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Innovative Applications of O.R.

A new MIP model for mine equipment scheduling by minimizing maintenance cost

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ABSTRACT

Mining investment has been recognized as capital intensive due mainly to the cost of large equipment. Equipment capital costs for a given operation are usually within the order of hundreds of million dollars but may reach to billion dollars for large companies operating multiple mines. Such large investments require the optimum usage of equipment in a manner that the operating costs are minimized and the utilization of equipment is maximized through optimal scheduling. This optimum usage is required to ensure that the business remains sustainable and financially stable. Most mining operations utilize trucks to haul the mined material. Maintenance is one of the major operating cost items for these fleets as it can reach approximately one hundred million dollars yearly. There is no method or application in the literature that optimizes the utilization for truck fleet over the life of mine. A new approach based on mixed integer programming (MIP) techniques is used for annually scheduling a fixed fleet of mining trucks in a given operation, over a multi-year time horizon to minimize maintenance cost. The model uses the truck age (total hours of usage), maintenance cost and required operating hours to achieve annual production targets to produce an optimum truck schedule. While this paper focuses on scheduling trucks for mining operation, concept can be used in most businesses using equipment with significant maintenance costs. A case study for a large scale gold mine showed an annual discounted (10% rate) maintenance cost saving of over $2M and more than 16% ($21M) of overall maintenance cost reduction over 10 years of mine life, compared with the spreadsheet based approach used currently at the operation.

1. Introduction

Mining is a capital intensive business requiring large size, expensive equipment, such as 20–40 trucks with over 200 tonnes capacity, large excavators, loaders and ancillary equipment fleet. The capital costs of these large fleets can be as high as a few hundred million dollars. To sustain the business in a financially strong and stable condition, all aspects of the mining operation must be managed in an optimal manner as much as possible. Equipment maintenance cost is one critical financial aspect of a mining operation.

Maintenance cost can constitute around 30–50% of the overall haulage costs of a surface mining operation that uses truck and shovel fleets for overburden and ore removal. As part of the process of maximizing profit and minimizing costs, mining operations are constantly striving to obtain maximum equipment productivity. Due to the high operating costs associated with mining projects, even a small increase in mining equipment productivity will often result in savings of millions of dollars. As surface mining operations expand and become deeper, more material will need to be hauled longer distances with a consequent increase in truck cycle times. More trucks will need to be purchased to compensate for longer cycle times. There will also be a requirement to replace older trucks with very high maintenance costs and inefficiency (too much downtime reducing operation's productivity). This will result in an increase in demand for truck fleets, which ultimately increases the importance of future maintenance planning.

Large mining trucks are used at surface mines to move material to either a dumping area or processing plant, depending on the mineral content. The amount of material that needs to be moved periodically is identified by generating a mine production schedule. Based on the identified total material movement, the required periodical equipment hours are determined. Subsequently, the equipment schedule is produced to meet the periodically required truck hours. The age of a mining truck can be defined as the total hours that a truck has been operated. A mining operation can involve different truck types of varying ages and associated maintenance costs. These maintenance costs can be obtained from historical data at the existing operation, from other operations using the same trucks and/or estimated values from the truck manufacturer. These cost data are presented in a tabular form where a

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Table 1
Variable maintenance cost for different truck types ($/hour). A major repair (engine rebuild) cost is applied for trucks used above 70 K hours.

Minimum Hours K hours	Maximum Hours K hours	Truck Type 1	Truck Type 2	Truck Type 3	Truck Type 4	Truck Type 5	Truck Type 6
0	5	$40.0	$34.6	$22.7	$21.3	$32.0	$16.0
5	10	$59.9	$51.9	$34.0	$32.0	$47.9	$24.0
10	15	$94.5	$81.9	$53.6	$50.4	$37.8	$75.6
15	20	$207.0	$79.5	$97.3	$85.6	$82.8	$123.6
20	25	$75.5	$30.2	$42.6	$32.2	$96.0	$51.6
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
65	70	$55.8	$50.4	$71.4	$98.6	$125.9	$109.1
70	75	$28.9	$38.5	$40.9	$57.7	$72.2	$62.5
75	80	$41.1	$54.8	$58.2	$82.2	$102.8	$89.1
80	85	$44.7	$59.6	$63.3	$89.3	$111.7	$96.8
85	90	$88.3	$117.7	$125.1	$176.6	$220.7	$191.3
90	95	$32.9	$43.9	$46.6	$65.8	$82.2	$71.3
95	100	$30.4	$40.6	$43.1	$60.9	$76.1	$65.9

truck maintenance cost corresponds to a certain truck age. This means that when a truck has been operated for certain number of hours, maintenance is required at a cost as shown in Table 1. Also, after a certain number of operating hours, an engine rebuild and major overall maintenance are required. A rigorous optimization method must take these issues into account.

Since the early 1960s, optimization techniques have been applied to mining problems. Mixed integer programming (MIP) models are recognized as having significant potential for optimizing both surface and underground mining operations. MIP type optimization techniques to date have mainly been focused on production scheduling. The methods of production scheduling are discussed extensively in the literature by, for example, Topal (2008), and Kuchta et al. (2004) for underground mines and Ramazan (2007), Ramazan and Dimitrakopoulos (2004), Chanda and Ricciardone (2002) and Gershon (1987) for surface mines. Mine production scheduling identifies the total amount of material to be moved periodically, the location for extraction and the destination for unloading (processing plant, stockpile or waste dumps). Production scheduling methods usually consider the capacity of the processing plant to which the valuable material (ore material) is sent and the total amount of material that can possibly be moved with the available equipment.

A new MIP model is proposed to optimize the scheduling of a truck fleet with the objective of minimizing the overall discounted maintenance cost. Although this paper focuses on a truck fleet for a surface mining operation, the methodology can be applied for any businesses involving large equipment fleets requiring significant maintenance cost. The following section reviews scheduling literature and current practices in the mining industry. The proposed MIP model formulations are then discussed. Subsequently, a truck fleet for a gold mining operation is scheduled using both a traditional approach (TA) and the proposed MIP model approach. Finally, the results are evaluated and compared for benchmarking the proposed MIP model.

2. Current practices

The concept of scheduling mining equipment with the aim to achieve a budgeted maintenance cost over the life of a mine is not new; however, scheduling equipment via an approach to minimize the maintenance cost as the primary focus of the scheduling process is new. There is no mathematical based method that considers the entire truck fleet and entire mine life to minimize the equipment maintenance cost and properly integrates the cost of engine rebuild and overall maintenance at a certain age.

Pinedo (2008) discusses various types of machine scheduling problems including both deterministic and stochastic optimization models. In a multiple parallel machine scheduling problem, the objective usually focuses on makespan; that is, the total completion time of the job and expected number of tardy jobs. The job that takes the longest time is scheduled last to maximize the number of jobs completed. In the cases where the job completion times are exponentially distributed, the job with the largest variance is scheduled first to minimize the expected makespan. However, these models cannot be readily expanded to solve the mine truck scheduling problem, because the mine trucks have non-linearly varying maintenance cost and the trucks are used together to move as much material as possible, that is, discrete individual tasks for each truck cannot be isolated from other trucks and equipment.

Woolsey (1997) demonstrates the MIP modeling for sequence independent and sequence dependent changeovers in production planning and machine sequencing problems. The model was formulated for single machine multi-item lot sizing with changeover cost with a single item production in each time period. The paper does not provide real case application and how the system works rather it supports the formulations with other similar applications for different industry.

Caumond et al. (2009) developed an MIP model for the flexible manufacturing systems scheduling problem (FMSSP) with one vehicle. The model considers limited resource capacities for both jobs and machine scheduling, input/output buffer management, and the maximum number of jobs allowed simultaneously in the system. The proposed formulation provides an optimal solution to the demonstrated scheduling of small and medium complexity problem.

Dodin and Elimam (2008) proposed a new MIP model for integration of project scheduling with equipment planning. The model considers more than one activity at the same time and assigns the available equipment based on the trade-offs among several costs such as crashing cost, holding cost and transition costs. In order to reduce the CPU time, they have proposed to consider that any project schedule starting at time zero to eliminate the need to search all the schedules that may not start at time zero by assuming an optimal schedule with zero start time must exist. Furthermore, in order to make the MIP model more computationally tractable, a heuristic algorithm has been developed to determine routing for each piece of equipment between activities. The proposed MIP model was applied to eleven projects with four network structures and the generated solutions were presented.

Further formulations and applications of MIP to different areas can be seen in the literature, but as Ernst et al. (2004) indicate the unique characteristics of different industries and organizations requires development of specific mathematical models and algorithms for different areas of applications. The scheduling model proposed herein differs from those published previously in that it is the first model developed for application to a mine truck fleet with the unique characteristics discussed in Section 3.

A major focus of optimization related to truck fleets has revolved around the DISPATCH system for many years. This system assigns trucks to a loader and manages the truck destinations. Alarie and Gamache (2002) review available methods that exist for solving the dispatching problem and analyses the strategies. There are two main methods in the literature that relate to truck dispatching, these are single stage and multi stage. Single stage dispatches the trucks to loaders according to one or several criteria without considering any production targets and constraints. The multi-stage approach divides the dispatching problem into subproblems or stages. Generally these stages are an upper stage, which contains setting the production target for every loader, and a lower stage, which assigns trucks to a loader to minimize the deviation from the production targets suggested by the upper stage. Further literature in this area can be listed as Olivieri (1996), Osanloo and Saidy (1999), Zang et al. (2004) and Krause and Musingwini (2008).

The efforts in optimizing truck dispatching systems do not cover the equipment's schedule of utilization to minimize the maintenance cost. In the literature, the only related study has been reported by Burt et al. (2005). In this study, an MIP model was developed to select the best match of trucks to the loader fleet. The model aims to minimize the operating cost with the match while adhering to the production requirements of the operation. The model selects the best match for a mixed type fleet in a single time period using two decision variables; one is to identify the number of trucks of type *i* working with loader type *j* and the second is to identify the number of loaders of type *j* working with truck type *i*. Application of the model prove that it can generate optimal solutions within seconds for heterogeneous fleets. The model however does not consider the equipment age and maintenance cost relationship. Instead, it uses average cost values for equipment, which is not realistic and does not consider the global optimization for the mine life.

The most common way of scheduling trucks in the mining industry is manual scheduling through extensive spreadsheets that rely heavily on the experience and skill of the scheduler. Each year trucks are scheduled to satisfy the required truck hours. This approach relies on using newer trucks as much as possible assuming that the maintenance cost increases as the age of the truck increases. There is, however, no such relationship between truck age and maintenance cost. This approach also cannot handle properly the situation where, at a certain age, the truck needs an engine rebuild and overall high cost maintenance. Usually, after major maintenance on a truck, the cost of that truck is likely to be lower than that of newer trucks. Thus the distribution of the maintenance cost is often irregular throughout the life of the trucks. Furthermore, the problem becomes more complicated when various type of trucks are used; this is often the case for many large mining operations.

3. MIP model to minimize the truck maintenance cost

The proposed mathematical programming model is based on MIP techniques and is deterministic in nature. It aims to minimize truck maintenance cost while meeting the yearly required truck hours for a given operation. The proposed model considers the maintenance cost variation with truck age and the periodical required rate of material movement for the life of mine to produce a globally optimum truck schedule.

It is common for many operating mines to have fleets containing trucks of different ages. When a new mine is started, usually a fleet of new trucks are purchased. Due to different downtimes of each truck, the operating hours of all the trucks are not expected to stay the same throughout the mine life. Some trucks may need to be replaced by new trucks when they start to become inefficient for production (too excessive maintenance cost and frequent long down time).

The maintenance cost data of the truck fleet are usually available at mines for a range of truck ages (or age bins). There are no set rules for making the age bin ranges, but as the number of bins increases, the number of variables needed for the mathematical model also increases. In the case study presented in this paper, a 5000 hours range is used. That means when a truck age is less than 5000 hours, it is allocated to bin 1 and when it is between 5000 and 10000 hours, it is allocated to bin 2, etc. This data set includes planned maintenance as the main part of the cost and also some estimates for unexpected repair costs.

Solving the following MIP model provides values for decision variables that correspond to truck fleet schedule; that is, whether or not to use a given truck and age bin (s) in a given time period. This model addresses the variability of maintenance for truck types and ages over the life of the operation with its own restrictions, such as cost values that may not be exactly the same as in the historical data and the estimated costs for the new trucks obtained from the manufacturer that can vary depending on the conditions at the operations.

This proposed model has three main unique aspects. The first is that the sequencing of age bins is achieved by using binary variables while allowing the age bins to be used at less than full capacity. This means age bins can be used partially within a time period by implementing binary and linear variables in Eqs. (4) and (5). The second is that the model is able to handle multiple truck types of various ages and a major planned maintenance operation, engine rebuild, (relatively expensive maintenance) for trucks reaching a certain age bin. The final aspect is that the model is able to perform global optimization over 10 years of mine life using an entire truck fleet, while traditional approaches can only consider a single truck and one time period at each iteration.

The MIP model formulation is as follows:

Indices

t	truck ID
b	age bins
y	time period (year)
c	critical bin hours

Parameters

$C_{t,b,y}$	the discounted cost value ($/hour) for truck *t*, age bin *b* in the *y* th time period
FE_t	the amount of money for rebuilding the truck *t*'s engine
$A_{t,y}$	the available hours for truck *t* for a given time period *y*
$M_{t,b}$	the maximum available hours for truck *t* at age bin *b*
$H_{t,y}$	the cumulative used hours for truck *t* at time period *t*
R_y	the required truck hours for a given time period *y*

Decision variables

$X_{t,b,y}$	the number of hours scheduled for truck *t*, age bin *b* in the *y* th time period
$Y_{t,b,y}$	$\{1,$ if truck *t* at bin *b* used up all the available truck hours in time period y $0,$ otherwise$\}$
$Y_{t,c,y}$	$\{1,$ if the truck *t* is used more than the critical bin hours *c* in time period y $0,$ otherwise$\}$

Objective function:

$$\text{Min} \quad \sum_{y}^{y\max}\sum_{t}^{t\max}\sum_{b}^{b\max} C_{t,b,y} * X_{t,b,y} + Y_{t,c,y} * \text{FE}_t$$

Subject to:

$$\sum_{b}^{b\max} X_{t,b,y} <= A_{t,y} \quad \forall y = 1,\ldots,y\max \text{ and } \forall t = 1,\ldots,t\max, \tag{1}$$

$$\sum_{y}^{y\max} X_{t,b,y} <= M_{t,b} \quad \forall t = 1,\ldots,t\max, \text{ and } b = 1,\ldots,b\max \tag{2}$$

$$\sum_{b}^{b\max} X_{t,b,y} + H_{t,y-1} = H_{t,y} \quad \forall y = 1,\ldots,y\max; \quad \forall t = 1,\ldots,t\max \tag{3}$$

$$\sum_{k=1}^{y} X_{t,b,k} - M_{t,b} * Y_{t,b,y} \geqslant 0 \quad \forall t = 1,\ldots,t\ \max, \text{ and } b = 1,\ldots,b\max \tag{4}$$

$$X_{t,b+1,y} - M_{t,b+1}\sum_{k=1}^{y} Y_{t,b,k} \leqslant 0 \quad \forall t = 1,\ldots,t\max, \text{ and } b = 1,\ldots,b\max \tag{5}$$

$$\sum_{t=1}^{t\max}(H_{t,y} - H_{t,y-1}) = R_y \quad \forall\ y = 1,\ldots,y\max \tag{6}$$

$$X_{t,b,y} \geqslant 0 \quad \forall\ t,b,y \tag{7}$$

$$Y_{t,b,y}\ \text{binary} \quad \forall t,b,y \text{ and } Y_{t,c,y}\ \text{binary}\ \forall t,c,y \tag{8}$$

The objective function minimizes the maintenance cost for the available truck fleet for a mining operation. The value of the cost coefficient $C_{t,b,y}$ changes depending on the age bin that is current for a given truck. For a mining operation, many trucks can be in different age bins because the mine will purchase the trucks in different time periods. If truck t is used more than the critical bin hours (c), $Y_{t,c,y}$ takes the value of 1 and charges the FE_t cost, which includes the cost for re-building truck t's engine and the required replacement/repair of any parts necessary for further usage. Constraint (1) ensures that the total operating hours of a truck during a given time period not exceed the available truck hours $A_{t,y}$. A truck effective utilization factor is the percentage of the hours that the truck is moving to the total hours that the truck is available to move. The available operating hours in the MIP model in a time period for each truck is calculated based on the effective utilization factor (including planned maintenance times that a truck can be operated in production), and available work hours in a year. For example, if there are 6000 working hours in a year for a mine, the truck with 75% effective utilization cannot operate more than 4500 hours (6000×0.75) in that year.

Constraint (2) enforces that once the total operating hours in a bin reach the total bin hours (5000), the truck hour usage moves to next upper age bin. Every truck age bin contains certain operating hours. The age bins can be set depending on the type and class of trucks and the operating conditions. In this case study, age bins are formed using 5000 hours increments. The initial bin's limit is set considering the truck's current age. For example, if a truck's age is 23,500 hours, truck bins 1–4 would have a limit of 0 hour, bin 5 would have a limit of 1500 hours and the other bins would be set to 5000 hours. Eq. (3) calculates the age of the trucks at the end of each period. This constraint handles the amount of used hours by setting $H_{t,y}$ to the current age of truck t for $y = 0$; for $y > 0$, it is the cumulative used hours for a given time period.

Constraints (4) and (5) enforce the trucks to use the correct order of age bin usage sequentially so that the previous bin's age hours must be completed before using the hours from higher age bins. It prevents the random usage of age bins by the trucks. Constraint (6) satisfies the mine's required truck hours with available trucks in the system. The total quantity of the material to be moved, based on the production schedule, can be converted to truck hours since the distance to carry the material (location of waste dumps and crushers) and average truck speeds are known. Constraints (7) and (8) enforce non-negativity and integrality of the variables, as appropriate.

4. Case study at a gold mine

Data from a mine located in Western Australia are used to implement the formulations and enable a comparison between TA and the proposed MIP model. Table 1 presents the unit maintenance cost as dollar per operating hour for the truck types at the various age bins. As can be seen from Table 1, six different types of trucks are used and the number of age bins for a given truck type is 20. Truck types can be used to reflect the different brands and classes (capacities) such as HITACHI EH300, EH5000, CAT 777, 797, LIEBHERR T252, T282, KOMATSU 830E, 930E, etc. For this gold mine operation, the truck types have different costs based on the historic data from the operation, truck dealer's comments and the past experiences of the maintenance crew. The cost numbers used in the case study are modified for confidentiality purposes, but both the TA and proposed equipment scheduling approach use the modified information to generate a schedule.

After a truck is used for 70,000 hours (critical bin number, $c = 15$), it is assumed that the truck needs major maintenance work, which mainly constitutes an engine re-build and other repairs or part replacements if necessary. The cost of this maintenance is estimated to be approximately $700,000. It is also assumed that a truck cannot be used for more than 100,000 hours, even after performing major repair on a truck, and used trucks have no salvage value.

Table 2 details the truck hours required to move the material (ore and waste) that is specified by the production schedule. Currently, most of the available trucks for the schedule have certain used hours. The truck used hours (truck's current age) before the schedule and truck types can be seen in Table 3. The truck available hours that can be used in a year are calculated based on truck availability and utilization percent factors, which include estimated downtime for planned maintenance, operator break times and idle times during shift change. The varying capacities of the truck types are considered when converting all the truck hours to equivalent available truck hours in a year.

4.1. Truck fleet schedule using the traditional approach

The mine truck fleet scheduled using TA is based on Excel spreadsheets. The method aims to first use the new trucks and then older trucks, as it assumes that newer trucks have lower costs. This assumption is made to simplify the problem due to the limitations of the Excel spreadsheet model to incorporate the complex-

Table 2
Truck operating hours to move the material as required in the production schedule.

Year	Required truck operating hours
1	221,050
2	220,300
3	232,500
4	231,500
5	232,600
6	230,000
7	220,000
8	200,000
9	106,300
10	25,000

Table 3
The age of available trucks and types. Note that trucks 32, 33 and 34 were purchased recently.

Truck ID	Age (operating hours)	Truck Type	Truck ID	Age (operating hours)	Truck Type
1	43055	1	18	41571	2
2	43864	1	19	37766	2
3	42595	1	20	37936	2
4	43141	1	21	32033	2
5	43570	1	22	32503	3
6	42659	1	23	32479	3
7	42603	1	24	30384	3
8	42162	1	25	21762	4
9	42214	1	26	21686	4
10	42555	1	27	21310	4
11	42213	1	28	16585	5
12	41259	2	29	16734	5
13	42180	2	30	16311	5
14	41122	2	31	15682	5
15	41216	2	32	0	6
16	41472	2	33	0	6
17	41945	2	34	0	6

ities of the truck scheduling problem. Each year, it schedules the trucks to satisfy the required truck hours. The results of the truck schedule using the TA are presented in Table 4.

It is not possible for the TA to integrate the all the cost information and possible variations. For example, as new trucks age, their costs might increase and after an expensive repair, maintenance costs often decrease. The difficulty is mainly due to the interaction between trucks at certain age bins over the entire mine life.

The schedule produced using TA has some variations from the available truck hour capacities. This is caused because of that the total available truck hours are calculated in a year and it is averaged over the available trucks in that year. This averaged available truck hour is used as available truck capacity. For example, in the first year for truck 7, it is scheduled to run for 7261 hours, but the maximum possible available operating hours is 7138. Furthermore truck 19 has 7412 hours available, but it is still scheduled for 7261 hours. Since the schedule is completed using average available hours that a truck can run in a year, it does not violate the yearly total available truck hour capacity. It doesn't make any difference if it would consider individual truck hours availability or annual overall availability, because it cannot consider the cost of individual bins.

The schedule obtained using TA does not use trucks 1 and 2 for the first two years. These trucks are relatively older when compared with the rest of the fleet. The newer trucks, (i.e., 32, 33 and 34) are used as much as possible and the older trucks are used only when needed. Furthermore, the first 3 trucks (relatively old) are not used after the 70,000 hours limit and the major repair costs for them are avoided. The three newest trucks, however, also did not reach the 70,000 hours limit even though they are scheduled for high usage hours. The remaining 28 trucks are required to undergo major repair to satisfy the total required operating hours.

4.2. Equipment schedule using the proposed MIP model

In this section, the trucks are scheduled using the MIP model which was presented in Section 3. The advantage of the MIP model is that it can consider the entire mine life and interactions between

Table 4
The scheduled hours of truck fleet using the traditional approach.

Truck	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
1	0	0	3426	3426	4776	0	0	0	0	0
2	0	0	3426	3426	6904	3298	0	0	0	0
3	0	0	6087	6647	6904	7084	0	0	0	0
4	3679	1846	7083	7032	6904	7084	3362	0	0	0
5	6804	6807	7083	7032	6904	7084	7221	0	0	0
6	7261	7298	7083	7032	6904	7084	7221	1440	0	304
7	7261	7298	7083	7032	6904	7084	7221	6905	0	0
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
19	7261	7298	7083	7032	6904	7084	7221	7098	1726	1031
20	7261	7298	7083	7032	6904	7084	7221	7098	3443	1031
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
32	7261	7298	7083	7032	6904	7084	7221	7098	7000	2062
33	7261	7298	7083	7032	6904	7084	7221	7098	7000	2062
34	7261	7298	7083	7032	6904	7084	7221	7098	7000	2062

Table 5
The scheduled hours of truck fleet using the MIP model.

Truck	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
1	7138	7292	7320	7065	6916	6890	6929	6976	0	0
2	7054	7292	7320	7065	6916	6890	7065	6534	0	0
3	4585	7292	7320	7065	6916	6890	7337	6976	0	0
4	7138	7292	7320	7065	6916	6890	7065	6976	0	0
5	7138	7292	7320	7065	6916	6890	7065	6744	0	0
6	7138	7292	7320	7065	6916	6890	7337	6976	0	0
7	7138	7292	7320	7065	6916	6890	6929	6842	0	0
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
19	7412	7155	6519	7342	6916	6890	6929	6842	6229	0
20	7412	7155	6824	7252	6916	6890	6929	6842	5844	0
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
32	7618	7498	7320	7481	7052	7295	7065	7111	7122	6727
33	7618	7498	7320	7481	7052	7295	7065	7111	7122	6546
34	7618	7498	7320	7481	7052	7295	7065	7111	7122	6727

trucks at the age bins to produce the best truck schedule with minimum maintenance cost. Since the maintenance cost often reduces after major work, the proposed model is able to compare this effect with the cost of scheduling other trucks and make the best decision.

The proposed MIP model is programmed using the Visual Basic code and the formulation is solved with CPLEX solver, Version 11.2 (ILOG Corporation, 2009) using an Intel (R) Xeon (R) with 2.66 GHz CPU processor and 8 GB RAM. The model has been solved in less than 30 minutes with less than 5% gap from the optimality. The gap here refers to the difference between a theoretical optimum solution assuming all variables are linear and the actual result obtained with the binary variables. Table 5 presents the truck fleet schedule produced by the MIP model. The complete data can be provided upon request.

To measure the computational time of the problem, two more randomly generated instances have been solved. The optimal solution was obtained instantly (in 0.91 second) for the first case which contained 25 trucks and 3.45 hours for the second case which contained 45 trucks with 5% gap. As experimented, as the number of trucks increase so do the number of binary variables, which results in longer solution times. In order to obtain an optimal solution for the larger models within a reasonable time frame, binary variables can be reduced by increasing the age bin ranges. However, it would be very exceptional case to have a mine, which contains more than 45 trucks in a single operation.

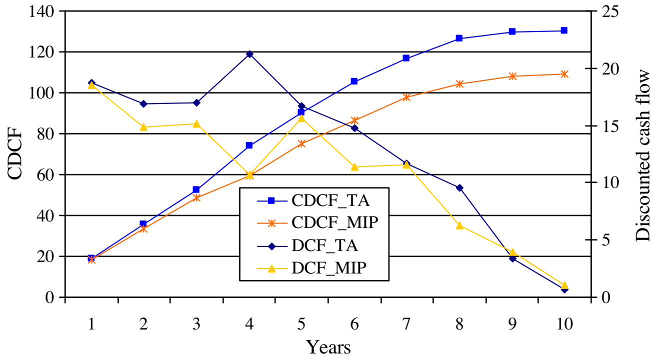

Fig. 1. Discounted annual cash cost (DCF) and cumulative discounted cash cost (CDCF) for both the traditional approach (TA) and the proposed MIP model.

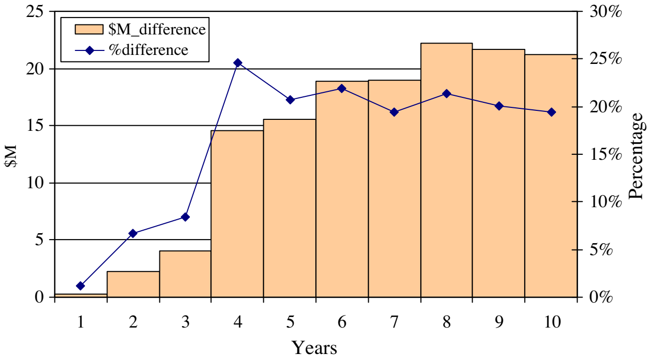

Fig. 2. Cumulative cost saving by the proposed MIP model compared with the traditional approach for mine equipment scheduling.

4.3. Financial comparison of the truck schedules

A financial evaluation of the truck schedules is performed using 10% discount rate with the maintenance costs provided in Table 1. In this case study, the MIP model provided a total $21.3M (16.3% less than the TA's cost) discounted cost saving over 10 years when compared to the traditional approach. This is over $2M in average savings annually on the operation's cash cost for truck maintenance. The discounted annual cash flows (DCF) and cumulative discounted cash flows (CDCF) for both the TA and proposed MIP model are given in Fig. 1. This figure shows that within the first 5 years the discounted cost savings reach as high as approximately $15.6M. This is a significant cost saving, particularly during the early years of an operation. Usually the financial outlook of an operation for the first 5 years is extremely important as revenue needs to be generated to pay for the capital spent for starting the project.

Fig. 2 shows the discounted cost savings in $M achieved using the MIP model instead of the traditional approach and also as percentage of the discounted cumulative cost. The schedule using the TA would cost the operation 19.5% more than the proposed MIP model. The percentage is calculated as follows:

$$\text{Difference}(\%) = 100 * (\text{CDCF}_{\text{TA}} - \text{CDCF}_{\text{MIP}})/\text{CDCF}_{\text{MIP}}$$

where CDCF_{TA} is the cumulative discounted cost for the schedule generated by the TA and CDCF_{MIP} is cumulative discounted cost for the schedule generated by the MIP model.

Fig. 3 shows the truck fleet ages at the end of mine life and the unit average cost for each truck for the schedules. The figure illus-

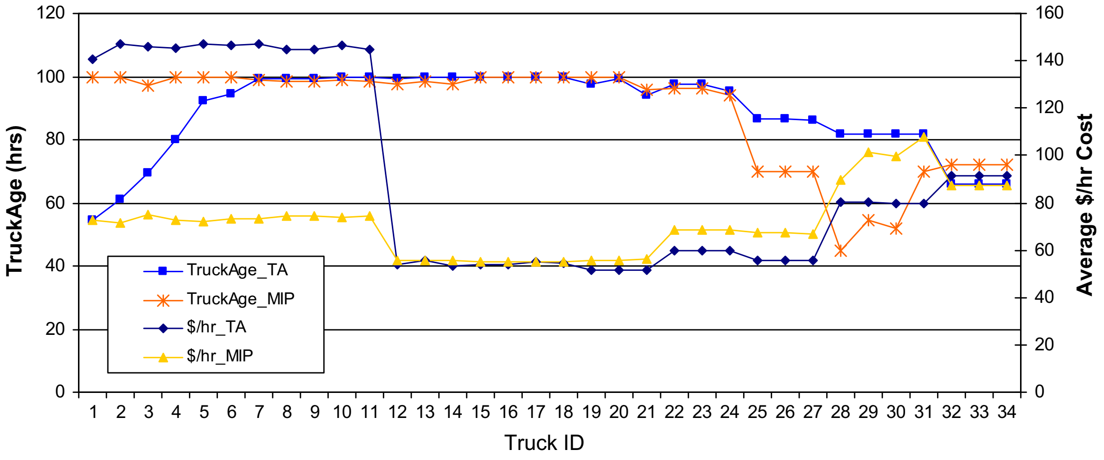

Fig. 3. Average unit cost ($/hour) and age of the trucks (operating hours) for both the traditional approach (TA) and the MIP model.

trates the unit cost savings for individual trucks. The TA schedule used truck numbers 1–5 much less than the MIP model. As those trucks were the oldest at the beginning of the mine life, the new trucks appeared more sensible to use. Since the proposed MIP model, however, is able to evaluate the entire age bin's cost over the mine life, it found it was still economical to also use the old trucks. As shown in Fig. 3, the average costs of these trucks are much lower for the MIP model than the TA model since they are used efficiently by the MIP truck scheduler.

5. Conclusions

A new MIP model has been proposed to provide substantial cost savings for equipment scheduling by optimizing truck usage. The MIP model used for this case study provides a saving of approximately \$15.6M in discounted cash costs for the first 5 years and \$21.3M over the 10 year mine life. While it is not possible to predict precisely the savings that the MIP model can generate for any mine, generally a 10–25% maintenance cost saving can be expected.

A great deal of experience and simplifying assumptions are required to produce the TA generated schedule. Moreover, this schedule will often vary from person to person and it is difficult to quantify its quality. On the other hand, the proposed MIP based model can generate the solution in a relatively short time period without simplifying assumptions. It also helps the operation to evaluate different scenarios within a reasonable time period.

There is a common misconception that truck scheduling can be successfully achieved by simply examining the cost bins and one may spend more time on it trying to reduce the cost by a trial-and error approach. There is, however, a complex interaction between the trucks and age bins due to the fact that the cost does not linearly increase with the truck age. This is why the globally optimal MIP model is able to produce substantial savings. Furthermore, the traditional approach also fails during the scheduling process to consider effectively some of the financial parameters, such as major engine re-build costs if trucks are used over a specified number of hours, the effect of this rebuild on the costs for the upper bins and also the interaction of age bin costs between trucks.

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