Western Australian School of Mines

A New MIP Model for Mining Equipment Scheduling
Under Variable Scenarios

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This thesis is presented for the Degree of
Master of Philosophy (Mining Engineering)
of
Curtin University

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DECLARATION

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgement has been made. This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

Signature: Zhou Fu

Date: 12 May 2014
PUBLICATIONS INCORPORATED INTO THIS THESIS

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ABSTRACT

Mining is a capital-intensive industry that requires hundreds of million-dollar investment in large equipment. Mine trucks are the most important mining equipment for the material haulage. However, their maintenance cost accounts for large proportion of the overall mining operational cost. An overview of the current studies reveals that although the truck scheduling issue has been researched for decades, there is no method that can take into account all major constraints with the objective of obtaining the minimised maintenance cost.

This research develops a mixed integer programming (MIP) model to optimise the heterogeneous truck fleet schedule that can minimise the maintenance cost in conjunction with satisfying the material movement schedule and considering a new truck purchase option. A hypothetical data set is implemented to validate the proposed MIP model. The validation results have proved that all formulated constraints are working correctly.

The proposed MIP model is applied to a real data set from a gold mine located in Western Australia. The result is compared with that of the traditional spreadsheet-based method and original MIP model using the same data set, which indicates that the proposed MIP model can provide 21.94% and 14.77% maintenance cost savings over the other two methods throughout a 10-year period of time respectively. Since the conditions in the real mining operation have uncertainty, the input variables of the proposed MIP model for truck scheduling are dynamic. Hence, the applications of the proposed MIP model with “what if” scenario-based variables, such as age bin size, material movement requirement and truck purchase cost, are conducted in this research. Their performance and solutions are demonstrated in this thesis.

An interface of the proposed MIP model is developed, which simplifies the process of dealing with a mass of data and constructing the MIP model. With the assistance of the interface, the truck scheduling time is decreased considerably. In addition, a manual of the interface is stated in the thesis.
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<tr>
<th>Abbreviation</th>
<th>Full Form</th>
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<tbody>
<tr>
<td>bfs</td>
<td>Basic Feasible Solution</td>
</tr>
<tr>
<td>CDC</td>
<td>Cumulative Discounted Cost</td>
</tr>
<tr>
<td>CDS</td>
<td>Cumulative Discounted Saving</td>
</tr>
<tr>
<td>CPU</td>
<td>Central Processing Unit</td>
</tr>
<tr>
<td>DAC</td>
<td>Discounted Annual Cost</td>
</tr>
<tr>
<td>FMSSP</td>
<td>Flexible Manufacturing Systems Scheduling Problem</td>
</tr>
<tr>
<td>ID</td>
<td>Identification</td>
</tr>
<tr>
<td>LP</td>
<td>Linear Programming</td>
</tr>
<tr>
<td>MIP</td>
<td>Mixed Integer Programming</td>
</tr>
<tr>
<td>PCDS</td>
<td>Percentage of Cumulative Discounted Saving</td>
</tr>
<tr>
<td>RAM</td>
<td>Random-Access Memory</td>
</tr>
<tr>
<td>TA</td>
<td>Traditional Approach</td>
</tr>
<tr>
<td>VBA</td>
<td>Visual Basic for Application</td>
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CHAPTER 1. INTRODUCTION

1.1 PROBLEM STATEMENT

Material haulage is one of the most significant components of a mining operation, as its cost typically constitutes more than 50% of the operational cost (Alarie and Gamache, 2002, Subtil et al., 2011). According to the annual production schedule, there is certain amount of ore and waste that requires to be hauled by the large mining equipment each year throughout the mine lifespan. Due to the large investments for the capital and operational cost of the large mining equipment, there must be an optimal approach to schedule the large equipment so as to maximise their utilisation and minimise their operational cost. Mine trucks are the most important materials haulage equipment in mining operations owing to their flexibility and efficiency. In order to sustain the stability of mining operations, the routine maintenance services need to be performed to truck fleet. However, the cost of maintenance service can account for 30-50% of the overall haulage cost of the surface mining operation (Topal and Ramazan, 2010). Therefore, it is necessary to develop a method which can optimise the schedule of truck fleet so that its overall maintenance cost is minimised and the utilisation is maximised.

A great deal of currently available studies focus on the research with respect to mine trucks scheduling and dispatching for various objectives, such as obtaining the optimal fleet size, minimising the waiting time and the deviation from the production target. However, few of them consider the truck scheduling problems from the point of minimising the maintenance cost. Topal and Ramazan (2010) is the only related study which aimed to develop a MIP model to optimise truck fleet schedule with an objective of minimum maintenance cost while satisfying the material movement schedule. However, there are two apparent limitations existing in this model. First, when the haulage capacity of the truck fleet being used currently cannot meet the annual material movement requirement, this model will fail to function. In addition, when the current trucks become inefficient to the mining operation, which is possibly due to the frequently long downtime or high maintenance cost, new trucks should be scheduled to be purchased to the fleet. Second, the model of Topal and Ramazan (2010) assumes homogeneous payload capacity of various types of trucks in the fleet. It is however obvious that the trucks with higher payload capacity can make
more contributions to the overall material haulage operation during the same working period. A new model is supposed to take into account all these key constraints of the truck haulage operations.

Due to the variability of the conditions in mining operations, the production schedule and the status of the truck fleet are not static. As a result, the input variables of the MIP model for the truck scheduling are dynamic. It is necessary to know the resulting schedules, computation time and other relevant information when different input variables are applied to the MIP model.

As mentioned above, the new MIP model should schedule the truck fleet for the minimised maintenance cost with consideration of a new truck purchase option and various payload capacities of different trucks, while satisfying the annual material movement schedule. Moreover, “what if” scenario-based input variables are required to be applied to the model, subsequently the corresponding solutions need to be explained and analysed.

### 1.2 Objectives

The main objectives of this research are as follows:

- To develop a MIP model to optimise the schedule of the heterogeneous truck fleet which minimises the maintenance cost while adhering the annual material movement requirement.
- To consider a new truck purchase option in the new MIP model which can compare the cost of continuously using old trucks versus purchasing new trucks. If the new truck purchase decision is made, the model can provide the optimal schedule for the new trucks.
- To implement the new MIP model to a real case study and present the optimal schedule.
- To apply “what if” scenario-based input variables into the new MIP model to test the function of the model and analyse the resulting schedules based on various input variables.

### 1.3 Scope

This research dedicates to develop a method which can provide optimised schedule for the heterogeneous truck fleet with the objective of achieving minimum
maintenance cost while considering a new truck purchase option and satisfying the material movement schedule. The solutions of scheduling model only suggest the optimal working hours for haul trucks in each year, and the detailed information concerning dispatching trucks to loaders and routine problems are not considered in this research.

1.4 **SIGNIFICANCES**

This research focuses on the truck scheduling optimisation with accounting for all major constraints; the significances of this research to the mining operation are as follows:

- The new MIP model can generate an optimal schedule for the truck fleet which determines the recommended annual working hours for each truck, which not only provides the minimised maintenance cost but also gives great convenience for the further truck dispatching. Moreover, this model integrates new equipment purchase with the truck fleet scheduling, which can benefit the system in a long period of time.

- The new MIP model is based on the MIP technique that has been scientifically proven to be a powerful mathematical method for the optimisation problem. Hence, the solutions generated by the model are optimal compared to the traditional approach which is based solely on the human skills and experience.

- The new MIP model is constructed by programming language and solved by CPLEX (ILOG Corporation, 2009), which saves considerable amount of the scheduling and computation time compared with the traditional approach. In other words, the new MIP model can provide a response promptly when the situations are changed in real mining operations.

- With the development of the interface, the new MIP model is rather flexible for modifications. Schedulers do not have to change the programming code when input data is different. This will further facilitate the schedulers in mine sites to meet the varying requirements that are associated with the material haulage issues.

- The solutions are summarised and analysed after the “what if” scenario-based input variables are applied to the model, which can provide general empirical
suggestions for truck scheduling that can help engineers to make preliminary plans for further problems.

1.5 ORGANISATION OF THE DISSERTATION

Chapter 1 indicates the confronted truck scheduling problems existing in the mining operations, then presents the objectives, scope and significances of the research.

Chapter 2 introduces the mining equipment scheduling and dispatching problems, subsequently provides the introduction and application of the MIP technique as the methodology.

Chapter 3 explains the mathematical formulation of the proposed MIP model and validates the model with a hypothetical data set.

Chapter 4 demonstrates an application of the proposed MIP model to a real case study. A comparison of different approaches based on the same data set is then performed. Finally, the “what if” scenario-based input variables are applied into the proposed MIP model.

Chapter 5 introduces the interface developed for the proposed MIP model.

Chapter 6 concludes the findings of this research and depicts the recommendations for the future research.
CHAPTER 2. LITERATURE REVIEW

2.1 MINING EQUIPMENT SCHEDULING AND DISPATCHING

All the mining companies throughout the world operate the fleets of various types of mining equipment; each of them faces with the scheduling and dispatching problems. Mine trucks are the most important mining equipment to complete the material haulage in the open pit mining operations; however, their capital and operational cost can reach hundreds of million dollars. Considering this tremendous investment, even a subtle adjustment which is made to the schedule can result in a great change up to millions of dollars on the overall operation cost. This research aims to determine the optimal mine truck schedule with the minimised maintenance cost for the mining operations. In the current practices and studies, there is a large amount of researches devoted to the mine truck fleets dispatching problems in operation, but few are to focus solely on the truck fleets scheduling, especially from the point of obtaining minimal maintenance cost. Therefore, it is important to understand the interrelationships between scheduling and dispatching.

The scheduling and dispatching problems are recognised as the significant stages in the process of production planning and control. Lansburgh and Spriegel (1946) provided the definition of scheduling in their book: scheduling involves planning the amount of work to be done, the time each component of this work is supposed to start and the order of work. This contains planning for the quantity and rate of output of the plant or departments as well as the time or order of the commencement of each work unit at each station based on the route provided. The dispatching involves meeting schedules by appropriately using machines, workplaces, materials and workforce, as designated by the routing. Ronen (1988) also presented the interpretation of the terms of vehicle scheduling and dispatching in his study. According to the definitions, it can be seen that scheduling is on the higher level than dispatching in the production control.

In order to know the actual tasks of scheduling and dispatching, further research was conducted by McKay and Wiers (2003). They introduced and distinguished the scheduling and dispatching through comparing three task characteristics: horizon and timing, decision making and context. According to their study, the horizon of the
scheduling is decreased when the number of the uncertainty increases, but is usually 1 week. The horizon of the dispatcher is usually in minutes, hours and days. While making decisions, the schedulers only access the information that can affect the constraints significantly, whereas the dispatchers must handle any detailed data that may be potentially relevant. From a point of context, the scheduler must take the responsibility of developing a feasible sequence for the dispatcher, while dispatcher’s decisions have direct effects on the use of personnel and resources. McKay and Wiers (2003) summarised the differences between schedulers and dispatchers in Table 2-1.

<table>
<thead>
<tr>
<th></th>
<th>Horizon</th>
<th>Availability of Information</th>
<th>Interaction with Lower level</th>
<th>Time Pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scheduler</td>
<td>Single, real time</td>
<td>Low</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Dispatcher</td>
<td>Single, real time</td>
<td>High</td>
<td>n.a.</td>
<td>Low</td>
</tr>
</tbody>
</table>

A large amount of researches that strive to optimise the mine truck dispatching can be found in the current studies. The major objective of these studies is to increase the productivity of the truck fleets and decrease the operational cost. Although the main focus of this research is optimisation of mine truck scheduling, there are few studies dedicated to this area. The methods and experience in the mine truck dispatching studies can be a helpful guidance to this research.

The truck and shovel system is the major hauling and loading system in the surface mining. The dispatch of trucks and shovels has attracted considerable attentions in the last few years due to the giant cost savings or productivity increments resulting from its successful implementation.

The approaches of the truck-shovel dispatch systems range from the heuristic methods to the complicated mathematical model based methods. Morgan and Peterson (1968) introduced the match factor to take account of the interaction of the capacity and cycle time of truck and loader fleets for the suitable size of truck fleets and the efficiency of the fleets. As presented in Figure 2-1, the capacity of the truck fleet limits the productivity of the truck and loader fleets before the intersection point,
and the capacity of the loader fleet limits the productivity of the fleets after the intersection point.

Figure 2-1 Theoretical “match point” occurring at the intersection (modified from Morgan and Peterson, 1968)

Kolonja et al. (1993) listed four main heuristic truck-shovel dispatching criteria including minimizing shovel waiting time, minimizing truck cycle time, minimizing truck waiting time, minimizing shovel saturation. Because truck and shovel dispatching problems, based on the heuristic rules, do not need complex computation, they are widely used in the dispatching related studies (Lizotte et al., 1987, Arelovich et al., 2010). However, heuristic rules are from empirical and logic analysis without a robust mathematical explanation. They can sometimes provide good result but not the optimal one.

Alarie and Gamache (2002) reviewed the truck dispatching related literatures and summarised that there are two major approaches to resolve the truck dispatching issue: the single stage and multistage. The single stage approach dispatches the trucks to shovels based on one or several criteria without considering production targets or constraints. The multistage approach divides the dispatching problem into two sub-stages, the upper sub-stage is to set the production target to every shovel and the lower sub-stage dispatches the trucks to shovels to minimise the deviation from the production targets suggested by the upper sub-stage. Subtil et al. (2011) applied the multistage approach to the real open-pit mine by obtaining the optimised truck number using the linear programming model in the upper sub-stage and
dispatching the trucks to the shovels with heuristic methods in the lower sub-stage. The steps running in the lower sub-stage for dynamic allocating trucks are presented in Figure 2-2. There are a variety of approaches used for the truck dispatching problems which can also be seen in the following studies (Temeng et al., 1997, Krause and Musingwini, 2007, Bastos et al., 2011, Osanloo and Saidy, 1999).

Figure 2-2 Dynamic allocation steps (modified from Subtil et al., 2011)

The truck dispatching can accomplish the trucks allocation and the selection of best match for shovels and trucks, but the solutions from truck dispatching cannot give exact answer to the truck scheduling problems, such as, what is the optimal number of trucks in the fleet for the current operation? what are the optimal working hours every truck can operate in each time period? what is the best sequence of operating trucks in the heterogeneous truck fleet? The truck scheduling should take into account all of these questions. However, the truck scheduling research has not received enough attentions. There are quite limited number of literature in regards to this area in the current practices and studies. Through the review of the available researches, MIP technique is one of the most important methods that have been widely implemented in the truck scheduling. The introduction of MIP technique and its application in the truck scheduling are demonstrated in the following section.

2.2 INTRODUCTION OF MIXED INTEGER PROGRAMMING (MIP) TECHNIQUE

Developing a mathematical model, especially with the MIP technique, is a widely used method to provide the optimal solutions to mining equipment scheduling and dispatching problems in mining operations. In this section, the mathematical
modelling method along with the introduction and application of the MIP technique are indicated.

2.2.1 Mathematical modelling

The mathematical model is a description of a system using mathematical concepts and language. The process of developing a mathematical model is recognised as mathematical modelling. In other words, mathematical modelling is the utilisation of mathematics to reveal and explain the real world problems.

The procedure of mathematical modelling described by Kallrath (2004) is as follows:

1. Construct a mathematical model that is based on a real-world problem;
2. Collect data for the problem generation;
3. Solve the problem and obtain the optimum solution;
4. Interpret the solution; and
5. Implement the solution to improve the system.

The mathematical modelling cycle, which can show the modelling process, is recommended to be iterated many times to obtain the optimal representation of the problems. A variety of representations of the modelling cycle can be found in literatures. Perrenet and Zwaneveld (2012) showed an example of a representation of modelling cycle with all the extra aspects (Figure 2-3) found in their research after reviewing a number of literatures.
2.2.2 MIP Technique

The MIP method has been recognised as an optimisation method that is able to provide solutions to large, complex, and highly constrained problems. MIP is a special form of the linear programming (LP) that is a widely used technique in operations research.

LP is a significant tool to solve optimisation problem. Since the unveiling of the simplex algorithm developed by George Dantzig for solving LP problems in 1947, LP has been applied to the various areas in industries such as banking, education, forestry, petroleum and trucking. A survey of Fortune 500 firms reported that 85% of them had used LP before (Winston, 1994).

LP requires an objective function as shown below:

Maximized or (Minimized) \[ Z = c_1x_1 + c_2x_2 + c_3x_3 + \cdots + c_nx_n \] with \( c_j, j = 1, \ldots, n \) (2-1)

In equation (2-1), \( Z \) is the value of the objective function which could represent maximised revenue and profit or minimised cost; \( x_j \) are decision variables that
describe the decisions to be made; the coefficient of each variable in the objective function \( c_j \) is called objective function coefficient.

Subject to a set of linear constraints:

\[
\begin{align*}
a_{11}x_1 + a_{12}x_2 + \cdots + a_{1n}x_n & \leq b_1 \\
a_{21}x_1 + a_{22}x_2 + \cdots + a_{2n}x_n & \leq b_2 \\
\vdots & \vdots \\
a_{m1}x_1 + a_{m2}x_2 + \cdots + a_{mn}x_n & \leq b_m
\end{align*}
\] (2-2)

Where \( a_{ij}, \{i = 1, \ldots, m \text{ and } j = 1, \ldots, n\} \) are the technological coefficients that are based on the nature of the problem; the constant value \( b_j \) in the constraints is called as the right-hand side which reflects the quantity of available resource.

In addition, a set of sign restrictions are required, which describe that all the decision variables in the LP are restricted to be nonnegative. The non-negativity restrictions are required as follows:

\[
x_1, x_2, \ldots, x_n \geq 0
\] (2-3)

If the additional restriction where all the variables in the LP must be nonnegative integers arises, this specific LP model is then defined as the pure integer programming (IP). The nonnegative integer variables in these pure IP models are applied in scheduling problems to represent entities, such as people or vehicles which cannot be divided. An LP in which only some of the variables are required to be integers and others are allowed to be continuous is called a MIP. A special case is that the integer variables are only restricted to be equal to zero and one, which is known as binary variables (Little and Topal, 2011).

### 2.2.3 Solution of the MIP model

#### 2.2.3.1 The graphical solution of two-variable LP problems

LP problems with only two decision variables can be solved by a graphical method. Two variables are always labelled \( x_1 \) and \( x_2 \), and coordinate axes are named as \( x_1 \) and \( x_2 \) axes. Then the feasible region can be determined in the coordinate system
by graphing the set of points \((X_1, X_2)\) that satisfy each of the linear constraints. As shown in Figure 2-4, the feasible region is marked by the dark shading.

After the feasible region is indicated in the graph, a line of the objective function \(Z\) is drawn. The optimal solution of the objective function value \(Z\) and corresponding point \((X_1, X_2)\) can be obtained by moving this line parallelly in a direction that increases (for maximised \(Z\)) or decreases \(Z\) (for minimised \(Z\)). The last point of the objective function line intersecting the feasible region is the optimal solution set \((X_1, X_2)\), and the intersection point of this line and \(X_2\) axis is the optimal \(Z\) value. The apparent limitation of the graphical method is that the graph can only be illuminated in two dimensions, that is, graphical method cannot solve the LP problems with more than two variables.

2.2.3.2 Simplex algorithm

The graphical method provides a simple way to solve the LP problems with two decision variables. However, the LP models developed in the real world comprise a number of variables, so an efficient method is required to solve the LP problems including more than two variables. In 1947, George Dantzig made it come true through developing the simplex algorithm (Gill et al., 2008), the process of the simplex algorithm indicated by Winston (1994) is as follows:

1. Convert the LP to standard form.
2. Obtain a basic feasible solution (bfs) from the standard form.
3. Decide whether the current bfs is optimal.
4. If the current bfs is not optimal, find a new bfs with a better objective function value by selecting which nonbasic variables should become a basic variable and which basic variable should become a nonbasic variable.
5. Use elementary row operations to find the new bfs with the better objective function value. Go back to Step 3.

2.2.3.3 The branch-and-bound method

The IP and MIP problems are solved by the branch-and-bound technique. The branch-and-bound method first solves the LP relaxation of the IP or MIP problem, if the values of the integer decision variables assume to be integer in the LP relaxation, the solution of the LP relaxation is the optimal solution of this IP or MIP problem. If some of the integer decision variables are fractional in the LP relaxation, a fractional variable is chosen arbitrarily and branched by being assigned the adjacent integers of both sides, which will result in two additional sub-problems. Subsequently, each of the sub-problems is solved by standard LP solution procedure. This process is iterated until all the sub-problems are solved and no better objective function value can be provided. The process of the branch-and-bound method is shown in Figure 2-5.
2.2.4 The application of MIP technique in mining industry

Operations research has been implemented in mine planning since the 1960s. With the development of the computer technology, optimisation methods, especially MIP technique, have been utilised in both surface and underground mine planning problems, such as ultimate pit limit and mine layout design, production scheduling, equipment selection and dispatching (Newman et al., 2010). The MIP mathematical model is mainly applied in the blocking sequencing problems that select the available mining block in a particular time period for both surface (Ramazan and Dimitrakopoulos, 2004a, Ramazan and Dimitrakopoulos, 2004b, Kumral, 2012, Ramazan, 2007, Chanda and Ricciardone, 2002) and underground mining (Sarin and West-Hansen, 2005, Rahal et al., 2003, Weintraub et al., 2008, Topal, 2008, Kuchta et al., 2004, Nehring et al., 2010). Barbaro and Ramani (1986) and Little and Topal (2011) also used MIP technique to optimise the mine layout design in their studies.

Equipment scheduling and dispatching is a rather important realm where MIP technique is widely implemented. Wolsey (1997) demonstrated the application of
MIP method to handle the sequence-independent and sequence-dependent changeovers in production planning and machine sequencing so that the time is modelled. A single machine multi-item lot-sizing model, which considers changeover costs and times and allows a single item to be produced in each period, is presented in this research. However, there is not much information provided in regards to the real case application and how the system works.

Caumond et al. (2009) formulated a MIP mathematical model for the Flexible Manufacturing Systems Scheduling Problem (FMSSP) that can consider the constraints of maximised number of jobs allowed in the system, limited input/output buffer capacities, empty vehicle trips and no-move-ahead trips concurrently. This proposed MIP model can provide the optimal solutions to small and medium size instances of the scheduling problems.

Dodin and Elimam (2008) developed a MIP model for the integrated problem of project and equipment planning with the new consideration of trade-offs including costs of activity crashing, equipment setup, transition, idle time, and operator’s overtime as well as the project worth, rewards for early completion and penalty for delayed completion. In order to solve the large size projects with this proposed MIP model, a heuristic algorithm is also developed to determine routing between each piece of equipment and activities. This proposed MIP model can provide the optimal route for each piece of equipment as well as start, end and duration of each activity.

Subtil et al. (2011) utilised a linear programming model to determine the number of trucks in the fleet with the objective of maximised mine’s productivity. This model takes into account main aspects of the problem, such as the allocations of shovels in multiple loading points, availability of the transport fleet, grade specifications and loading rate of the shovels. The solutions are proved to be realistic, which can be further used in the second stage for the truck dispatching.

Peng and Zhang (2009) developed a MIP model to consider the restrictions of capacities and productions of the loading and dumping points, grade constraints and the capacity of the road transport simultaneously. This model can decide the optimal number of loaders and trucks for open pit mines with the objective of minimized total haulage volume. In the reality, there are always unexpected incidents, which will result in the change to the original schedule. Song and Rong (2003) discussed the
possible uncertainty problems in the vehicles scheduling. They developed a MIP model that can provide the optimal vehicle schedule and re-optimise the schedule according to the real-time environment when uncertainty arises.

Burt et al. (2005) developed a MIP model to determine the optimal match of the trucks to the loaders while adhering to the production demands in a single time period. This MIP model aims to minimise the cost of operating the fleet through introducing two decision variables: one is the number of trucks of type $i$ working with loader type $j$, the other one is the number of loaders of type $j$ working with truck type $i$. In addition, a set of binary variables, which represent whether the pair $i, j$ is selected, are used in the model. The application of the MIP model demonstrates that it can provide optimal solutions for the heterogeneous fleet rapidly.

Most of the available practices and studies on truck scheduling ignore or misunderstand the impact of the maintenance cost that can account for approximately 30-50% of the total haulage cost of the truck-shovel-based surface mining operation. The most widely used method for truck scheduling in practice is scheduling the truck fleet with Excel by assigning the working hours to every truck manually under the condition of satisfying the production target and truck specifications. However, this manual method relies heavily on the people experience and skills, and more likely generates different schedules if conducted by different operators. In addition, this traditional approach (TA) chooses the newer trucks prior to the older trucks because it assumes that the maintenance cost will increase as the truck age grows, which is in fact not true. The routine maintenance cost of trucks generally decrease to some degree after the maintenance service or the engine refurbishment, which can make maintenance cost fluctuate over the lifespan of each truck. In order to get over the myth about maintenance cost of the traditional truck scheduling method, Topal and Ramazan developed a new MIP model to schedule a mixed mine truck fleet over a multi-year time period to minimize the maintenance cost. This model takes into account the different maintenance cost of different truck types and ages and the truck engine refurbishment after continuous working for a certain number of hours. The solution of this MIP model is able to provide a much more economical truck fleet schedule than TA. In order to handle the uncertainty of the maintenance cost data, Topal and Ramazan (2012) created a stochastic based MIP model, subsequently generated 20 simulation realisations based on the original
maintenance cost data, and eventually applied these realisations into the MIP model. The model can generate the possible maintenance cost range for the truck fleet, which can provide a distribution of cost values allowing for the calculation of the confidence interval, the possible risk profile of the truck fleet plan and potential cost savings. However, these two MIP models only optimise the schedule for the current existing trucks to minimise the maintenance cost without considering what would happen if the current trucks became inefficient to the haulage system or the capacity of current truck fleet could not meet the material movement requirement. In this case, purchasing new trucks to the fleet might be a feasible option to achieve better performance of the truck fleet. Apart from this, it is not possible that all the trucks in the fleet are from the same type. In the heterogeneous truck fleet, the trucks with different payloads, without a doubt, can make different contributions to the overall material movement operation, which is also quite important when scheduling the trucks to satisfy the material movement requirement.

2.3 SUMMARY

Previous studies suggest that the MIP technique-based mathematical model is an important method of operations research to optimise the truck fleet scheduling and dispatching problems in mining industry. However, currently there is no MIP model that is capable of determining an optimal truck fleet schedule for the minimum of the maintenance cost while taking into account all the significant constraints. Therefore, a new MIP model is required to be developed in this research.
CHAPTER 3. MATHEMATICAL MODEL FORMULATION AND VALIDATION

This chapter demonstrates the formulation of the proposed MIP model that is developed to provide the optimal truck fleet schedule for minimised maintenance cost. In addition, a hypothetical data set is used to validate the proposed MIP model.

3.1 PROPOSED MIP MODEL

3.1.1 Indices

\( t \)  
truck ID (includes old and new trucks), subset \( tc \) for old trucks ID and subset \( tn \) for new trucks ID

\( b \)  
age bins

\( y \)  
time period (year)

\( c \)  
critical bin hours

3.1.2 Parameters

\( C_{t,b,y} \)  
The discounted maintenance cost value ($/hour) for truck \( t \), age bin \( b \) in the \( y \)th year

\( FE_{t,y} \)  
The discounted cost for rebuilding truck \( t \)'s engine in the \( y \)th year

\( PC_{t,y} \)  
The discounted purchase cost for new truck \( tn (tn \epsilon t) \) in the \( y \)th year

\( A_{t,y} \)  
The available working hours for truck \( t \) in the \( y \)th year

\( M_{t,b} \)  
The maximum available working hours for truck \( t \) at age bin \( b \)

\( H_{t,y} \)  
The cumulative used hours for truck \( t \) at time \( y \)

\( R_{y} \)  
The overall required working hours for the \( y \)th year

\( CF_{t} \)  
The fill factor for the truck \( t \)
3.1.3 Decision variables

\( X_{t,b,y} \) The number of working hours scheduled for truck \( t \) in the age bin \( b \) at the \( y \)th year

\[
Y_{t,b,y} = \begin{cases} 
1, \text{if the truck } t \text{ at bin } b \text{ used up all the available working hours} \\
\text{in the } y \text{th year} \\
0, \text{otherwise}
\end{cases}
\]

\[
Y_{t,c,y} = \begin{cases} 
1, \text{if the truck } t \text{ is used more than the critical bin hours } c \\
\text{in the } y \text{th year} \\
0, \text{otherwise}
\end{cases}
\]

\[
Z_{t,n,y} = \begin{cases} 
1, \text{if the truck } t_n \text{ is purchased in the } y \text{th year} \\
0, \text{otherwise}
\end{cases}
\]

3.1.4 Objective function

\[
MIN \sum_{y} \sum_{t} \sum_{b} C_{t,b,y} \times X_{t,b,y} + \sum_{y} \sum_{t} Y_{t,c,y} \times FE_{t,y} + \sum_{y} \sum_{t} Z_{t,n,y} \times PC_{t,y} \tag{3-1}
\]

The objective function given in equation (3-1) aims to minimise the maintenance cost for the heterogeneous truck fleet over the given period of time. In this study, the cost of purchasing new trucks is also regarded as a part of the maintenance cost. This is because a decision needs to be made between purchasing a new truck and using the available truck existing in the fleet. Trucks in the fleet are not the same type and also they are used at different level, which results in different unit maintenance cost for each truck type at the different age bin. The maintenance cost \( C_{t,b,y} \times X_{t,b,y} \) will be charged for truck \( t \), if it works \( X_{t,b,y} \) hours in age bin \( b \) in the \( y \)th year. If the age of truck \( t \) exceeds critical bin hours, \( Y_{t,c,y} \) is supposed to be 1 and the major maintenance cost \( FE_{t,y} \) including engine refurbishment and replacement of other parts will be charged. If the decision of purchasing the new truck \( t_n \) at the \( y \)th year is made, \( Z_{t,n,y} \) will take the value of 1 and the discounted purchase cost \( PC_{t,y} \) will be charged.
3.1.5 Annual available working hours constraints

Since each truck has the maximum allowable operating hours in every year, the annually accumulated working hours of each truck should not exceed the maximum available operating hours with the consideration of safety.

\[ \sum_b X_{t,b,y} \leq A_{t,y}, \forall y, t \in tc \] (3-2)

\[ \sum_b X_{t,b,y} \leq A_{t,y} \times \sum_{y'} Z_{t,y'}, \forall y, t \in tn \text{ and } y' \leq y \] (3-3)

Constraints given in equations (3-2) and (3-3) ensure that the total working hours for truck \( t \) in the \( y \)th year do not exceed the available working hours in this year. In order to avoid the new trucks being operated before purchase, a set of binary variables are introduced to the right-hand side of the constraint given in equation (3-3). For instance, if the new truck \( t (t \in tn) \) is purchased to the current fleet at the \( y \)th year, \( Z_{t,y} \) should be equal to 1. Multiplying \( A_{t,y} \) with binary variable \( Z_{t,y} \) ensures that \( X_{t,b,y} \) is not available to be used \( (X_{t,b,y} = 0) \) before the \( y \)th year.

3.1.6 Available working hours for each age bin constraints

As the truck unit maintenance cost varies with the truck age, and this interrelationship between truck age and maintenance cost is usually non-linear, the term of truck age bin is introduced to the proposed model. There are certain numbers of truck operating hours assigned in each age bin, and a corresponding unit maintenance cost to each age bin can be obtained from the data of the existing operations of the truck manufacturer. That is, if the age of one truck is in the interval of one truck age bin, the maintenance cost of this truck age bin will be assigned to this truck until it uses up the working hours in this bin and falls into the next age bin with being assigned a new maintenance cost. This requires that the truck in the current age bin cannot use more than the maximum available working hours of this age bin.

\[ \sum_y X_{t,b,y} \leq M_{t,b}, \forall t, b \] (3-4)
Constraint in equation (3-4) enforces that the total working hours for truck \( t \) in the age bin \( b \) do not exceed the available working hours of this bin. For example, each age bin is assumed to have 3000 hours. That is, if the age of a truck is 3500 hours, it has used all the hours in the first age bin and 500 hours in the second bin. There are 2500 hours that can be used in the second age bin and 3000 hours available for the next age bins.

### 3.1.7 Material movement requirement constraints

The total amount of material movement based on production schedule has been decided by the mine planning schedule software or other mathematical models. According to the given production plan, there must be certain amount of ore and waste rocks that need to be hauled during each period of time. Therefore, in order to sustain the stability of the production, the capacity of the truck fleet must complete overall material movement based on the production schedule annually. The overall material movement given by the production schedule is usually calculated at the unit of tonnage (ton), however, the schedule determined by the proposed MIP model provides the recommended working hours for each truck. As a result, the overall amount of materials to be moved every year must be transferred to the annual required working hours. The overall available working hours of the truck fleet must be greater than the transferred annual required working hours.

\[
\sum_b X_{t,b,y} + H_{t,y-1} = H_{t,y}, \forall y,t \tag{3-5}
\]

\[
\sum_t CF_t \ast (H_{t,y} - H_{t,y-1}) \geq R_y, \forall y \tag{3-6}
\]

Constraint given in equation (3-5) calculates the truck age \( H_{t,y} \) after each time period. When \( y \) is equal to zero, \( H_{t,0} \) represents initial truck age; as \( y \) increases, \( H_{t,y} \) is the cumulative used hours for truck \( t \), namely real-time truck age. Constraint in equation (3-6) enforces that the total working hours of all the trucks in the fleet can satisfy the annual required working hours. As mentioned above, the annual required working hours can be calculated from the overall amount of materials. However, the drawback is that the conversion is based on the payload of only one type of truck, while generally a truck fleet is composed of various types of trucks with different
payloads. These trucks can, without a doubt, transport different amount of materials during the same time period; that is, one working hour of high payload truck is more valuable than that of other trucks when processing the material haulage project. Hence, the working hours of different types of trucks must be converted to the working hours of the specific truck type used for conversion by multiplying the truck fill factor. The truck fill factor is defined as the ratio between the payload of one truck and the basic truck which is used to calculate the total required working hours. For example, if the haulage payload of a truck is 200t and the basic truck payload is 400t, then the truck fill factor of this truck will be 0.5 (200/400=0.5). In other words, one working hour from this truck is equal to the 0.5 working hours of the basic truck. Although working hours for removing a given amount of materials is also impacted by the road condition and truck operators’ behaviours, these influences to an individual truck in the mining operations are not fixed and data for these cannot be collected readily in practice.

3.1.8 Sequencing for each age bin constraints

Constraint in equation (3-4) gives the upper bound of permitted working hours in each age bin which prevents the actual truck working hours in the age bin from outnumbering the maximum limit. In addition to this constraint, the restriction on the right order of the age bin utilisation needs to be considered in this mathematical model.

\[
\sum_{y} X_{t,b,y} - M_{t,b} \cdot Y_{t,b,y} \geq 0, \forall t, b, y \text{ and } y \leq y
\]

\[
X_{t,b+1,y} - M_{t,b+1} \cdot \sum_{y} Y_{t,b+1,y} \leq 0, \forall t, b, y \text{ and } y \leq y
\]  

(3-7)

Constraint defined in equation (3-7) ensures the right sequence of the age bin usage. It restricts trucks from utilising the hours of next age bin prior to using up all the hours in the current age bin. That is, for truck \( t \) in the age bin \( b \), if this truck uses up all the hours in this age bin at the \( y \) th year, \( Y_{t,b,y} \) can be equal to 1. If \( Y_{t,b,y} \) is equal to 1, the second constraint of the equation (3-7) makes \( X_{t,b+1,y} \) available to be used after the \( y \) th year.
### 3.1.9 Set packing constraints

\[ \sum_{y} Z_{t,y} \leq 1, \forall t \]  
\[(3-8)\]

\[ \sum_{y} Y_{t,b,y} \leq 1, \forall t,b \]  
\[(3-9)\]

Constraint in equation (3-8) precludes each truck from being purchased more than once, and constraint in equation (3-9) enforces each age bin to be used up only once in a given time period.

### 3.1.10 Non-negativity and Integrity constraints

\[ X_{t,b,y} \geq 0, Y_{t,b,y}, Y_{t,a,y}, Z_{t,y}, \text{binary}, \forall t, b, y \]  
\[(3-10)\]

Non-negativity and integrity of the variables are enforced by constraint in equation (3-10), as required.

### 3.2 Validation of the Proposed MIP Model

Due to the large amount of constraints and variables in the proposed model, the formulations of the model cannot be written manually. The Visual Basic for Application (VBA) code is applied to filter and select the data stored in Microsoft Excel for building the proposed MIP model. The advantage of using the VBA programming language embedded in the Excel is that it can easily utilise the data in Excel regardless of making connections to other database and importing the relevant data. Moreover, Excel is the most frequently used spreadsheet application in industries with the features of calculation, graphing tools, pivot tables, which can be easily conducted by the ordinary people. To examine the function of the proposed MIP model, a simplified truck fleet data and a hypothetical material movement schedule are applied to the model for the optimal truck schedule. This section is concentrated on the validation of the MIP model including the introduction to the input data, model size and solution time as well as the solution validation.

#### 3.2.1 Input data set

A simplified data set of truck fleet information and material movement requirement are developed for validation of this MIP model. In the hypothetical data set, there are
5 old trucks in the current fleet which are in different types and used at different level. The type and age of these five old trucks in the system are presented in Table 3-1.

<table>
<thead>
<tr>
<th>Truck ID</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (hours)</td>
<td>63000</td>
<td>58000</td>
<td>55000</td>
<td>43000</td>
<td>37000</td>
</tr>
<tr>
<td>Truck Type</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

The proposed model can make a decision about whether to purchase new trucks to the current fleet for the better haulage performance and less maintenance cost. The simplified data provide three potential options of truck type: first two types are the same as the currently being used types; a new truck type is also given to the MIP model to select. In addition, it is required that maximum three trucks can be purchased from each of types of trucks due to the material movement schedule. The maintenance cost of these three types of trucks in 20 different age bins with 5,000 hours in each along with payload capacities and purchase cost are illuminated in Table 3-2. In addition, every truck that has been used more than 70,000 hours is compulsory to receive a major maintenance, such as engine refurbishment which costs $700,000.

<table>
<thead>
<tr>
<th>Age bin</th>
<th>Min Hours</th>
<th>Max Hours</th>
<th>Truck type 1 ($/hour)</th>
<th>Truck type 2 ($/hour)</th>
<th>Truck type 3 ($/hour)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>5</td>
<td>40.0</td>
<td>32.0</td>
<td>16.0</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>10</td>
<td>60.0</td>
<td>61.0</td>
<td>24.0</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>15</td>
<td>97.0</td>
<td>71.0</td>
<td>75.0</td>
</tr>
<tr>
<td>…</td>
<td>…</td>
<td>…</td>
<td>…</td>
<td>…</td>
<td>…</td>
</tr>
<tr>
<td>18</td>
<td>85</td>
<td>90</td>
<td>85.0</td>
<td>117.0</td>
<td>191.0</td>
</tr>
<tr>
<td>19</td>
<td>90</td>
<td>95</td>
<td>136.0</td>
<td>38.0</td>
<td>71.0</td>
</tr>
<tr>
<td>20</td>
<td>95</td>
<td>100</td>
<td>79.0</td>
<td>45.0</td>
<td>65.0</td>
</tr>
<tr>
<td>Average maintenance cost($/hour)</td>
<td>93.75</td>
<td>55.9</td>
<td>90.25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Payload capacity (tonnes)</td>
<td>313</td>
<td>226</td>
<td>363</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Purchase cost (million dollars)</td>
<td>3.2</td>
<td>2.8</td>
<td>3.4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3-3 presents the maximum available working hours for each truck in each year. Trucks 1 to 5 are old trucks that have already been in the fleet, trucks 6 to 14 are potential new trucks that might be purchased into the fleet.
Table 3-3 Maximum available working hours for each truck in each year

<table>
<thead>
<tr>
<th>Truck number</th>
<th>Year 1</th>
<th>Year 2</th>
<th>Year 3</th>
<th>...</th>
<th>Year 8</th>
<th>Year 9</th>
<th>Year 10</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7100</td>
<td>7200</td>
<td>7300</td>
<td>...</td>
<td>7000</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>7100</td>
<td>7200</td>
<td>7300</td>
<td>...</td>
<td>7020</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>7100</td>
<td>7200</td>
<td>7300</td>
<td>...</td>
<td>7100</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>12</td>
<td>7600</td>
<td>7500</td>
<td>7320</td>
<td>...</td>
<td>7110</td>
<td>7200</td>
<td>6700</td>
</tr>
<tr>
<td>13</td>
<td>7600</td>
<td>7500</td>
<td>7320</td>
<td>...</td>
<td>7110</td>
<td>7200</td>
<td>6700</td>
</tr>
<tr>
<td>14</td>
<td>7600</td>
<td>7500</td>
<td>7320</td>
<td>...</td>
<td>7110</td>
<td>7200</td>
<td>6700</td>
</tr>
</tbody>
</table>

The data set is for a ten-year truck scheduling, the annual required working hours of the truck fleet that is converted from material movement schedule and available working hours of the current fleet are shown in Table 3-4. As presented in Table 3-4, the existing trucks in the fleet can meet the required working hours every year.

Table 3-4 Required and available truck fleet working hours annually

<table>
<thead>
<tr>
<th>Year</th>
<th>Required working hours</th>
<th>Available working hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>43000</td>
<td>43699.56</td>
</tr>
<tr>
<td>2</td>
<td>44000</td>
<td>44315.04</td>
</tr>
<tr>
<td>3</td>
<td>44000</td>
<td>44980.53</td>
</tr>
<tr>
<td>4</td>
<td>42000</td>
<td>43709.56</td>
</tr>
<tr>
<td>5</td>
<td>42000</td>
<td>42510.13</td>
</tr>
<tr>
<td>6</td>
<td>42000</td>
<td>42468.58</td>
</tr>
<tr>
<td>7</td>
<td>42000</td>
<td>42591.68</td>
</tr>
<tr>
<td>8</td>
<td>42000</td>
<td>43250.27</td>
</tr>
<tr>
<td>9</td>
<td>14000</td>
<td>14200.00</td>
</tr>
<tr>
<td>10</td>
<td>13500</td>
<td>14000.00</td>
</tr>
</tbody>
</table>

3.2.2 Problem size and solution time

The problem is constructed by the MIP model using the abovementioned data set. There are 6193 linear constraints and 5844 variables in total involved in the problem, 2890 of them are binary variables and other 2954 variables are linear variables that have the default nonnegative bounds \((0 \leq x \leq +\infty)\). The problem can be solved by the CPLEX solver, Version 11.2 (ILOG Corporation, 2009) using an Intel (R) Xeon (R) with 2.8 GHz CPU processor and 24 GB RAM in approximately 914 seconds.
3.2.3 Solutions validation

The solutions resulted from the CPLEX solver will be written to the SOL file by typing the command code, subsequently the solutions can be automatically read and filtered from SOL file and exported to the Excel worksheets. The solutions indicate that the optimal schedule determined by the new MIP model provides the minimum maintenance cost of $18.78M over a ten-year production plan, and suggests truck #14 (from truck type 3) needs to be purchased at the second year. The validation of the solutions includes checking the actual working hours in each age bin and each year, the age bin usage sequence, the overall working hours of the fleet in each year and the details of the major maintenance service.

3.2.3.1 Annual working hours of each truck and whole truck fleet

According to the truck schedule, a new truck from type three is recommended to be added into the fleet at the second year. The proposed annual working hours of each of these six trucks along with the total annual working hours of the whole truck fleet are presented in Table 3-5. The total working hours of the truck fleet in each year is the summary of converted hours of each truck by multiplying the truck fill factor.

<table>
<thead>
<tr>
<th>Year</th>
<th>Truck 1</th>
<th>Truck 2</th>
<th>Truck 3</th>
<th>Truck 4</th>
<th>Truck 5</th>
<th>Truck 14</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7000</td>
<td>7100</td>
<td>6694.9</td>
<td>7100</td>
<td>7100</td>
<td>0</td>
<td>43000</td>
</tr>
<tr>
<td>2</td>
<td>7200</td>
<td>4900</td>
<td>1005.1</td>
<td>7200</td>
<td>6603.5</td>
<td>7500</td>
<td>44000</td>
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<tr>
<td>3</td>
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<td>0</td>
<td>7300</td>
<td>7350</td>
<td>4672.3</td>
<td>7320</td>
<td>44000</td>
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<tr>
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<td>7100</td>
<td>5350</td>
<td>4276.8</td>
<td>7480</td>
<td>42000</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>6900</td>
<td>6930</td>
<td>6842.3</td>
<td>4599.8</td>
<td>7100</td>
<td>42000</td>
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<tr>
<td>6</td>
<td>4757.6</td>
<td>6000</td>
<td>1970</td>
<td>6900</td>
<td>5747.6</td>
<td>7300</td>
<td>42000</td>
</tr>
<tr>
<td>7</td>
<td>3242.4</td>
<td>6960</td>
<td>6900</td>
<td>6910</td>
<td>0</td>
<td>7100</td>
<td>42000</td>
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<tr>
<td>8</td>
<td>7000</td>
<td>3040</td>
<td>7100</td>
<td>6912.3</td>
<td>0</td>
<td>7066.1</td>
<td>42000</td>
</tr>
<tr>
<td>9</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2435.4</td>
<td>0</td>
<td>7200</td>
<td>14000</td>
</tr>
<tr>
<td>10</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>7000</td>
<td>4046.8</td>
<td>13500</td>
</tr>
</tbody>
</table>

Comparing Table 3-5 with Table 3-3 and 3-4, the annual working hours of each truck does not exceed the maximum available working hours, and the truck fleet can satisfy the haulage requirement in each year under the constraint of not overworking the total available working hours.
### 3.2.3.2 Working hours in each age bin

In order to check whether the suggested working hours of each truck in each age bin outnumber the capacity of the age bin, the solutions are re-organised in the form of scheduled working hours in each age bin, as shown in Table 3-6. Consider that there are maximum 5000 hours in each age bin in this validation data set combined with the initial age of these six trucks provided in Table 3-1, the proposed schedule does not violate the constraints of age bin utilisation.

**Table 3-6 Scheduled working hours in each age bin**

<table>
<thead>
<tr>
<th>Age bin</th>
<th>Truck 1</th>
<th>Truck 2</th>
<th>Truck 3</th>
<th>Truck 4</th>
<th>Truck 5</th>
<th>Truck 14</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>5000</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>5000</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>5000</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>5000</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>5000</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>5000</td>
</tr>
<tr>
<td>7</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>5000</td>
</tr>
<tr>
<td>8</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3000</td>
</tr>
<tr>
<td>9</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2000</td>
<td>5000</td>
<td>5000</td>
</tr>
<tr>
<td>10</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>5000</td>
<td>5000</td>
<td>5000</td>
</tr>
<tr>
<td>11</td>
<td>0</td>
<td>2000</td>
<td>5000</td>
<td>5000</td>
<td>5000</td>
<td>5000</td>
</tr>
<tr>
<td>12</td>
<td>2000</td>
<td>5000</td>
<td>5000</td>
<td>5000</td>
<td>5000</td>
<td>2112.9</td>
</tr>
<tr>
<td>13</td>
<td>5000</td>
<td>5000</td>
<td>5000</td>
<td>5000</td>
<td>5000</td>
<td>0</td>
</tr>
<tr>
<td>14</td>
<td>5000</td>
<td>5000</td>
<td>5000</td>
<td>5000</td>
<td>5000</td>
<td>0</td>
</tr>
<tr>
<td>15</td>
<td>5000</td>
<td>5000</td>
<td>5000</td>
<td>5000</td>
<td>5000</td>
<td>0</td>
</tr>
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<td>16</td>
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<td>5000</td>
<td>5000</td>
<td>2000</td>
<td>0</td>
</tr>
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<td>5000</td>
<td>5000</td>
<td>5000</td>
<td>5000</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>18</td>
<td>5000</td>
<td>5000</td>
<td>5000</td>
<td>5000</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>19</td>
<td>5000</td>
<td>5000</td>
<td>5000</td>
<td>5000</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>20</td>
<td>5000</td>
<td>5000</td>
<td>5000</td>
<td>5000</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

### 3.2.3.3 Age bin usage sequence

To ensure the truck age bins are used in the right sequence, the age bin usage of truck one in different year is demonstrated in Table 3-7. Since the initial age of truck one is 63000 hours: that is, there are no more hours that can be used in the first 12 age bins, therefore, the uses of age bin 1 to 12 are not given in the table. As shown in Table 3-7, the resulting schedule of truck one obeys the rule of truck age bin usage sequence that demands trucks to use up all the available hours in the current
age bin before going to the next age bin. The same validation is processed on the truck 2 to truck 6, the results indicate that the proposed schedule satisfies the constraint of age bin usage sequence.

Table 3-7 Age bin usage of truck one in different year

<table>
<thead>
<tr>
<th>Year</th>
<th>Bin 13</th>
<th>Bin 14</th>
<th>Bin 15</th>
<th>Bin 16</th>
<th>Bin 17</th>
<th>Bin 18</th>
<th>Bin 19</th>
<th>Bin 20</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2000</td>
<td>5000</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<td>7000</td>
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<td>5000</td>
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<td>7200</td>
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<td>7300</td>
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</tr>
<tr>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<td>0</td>
<td>0</td>
<td>4757.6</td>
</tr>
<tr>
<td>7</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>242.4</td>
<td>3000</td>
<td>0</td>
<td>3242.4</td>
</tr>
<tr>
<td>8</td>
<td>0</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>2000</td>
<td>5000</td>
<td>7000</td>
</tr>
<tr>
<td>9</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<td>0</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

### 3.2.3.4 Major maintenance service

When the total truck working hours exceed 70,000, this truck is required to go through a major maintenance service, such as engine refurbishment, which costs $700,000. In the proposed MIP model, a set of binary variables are used to represent whether the truck should undergo a major maintenance service at a certain year. The details on these binary variables of the five old trucks and one new truck are indicated in Table 3-8. For example, according to the proposed schedule, truck 1 need to receive the major maintenance service in the second year, and truck 2 in the fourth year. Combining the truck age provided in Table 3-1 and the scheduled annual truck working hours in Table 3-5, the details on the major maintenance service given in Table 3-8 are consistent with the actual situations.
Table 3-8 Details of the major maintenance service

<table>
<thead>
<tr>
<th>Year</th>
<th>Truck 1</th>
<th>Truck 2</th>
<th>Truck 3</th>
<th>Truck 4</th>
<th>Truck 5</th>
<th>Truck 14</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>8</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>9</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<td>10</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

3.3 SUMMARY

The proposed MIP model can schedule the heterogeneous truck fleet for the minimum maintenance cost with satisfying the material movement schedule simultaneously. In the meantime, this model can compare the cost of continuously using the currently existing trucks with purchasing new trucks to the fleet. Subsequently, it can provide the detailed schedule for new trucks usage if the decision of purchasing new trucks is made.

The validation of the solutions given by the proposed MIP model using the simplified data set proves that the constraints of maximum available working hours in each year and age bin, the age bin usage sequence, overall material movement target, and binary variables that represents whether to undergo the major maintenance service, are all working appropriately. Therefore, the proposed MIP model can be a potential truck scheduling tool for the mining industry.
CHAPTER 4. IMPLEMENTATION OF THE PROPOSED MIP MODEL

Through the validation of the proposed MIP model using the hypothetical data set, it has been proved that the proposed MIP model can meet all the key constraints of the truck haulage operation and provide the schedule for the truck fleet with the object of minimum maintenance cost. In this section, the MIP model is first applied to the data set obtained from a gold mine located in Western Australia, the resulting optimal schedule and corresponding results are presented. Subsequently, the schedules determined by the different approaches using the same data set are compared with the proposed MIP model, which can show its superiority. Due to the complexity of the mining operation, situations can be never static, which requires the mining related mathematical model or the software to provide proper solutions promptly when facing the stochastic input variables. Therefore, at the end of this section, the “what if” scenario-based input variables are implemented in the MIP model to test its performance and the corresponding results are analysed and sorted in the table.

4.1 CASE STUDY AT A GOLD MINE

The maintenance cost data collected from a gold mine in Western Australia has been used to assess the reliability of the proposed MIP model. The values used in the case study are modified for confidentiality purposes. The description of the data set, the problem size and solution time and the solutions are demonstrated in the succeeding section.

4.1.1 Implementing the proposed MIP model to the real data set

This data set is representing a 10-year-plan mining operation. There are different material movement requirements in each year, which have already been converted to the annually required working hours, as shown in Table 4-1. Furthermore, the total available working hours of the truck fleet in each year are also listed in Table 4-1. It is clear that the trucks currently being used in the fleet can satisfy the material movement requirement regardless of purchasing new trucks.
Table 4-1 Required and available truck fleet working hours annually

<table>
<thead>
<tr>
<th>Year</th>
<th>Required working hours</th>
<th>Available working hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>221050</td>
<td>244022.0</td>
</tr>
<tr>
<td>2</td>
<td>220300</td>
<td>246482.2</td>
</tr>
<tr>
<td>3</td>
<td>222500</td>
<td>247448.3</td>
</tr>
<tr>
<td>4</td>
<td>211500</td>
<td>242531.7</td>
</tr>
<tr>
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<td>235737.9</td>
</tr>
<tr>
<td>6</td>
<td>200000</td>
<td>234884.7</td>
</tr>
<tr>
<td>7</td>
<td>190000</td>
<td>237253.4</td>
</tr>
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<td>8</td>
<td>190000</td>
<td>232690.3</td>
</tr>
<tr>
<td>9</td>
<td>96300</td>
<td>106982.9</td>
</tr>
<tr>
<td>10</td>
<td>63272</td>
<td>64652.7</td>
</tr>
</tbody>
</table>

As the maintenance cost varies with the truck age and types, the age bins are introduced into the model. Although more age bins can increase the accuracy of the model, they also increase the amount of variables, as a result of which the computation time is increased for reliable results. In this case study, to obtain the optimal performance of the proposed MIP model, 20 age bins with 5000 hours each are set. The maintenance cost data for six types of truck in each age bin as well as their respective payload capacity and purchasing cost are presented in Table 4-2. Moreover, every truck must accept a major maintenance service including the engine refurbishment after being operated for over 70,000 hours, and the cost of this major maintenance service is assumed to be $700,000. This case study considers that trucks have a total life of 100,000 hours and that no salvage fees for the old trucks are compensated.

Table 4-2 Cost and payload capacity for different types of trucks

<table>
<thead>
<tr>
<th>Age bin</th>
<th>Min Hours</th>
<th>Max Hours</th>
<th>Truck type 1 ($/hour)</th>
<th>Truck type 2 ($/hour)</th>
<th>Truck type 3 ($/hour)</th>
<th>Truck type 4 ($/hour)</th>
<th>Truck type 5 ($/hour)</th>
<th>Truck type 6 ($/hour)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>5</td>
<td>40.0</td>
<td>34.6</td>
<td>22.7</td>
<td>21.3</td>
<td>32.0</td>
<td>16.0</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>10</td>
<td>59.9</td>
<td>51.9</td>
<td>34.0</td>
<td>32.0</td>
<td>47.9</td>
<td>24.0</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>15</td>
<td>94.5</td>
<td>81.9</td>
<td>53.6</td>
<td>50.4</td>
<td>37.8</td>
<td>75.6</td>
</tr>
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<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
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<tr>
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<td>85</td>
<td>90</td>
<td>88.3</td>
<td>117.7</td>
<td>125.1</td>
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<td>220.7</td>
<td>191.3</td>
</tr>
<tr>
<td>19</td>
<td>90</td>
<td>95</td>
<td>32.9</td>
<td>43.9</td>
<td>46.6</td>
<td>65.8</td>
<td>82.2</td>
<td>71.3</td>
</tr>
<tr>
<td>20</td>
<td>95</td>
<td>100</td>
<td>30.4</td>
<td>40.6</td>
<td>43.1</td>
<td>60.9</td>
<td>76.1</td>
<td>65.9</td>
</tr>
</tbody>
</table>

Average maintenance cost($/hour) 87.7 54.5 62.1 69.1 98.2 90.7
Payload capacity (tonnes) 313 226 177 181 218 363
Purchase cost (million dollars) 3.2 2.8 2.5 2.55 2.7 3.4
In the current fleet, there are 31 old trucks that are selected from different types and are operated at different working hours. In this case study, it is assumed that 18 potential new trucks including maximum 3 trucks from each of 6 truck types can be purchased. The respective initial ages and types of these 49 trucks (31 old trucks plus 18 potential new trucks) are shown in Table 4-3.

<table>
<thead>
<tr>
<th>Old Truck ID</th>
<th>Age (hours)</th>
<th>Truck Type</th>
<th>Old Truck ID</th>
<th>Age (hours)</th>
<th>Truck Type</th>
<th>New Truck ID</th>
<th>Age (hours)</th>
<th>Truck Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>43 055</td>
<td>1</td>
<td>17</td>
<td>41 945</td>
<td>2</td>
<td>32</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>43 864</td>
<td>1</td>
<td>18</td>
<td>41 571</td>
<td>2</td>
<td>33</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>42 595</td>
<td>1</td>
<td>19</td>
<td>37 766</td>
<td>2</td>
<td>34</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>43 141</td>
<td>1</td>
<td>20</td>
<td>37 936</td>
<td>2</td>
<td>35</td>
<td>0</td>
<td>2</td>
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<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>8</td>
<td>42 162</td>
<td>1</td>
<td>24</td>
<td>30 384</td>
<td>3</td>
<td>39</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>9</td>
<td>42 214</td>
<td>1</td>
<td>25</td>
<td>21 762</td>
<td>4</td>
<td>40</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>14</td>
<td>41 122</td>
<td>2</td>
<td>30</td>
<td>16 311</td>
<td>5</td>
<td>47</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td>15</td>
<td>41 216</td>
<td>2</td>
<td>31</td>
<td>15 682</td>
<td>5</td>
<td>48</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td>16</td>
<td>41 472</td>
<td>2</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

Table 4-4 presents the maximum available working hours of each truck in each year. For instance, truck 1 can operate maximum 7137.78 hours in the first year and is not allowed to operate in the ninth and tenth year.

<table>
<thead>
<tr>
<th>Truck ID</th>
<th>Year 1</th>
<th>Year 2</th>
<th>Year 3</th>
<th>...</th>
<th>Year 8</th>
<th>Year 9</th>
<th>Year 10</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7137.78</td>
<td>7292.11</td>
<td>7320.33</td>
<td>...</td>
<td>6976.37</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>7137.78</td>
<td>7292.11</td>
<td>7320.33</td>
<td>...</td>
<td>6976.37</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>7137.78</td>
<td>7292.11</td>
<td>7320.33</td>
<td>...</td>
<td>6976.37</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>30</td>
<td>7275.05</td>
<td>7429.7</td>
<td>7182.22</td>
<td>...</td>
<td>6842.21</td>
<td>6853.21</td>
<td>6727.21</td>
</tr>
<tr>
<td>31</td>
<td>7275.05</td>
<td>7429.7</td>
<td>7182.22</td>
<td>...</td>
<td>6842.21</td>
<td>6853.21</td>
<td>6727.21</td>
</tr>
<tr>
<td>32</td>
<td>7618.21</td>
<td>7498.49</td>
<td>7320.33</td>
<td>...</td>
<td>7110.53</td>
<td>7121.96</td>
<td>6727.21</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>47</td>
<td>7618.21</td>
<td>7498.49</td>
<td>7320.33</td>
<td>...</td>
<td>7110.53</td>
<td>7121.96</td>
<td>6727.21</td>
</tr>
<tr>
<td>48</td>
<td>7618.21</td>
<td>7498.49</td>
<td>7320.33</td>
<td>...</td>
<td>7110.53</td>
<td>7121.96</td>
<td>6727.21</td>
</tr>
<tr>
<td>49</td>
<td>7618.21</td>
<td>7498.49</td>
<td>7320.33</td>
<td>...</td>
<td>7110.53</td>
<td>7121.96</td>
<td>6727.21</td>
</tr>
</tbody>
</table>
4.1.2 Problem size and solution time

The problem is programmed with Visual Basic code (Microsoft Corporation, 2010) and solved with CPLEX solver (ILOG Corporation, 2009) using an Intel (R) Xeon (R) with 2.8 GHz CPU processor and 24 GB RAM. The problem size and the solution time are presented in Table 4-5.

<table>
<thead>
<tr>
<th>Model Name</th>
<th>Number of</th>
<th>MIP model using real data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Problem size</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>variables</td>
<td>20319</td>
</tr>
<tr>
<td></td>
<td>liner variables</td>
<td>10399</td>
</tr>
<tr>
<td></td>
<td>binary variables</td>
<td>9980</td>
</tr>
<tr>
<td></td>
<td>Constraints</td>
<td>21637</td>
</tr>
<tr>
<td>Solution time (minutes)</td>
<td></td>
<td>111.46</td>
</tr>
</tbody>
</table>

The model is stopped when optimal solution has been generated with 3.11% gap. Gap is the difference between the best integer objective and the theoretical optimal solution.

4.1.3 Result Analysis

The overall discounted maintenance cost of the optimal truck fleet schedule generated by the proposed MIP model is approximately $91.57M over 10-year time period. According to the schedule, a new truck with Truck ID 48, which is from type 6, will be purchased at the second year. The recommended number of working hours for every single truck operating in each year provided by the schedule is illuminated in Table 4-6. For instance, the recommended working hours for the Truck 1 are 7138 hours in year 1, 6976 hours in Year 8 and zero hours in Year 9. The total converted working hours of the whole truck fleet is also presented in Table 4-6, which apparently indicates that the schedule of the new fleet can meet the material movement schedule.
Table 4-6 Recommended truck working hours by the MIP model

<table>
<thead>
<tr>
<th>Truck ID</th>
<th>Year 1</th>
<th>Year 2</th>
<th>Year 3</th>
<th>....</th>
<th>Year 8</th>
<th>Year 9</th>
<th>Year 10</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7138</td>
<td>7292</td>
<td>7320</td>
<td>....</td>
<td>6976</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>7138</td>
<td>7292</td>
<td>7320</td>
<td>....</td>
<td>6450</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>7138</td>
<td>7292</td>
<td>7320</td>
<td>....</td>
<td>6976</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>7138</td>
<td>7292</td>
<td>7320</td>
<td>....</td>
<td>6976</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>....</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>27</td>
<td>7412</td>
<td>6616</td>
<td>7458</td>
<td>....</td>
<td>0</td>
<td>5000</td>
<td>5000</td>
</tr>
<tr>
<td>28</td>
<td>3415</td>
<td>0</td>
<td>433</td>
<td>....</td>
<td>6420</td>
<td>6853</td>
<td>6727</td>
</tr>
<tr>
<td>29</td>
<td>0</td>
<td>0</td>
<td>112</td>
<td>....</td>
<td>0</td>
<td>0</td>
<td>3154</td>
</tr>
<tr>
<td>30</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>....</td>
<td>0</td>
<td>0</td>
<td>6229</td>
</tr>
<tr>
<td>31</td>
<td>2581</td>
<td>0</td>
<td>0</td>
<td>....</td>
<td>0</td>
<td>0</td>
<td>1737</td>
</tr>
<tr>
<td>New truck ID: 48</td>
<td>0</td>
<td>7498</td>
<td>7320</td>
<td>....</td>
<td>7111</td>
<td>7122</td>
<td>6727</td>
</tr>
<tr>
<td>Total</td>
<td>221050</td>
<td>220300</td>
<td>222500</td>
<td>....</td>
<td>190000</td>
<td>96300</td>
<td>63272</td>
</tr>
</tbody>
</table>

In addition, the truck fleet schedule is demonstrated in Figure 4-1. It shows the initial truck age and summarises the usage of each truck in each year of the 10-year plan. Although the trucks of types 3, 4 and 5, especially type 5, have comparatively younger ages, they are not scheduled to be used frequently over the given period of time. This is because they are not economical to the whole truck fleet haulage project from the point of achieving minimum maintenance cost.

Figure 4-1 Truck working hours by the MIP model
The overall maintenance cost of the schedule is about $91.57M over 10 years. The maintenance cost in each year, which includes the normal maintenance cost that is equal to unit maintenance cost times working hours, major maintenance cost caused by engine refurbishment and the new truck purchase cost, is shown in Figure 4-2. Furthermore, the percentage of the annual maintenance cost to the total cost is also presented, which drops from 20.09% in the first year to 2.01% in the final year due to the decrease of the material movement requirement. As can be seen from the graph given in Figure 4-2, the new truck is suggested to be purchased at the second year with the discounted cost of $3.09M that accounts for 19.64% of the total maintenance cost of the same year and 3.38% of the overall maintenance cost throughout 10 years. In addition, the major maintenance cost only happens in the fourth, fifth and sixth years. The major maintenance cost of each of these three years and its percentage to the total maintenance cost of same year and total maintenance cost over 10 years are summarised in Table 4-7.

![Figure 4-2 Annual maintenance cost and its percentage of the overall maintenance cost](image-url)

**Table 4-7 Major maintenance cost and its percentage**

<table>
<thead>
<tr>
<th>Issue</th>
<th>Year 4</th>
<th>Year 5</th>
<th>Year 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major maintenance cost/$</td>
<td>5785124.0</td>
<td>4302984.8</td>
<td>4346444.9</td>
</tr>
<tr>
<td>Percentage of major maintenance cost to the total maintenance cost of same year</td>
<td>43.29%</td>
<td>45.07%</td>
<td>6.72%</td>
</tr>
<tr>
<td>Percentage of major maintenance cost to total maintenance cost</td>
<td>6.32%</td>
<td>4.70%</td>
<td>0.47%</td>
</tr>
</tbody>
</table>
4.2 COMPARISON OF THE DIFFERENT APPROACHES

4.2.1 Application of Traditional Approach (TA)

In order to compare different scheduling approaches for the truck fleet, first, TA is applied to the same data set as the one used in the abovementioned case study. As discussed in the literature review, TA makes use of Excel spreadsheets and relies heavily on the experience and skill of the scheduler. The principle of this approach is to satisfy the required truck hours by manually scheduling the available truck fleet. It aims to use newer trucks as much as possible assuming that the maintenance cost increases as the truck age grows (Topal and Ramazan, 2010). However, this relationship does not exist between truck age and maintenance cost, as presented in Table 4-2. Moreover, since this approach is conducted manually in Excel, the resulting schedule can be different each time and the long solution time is a major drawback.

It takes about two days with TA to generate the schedule and the overall discounted maintenance cost of this schedule is $117.31M. The schedule is presented in Table 4-8 and graphed in Figure 4-3. From Figure 4-3, assigning the working hours in Excel manually can violate the total truck life limit of 100000 hours in the last year, while other trucks are not fully used. Figure 4-4 demonstrates the maintenance cost in each year of the schedule.

<table>
<thead>
<tr>
<th>Truck ID</th>
<th>Year 1</th>
<th>Year 2</th>
<th>Year 3</th>
<th>....</th>
<th>Year 8</th>
<th>Year 9</th>
<th>Year 10</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4188</td>
<td>1960</td>
<td>5465</td>
<td>....</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>7137</td>
<td>7292</td>
<td>7217</td>
<td>....</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>7137</td>
<td>7292</td>
<td>7217</td>
<td>....</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>7137</td>
<td>7292</td>
<td>7217</td>
<td>....</td>
<td>5320</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>27</td>
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<td>7154</td>
<td>7453</td>
<td>....</td>
<td>6840</td>
<td>6825</td>
<td>6500</td>
</tr>
<tr>
<td>28</td>
<td>7275</td>
<td>7429</td>
<td>7180</td>
<td>....</td>
<td>6840</td>
<td>6825</td>
<td>6500</td>
</tr>
<tr>
<td>29</td>
<td>7275</td>
<td>7429</td>
<td>7180</td>
<td>....</td>
<td>6840</td>
<td>6825</td>
<td>6500</td>
</tr>
<tr>
<td>30</td>
<td>7275</td>
<td>7429</td>
<td>7180</td>
<td>....</td>
<td>6840</td>
<td>6825</td>
<td>6500</td>
</tr>
<tr>
<td>31</td>
<td>7275</td>
<td>7429</td>
<td>7180</td>
<td>....</td>
<td>6840</td>
<td>6825</td>
<td>6394</td>
</tr>
</tbody>
</table>
4.2.2 Application of the previous MIP model

Second, the truck schedule is determined based on the previous MIP model (Topal and Ramazan, 2010), which does not consider new truck-purchase option and various payloads of trucks. The problem can be solved in 1.01 second with the gap of 2.95%, and the problem size and solution time is described in Table 4-9. The
previous MIP model provides an overall discounted maintenance cost of $107.44M over 10 years, and the schedule is depicted in Table 4-10 and Figure 4-5.

### Table 4-9 Problem size and solution time

<table>
<thead>
<tr>
<th>Model Name</th>
<th>Number of Variables</th>
<th>Previous MIP model using real data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Problem size</td>
<td></td>
<td></td>
</tr>
<tr>
<td>variables</td>
<td>12741</td>
<td></td>
</tr>
<tr>
<td>linear variables</td>
<td>6541</td>
<td></td>
</tr>
<tr>
<td>binary variables</td>
<td>6200</td>
<td></td>
</tr>
<tr>
<td>Constraints</td>
<td>13681</td>
<td></td>
</tr>
<tr>
<td>Solution time (seconds)</td>
<td>1.01</td>
<td></td>
</tr>
</tbody>
</table>

### Table 4-10 Truck schedule generated by previous MIP model

<table>
<thead>
<tr>
<th>Truck ID</th>
<th>Year 1</th>
<th>Year 2</th>
<th>Year 3</th>
<th>....</th>
<th>Year 8</th>
<th>Year 9</th>
<th>Year 10</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7138</td>
<td>7292</td>
<td>7320</td>
<td>....</td>
<td>6976</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>7138</td>
<td>6766</td>
<td>7320</td>
<td>....</td>
<td>6976</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>7138</td>
<td>7292</td>
<td>7320</td>
<td>....</td>
<td>6976</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>7138</td>
<td>7292</td>
<td>7320</td>
<td>....</td>
<td>6976</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>....</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>27</td>
<td>7412</td>
<td>6616</td>
<td>7458</td>
<td>....</td>
<td>4416</td>
<td>6853</td>
<td>6727</td>
</tr>
<tr>
<td>28</td>
<td>7275</td>
<td>7430</td>
<td>7018</td>
<td>....</td>
<td>5000</td>
<td>3273</td>
<td>6727</td>
</tr>
<tr>
<td>29</td>
<td>7275</td>
<td>7174</td>
<td>7124</td>
<td>....</td>
<td>6842</td>
<td>6853</td>
<td>1369</td>
</tr>
<tr>
<td>30</td>
<td>7275</td>
<td>7430</td>
<td>6504</td>
<td>....</td>
<td>5000</td>
<td>3273</td>
<td>6727</td>
</tr>
<tr>
<td>31</td>
<td>7275</td>
<td>7430</td>
<td>7133</td>
<td>....</td>
<td>6420</td>
<td>6853</td>
<td>6727</td>
</tr>
</tbody>
</table>

![Figure 4-5 Truck schedule generated by previous MIP model](image-url)
Similarly, the annual maintenance cost of the schedule is summarised and graphed in Figure 4-6. The years at which the major maintenance service will take place range from year 4 to year 9.

![Figure 4-6 Annual maintenance cost of the schedule by previous MIP model](image)

4.2.3 Comparison of the proposed, previous MIP model and TA

First, the solution time using different approaches is apparently different, which can be seen from Table 4-11. Developing a schedule with MIP model is considerably time efficient compared with TA which is based on manually scheduling. Due to the increment of the number of the binary variables in the proposed MIP model resulted from considering the new truck purchase option, the solution time increase exponentially with setting the same gap for both MIP models. However, it is acceptable to solve a medium size truck scheduling problem in two hours.

<table>
<thead>
<tr>
<th>Model name</th>
<th>TA</th>
<th>Previous MIP</th>
<th>Proposed MIP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solution time</td>
<td>2 days</td>
<td>1.01 seconds</td>
<td>111.46 minutes</td>
</tr>
</tbody>
</table>

Second, considering the maintenance cost of the schedule, discounted annual cost (DAC) and cumulative discounted cost (CDC) of the proposed, previous MIP model and TA are presented in Figure 4-7. Since the DAC of schedules of three approaches are descending as the annual required hours decrease, the increment of
the CDC tend to be slowed down. However, at the end of the 10-year schedule, it is clear from Figure 4-7 that the proposed model can provide the optimal schedule with the minimum maintenance cost while the previous MIP model gives a sub-optimal solution but still outperforms TA in CDC.

Figure 4-7 Discounted annual cost (DAC) and cumulative discounted cost (CDC) of the proposed, previous MIP model and traditional approach

Figure 4-8 shows the cumulative discounted saving (CDS) which is calculated by the following formula: \( CDS = CDC \text{ of the previous MIP model (or TA)} - CDC \text{ of the proposed MIP model} \) and the percentage of this cumulative discounted saving (PCDS) is defined by: \( PCDS = CDS / CDC \text{ of the previous MIP model (or TA)} \). In the final year, schedule by the proposed model is indicated to provide $15.87M and $25.74M CDS in maintenance cost over 10 years, which account for 14.77% and 21.94% of the total maintenance cost of the schedule by previous MIP model and TA respectively.
Figure 4-8 Cumulative discounted saving (CDS) by the proposed MIP compared to the previous MIP model and TA model and its percentage (PCDS)

Finally, the focus will be on the component of the overall maintenance cost of the different schedules. As described in the methodology section, the overall maintenance cost is composed of normal maintenance and major maintenance service cost along with the new truck cost. The respective cost and percentage of these three components of different approached are listed in Table 4-12. Although purchase of new truck costs $30.9M that makes up 3.38% of the overall cost of the schedule generated by the proposed model, a distinct decline in normal and major maintenance cost can offset the purchase cost, which results in less total cost than previous MIP model and TA.

Table 4-12 Cost and percentage of the components of the overall maintenance cost

<table>
<thead>
<tr>
<th>Model name</th>
<th>Normal maintenance</th>
<th>Major maintenance</th>
<th>New truck purchase</th>
</tr>
</thead>
<tbody>
<tr>
<td>TA</td>
<td>Cost($M)</td>
<td>97.01</td>
<td>20.30</td>
</tr>
<tr>
<td></td>
<td>Percentage</td>
<td>82.70%</td>
<td>17.30%</td>
</tr>
<tr>
<td>Previous MIP model</td>
<td>Cost($M)</td>
<td>94.37</td>
<td>13.07</td>
</tr>
<tr>
<td></td>
<td>Percentage</td>
<td>87.83%</td>
<td>12.17%</td>
</tr>
<tr>
<td>Proposed MIP model</td>
<td>Cost($M)</td>
<td>77.96</td>
<td>10.52</td>
</tr>
<tr>
<td></td>
<td>Percentage</td>
<td>85.13%</td>
<td>11.49%</td>
</tr>
</tbody>
</table>
4.3 PERFORMANCE AND SOLUTION ANALYSIS OF PROPOSED MIP MODEL UNDER DIFFERENT SCENARIOS

Since the input variables of the MIP model in the real mining operation are not static, which can be changed with the variability of the operational conditions in mines, it is necessary to understand the performance and solution of the proposed MIP model using “what if” scenario-based input variables. This section details the problem size, solution time and solutions of the proposed MIP model applying various input variables, such as the size of age bins, the new truck purchase cost and material movement requirement. The original data set from the case study will be modified and utilised in this section.

4.3.1 The application of the proposed MIP model with different age bin sizes

The original data set from the gold mine in Western Australia contains 20 age bins with 5000 hours in each, which restricts the truck life to 100,000 hours in total. When modifying the age bin size of the original data, the new unit maintenance cost will be assigned to each new age bin based on the original maintenance cost with the same assumption of truck life of 100,000 hours. For instance, if the age bin size tends to decrease to 3000 hours, 34 truck age bins will be set including first 33 age bins with 3000 hours in each and last age bin with only 1,000 hours (33×3,000+1×1000=100,000 hours). Since the first age bin with 3,000 hours of the modified data is still in the first age bin (5,000 hours) of the original data, they are assumed to have the same maintenance cost. However, as for the second age bin of the modified data, 2,000 hours of it are in the first age bin of original data and 1000 hours are in the second age bin. Therefore, its maintenance cost is equal to the summary of two thirds of the first age bin maintenance cost and one third of the second age bin maintenance cost of original data. Similarly, new maintenance cost can be assigned to each age bin of the modified data.

In this part, the original data set, which has 5,000 hours in each age bin, is modified to contain 3,000, 8,000 and 10,000 hours in each age bin respectively. The maintenance cost distributions of truck type one based on different age bin size are illuminated in Figure 4-9, which indicates that there is an obvious smoothing effect to the maintenance cost profile using this method to modify the truck age bin size.
Implementing these three modified data sets with various age bin sizes to the proposed MIP model, their problem size and solution time are listed in Table 4-13. The models are solved with the gap of about 3%. As the truck age bin size increases, less variables are included in the problem so that the solution time decreases dramatically from 538.14 minutes for 3000 hours in each age bin model to only 4.84 seconds for 10000 hours model.

**Table 4-13 Problem size and solution time of the MIP model using data with various age bin sizes**

<table>
<thead>
<tr>
<th>Model Name</th>
<th>Number of variables</th>
<th>3000 age bin</th>
<th>5000 age bin</th>
<th>8000 age bin</th>
<th>10000 age bin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Problem size</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>variables</td>
<td>34039</td>
<td>20319</td>
<td>13459</td>
<td>10519</td>
<td></td>
</tr>
<tr>
<td>liner variables</td>
<td>17199</td>
<td>10399</td>
<td>6909</td>
<td>5439</td>
<td></td>
</tr>
<tr>
<td>binary variables</td>
<td>16840</td>
<td>9980</td>
<td>6550</td>
<td>5080</td>
<td></td>
</tr>
<tr>
<td>Constraints</td>
<td>36729</td>
<td>21637</td>
<td>14091</td>
<td>10857</td>
<td></td>
</tr>
<tr>
<td>Solution time</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>538.14mins</td>
<td>111.46mins</td>
<td>7.71secs</td>
<td>4.84secs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gap</td>
<td>3.11%</td>
<td>3.11%</td>
<td>2.58%</td>
<td>2.95%</td>
<td></td>
</tr>
</tbody>
</table>

The overall maintenance cost and the new truck purchase schedules generated by the MIP model applying data with various age bin sizes are summarised in Table 4-14, and the truck usage schedules are graphed in Figure 4-10.
Table 4-14 Solutions of the MIP model using data with various age bin sizes

<table>
<thead>
<tr>
<th>Model name</th>
<th>Overall maintenance cost($M)</th>
<th>New truck ID</th>
<th>New truck type</th>
<th>Purchase time(Year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3000 age bin</td>
<td>91.71</td>
<td>49</td>
<td>6</td>
<td>1st</td>
</tr>
<tr>
<td>5000 age bin</td>
<td>91.57</td>
<td>48</td>
<td>6</td>
<td>2nd</td>
</tr>
<tr>
<td>8000 age bin</td>
<td>92.89</td>
<td>47,48</td>
<td>6</td>
<td>1st</td>
</tr>
<tr>
<td>10000 age bin</td>
<td>91.64</td>
<td>47,49</td>
<td>6</td>
<td>1st</td>
</tr>
</tbody>
</table>

Figure 4-10 Truck schedules of the MIP model using data with various age bin sizes

The schedules of the age bin size of 3000 and 5000 hours suggest the similar new truck purchase plan which only purchases one truck from type six at the first and second year respectively and eventually provide the similar overall maintenance cost. Furthermore, the truck schedules of the age bin size of 3000 and 5000 hours presented in Figure 4-10 are rather similar. However, the solution time for the problem of 5000 hours in each age bin is only one fifth of that of 3000 hours one. Hence, in the real mining operation, 5000 hours age bin model can be a more efficient one considering the computation time.

As for the problem of 8000 and 10000 age bin models, the same new truck purchase plan is decided, which recommends to purchase two trucks of type six in the first year. As one more new truck is to be purchased to the fleet, the schedules of these two problems are slightly different from the previous two. Although one more truck is
added into the fleet which should increase capital cost, the overall maintenance cost is still similar with the previous ones, which is mainly due to the smoothing effect when converting the original maintenance cost data. In other words, in mining practice, if two new trucks are purchased based on these two schedules, the actual maintenance cost will be definitely more than the planned one. Therefore, adequate data can increase the accuracy of the MIP model.

### 4.3.2 The application of the proposed MIP model with different material movement requirements

According to the schedules discussed above, the proposed MIP model tends to purchase new trucks in the early years of the 10-year plan. However, the current available truck fleet can meet the annual required working hours in the abovementioned problem. Therefore, a question is how the proposed MIP model will determine the new truck purchase plan when the truck fleet capacity cannot satisfy the annual material movement requirement. Will it purchase a new truck at the exact year at which the current fleet capacity is less than the required working hours of that year or still at the initial years of the plan? In order to answer this question, a new material movement schedule is set as presented in Table 4-15. The capacity of the current fleet can meet the required working hours in the first 5 years but fails to meet the requirements of the last 5 years. All the other data is the same as in the case study.

<table>
<thead>
<tr>
<th>Year</th>
<th>Required working hours</th>
<th>Available working hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>221050</td>
<td>244022.0</td>
</tr>
<tr>
<td>2</td>
<td>220300</td>
<td>246482.2</td>
</tr>
<tr>
<td>3</td>
<td>222500</td>
<td>247448.3</td>
</tr>
<tr>
<td>4</td>
<td>211500</td>
<td>242531.7</td>
</tr>
<tr>
<td>5</td>
<td>202600</td>
<td>235737.9</td>
</tr>
<tr>
<td>6</td>
<td>243000</td>
<td>234884.7</td>
</tr>
<tr>
<td>7</td>
<td>242000</td>
<td>237253.4</td>
</tr>
<tr>
<td>8</td>
<td>240000</td>
<td>232690.3</td>
</tr>
<tr>
<td>9</td>
<td>120000</td>
<td>106982.9</td>
</tr>
<tr>
<td>10</td>
<td>80000</td>
<td>64652.7</td>
</tr>
</tbody>
</table>

The solution is generated in 467.62 minutes with the gap of 3% providing the overall maintenance cost of $101.96M. There are three new trucks in total that need to be purchased and its details are listed in Table 4-16. Based on the new truck purchase
plans provided here and previously, the proposed MIP model prefers to purchase new trucks in the early years, which can yield the greatest returns on investment so as to gain the minimised maintenance cost.

Table 4-16 New truck purchase plan based on new material movement schedule

<table>
<thead>
<tr>
<th>Number</th>
<th>New truck ID</th>
<th>New truck type</th>
<th>Purchase time(Year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>47</td>
<td>6</td>
<td>2nd</td>
</tr>
<tr>
<td>2</td>
<td>48</td>
<td>6</td>
<td>1st</td>
</tr>
<tr>
<td>3</td>
<td>49</td>
<td>6</td>
<td>1st</td>
</tr>
</tbody>
</table>

4.3.3 The application of the proposed MIP model with different new truck purchase cost

The new truck purchase cost is another input variable that can be changed. All of schedules discussed above choose truck type 6 when the new truck purchase decision is made. In this part, the original data is modified so that the purchase cost of truck from type 6 is assumed to be $5M instead of $3.4M. The problem is solved in 665.34 seconds at the gap of 2.87%. The resulting schedule suggests that two trucks of type 2 should be purchased at the first year, and provides the overall maintenance cost of $92.06M. It is clear that this schedule is sub-optimal compared with the one that chooses type 6 in the case study section. This states that the proposed MIP model can adjust the purchase plan and the truck schedule when the new truck purchase cost is changed. As can be seen from the average maintenance cost, payload capacity and purchase cost given in Table 4-2, there are not clear rules to follow to select the new truck. Selecting new trucks is a process that considers the complex interaction of varying maintenance cost with different age bins, payload capacities and the purchase cost based on the mathematical computation.

4.4 SUMMARY

In this section, first, a medium size data set from a gold mine located in Western Australia is applied to the proposed MIP model in the case study. The characteristics of the input data set, problem size, solution time and the optimal schedule are presented and analysed. Subsequently, the comparison of the proposed MIP model, the previous MIP model and TA using this data set is conducted and demonstrated. It indicates that the proposed MIP model can provide 14.77% and 21.94% cost savings compared to the previous MIP model and TA. In addition, the MIP technique
based model apparently outperforms TA in faster solution time. Eventually, various “what if” scenario-based input variables, such as age bin size, material movement requirement and new truck purchase cost, are applied into the model and their solutions are generated and analysed. Although more age bins can increase the accuracy of the model, they can also cause the unacceptable computation time. It is necessary to find a suitable age bin size to achieve the optimal performance of the MIP model. In this case, 5000 hours are assumed in each age bin. The proposed MIP model can adjust the schedule when required hours and truck purchase cost vary. In addition, the new MIP model tends to purchase new trucks at initial years, and decides the new truck purchase plan while considering the interaction of varying maintenance cost with different age bins, payload capacities and the purchase cost.
CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS
FOR THE FUTURE RESEARCH

5.1 CONCLUSIONS

A new MIP model that considers the new truck purchase option is developed in this research to optimise the heterogeneous truck fleet schedule based on the minimised maintenance cost. The proposed MIP model takes into account all the key constraints that exist in the material haulage project, such as the material movement requirements and different truck payload capacities. In addition, the new model considers a new truck purchase option which can compare the cost of purchasing new trucks versus that of using old trucks. Subsequently, if the decision of purchasing new trucks is made, the model can determine the optimal new truck purchase plan with the consideration of the complex interaction of varying maintenance cost with different age bins, payload capacities and the purchase cost.

The application of the proposed MIP model to a real data set from a gold mine in Western Australia recommends that a new truck from type 6 should be purchased at the second year. The resulting schedule can provide 21.94% ($25.74M) discounted savings on maintenance cost over 10 years compared with schedules determined by current practice as TA. The new MIP model outperforms the TA not only in the maintenance cost savings but also in the faster computation time, which is due to that MIP technique-based model is a proven mathematical optimisation method, TA is however an arbitrary manual scheduling method.

Since the conditions in mining operation are uncertain, “What if” scenarios have been generated for age bin size, material movement requirement and truck purchase cost, which are applied to the proposed MIP model. The analysis of schedules generated indicates that larger age bin size can decrease the computation time, and decrease the accuracy of the schedule in the meantime. The new trucks are suggested to be purchased in the initial years, which can help to yield the greatest returns on investment and benefit the mining operation in the long term. The proposed model can also generate a different optimised truck purchase plan when truck purchase cost varies.
The development of the interface makes the proposed MIP model accessible to the ordinary professionals without specialised mathematical and programming background. The interface can concurrently generate the LP file containing the formulations of MIP model and summarise and present the data in Excel worksheets that enables the better understanding of the problem. Moreover, the truck scheduling time is further decreased with the help of the interface.

### 5.2 Recommendations for the Future Research

The further research will continuously focus on the stochasticity of the input variables of the model. Although different data are applied into the new model in this research, these data cannot clearly reflect the stochasticity of the input variables. This is because all of these data are not simulated from the original data due to the lack of data. Therefore, adequate data will be needed in the following research. The data can be simulated and used in the model, which will assist decision-making in mine planning under uncertainty. In addition, the maximum number of new truck that can be purchased from each type is assumed in the model. If this number is assumed to be large, it will increase the computation time dramatically; if this number is set too small, it may result in sub-optimal solution. Hence, the proposed model will be improved to select the number of new trucks automatically in the future research.
REFERENCES


Microsoft Corp., Microsoft Excel 2010, 2010


*Every reasonable effort has been made to acknowledge the owners of copyright material. I would be pleased to hear from any copyright owner who has been omitted or incorrectly acknowledged.*
APPENDIX 1-VISUAL BASIC CODE

Option Explicit

Private Sub CommandButton1_Click()
    iold = TextBox1.Text
    inew = TextBox2.Text
    iperE = TextBox3.Text
    ibin = TextBox4.Text
    ibinH = TextBox5.Text
    id = TextBox6.Text
    itype = TextBox7.Text
    iCBin = TextBox9.Text
    ICBincost = TextBox10.Text
    itruck = iold + inew * itype
    Dim i, j, K, n
    'sheet1
    Worksheets(1).Activate
    Worksheets(1).Range("a3").Select
    For i = 1 To itruck
        ActiveCell.Offset(i - 1, 0) = i
    Next
    For i = 1 To iperE
        ActiveCell.Offset(-1, i) = i
    Next
    'sheet2

    Inputting, summarising and writing data in Excel worksheets
Worksheets(2).Activate
Worksheets(2).Range("a3").Select
For i = 1 To itruck
    ActiveCell.Offset(i - 1, 0) = i
Next
For i = 1 To ibin
    ActiveCell.Offset(-2, i + 1) = i
    ActiveCell.Offset(-1, i + 1) = i * ibinH
Next
'Sheet3
Worksheets(3).Activate
Worksheets(3).Range("a2").Select
For i = 1 To itype
    For j = 1 To ibin
        ActiveCell.Offset((i - 1) * ibin + j - 1, 0) = i
        ActiveCell.Offset((i - 1) * ibin + j - 1, 1) = j
    Next j
Next i
For i = 1 To iperE
    ActiveCell.Offset(-1, i + 1) = i
Next
'Sheet4
Worksheets(4).Activate
Worksheets(4).Range("a3").Select
For i = 1 To iperE
ActiveCell.Offset(i - 1, 0) = i
Next
For i = 1 To itype
ActiveCell.Offset(-1, i) = i
Next
Label9.Caption = iold & " old trucks in current system"
Label10.Caption = iperE & " scheduled years"
Label11.Caption = itype & " types of trucks"
End Sub

Private Sub CommandButton2_Click()
Dim i, j, K, n
For i = 1 To iold
 UserForm2.Label1.Caption = "Truck No." & i
 UserForm2.TextBox1.Text = ""
 UserForm2.TextBox2.Text = ""
 UserForm2.TextBox3.Text = ""
 UserForm2.Show
 Next
End Sub

Private Sub CommandButton3_Click()
UserForm3.Show
End Sub
Private Sub CommandButton4_Click()
Dim i, j, K, n
    For i = 1 To itype
        UserForm4.Label1.Caption = "Type No." & i
        UserForm4.TextBox1.Text = ""
        UserForm4.TextBox2.Text = ""
        UserForm4.TextBox3.Text = ""
        UserForm4.TextBox4.Text = ""
        UserForm4.Show
    Next
End Sub

Private Sub CommandButton5_Click()
Dim i, j, K, n
'sheet2
Worksheets(2).Activate
Worksheets(2).Range("b3").Select
    For i = 1 To iold
        ActiveCell.Offset(i - 1, 0) = e(i)
    Next
    For i = 1 To inew * itype
        ActiveCell.Offset(i + iold - 1, 0) = 0
    Next
For i = 1 To iold + inew * itype
For j = 1 To ibin
Worksheets(2).Cells(2 + i, 2 + j).Select
If Cells(ActiveCell.Row, 2) > Cells(2, ActiveCell.Column) Then
ActiveCell.Value = 0
Else
    If Cells(2, ActiveCell.Column) - Cells(ActiveCell.Row, 2) < Val(ibinH) Then
        ActiveCell.Value = Cells(2, ActiveCell.Column) - Cells(ActiveCell.Row, 2)
    Else
        ActiveCell.Value = ibinH
    End If
End If
Next j
Next i

'sheet2 index
ibasic = UserForm1.TextBox8.Text
Worksheets(2).Activate
For i = 1 To iold
Worksheets(2).Cells(2 + i, 3 + ibin) = r(d(i)) / r(ibasic)
Worksheets(2).Cells(2 + i, 4 + ibin) = d(i)
Next
For i = 1 To itype
For j = 1 To inew
Worksheets(2).Cells(2 + iold + (i - 1) * inew + j, 3 + ibin) = r(i) / r(ibasic)

Worksheets(2).Cells(2 + iold + (i - 1) * inew + j, 4 + ibin) = i

Next

Next

'sheet1

'from userform2

Worksheets(1).Activate

Worksheets(1).Range("b3").Select

For i = 1 To iold

K = Split(f(i), ",")

For j = 1 To iperE

ActiveCell.Offset(i - 1, j - 1) = K(j - 1)

Next j

Next i

'from userform3

Worksheets(1).Activate

Worksheets(1).Range("b1").Select

K = Split(m, ",")

For i = 1 To iperE

ActiveCell.Offset(0, i - 1) = K(i - 1)

Next

'sheet1 available hours for new truck

Worksheets(1).Activate
For i = 1 To itype
K = Split(t(i), ",")
    For j = 1 To inew
        For n = 1 To iperE
            Worksheets(1).Cells(2 + iold + (i - 1) * inew + j, 1 + n) = K(n - 1)
        Next
    Next
Next
Next

'sheet4
'buy cost
Worksheets(4).Activate
Worksheets(4).Range("b3").Select
    For i = 1 To itype
        ActiveCell.Offset(0, i - 1) = p(i)
        For j = 1 To iperE - 1
            ActiveCell.Offset(j, i - 1) = ActiveCell.Offset(0, i - 1).Value / (1 + id) ^ j
        Next
    Next
Next

'capacity
For i = 1 To itype
    ActiveCell.Offset(iperE, i - 1) = r(i)
Next
'sheet3
Worksheets(3).Activate
Worksheets(3).Range("c2").Select
For i = 1 To itype
K = Split(q(i), ",")
For j = 1 To ibin
ActiveCell.Offset((i - 1) * ibin + j - 1, 0) = K(j - 1)
For n = 1 To iperE - 1
ActiveCell.Offset((i - 1) * ibin + j - 1, n) = ActiveCell.Offset((i - 1) * ibin + j - 1, 0) / (1 + id) ^ n
Next n
Next j
Next i
End Sub

Private Sub CommandButton1_Click()
Dim i
i = Val(Right(UserForm2.Label1.Caption, Len(UserForm2.Label1.Caption) - 9))
ReDim Preserve d(i)
ReDim Preserve e(i)
ReDim Preserve f(i)
d(i) = TextBox1.Text
e(i) = TextBox2.Text
f(i) = TextBox3.Text
Me.Hide

End Sub

Private Sub CommandButton1_Click()
    m = UserForm3.TextBox1.Text
    Me.Hide
End Sub

Private Sub CommandButton1_Click()
    Dim i
    i = Val(Right(UserForm4.Label1.Caption,
                  Len(UserForm4.Label1.Caption) - 8))
    ReDim Preserve r(i)
    ReDim Preserve p(i)
    ReDim Preserve q(i)
    ReDim Preserve t(i)
    r(i) = TextBox3.Text
    p(i) = TextBox4.Text
    q(i) = TextBox1.Text
    t(i) = TextBox2.Text
    Me.Hide
End Sub
Private Sub CommandButton10_Click()

' name the range
Worksheets(1).Activate
Worksheets(1).Range("b1").Select
Set totalYtime = ActiveCell.Resize(1, iperE)
Worksheets(1).Range("b3").Select
Set Ytime = ActiveCell.Resize(itruck, iperE)

Worksheets(2).Activate
Worksheets(2).Range("b3").Select
Set truckage = ActiveCell.Resize(itruck, 1)
Worksheets(2).Range("c3").Select
Set Btime = ActiveCell.Resize(itruck, ibin)
Set index = ActiveCell.Offset(0, ibin).Resize(itruck, 1)
Set trucktype = ActiveCell.Offset(0, ibin + 1).Resize(itruck, 1)

Worksheets(3).Activate
Worksheets(3).Range("c2").Select
Set fixcost = ActiveCell.Resize(itype * ibin, iperE)

Worksheets(4).Activate
Worksheets(4).Range("b3").Select
Set buycost = ActiveCell.Resize(iperE, itype)
Set capacity = ActiveCell.Offset(iperE, 0).Resize(1, itype)
End Sub
Private Sub CommandButton6_Click()

Dim i, j, K, n As Long
Dim sLine As String
Dim sLine1 As String
Dim sLine2 As String
Dim iperS As Integer
iperS = 1

Open fileSaveName For Output As #1
Print #1, "minimize"

'objective function

n = 0

For i = 1 To iold
    For j = 1 To ibin
        n = n + 1
        sLine = ""
        For K = iperS To iperE
            sLine = sLine & "+" & fixcost.Cells((trucktype.Cells(i, 1) - 1) * ibin + j, K) & "X" & i & "B" & j & "T" & K
        Next K
        Next j
    Next i

Next K

Constructing MIP model and writing it to LP file
'new truck cost
For n = 1 To itype * inew
    For j = 1 To ibin
        sLine = ""
        For K = iperS To iperE
            sLine = sLine & "+" & fixcost.Cells(Int((n - 1) / inew) * ibin + j, K) & "X" & iold + n & "B" & j & "T" & K
        Next K
        Print #1, sLine
    Next j
Next n

For i = 1 To itruck
    sLine = ""
    For K = iperS To iperE - 1
        sLine = sLine & "+" & ICBincost / (1 + id) ^ (K - 1) & "Y" & i & "B" & iCBin & "T" & K
    Next K
    Print #1, sLine
Next i
'purchase cost in objective

For n = 1 To itype * inew
    sLine = ""
    For K = iperS To iperE
        sLine = sLine & "+" & buycost.Cells(K, Int((n - 1) / inew) + 1) & "Z" & iold + n & "T" & K
    Next K
    Print #1, sLine
Next n

'constraints

Print #1, "subject to"

'working time constraint in each year

For i = 1 To iold
    For K = iperS To iperE
        sLine = ""
        For j = 1 To ibin
            sLine = sLine & "+X" & i & "B" & j & "T" & K
        Next j
        sLine = sLine & "<=" & Ytime.Cells(i, K)
        Print #1, sLine
    Next K
Next i

'new trucks constraints
For $i = i_{old} + 1$ To $i_{truck}$

    sLine2 = ""

    For $K = i_{perS}$ To $i_{perE}$
        sLine = ""
        For $j = 1$ To $ibin$
            sLine = sLine & "+X" & $i$ & "B" & $j$ & "T" & $K$
        Next $j$

        sLine1 = ""
        For $n = 1$ To $K$
            sLine1 = sLine1 & "-" & Ytime.Cells($i$, $K$) & "Z" & $i$ & "T" & $n$
        Next $n$

        sLine2 = sLine & sLine1 & "<=0"

        Print #1, sLine2
    Next $K$

Next $i$

'ZT<=1 constraints

For $i = i_{old} + 1$ To $i_{truck}$

    sLine = ""

    For $K = i_{perS}$ To $i_{perE}$
        sLine = sLine & "+" & "Z" & $i$ & "T" & $K$
    Next $K$

    sLine = sLine & "<=1"
'truck age constraint
For i = 1 To itruck
    sLine = "+C" & i & "T" & 0 & "=" & truckage.Cells(i, 1)
    Print #1, sLine
Next i

For i = 1 To itruck
    For K = iperS To iperE
        sLine = ""
        If (K = 1) Then
            For j = 1 To ibin
                sLine = sLine & "+X" & i & "B" & j & "T" & K
            Next j
            sLine = sLine & "-" & "C" & i & "T" & K & "=" & "-" & truckage.Cells(i, 1)
            Print #1, sLine
        End If
    Next K
Next i
If (K > 1) Then
    For j = 1 To ibin
        sLine = sLine & "+X" & i & "B" & j & "T" & K
    Next j
    sLine = sLine & "+C" & i & "T" & K - 1 & "," & "C" & i & "T" & K & ",=0"
    Print #1, sLine
    End If

    Next K

Next i

'age bin constraint

For i = 1 To itruck
    For j = 1 To ibin
        sLine = ""
        For K = iperS To iperE
            sLine = sLine & "+X" & i & "B" & j & "T" & K
        Next K
        sLine = sLine & ",<=" & Btime.Cells(i, j)
        Print #1, sLine
    Next j
Next i

'age bin consequence constraint

For i = 1 To itruck
For j = 1 To ibin - 1
    sLine1 = ""
    sLine2 = ""
    sLine = ""
    For K = iperS To iperE
        sLine1 = sLine1 & "+X" & i & "B" & j & "T" & K
        sLine2 = "-" & Btime.Cells(i, j) & "Y" & i & "B" & j & "T" & K
        sLine = sLine1 & sLine2 & ">=0"
        Print #1, sLine
    Next K
    sLine2 = ""
    For K = iperS To iperE
        sLine1 = "+X" & i & "B" & j + 1 & "T" & K
        sLine2 = sLine2 & "-" & Btime.Cells(i, j + 1) & "Y" & i & "B" & j & "T" & K
        sLine = sLine1 & sLine2 & "<=0"
        Print #1, sLine
    Next K
    Next j
Next i

'overall required hours constraint
For K = iperS To iperE
    sLine = ""
    For i = 1 To itruck

sLine = sLine & "+" & index.Cells(i, 1) & "C" & i & "T" & K & "-" & index.Cells(i, 1) & "C" & i & "T" & K - 1

Next i

sLine = sLine & ">=" & totalYtime.Cells(1, K)

Print #1, sLine

Next K

'additional constraint

For i = 1 To itruck
    For j = 1 To ibin
        sLine = ""
        For K = iperS To iperE
            sLine = sLine & "+" & "Y" & i & "B" & j & "T" & K
        Next K
        sLine = sLine & "<=1"
        Print #1, sLine
    Next j
Next i

'write binaries

Print #1, "binaries"

n = 0

For i = 1 To itruck
    For j = 1 To ibin
        For K = iperS To iperE
            n = n + 1
        Next K
    Next j
Next i
sLine = "Y" & i & "B" & j & "T" & K
Print #1, sLine
Next K
Next j
Next i

'new binaries
For i = iold + 1 To itruck
    For K = iperS To iperE
        n = n + 1
        sLine = "Z" & i & "T" & K
        Print #1, sLine
        Next K
    Next i
Print #1, "end"
MsgBox n & "binary variables"

Close #1
End Sub
Private Sub CommandButton7_Click()
Label9.Caption = ""
Label10.Caption = ""
Label11.Caption = ""
index.ClearContents
Btime.ClearContents
Ytime.ClearContents
truckage.ClearContents
buycost.ClearContents
capacity.ClearContents
fixcost.ClearContents
totalYtime.ClearContents
trucktype.ClearContents

    Worksheets(1).Activate
    Worksheets(1).Range("a3").Select
    ActiveCell.Resize(itruck, 1).ClearContents

    Worksheets(1).Range("b2").Select
    ActiveCell.Resize(1, iperE).ClearContents

    Worksheets(2).Activate
    Worksheets(2).Range("a3").Select
    ActiveCell.Resize(itruck, 1).ClearContents

    Worksheets(2).Range("c1").Select

Clearing data stored in Excel worksheets
ActiveCell.Resize(2, ibin).ClearContents

Worksheets(3).Activate
Worksheets(3).Range("a2").Select
ActiveCell.Resize(itype * ibin, 2).ClearContents
Worksheets(3).Range("c1").Select
ActiveCell.Resize(1, iperE).ClearContents

Worksheets(4).Activate
Worksheets(4).Range("a3").Select
ActiveCell.Resize(iperE, 1).ClearContents
Worksheets(4).Range("b2").Select
ActiveCell.Resize(1, iperE).ClearContents
End Sub
APPENDIX 2-INTERFACE DEVELOPMENT OF THE PROPOSED MIP MODEL

In order to further simplify the process of handling vast data and constructing the MIP model, an interface is developed with the VBA programming language. This section details how the interface works to generate a LP file that contains the MIP model for computation in the next stage. The abovementioned case study is used as an example to show the interface utilisation step by step.

In the first step, all of the basic information of the specific truck scheduling project should be inputted to the corresponding Textbox on the left hand side of the interface, such as old truck number, age bin interval, engine rebuild age bin (14×5000=70000 hours) and engine rebuild cost, as shown in Figure Appendix 2-1. Then click on the OK button, the basic information will be presented on the right hand side, like 31 old trucks in the current system, 10 scheduled years and 6 truck types are considered.

![Figure Appendix 2-1 Step 1: input basic information of the scheduling problem](image)

After the step 1, the scheduling problem contains 31 old trucks currently, takes into account 6 truck types and is for a 10-year plan. Subsequently, the detailed information will assigned to each truck and year:

Step 2: Click on the Set button next to “31 old trucks in current system”, a new window named “Current available truck information” will pop up. Input the truck type,
truck age and available working hours in each year of the old truck 1, as presented in Figure Appendix 2-2, click OK button and a same window for old truck 2 will pop up. Similarly, input data for all the other old trucks.

![Figure Appendix 2-2 Step 2: input data of the old trucks in the current fleet](image)

Step 3: Click on the Set button next to “10 scheduled years”, a new window named “Annual production requirement” will pop up. Input the required working hours in each year, as presented in Figure Appendix 2-3, click OK button to confirm and close the window.
Step 4: Click on the Set button next to “6 types of trucks”, a new window named “Truck basic information” will pop up. Input the truck capacity, truck purchase cost, maintenance cost in each age bin and available working hours in each year of the truck type 1, as presented in Figure Appendix 2-4, click OK button and a same window for truck type 2 will pop up. Similarly, input data for all the other truck types.
After inputting all the data set to the interface, one truck type should be selected as the basic one used for converting working hours, as shown in Figure Appendix 2-5 in which truck type 2 is selected. Then click on the **Write to Excel** button, all the information can be summarized and listed in four worksheets of Excel, as illuminated in Figure Appendix 2-6, 2-7, 2-8 and 2-9.

After that, click on the **Define Name** button to give names to the data stored in different zones in Excel worksheets. Click on **Save as** button to select the LP file to write the MIP model in. Finally, click on the **Export** button to start writing MIP model to the LP file selected so that it can be loaded to solver to obtain the solution.

![Figure Appendix 2-5 Step 5 and 6: displaying data in Excel and exporting LP file](image)
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**Figure Appendix 2-6 Annual required and available working hours**

**Figure Appendix 2-7 Available working hours in each age bin**
This section describes how to use developed interface based on the proposed MIP model to establish the MIP model for the truck scheduling problem. This interface can facilitate the process of handling data by summarising and presenting all input
data in Excel, which makes it easy for professionals to understand the detailed information of the problem. In addition, this verified interface hides the programming code behind, which can be readily accessed by professionals without process of debugging programme when confronting different problems.