of this problem is the door-to-door shuttles in large North American cities. The repair service problem consists of telling each customer, at the moment of the request, when the repair will occur, considering some optimization criteria in the scheduling of repairmen. The courier service problem deals with the problem of collecting parcels at different locations in a city and bringing them at a central point for their international shipments. Finally, the express mail delivery problem involves the collection and the delivery of parcels by the same vehicle within a local area during one day. Since these problems must be frequently solved during normal business operations, they require fast solution methods. In fact, the time allowed to the solution must be shorter than the rate at which the events change in the reality if one wants to take advantage of any dispatching opportunities. This explains why heuristic solutions are often the only way to solve real-world applications of the above problems.

The use of automated guided vehicle systems (AGVS) in the manufacturing industry also presents some similarities with the truck dispatching problems encountered in the mining industry (see Co and Tanchoco [4] and Ganesharajah et al. [5] for a survey of dispatching and related problems in the AGVS literature). The two questions of the dynamic vehicle allocation problem remain applicable in AGVS since an automated guided vehicle (AGV) can be sent to a parking area after its delivery. These parking areas are used to avoid vehicle queues at pickup points and keep the fleet size as small as possible. Moreover, routing problems can occur since the completion of a delivery may necessitate several loadings at different locations.

However, the dispatching of AGVs has the advantage to arise on a closed system, which is often a factory or a plant. Since the near future demand of pickup points may be well known (the manufacturing process being well defined on this point), it follows that the events in this future can be easily forecasted from the current state of the system. But as the vehicles in an AGVS have some routing requirements to satisfy, and they are not sent immediately to a loading point after a delivery, heuristic solutions were mainly suggested in the related literature. As previously, exact solutions are considered as being computationally impractical for real-time applications.

3 CHARACTERISTICS AND SOLUTION APPROACHES OF THE TRUCK DISPATCHING PROBLEM IN THE OPEN PIT MINING INDUSTRY

The truck dispatching problem in open-pit mines consists of answering the following question each time a truck leaves a site in the mine: ‘‘Where should this truck go now?’’ Hence, the fleet controller has to find the best destination to send the truck to satisfy the production requirements. Usually, the best destination for a haulage truck is the one that seeks to maximize the satisfaction of one or many dispatching objectives, called in this paper dispatching criteria. There are various criteria used to dispatch haulage trucks and they either try, directly or not, to maximize the tonnage production or to minimize the equipment inactivity (such as the truck waiting time and the shovel idle time) for a given amount of production. Munirathinam and Yingling [6] provide a good description of these criteria and the different methods proposed in the literature for dispatching haulage trucks.

The present truck-dispatching problem differs from the dispatching contexts of those presented in the previous section in many ways. First of all, truck dispatching in a mine is not as complicated as the problems described by Gendreau and Potvin [3] and the one encountered in AGVS. Every time a truck is dispatched, it will pick up only one item, instead of many. The size and weight of the material loaded in the truck almost always reaches the truck capacity. It, therefore, follows that the routing aspects of the above problems disappear. Moreover, the second question of the dynamic vehicle allocation problem does not hold anymore since a truck is immediately sent to a shovel after it dumps.

Hence, the truck-dispatching problem applied in the mining industry could be seen as a simplification of the problems encountered in the other industries. However, truck dispatching in mines presents some characteristics that are not reported in the usual truck dispatching literature. Mines are closed systems; that is, the pickup and delivery points stay the same during a long period of time (which generally corresponds to a shift of 8 or 12 hr). Moreover, the travelling distances are short comparatively to the length of the shift (10 –25 min) and the frequency of demands at each pickup point is high (each 3 – 5 min). If the size of the fleet is too large, truck queues will appear. But since the system is closed and the demand well known, the events can be forecasted in the near future with a fair reliability. More specifically, the near future for the truck-dispatching problem in a mine is largely determined by the actual status of the system, although it tends to be stochastic when we look too far in the future (due to production hazards). With the exception of AGVS, this is a significant departure from the other dispatching problems found in the literature, which normally keep a stochastic nature at any moment.

The efficiency of a haulage fleet depends on its size and the haulage distances. Hence, not enough trucks mean that the shovels will have substantial unproductive periods and too many trucks will increase the length of queues at shovels. In the first case, the mine is said to be *under-trucked*, and *over-trucked* in the second one. Kappas and Yegulalp [7], Tan and Ramani [8], Kesimal [9] and Blackwell [10] are some authors who studied the problem of correctly setting the size of the truck fleet to avoid these situations. From these works, it appears that the analytical determination of the fleet size will generally overestimate the optimal number of trucks since they often assume that trucks always go to the same pickup and delivery points. Simulations are therefore required to get a better evaluation of the optimal fleet size. However, to be able to make the simulations, one must previously have chosen a way to dispatch the trucks. It follows that the fleet size will only be optimized for the chosen dispatching method.

There are two main approaches to truck dispatch in the related literature, the single stage and the multistage system. Systems using a single stage approach simply dispatch trucks to shovels according to one or several criteria without taking into account any specific production targets or constraints. They are often heuristic methods based on rules of thumb. Systems using the multistage approach divide the dispatching problem into subproblems or stages. These systems can be usually reduced to two components: an upper stage that consists in setting production targets for every shovel and a lower stage that assigns trucks to shovels to minimize the deviation from the production targets suggested by the upper stage. Such systems are denoted *plan-driven dispatching systems* in Munirathinam and Yingling [6]. A linear or nonlinear programming model is usually used for determining the production targets in the upper stage while a heuristic method is used instead in the lower stage since the dispatching decision has to be taken in real-time. Over the years, authors have preferred the quick solution of an approximated method in the lower stage to the exact solution of optimal methods arguing that the exact solutions are too time consuming.

Bonates and Lizotte [11] mention that when people use the multistage approach they must make sure that the production plan produced by the upper stage represents the mine conditions as accurately as possible to have an optimal solution that represents the most realistic situation. However, since conditions in the mine are not static and may change quite rapidly, multistage systems must, therefore, quickly respond to these changes to be efficient.

In addition to the two approaches above, we have identified in the literature on truck dispatching in the mining industry that there are three strategies to get the right assignment for a truck. We designated them as being the *1-truck-for-n-shovels*, the *m-trucks-for-1-shovel* and the *m-trucks-for-n-shovels* strategies. They are discussed in the following three sections.

4 THE *1-TRUCK-FOR-N-SHOVELS* DISPATCHING STRATEGY

The *1-truck-for-n-shovels* strategy can be described as the following. First a truck operator asks for a new assignment. Considering the *n* shovels where the truck can be dispatched, the system evaluates the cost or the benefits of assigning the truck at each of these shovels according to the chosen dispatching criterion. This evaluation done, the truck is sent to the shovel offering the best potential, that is, the one offering the least cost or the maximum benefit. This procedure is repeated every time a truck operator asks for a new assignment. In this strategy, the impact of the decision made to dispatch the current truck to dispatch on the following ones is not considered.

The *1-truck-for-n-shovels* strategy is the oldest and the most commonly suggested in the mine literature. This strategy is usually implemented according to the single stage approach. Descriptions of such dispatching methods can be found in Chatterjee and Brake [12], Tu and Hucka [13], Lizotte and Bonates [14], Sadler [15], Bonates [16], Forsman et al. [17], Panagiotou and Michalakopoulos [18] and Ataeepour and Baafi [19].

These dispatching methods are implemented using a wide variety of criteria, but their purpose is always to maximize production. We refer to Munirathinam and Yingling [6] for their description. However, it appears from the literature that whatever the criterion used in such a scheme, drawbacks must be expected. Hence, the *truck waiting time minimization criterion* must not be used when the mine is under-trucked. According to this criterion, the dispatching method will send the current truck to dispatch to the shovel offering the least waiting time. Since the probability of having a queue at shovels is low in an under-trucked mine, the present criterion will be as valuable as choosing randomly any shovel among the set of eligible shovels. In the same manner, the *shovel idle time minimization criterion* must not be used when the mine is over-trucked. With such a criterion, the corresponding dispatching method will always assign a truck to the shovel that has been waiting the longest. This situation will not produce efficient results since the probability that a shovel will wait is low. Munirathinam and Yingling [6] report that it is difficult to suggest one of the dispatching criteria since any of them dominates the other ones. They all depend on mine status.

Most of the drawbacks result from the lack of a global vision of the truck-dispatching problem since only one truck is considered at a time. The rest is due to the fact that each dispatching criterion suggested in the literature only considers a particular aspect of the production, like the shovel idle time or the truck cycle time. For these reasons, the dispatching methods using the *1-truck-for-n-shovels* strategy on the basis of the single stage approach can be considered *myopic*. Since different mine configurations can produce different results, one must carefully choose the dispatching criterion to use to maximize the production; otherwise, one can obtain poor performance. However, it appears that no efficient rule allowing determining the correct criterion exists and people must therefore rely on some heuristic principles to make their choice.

Since the above myopic methods cannot guarantee the same behavior in all situations, some authors have suggested to resort to simulators to determine the dispatching criterion that will better fit the needs of the mine for the current shift. The chosen criterion is usually applied for the duration of the shift, but it can be reevaluated each time an important modification to the mine configuration occurs. Lizotte and Bonates [14] and Panagiotou and Michalakopoulos [18] present such integrated dispatching systems. Bonates and Lizotte [11] propose a variant where the results from the simulator are compared to an optimal production plan obtained from a linear programming model before choosing which criterion should be used to reach the optimal production target between each shovel and dump point. In this way, the choice of the right dispatching criterion can be made by taking into account higher considerations, such as ore grade requirements and stripping ratio instead of only maximizing the total tonnage production. However, one must notice in the latter case that the retained criterion does not necessarily ensure the achievement of the production plan, particularly when the production requirements go against the natural production tendency of the criterion.

The above dispatching methods integrating a simulator in combination with or without a production plan generator must not be considered as a multistage system. To obtain a multistage dispatching system, the information from the upper stage must be directly used by the lower stage for each truck assignment. This is not the case with the present methods. They only use the simulator and the production plan generator to determine which dispatching criterion should be applied to make more efficient truck assignments according to a given mine configuration. It, therefore, follows that the simulator and the production plan generator are not components of the dispatching method itself. Hence, such dispatching systems remain sensitive to the drawbacks affecting the myopic dispatching methods.

Dispatching methods using the *1-truck-for-n-shovels* strategy according to the multistage approach can be found in Li [20] and Xi and Yegulalp [21]. In the upper stage of the corresponding methods, both papers suggest the use of linear programming to identify the optimal number of trucks that should be associated to each path between any shovel and dump point and between each dump point and shovel to minimize a specific measure of haulage costs. Since the present dispatching methods propose to minimize the production cost instead of maximizing the total tonnage production, minimal tonnage production is specified for each shovel in the linear programs. Knowing the duration of the production, one can, therefore, determine for each shovel the optimal time between two truck arrivals from a given dump point. The purpose of the lower stage is to dispatch trucks to obtain these interarrival times in the field. Hence, the principle behind these two dispatching methods is that if one can achieve the optimal interarrival times deduced from the upper stage, one should make the required production by minimizing the cost.

The dispatching methods suggested by Li [20] and Xi and Yegulalp [21] involve a homogeneous truck fleet while most of the mines use heterogeneous fleets. To consider the fleet as homogeneous, a representative typical truck must be defined for the needs of the upper stage. Therefore, when the fleet is heterogeneous, there is no guarantee that the required production at shovels will be achieved since the lower stage will only dispatch trucks in the field on the basis of the typical truck interarrival times at shovel without taking into account the real size of trucks in its decisions (this being implicitly done by the homogeneous fleet assumption).

Since the information from the upper stage provides to the lower stage a guideline on how trucks should be dispatched in the field, *1-truck-for-n-shovels* dispatching methods implemented according to the multistage approach should be theoretically more efficient than the methods using the same strategy but following the single stage approach. This is expected since the upper stage brings to the lower stage a global vision of the dispatching problem. Some preliminary experiments show such a behavior. However, the fact that the lower stage considers in its assignments only one truck at the time, the addition of an upper stage is not sufficient to avoid the drawbacks occurring with the single stage methods. As Munirathinam and Yingling [6] have illustrated, such multistage methods can miss good dispatching opportunities even in the simplest situations.

5 THE *M-TRUCKS-FOR-1-SHOVEL* DISPATCHING STRATEGY

According to this strategy, truck-dispatching decisions will be made by taking into account the m next trucks to dispatch in the near future but only considering one shovel at the time. More specifically, the shovels are first ordered according to a measure indicating by how much they are behind schedule on their production. Next, considering each shovel in that order, one assigns to the current shovel the truck that will reduce the particular measure.

In the literature, only one dispatching method using the present strategy was found: It is the one developed for DISPATCH™ by Modular Mining Systems. General overviews of the use and the features of DISPATCH^{TM} are described by White et al. [22] and Arnold and White [23]. Since DISPATCH^{TM} is a commercial package, all details of its dispatching method are certainly not divulged in the literature. However, some of the most significant technical details are given by White and Olson [24] and White et al. [25]. Munirathinam and Yingling [6] summarize the information from the two latter papers.

The assignment of trucks by DISPATCH^{TM} is based on the multistage approach. In the upper stage, linear programming is used to determine the optimal flow rates in tons per hour to reach on the shortest paths between each shovel and each dump point. The proposed linear program takes into account the current pit configuration, maximum digging rate at each shovel, maximum capacity at dump points, and blending requirements at stockpiles and crushers. Its objective function includes pseudo-costs by which the desired digging rate of shovels is set. To keep the required flow rates on the paths as accurate as possible, the upper stage module is called whenever the rate of shovels changes significantly, any equipment is added to or removed from the field, or any normal transaction path travel time varies; otherwise, when any special event occurs in the field, an update is systematically done, after a given amount of time predetermined by the mine managers.

The trucks are dispatched in the field by the lower stage, which attempts to achieve as close as possible the flow rates determined by the upper stage. For this purpose, at the lower stage two lists are created at the beginning of the dispatching decision process: one for the paths and one for the trucks. The path list is ordered according to the need time, which is a measure indicating how the current production on a path is behind schedule comparatively to the flow rate indicated by the solution results obtained in the upper stage. The path with the neediest time is the first element of the list. The truck list contains all trucks currently dumping at a dump point or en route for a dump point. The trucks are, therefore, assigned to shovels by matching the best truck to the neediest path. The best truck is the one minimizing the lost-tons, which is a measurement of nonproductivity considering the resulting idle time of the shovel, the waiting time of the truck, the additional travel time that the truck must make to reach the shovel instead of the nearest one and the required flow rates from the upper stage. Following the assignment of the best truck to the shovel corresponding to the neediest path, the best truck is removed from the truck list and the neediest path is moved to the end of the path list letting the second neediest path as being the new neediest one. The matching process is repeated as long as the truck list is not empty. The dispatching decision process ends by sending the assignment for the truck requiring an immediate assignment, all the others being discarded since they will be overridden by the forthcoming decisions.

Hence, the lower stage assigns trucks to shovels by subdividing the dispatching problem into subproblems that are sequentially solved. The solution of each subproblem is built on the results of the previous ones. More exactly, when a truck is matched with a shovel at a given iteration of the matching process, all trucks previously matched at the shovels are considered in the calculation of related lost-tons. However, the effect of the current matching on the forthcoming ones is neglected.

White and Olson [24] as well as White et al. [25] argue that the way the lower stage takes its dispatching decisions is based on dynamic programming. According to the authors of this paper, this is not really the case and this is probably due to a misunderstanding of Bellman's principle. Dynamic programming is an exact solution method developed for some combinatorial problems that can be formulated as a sequence of decisions. People who want to solve such a problem by dynamic programming will first consider the last decision (called *stage*) of the sequence and determine the best action for all possible situations (called *states*) that can be encountered at that moment. The aim of this enumeration is to provide the optimal sequence of decisions to apply from the current stage to the last one for all states of the current stage. It follows that by backtracking on the previous decision of the sequence, one can extend its optimal sequence of decisions for all the possible states at this stage since the different optimal sequences of decisions are already known for the subsequent stages. This backtracking process is repeated up to the first decision of the sequence, where one is able to determine the overall optimal sequence of decisions since there is only one possible state at the first stage. For more details about dynamic programming, consult Hillier and Lieberman [26]. Hence, solving a problem by determining first the best decision to take for the initial situation and pursuing with the following decisions always considering the situation resulting from the application of previous best decisions from the initial situation does not correspond to the dynamic programming scheme. Such a process only allows taking into account one possible sequence of decisions considered by dynamic programming. Therefore, it results that the lower stage cannot dispatch trucks according to a global vision of the dispatching problem. We must conclude that the lower stage of the present dispatching system is a heuristic method.

However, since the lower stage retains only the assignment for the truck requiring an immediate assignment, the dispatching system defines a rolling time horizon algorithm when a sequence of assignments is considered. This is a positive feature in DISPATCH$^{\text{TM}}$ since it makes dispatching decisions using the latest data from the field.

6 THE *M-TRUCKS-FOR-N-SHOVELS* DISPATCHING STRATEGY

In this strategy, one simultaneously considers the assignment of the *m* forthcoming trucks to dispatch in the near future to *n* shovels in the field. This is possible using combinatorial optimization methods. Hence, this strategy should produce dispatching decisions according to a global vision because the related solution algorithms take into account the interconnection of the different aspects of the problem.

The dispatching problem is either formulated in the literature as an *assignment problem* or a *transportation problem*, both being classical problems within operations research. The assignment formulation of the dispatching problem consists of assigning trucks to shovels on a one-to-one basis, i.e., each shovel must only receive one truck and each truck may be assigned to at most one shovel. Consequently, it follows that m is greater or equal to n in this formulation. With the transportation formulation, one will instead consider the problem of shipping some commodity from a group of supplier centers to a group of receiving centers. The aim is to minimize the total shipping cost by satisfying both the supply capacities and the demand requirements. In the dispatching perspective, the supplier centers are the m trucks and the receiving centers are the n shovels. The unit of commodity is the truck. Each supplier center offers one unit of commodity and each receiving center demands a number of units such that the total number of units demanded by the receiving centers is equal to m. For more information about the assignment and transportation problems and their related solution methods, consult Hillier and Lieberman [26].

Due to the combinatorial nature of the *m-trucks-for-n-shovels* strategy, the value of m and n must not be too large, otherwise the dispatching problem can become unsolvable in a reasonable time. Moreover, note that each of the truck assignments generated by the *1-truck-for-n-shovels* and the *m-trucks-for-1-shovel* strategies are all considered among a great number of other possibilities by the *m-trucks-for-n-shovels* strategy. This means that the present strategy should provide, at least theoretically, more efficient truck dispatching than the two previous ones.

Hauck [27,28] suggests a single-stage system that determines the forthcoming truck dispatching decisions in the field by solving a sequence of assignment problems, which attempt to maximize the production of the mine by minimizing the total lost tonnage due to the idle time of shovels. The optimal truck dispatching sequence according to Hauck is made as follows. From the current mine state, an assignment problem is solved considering all trucks and shovels. From the optimal solution, only the assigned truck(s) with the minimum load completion time is (are) kept. This guarantees that the idle time at the shovels will be minimal. The rest of the solution is discarded and the mine state is correspondingly updated. If one wishes to forecast the evolution of the mine in the future, one just has to reiterate until the end of the shift. For real-time purposes, iterations are performed until each truck has at least one load completion in the future and they are resumed as soon as a truck does not have any more future load completion. To ensure that the dispatching decisions will not violate any operational constraints such as stripping-ratio requirements between ore and waste shovels, production capacity restrictions and blending requirements, the solution at the current iteration is rejected when one of these constraints is not satisfied. The assignment problem is, therefore, modified to avoid the unfeasible solution and solved again. This process is repeated until a solution that satisfies all the production constraints is obtained. This method is presented by Hauck [27] and it is also described in details by Munirathinam and Yingling [6]. One will find complementary mathematical foundation by Hauck [28].

Munirathinam and Yingling [6] report that Hauck's method does not allow a short term relaxation of the operating constraints, which may be acceptable for the mine managers if the relaxation could improve the productivity without violating the constraints over a long period. In addition to their comments, one must also notice that Hauck cannot ensure that each dispatching decision is based on the most accurate data from the field since the precomputed decisions are discarded and reevaluated only when one of the trucks has no more precomputed dispatching, which can take some time to arise, allowing several precomputed truck assignments in the meantime. In the case where some unexpected events occur between two reevaluations of future assignment decisions, the precomputed truck assignments can, therefore, become unacceptable decisions. Hauck [28] specifies that the proposed dispatching method correspond to a dynamic programming framework. For the same reasons previously given by White and Olson [24] and White et al. [25], it appears that this is not the case since Hauck builds his *optimal* sequence of decisions without considering all the possibilities.

A multistage approach for the *m-trucks-for-n-shovels* strategy is proposed by Elbrond and Soumis [29]. Complementary technical details are given by Soumis et al. [30]. These authors suggest not only a truck dispatching method, but also an allocation module for the shovels. Since our interest is limited to the truck-dispatching problem, we will assume that the location of shovels is already determined for the purpose of the upper stage.

Hence, knowing the location of shovels in the field and the number of trucks available for the whole shift, Elbrond and Soumis suggest to solve a nonlinear programming model to obtain the optimal production rates, which are expressed in term of trucks per unit of time, between each shovel and each dump point. These production rates are set to maximize the total production. More specifically, the optimal solution of the nonlinear model will be such that the shovels will be maintained as close as possible to their maximal capacity, all available trucks will be used and the blending requirements will be satisfied as much as possible. The use of trucks includes the truck waiting time, which is derived from queuing theory. The authors argue that the use of a nonlinear model at the upper stage instead of a linear one is preferable. They justify their assertion giving two reasons. First, the time that a truck will wait at a shovel does not follow a linear function. Next, a nonlinear model can generate a more balanced solution than a linear one since the latter produces extreme solutions. Hence, for two shovels at the same location, a linear model may suggest to use only one of the two shovels at its full capacity and keeping the other one inactive while the nonlinear model will rather propose to use both shovels at the half of their capacity.

The lower stage will dispatch trucks to shovels by solving for each dispatching decision an assignment problem, which will consider, in addition to the truck requiring its immediate assignment, the 10–15 next trucks to dispatch in the near future. The cost to minimize is the sum of squared deviations between the average waiting times of trucks and shovels determined by the upper stage and the ones that will result in the field by sending a truck to a shovel instead of another. As for DISPATCH$^{\mathrm{TM}}$, only the assignment for the truck requiring an immediate dispatching is returned. The other ones are discarded since the corresponding trucks will be again considered in the following dispatching decisions. It follows that the way that the lower stage dispatches trucks in the field corresponds to a rolling time horizon algorithm.

However, the dispatching method suggested by Elbrond and Soumis does not consider the possibility of assigning more than one truck at a shovel, even when it is obvious that one should send two trucks at a shovel and none to another. This justifies the rolling time horizon structure of the lower stage, which provides a corrective mechanism to the limitations of the assignment formulation. Another important drawback of the present dispatching method is the implicit assumption that the truck fleet is homogeneous. Since this case is very similar to the works of Li [20] and Xi and Yegulalp [21], the arguments previously given for these authors remain applicable for the work of Elbrond and Soumis.

Another multistage approach for the *m-trucks-for-n-shovels* strategy is suggested by Temeng et al. [31, 32]. The mathematical model proposed for the purpose of the upper stage is given by Temeng et al. [32]. To maximize the tonnage production as well to satisfy the blending requirements at dump points, these authors solve a goal programming model to determine the optimal amount of tons to haul between each shovel and each dump point for the whole production period. A goal programming model is nothing other than linear programming with an objective function that includes penalties. Such programming models are very useful when it is practically impossible to find a feasible solution satisfying all the constraints of a problem. Therefore, one wants to get the solution that violates the smallest number of constraints or the least important ones. Here, the goal program is formulated in a manner to keep the shovels as close as possible to their maximal capacity and the blend materials produced at dump points as close as possible to the center of blending requirements. Minimal production requirements at shovels, maximal capacity of dump points, stripping ratio and fleet capacity are also considered by the goal program.

The lower stage is described by Temeng et al. [31]. Dispatching decisions are taken by solving a transportation problem. As previously mentioned, each supplier center of the transportation problem is associated with a truck to dispatch in the near future and at each receiving center corresponds a shovel. The demand at the receiving centers is expressed in terms of the number of trucks needed to achieve the production targets, which are specified by the upper stage. This determination of the number of trucks does not require a homogeneous fleet. The authors provide indications on how to deal with heterogeneous fleets. Finally, the cost of sending a truck to a shovel is given by the expected waiting time that will result from assigning this truck to the shovel. Hence, the approach of the authors is to eliminate the gap of productivity of all needy shovels by minimizing a sum of waiting times.

By using this model, one has a broader view of the problem compared to the assignment model since more than one truck can be assigned at a shovel and the number of trucks considered could be greater than the number of shovels. However, there is a major drawback with the suggested transportation formulation. The use of the transportation model requires that the cost by unit of commodity from a supplier center to a demand center is constant as well as independent of the units coming from the other supplier centers. But the waiting time of a truck at a shovel depends on the assignment of other trucks to this shovel, particularly when the mine is over-trucked. The cost calculation suggested by Temeng et al. [31] can only provide the waiting time resulting from the trucks currently en route to, or already arrived at, the corresponding shovel. Since there is no way to consider the supplementary waiting time due to the future assignment of several trucks at a same shovel, the dispatching decisions resulting from the solution of the transportation problem will be based on a underestimated waiting times. This is inappropriate, especially in the present dispatching system since the lower stage makes dispatching decisions only on the basis of waiting times. However, the dispatching system proposed by Temeng et al. [31, 32] remains interesting.

7 THE IDEAL TRUCK DISPATCHING SYSTEM

According to the description of the different approaches and strategies from the previous sections, as well as from the potential offered by new technologies, we propose here different features that should be part, in the future, of any good truck dispatching system for the open pit mines.

First of all, such a dispatching system should be based on the multistage approach since this approach has a great advantage over the single-stage one. This advantage is the use of a guideline that introduces to the dispatching system a level of knowledge improving the quality of assignments. The guideline is computed by the upper stage of multistage systems, which is obtained by solving a mathematical program. It is next used by the lower stage as a reference while making the real-time dispatching decisions. The mathematical program solved into the upper stage can consider a lot of factors that are difficult for the single stage systems to deal with. These considerations include blending requirements at crushers, stripping ratios, minimum and maximum capacity constraints at shovels. One can also add many other constraints, which could arise from practical consideration and the need of the mine managers. For a given set of production constraints, one can determine several guidelines: maximizing the production, minimizing the costs, and even maximizing a measure of the profit if the related data are available. However, the guideline must be expressed in such a way that avoids the reference to a homogeneous fleet in the lower stage. The mathematical program suggested by White and Olson (1986) [24] and Temeng et al. [32] in their upper stage satisfies this requirement while the ones by Li [20], Xi and Yegulalp [21] and Elbrond and Soumis [29] do not.

To be efficient, the multistage systems must be able to adapt their guidelines quickly when any major change occurs in the mine status, i.e., when a shovel breaks down or becomes operational. This is now possible with the new available data acquisition technologies and the efficiency of the latest versions of mathematical programming software. It follows that the problem highlighted by Lizotte and Bonates [14] on the difficulty of multistage systems to deal with the constant changes in mine status does not exist anymore. We can even go further: The update of the guidelines must not only represent the actual mine state, it must also take into account the forthcoming events that will change the operational conditions in the near future when such an information is available.

We must now determine under which strategy the lower stage of the proposed multistage system will make its real-time dispatching decisions. It appears that with the continual increase of capacity and reducing cost of computers, plus the constant improvement of solution methods proposed by operations research people, it is now possible to increase the combinatorial nature of the truck-dispatching problem to integrate the sequence of dispatching decisions. Instead of considering an egotist behavior for the trucks, i.e., each truck goes to its best destination ignoring the effect on the forthcoming assignments, we should consider that trucks are able to cooperate. Only the *m-trucks-for-n-shovels* strategy can ensure this since all assignment possibilities for the trucks considered in the current dispatching problem are, therefore, taken into account. However, one must avoid the drawbacks based on the assignment and transportation formulations of the dispatching problem. We must rather consider more general mathematical formulations to take into account the possible interactions between the trucks coming from different locations, particularly in regard to the resulting truck waiting time, which can change significantly from one possible assignment of trucks to the other.

Since mines are dynamic systems, information changes continuously and has to be updated frequently. The efficiency of the above suggested dispatching system requires that the information on the mine status is available in real time. As mentioned before, the necessary technologies are already there. Richards [33], Zoschke and Vesterdal [34], and Phelps [35] give good indications of the new trends in applicable technologies.

These technologies are mostly constituted by the integration of the Global Positioning System (GPS) with the coming of *vital sign* monitors and computers on board the mobile equipment. Such integration allows using the GPS in a more general way than just localizing in real time the trucks and shovels in the field. The use of *virtual beacons* is a good illustration of this. The virtual beacons are positioned by the mine manager on a computer screen displaying a field model with the faces, the dumps and the road network connecting them. The coordinates of the virtual beacons are next transferred to the on-board computers of trucks. Since a truck always knows its position in the field by using the GPS, its on-board computer is therefore able to notify to the computer in front of the mine dispatcher when the truck crosses a virtual beacon. From these crossing notifications, one can, therefore, for instance, monitor truck speed and identify if each truck is reaching its destination using the correct route. It is therefore possible to compute and update dynamically the statistical data on the different travel times, which must be kept as accurate as possible all along the shift to obtain quality decisions from dispatching systems like the one described above. Finally, one can even monitor the variation of the statistical data on the travel times to detect the road deterioration of some or all road segments, from which the scheduling of their restorations can be planned.

The first purpose of vital sign monitors aboard trucks is to allow the detection of potential mechanical failures. Hence, to avoid the negative effects of truck breakdowns on the production, one can immediately send the truck to the maintenance or schedule it later depending on the seriousness of the case. But it is also possible to use the information from the vital sign monitors for the purpose of the dispatching system to increase the quality of its decisions. With these monitors, it is now possible to quantify each load weight. It is also possible to compute statistical data for the time it takes to load a truck at a given shovel or empty it at dumps since the vital sign monitors can detect when a truck receives the first bucket of material from the shovel, start moving or dumping. In the same way, one can improve the statistical data of travel times since the current truck speed is always available. Moreover, by monitoring break and engine heat, for example, one can identify poor and good operating conditions, which may influence the different statistical data deduced from the field.

All of this is possible by only considering the information coming from the trucks in the field. But we can go further if we also take into account the information generated by the shovels. For example, using the vital sign monitors of shovels in conjunction with the GPS and a geological description of the face, one can identify the type of material dug by a shovel. Therefore, it is possible to know the qualitative information on each truckload. Having this information plus the amount of material loaded into the trucks, it becomes possible to control accurately the material sent to the crushers, that is, to integrate the blending requirements within the dispatching decisions.

Since it appears that the data acquisition technologies are available to allow the implementation of very sophisticated dispatching systems, we should, therefore, start to design and develop such systems satisfying the minimal requirements described above.

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