Matching truck-and-shovel operations in open-pit mines using statistical data - dispatching strategies, match factor, and age-based maintenance

Patarawan Chaowasakoo
Matching truck-and-shovel operations in open-pit mines using statistical data - dispatching strategies, match factor, and age-based maintenance

Patarawan Chaowasakoo

A doctoral dissertation completed for the degree of Doctor of Science (Technology) to be defended, with the permission of the Aalto University School of Electrical Engineering, at a public examination held at the lecture hall AS1 of the school on the 22nd of September 2017 at 12 noon.

Aalto University
School of Electrical Engineering
Department of Electrical Engineering and Automation
Supervising professor
Professor Quan Zhou

Thesis advisor
Professor Emeritus Heikki Koivo

Preliminary examiners
Associate Professor Hooman Askari-Nasab, University of Alberta, Canada
Assistant Professor Snehamoy Chatterjee, Michigan Technological University, United States

Opponent
Professor Michel Gamache, Polytechnique Montréal, Canada

Aalto University publication series
DOCTORAL DISSERTATIONS 117/2017

© Patarawan Chaowasakoo

ISBN 978-952-60-7491-7 (pdf)
ISSN-L 1799-4934
ISSN 1799-4934 (printed)
ISSN 1799-4942 (pdf)

Unigrafia Oy
Helsinki 2017

Finland
Abstract

Economics today force mining companies to maximize profit over the life time of a mine. Especially in the context of open-pit mines, it is essential to acquire production with minimum cost. The ability to reduce operation costs can be directly achieved by utilizing trucks and shovels in an efficient manner. Dispatching approaches in the literature have considered different objectives in varying degrees of sophisticated assignments ranging from simple heuristic rules to complex mathematical programming. However, most approaches assume that all trucks and shovels have the same operating performance or ignore the stochastic nature of the truck-and-shovel operations.

This thesis investigates one of the primary problems in an open-pit mine: efficient matching trucks and shovels. In other words, the aim is to determine the required number of trucks and shovels and their types to make the best match in order to satisfy the production target. This problem is investigated using different simulation and optimization models, which contain the behaviours of dispatching strategy, match factor, and age-based maintenance under an ideal operation and breakdown event.

The results of this thesis show that the match factor ratio is able to determine limits for an appropriate fleet size selection, and can be used to estimate the relative efficiency of existing fleets. However, it cannot be used alone for fleet optimization. The choice of truck dispatching strategies and heuristic truck dispatching methods plays a crucial role to minimize the queuing time. Maintenance schedules are necessary to reduce breakdown, directly influencing equipment availability. Optimal preventive and corrective maintenance schedules are proposed for different truck age levels, providing cost savings. These proposed models offer potential applications to any situations in which truck fleets are used to transport material.
Tiivistelmä

Tässä työssä tarkastellaan yhtä avokaivosten pääangelmista: kuinka päättää kuroma-autojen ja kauhuokuormaajien tarvittava määrä ja niiden tyypit, niin että ne toimivat parhaalla mahdollisella tavalla toteuttaakseen tuotantotavoitteet. Ongelmaan esitettävä ratkaisuksi eri simulointi- ja optimointimalleja, jotka ottavat huomioon ajojärjestysstrategian, kaluston ikäperusteiset huollot sekä kuroma-autojen ja kauhuokuormaajien välisen yhteensovituksen (match factor).

I would like to express the most profound gratitude and appreciation to Professor Emeritus Heikki Koivo respectively my thesis advisor, for his valuable support, guidance, constructive suggestions, and constant encouragement throughout the research work. In addition, I wish to express sincere thanks to my supervising professor, Professor Quan Zhou for his instructive comments and creative suggestions for research papers. I also would like to express my sincere gratitude to Professor Jan Holmström and Dr. Heikki Seppälä for their valuable encouragement and constructive motivation during the thesis process. The main part of the actual research work was conducted in close collaboration with the team in Banpu Public Company Limited, Thailand and Indonesia. This research could not have been completed without their assistance, cooperation, encouraging feedback, positive attitude, and incentive grant in May 2015. Furthermore, the pre-examination of the thesis manuscript was performed by Associate Professor Hooman Askari-Nasab (University of Alberta) and Assistant Professor Snehamoy Chatterjee (Michigan Technological University). Their valuable comments and corrections are highly appreciated. Moreover, I am thankful to Professor Michel Gamache (Polytechnique Montréal) for opposing me in the defence of this thesis.

I would like to express genuine thanks to Professor Arto Visala, Assistant Professor Winai Wongsurawat, Assistant Professor Cheowchan Leelasukseree, Dr. Kai Zenger, Dr. Olli Haavisto, faculty members and staffs at the Department of Electrical Engineering and Automation, Aalto University for their support and academic guidance. Furthermore, Dr. Gordon McConnachie, Jan-Mikael Rybicki, and anonymous reviewers are acknowledged for the review and comments on the research papers. Finally, I would like to express my deepest thanks to my parents, brother, sister, and friends for their love, precious support, encouragement and understanding. This research is gratefully dedicated to all of them.

Espoo, 4 August 2017
Patarawan Chaowasakoo
List of Abbreviations and Symbols

Abbreviations

- bcm: bank cubic metre
- FPC: Fleet Production and Cost model
- GPS: Global Positioning System
- G-TiMDP: Genetic Time Dependent Markov Decision Process
- IP: Integer Programming
- LP: Linear Programming
- MIP: Mixed Integer Programming
- mm: millimetre
- MR: Multiple Regression
- MSC: Minimizing Shovel Saturation and Coverage
- MSWT: Minimizing Shovel Waiting Time
- MTCT: Minimizing Truck Cycle Time
- MTWT: Minimizing Truck Waiting Time
- NN: Neural Network
- OB: Overburden
- VBA: Visual Basic for Application

Symbols

- $b_i$: The simulated indicator of truck type $i$
- $d$: The shovel for which the truck is assigned
- $d_{-t_i}$: The simulated travelling distance of truck type $i$
- $h_{-t_i}$: The simulated hauling distance of truck type $i$
Symbols

$lcm(u_l)$ The least common multiple of unique loading times for all shovels of type $j$

$lcm(u_l)_j$ The least common multiple of all truck loading times for shovel type $j$

$lcm(u_l_{c_j})$ The least common multiple of the cycle time of the shovel type $j$ when working with a truck type $i$

$m^3$ Cubic metre

$MF_j$ Match factor ratio of a heterogeneous shovel fleet

$MF_i$ Match factor ratio of a heterogeneous truck fleet

$MF_{st}$ Match factor ratio of heterogeneous truck and shovel fleets

$ns$ The number of shovels

$ns_j$ The number of shovels type $j$

$nt_i$ The number of trucks type $i$

$O_i$ The analysis number of trips of each type of trucks in one month

$P$ The production requirement per month

$p_i$ The probability of spotting and backing in a cyclic operation of truck type $i$

$R_{i(j)}$ The binary indicates the possible shovels where the truck could be sent

$t_{-b_i}$ The simulated backing time of truck type $i$

$t_{-s_i}$ The simulated spotting time of truck type $i$

$tc$ The average cycle time for all trucks in the current period

$tc_i$ The cycle time for truck type $i$

$tc_j$ The truck cycle time for shovel $j$

$tl_i$ The time required for loading truck type $i$ with shovel

$tr_j$ The expected time of the assigned truck hauls its load from shovel $j$ to the waste dump and tipping
Symbols

t_{sj}  \quad \text{The completed loading time of shovel } j

\eta_{tj}  \quad \text{The expected truck travel time from the dispatching point to the shovel } j

ul_{ij}  \quad \text{The cycle time of the shovel type } j \text{ when working with truck type } i

ul_j  \quad \text{The cycle time of the shovel type } j \text{ when working with one truck type}

v_{d_{ti}}  \quad \text{The average downhill velocity of truck type } i

VS_j  \quad \text{The total volume of shovel } j \text{ when it has completed loading of the assigned truck over the shift}

VT_{ij}  \quad \text{The volume of truck } i \text{ on the selected shovel } j

v_{u_{ti}}  \quad \text{The average uphill velocity of truck type } i

v_{ud_{ti}}  \quad \text{The expected velocity of truck type } i

X  \quad \text{The set of all truck types}

Y  \quad \text{The set of all shovel types}
List of Publications

This doctoral dissertation consists of a summary and of the following publications which are referred to in the text by their numerals


Author’s Contribution

**Publication 1:** Introducing GPS in fleet management of a mine: impact on hauling cycle time and hauling capacity

The author was responsible for designing the tailor-made low cost GPS tracking system and implementing the system at the mine operation. The data modelling and analysis of cyclic activity time results were conducted by Assistant Professor Cheowchan Leelasukseree. The author wrote the manuscript except for Section 4.1, which was written by Leelasukseree. The manuscript was commented by Assistant Professor Cheowchan Leelasukseree and Assistant Professor Winai Wongsurawat.

**Publication 2:** Digitalization of mine operations: Scenarios to benefit in real-time truck dispatching

and

**Publication 3:** Improving fleet management in mines: The benefit of heterogeneous match factor

The author performed the modelling and analysis of the differences between truck dispatching strategies by conducting a stochastic simulation study based on the data gathered from the actual mine, and produced the corresponding results. The author wrote both manuscripts of publications 2-3. Dr. Heikki Seppälä provided expertise on statistics and commented on the manuscripts. Professor Emeritus Heikki Koivo and Professor Quan Zhou supervised the research and commented on the manuscripts.

**Publication 4:** Age-based maintenance for a fleet of haul trucks

The author was responsible for the contents of the publication and wrote the manuscript. Dr. Heikki Seppälä commented on the manuscript and Professor Emeritus Heikki Koivo supervised the research.
1. Introduction

After yet another difficult year, the global thermal coal markets were faced with a severe drop of collapsing energy prices. The economics today force mining industry to maximize the mining profits by extracting coal at the lowest possible cost over the life time of a mine. Especially in the context of open-pit mine operations, an essential issue is to acquire a close to the plan production with minimum cost. Typically open-pit mines are highly capital intensive which consist of 50-80 trucks, 10-30 shovels, and 10-15 auxiliary units. The amount of materials to be daily transported within and from the site is massive. To move these materials, a truck-and-shovel system has been the most widely used because it has significant advantages [1]–[3]. However, trucks and shovels constitute more than a half of the overall operating costs in an open-pit mine [4]–[13]. The ability to reduce the operation costs has been made directly to utilize trucks and shovels in an efficient manner.

1.1 Background and motivation

Efficient truck dispatching represents the traditional approach to improve production and equipment utilization. Truck dispatching can be seen as a simplified problem. Every time a truck is dispatched, it will pick up only one type of material, instead of many. The size and weight of the material loaded in the truck almost always reaches the truck capacity. The truck hauls the material to a dump point following the routing aspects. After dumping the material, the truck is immediately free for future loading demands.

However, truck dispatching in an open-pit mine presents three characteristics that are complicated and different from the usual truck dispatching in other industries [6], [14]–[19]. First, the pickup and delivery points stay the same during a long period of time, which generally corresponds to an eight or twelve-hour shift. One cycle travelling time of each truck is short, only 12-18 minutes, compared to the length of the overall shift and the timing demands at each pickup point are frequently high, 2-3 minutes. Second, the raw material is highly variable and encumbered with estimation errors because the operation is in the midst of coal and overburden, which are not well characterized. Third, operational uncertainties contain the varying topography of the pit, a network of haul routes, weather conditions, road conditions, visibility, and the variability in the status of operating equipment. These three characteristics contribute to the complexity of the system.
Previous research studies have presented different approaches to improve the operation of truck-and-shovel systems. Some of these approaches are based on the optimization of differently defined objective functions that affect a number of main problems, such as minimizing the transportation and maintenance costs, minimizing the truck-shovel waiting time and cycle times, as well as maximizing the amount of transported material [4], [20]–[35]. Some others rely on the size of the truck fleet to avoid the event of trucks being over-trucked or under-trucked, which requires simulations or dispatching methods to acquire a better evaluation of the optimal fleet size [6], [12], [21], [25], [27], [29], [36]–[46]. Most approaches assume that all trucks and shovels have the same operating performances or ignore the stochastic nature of the truck-and-shovel operations.

Operationally, each truck and shovel has its own reliability, availability, and maintainability. One of the prior research studies introduces an improved simulation and optimization model, in which equipment availability is one of the variables in the expected productivity function [31]. The model is used for allocating trucks by route according to their operating performances in a real open-pit mine, which aims to maximize the overall productivity of the fleet. Scheduled maintenance plays a major role in the operations as it directly influences the equipment availability and reliability [30], [36], [47]. Effective maintenance provides sustaining the long-term profitability [30]–[32], [48]–[51]. As a result, finding a close to optimal mixed truck-and-shovel fleet, which includes the stochastic equipment behaviour and environmental changes in the operations, is extremely important. This thesis utilizes some of the new possibilities enabled by the previous approaches.

1.2 Objectives and scope of the thesis

One of the primary problems in an open-pit mine is determining the required number of trucks and shovels as well as their types, to make the best match between them in order to satisfy the production target. Such a problem can occur in the mine design phase or during the operation. This thesis considers the specific problem in an actual open-pit mine and necessary data is collected through a Global Positioning System (GPS) technology. The amount of data is statistically significant to ensure that a result from a discrete event simulation model mimics the real system. The following explicit research questions are defined.

1. How to maximize the amount of material transported during a shift in open-pit mines?
2. How to minimize equipment inactivity?
3. What are the significant factors affecting the system performance?

The specific objectives are as follows. First is to reveal the bottlenecks in a truck haulage system and study the possibility of reducing truck cycle times. Second is to analyze the behaviour of dispatching strategy in an open-pit mine in conjunction with different heuristic truck dispatching methods. Third is to determine the necessary number and type of trucks and shovels to meet the
production target. This objective is achieved by evaluating different scenarios based on the choice of truck dispatching strategies and heuristic truck dispatching methods. Each scenario has different number and type of trucks and shovels. Fourth is to design a close to optimal scheduled maintenance for different truck age levels. As a way of investigating the research questions, these four steps are intensively utilized.

In order to obtain the maximum efficiency and minimum cost, the goal of this thesis is to integrate the optimization and simulation models to solve the problem in the fleet design and operation phases. The major focus concentrates in the area of improving truck-and-shovel system, especially in the extraction of overburden.

1.3 Contribution of the thesis

The main contribution of the thesis is the combination of determining a number of trucks and evaluating production optimally based on different behaviours of dispatching, match factor, and age-based maintenance in an actual open-pit mine. More specifically, the thesis contains the following contributions.

1. A reliable data input modelling from a tailor-made low cost GPS tracking system, which is implemented at a coal hauling operation in a coal mine. The data of each cyclic activity or event of truck is specified based on start zone and end zone contour of a mine map (Publication 1).

2. New knowledge about the effectiveness of different dispatching strategies by developing a realistic stochastic production simulation model, that takes main uncertainties in an actual open-pit mine into account (Publications 2-4).

3. For the first time a match factor is applied in a cyclic operating time of truck and shovel, in order to gain maximal efficiency from an existing fleet and to determine limits for an appropriate fleet size from an equipment selection phase. Moreover, it is reported for the first time that the choice of the heuristic truck dispatching method has a significant influence on the performance of the mine. Simulation results reveal remarkable differences in production figures under different heterogeneous fleet types (Publication 3).

4. A novel truck dispatching simulation model with consider age-based maintenance is developed. The model provides an alternative option for maintenance scheduling in a fleet which considers the maintenance cost variation with truck age levels along with the production requirement (Publication 4).

1.4 Publications

The work described in this thesis has led to four journal publications (reproduced in the appendices). This section summarizes their contents and lists the author’s contributions.
1.4.1 Summaries

Publication 1 This publication introduces a tailor-made low cost GPS tracking system and examines the benefits achieved by applying the system at a coal hauling operation in Indonesia. The simulation model is formulated based on the collected data by the GPS tracking system. Simulation results show that the improved cycle time allows decreasing the required number of trucks, while maintaining a particular haulage capacity.

Publication 2 This publication addresses one of the key factors in a profitable open-pit mine: the efficiency of overburden extraction system. The GPS system improves efficiency by allowing truck dispatching decisions to be made in real-time, but the chosen strategy plays a crucial role. This article illustrates the differences between the strategies by formulating a stochastic simulation model based on the data gathered from an actual mine. The findings underline the importance of the global perspective in dispatching decisions.

Publication 3 The article addresses the main benefit of measuring a match factor, which can be used to determine an appropriate fleet size in equipment selection phase. However, in case a fleet is already selected or in place, the approach can be used to estimate the relative efficiency of the fleet. Simulation results reveal remarkable differences between production figures using different heterogeneous fleet types. The paper emphasizes the optimal mixed truck-shovel fleet in the system, which can lead to substantial operating cost reductions.

Publication 4 This article introduces a close to optimal scheduled maintenance for different truck age levels. The approach is based on a case study taking into account the stochastic equipment behaviour and environment in a real open-pit mine. This approach can be used more generally in situations in which truck fleets are used to transport material.

1.4.2 Author contributions

Publication 1 The author was responsible for designing the tailor-made low cost GPS tracking system and implementing the system at the mine operation. The data modelling and analysis of cyclic activity time results were conducted by Assistant Professor Cheowchan Leelasukseree. The author wrote the manuscript except for Section 4.1, which was written by Leelasukseree. The manuscript was commented by Assistant Professor Cheowchan Leelasukseree and Assistant Professor Winai Wongsurawat.

Publications 2-3 The author performed the modelling and analysis of the differences between truck dispatching strategies by conducting a stochastic simulation study based on the data gathered from the actual mine, and produced the corresponding results. The author wrote the manuscripts of publications 2 and 3. Dr. Heikki Seppälä provided expertise on statistics and commented on the manuscripts. Professor Emeritus Heikki Koivo and Professor Quan Zhou supervised the research and commented on the manuscripts.
Publication 4 The author was responsible for the contents of the publication and wrote the manuscript. Dr. Heikki Seppälä commented on the manuscript and Professor Emeritus Heikki Koivo supervised the research.

1.5 Structure of the thesis

This thesis is an article dissertation consisting of a compendium part and four publications. The compendium can be divided into four chapters: Chapter 2 provides a concise literature survey in order to familiarize the reader with the background of the presented research. The measurement arrangements and modelling methods used in the publications are illustrated in Chapter 3, whereas Chapter 4 discusses the obtained results. Finally, Chapter 5 summarizes the research results and provides comments about future research issues.
2. Review of traditional dispatching strategies

Dispatching approaches consider different objectives in varying degrees of sophisticated assignment range from simple heuristic rules to complex mathematical programming. Therefore, in line with these principles, the purpose of this chapter is to define the basic concepts of truck dispatching strategies and different methods to solve truck dispatching problems, which are reported in literature.

2.1 Truck dispatching strategies

This section presents an overview of truck dispatching strategies in the mining industry [6], [14]–[19]. There are three strategies to specify the right assignment for a truck, designate them as being the 1-truck-for-n-shovels, the m-trucks-for-1-shovel, and the m-trucks-for-n-shovels [29], [41], [52]–[66].

2.1.1 The 1-truck-for-n-shovels dispatching strategy

The 1-truck-for-n-shovels dispatching strategy is the oldest and the most commonly used in open-pit mine operations, illustrated in Fig. 1. A truck operator asks for a new assignment. There are n possible shovels where the truck could be sent. The truck is sent to the shovel which offers the highest potential, that is, the one offering the least cost or the maximum benefit. Typically, this strategy is implemented based on the single-stage approach [52]–[60].

2.1.2 The m-trucks-for-1-shovel dispatching strategy

The m-trucks-for-1-shovel dispatching strategy is based on the multi-stage approach. Truck dispatching decisions are made by taking into account the m next trucks to dispatch, considering one shovel at a time. More specifically, the shovels are first sorted according to a priority scheme based on how much they are behind their production schedule. Subsequently, the dispatcher assigns the best truck to the shovel that is the first on the priority list, see middle of Fig. 1 [61]–[64].
2.1.3 The m-trucks-for-n-shovels dispatching strategy

The *m*-trucks-for-*n*-shovels dispatching strategy is based on the *multi-stage approach*. The dispatcher simultaneously considers *m* forthcoming trucks and *n* shovels, and the next requesting truck is assigned to the most suitable shovel, based on forecasted availability of trucks and shovels. Only the truck that has submitted the request is assigned. This is illustrated in the rightmost panel of Fig. 1. In this strategy, *m* should be greater than or equal to *n* [29], [41], [65]–[66].

![Figure 1. Truck dispatching strategies. (Reproduced from Publication 4)](image)

2.2 Heuristic truck dispatching methods

The most used heuristic methods in truck dispatching are explained below. For further details see [6], [15], [22], [44].

2.2.1 Minimizing Shovel Waiting Time

*Minimizing Shovel Waiting Time* (MSWT): An empty truck is assigned to the shovel with the longest idle time or to the shovel that is expected to be idle first with the purpose of maximizing the utilization of both trucks and shovels.

2.2.2 Minimizing Truck Cycle Time

*Minimizing Truck Cycle Time* (MTCT): An empty truck is assigned to the shovel that allows the shortest truck cycle time in order to maximize the total tonnage productivity.

2.2.3 Minimizing Truck Waiting Time

*Minimizing Truck Waiting Time* (MTWT): An empty truck is assigned to the shovel where the loading operation starts first with the aim to maximize the utilization of a shovel by minimizing the truck waiting time.

2.2.4 Minimizing Shovel Saturation and Coverage

*Minimizing Shovel Saturation and Coverage* (MSC): An empty truck is assigned to the shovel at equal time intervals to keep the shovels busy. The aim of this method is to minimize the shovel waiting time.
2.3 Mathematical programming methods

Mathematical programming based on dispatching approaches has been developed for truck-and-shovel systems since 1970s. The approaches use optimization tools, such as linear programming (LP) [8], [12], [29], [59]–[60], [62]–[71], integer programming (IP) [72]–[73], mixed integer programming (MIP) [21], [30]–[31], [41], [47], [71], [74]–[76], non-linear programming [77]–[78], dynamic programming [60], [62]–[64], [79] or queuing theory [12], [80]–[84], to optimize operational objective functions, such as production or operation costs.

Temeng et al. (1997) propose a multi-stage dispatching model depending on the capability of the real-time dispatching algorithm, which aims to maximize the production and ore quality. The model ensures that trucks are assigned to needy shovels in order to minimize the total waiting time and maximize the production. The needy shovel is selected to minimize the deviation of the cumulative tonnage of each shovel route from the target. The investigation of truck and shovel breakdown is presented. The algorithm results in a significant production increase, and the running average of each ore quality is kept on the target, even in the event of a shovel breakdown [29].

Burt and Caccetta (2007) use match factor ratios to indicate the efficiency of truck-and-shovel systems, determining productivity and fleet size. A match factor is the ratio of the truck arrival time to the shovel service rate. An improved match factor is proposed for three different cases: (i) a heterogeneous truck fleet refers to the case where there are different types of trucks in the fleet, while shovels remain uniform in type, (ii) a heterogeneous shovel fleet refers to the case where only one type of truck operates in the fleet, while shovels are of different types, and (iii) heterogeneous truck and shovel fleets refer to the case of multiple types of trucks and shovels operates in the fleet. These three cases provide a sensible extension to the original equation of match factor and bring greater accuracy to the cases where queues and waiting times are included in the cycle times [46].

Fioroni et al. (2008) propose a simulation and optimization model to provide the short-term planning schedules, which seeks cost reduction while maximizing mass production plans and focusing in quality, operation requirements, as well as asset utilization. The proposed model is developed in the Arena software and Visual Basic for Applications (VBA), which is used for communication between the simulator and Lingo optimizer software. The optimization model runs each time when the simulator program begins, to initially allocate shovels, and to schedule the trips for trucks. The optimization model also runs during the simulation, when the state of the system changes, such as during an equipment breakdown. The model seeks a new optimal allocation for available shovels and remaining trucks, or generates shovels allocation to different mining areas and calculates amount of trips that each truck should take to each area, in order to reach the production goal [20].

He et al. (2010) construct a truck dispatching model based on the fixed transport routes using the MATLAB® Genetic Algorithm Toolbox. The pro-
posed model defines the number of trucks on each route to meet the demand of discharge points, while minimizing freight and maintenance costs [4].

Souza et al. (2010) present an improved hybrid heuristic algorithm based on two characteristics of Greedy Randomized Adaptive Search Procedures and General Variable Neighbourhood Search. Another approach is the CPLEX optimizer, which uses an improved mixed integer programming approach. The objective of both approaches is to minimize the deviations of the production and quality goals as well as to reduce the number of trucks required for the operation. The improved heuristic algorithm is compared to the CPLEX optimizer with the same data set from a real mine in Brazil. The results show that the proposed algorithm is very competitive as a decision support tool for the open-pit-mining operational planning problem with dynamic truck allocation [21].

Topal and Ramazan (2010) develop a mixed integer programming (MIP) model to schedule a fixed fleet of trucks for a yearly basis over a multi-year of mine life. The objective function is to minimize truck maintenance costs while considering constraints, such as the total hours of truck usage, maintenance costs, and required operating hours, to achieve annual production targets and to obtain an optimum truck schedule. The proposed model is applied on a large-scale gold mine in Western Australia. The result of the optimum truck schedule provides significant maintenance cost savings by more than 16% of overall maintenance costs over 10 years, compared with the spreadsheet-based approach used currently at the operation [30].

Mena et al. (2013) implement a simulation and optimization model to allocate trucks on the transport routes according to their different operating performances in a truck-and-shovel system at a real open-pit mine, so as to maximize the total productivity of the fleet. Two models are obtained: the first model considers the variables, such as reliability, availability, and maintainability to perform the total system production, while the second model does not [31].

### 2.4 Simulation methods

Simulation is widely accepted as an approach to assess the performance of mining operations because it enables to incorporate the inherent variability and the complexity of the system [15], [38], [56], [59], [85]–[92]. The simulation studies about truck-and-shovel systems are mostly implemented for specific cases [25]–[26], [32]–[33], [36]–[37], [45]. Each of these studies aims to apply the simulation modelling for a real mine.

Bonates and Lizotte (1988) develop a simulation model for dispatching truck in open-pit mines based on different operating approaches, including fixed dispatch, maximizing trucks utilization, maximizing shovels utilization, and match factor. The results show that the maximizing trucks utilization yields higher production, except when the grade control is required or the differences in travel times between the shovels are significant. The maximizing shovels utilization and match factor cause all the working shovels to operate at the
same rate, which is generally more desirable. The effectiveness of both approaches depends significantly on the available number of trucks [38].

Awuach-Offei et al. (2003) propose a simulation technique to forecast the shovel and truck requirements in an actual mine over a four year period. The collected data, such as excavator loading times, truck travel times, frequency of excavator breakdowns, and production, are tested and fitted with the chi-squared distribution. Truck-and-shovel systems are modelled in the SIMAN computer simulation package using the process of object-oriented simulation. The trucks are identified as entities, and the essential processes to model the system consist of the arrival of entities, loading, the movement of entities, unloading, maneuvering, and queuing [45].

Krause and Musingwini (2007) demonstrate the modified machine repair model to estimate truck-and-shovel fleet size requirements. The model emulates a system in an open-pit mine which consists of input parameters, such as a finite number of machines, a finite number of repair bays, an inter-arrival rate, and a service rate. The proposed method is implemented on different simulation models, which are the Arena, Winston, FPC, Elbrond, and TALPAC. All of them are applied on a virtual case and a real open-pit coal mine. The result from the Arena model is chosen as a benchmark to compare with the four simulation models [36].

Yuriy and Vayenas (2008) combine a reliability assessment model with a discrete event simulation model. The output in the form of times between failures of the reliability assessment model based on genetic algorithms provides the input to the discrete event simulation model. The simulation model emulates the operations in the mine to evaluate the effect of equipment failures on the production throughput, the equipment availability and utilization [33].

Jaoua et al. (2009) propose microscopic simulators to emulate real-time truck dispatching technique for open-pit mines, especially on the dynamic traffic road network. Two case studies are performed on an extended and realistic open-pit mine to explore potential application of the proposed model. The results illustrate that the microscopic approach leads to a reliable evaluation model and a robust decision tool for mining transport system design in the off-line decision and the on-line updater [25]. Jaoua et al. (2012) integrate microscopic traffic approach in the classical discrete event simulation model of internal transportation systems. The simulation model is embedded as the kernel of a simulation-based control architecture, in which the experiments are conducted on two realistic open-pit mines to assess the benefit of embedding the proposed simulation model [26].

Chanda and Gardiner (2010) compare the ability of three simulation methods to estimate the truck cycle times for various truck haulage routes at a large open-pit gold mine in Western Australia. These methods consist of computer simulation (TALPAC software), artificial neural networks (NNs), and multiple regressions (MRs), in which the predicting cycle time is limited to the truck travel time when it is loaded and when it is empty. The results appear to indicate that both NNs and MRs are the superior methods in predictive abilities of
cycle times. TALPAC software intends to underestimate cycle times for shorter haul routes and overestimate for the longer haul routes [37].

Silva et al. (2016) present a methodology to forecast the availability of off-highway trucks, which are used in a fleet at an open-pit mine. The methodology determines the optimal time to be spent on preventive and corrective maintenance. The historical data of service hours, corrective, and non-corrective maintenance is used in the simulation model to obtain a projection of the daily availability. The simulation results present the range of operational availability for the entire fleet, which consist of more conservative (85%), typical (50%), or challenging (15%) estimates [32].

2.5 Other stochastic methods

The amount of literature on stochastic programming applications in the field of open-pit mine operations is limited. Two articles using stochastic programming directly evaluating a truck-and-shovel system are reviewed as follows.

Ta et al. (2005) propose a truck allocation model accommodating uncertain parameters, such as truckload and cycle time. The main objective of the chance-constrained model is to minimize the number of trucks to satisfy the production requirement based on the resource-based stochastic programming. A real-time allocation process for a time horizon with a data feedback loop is applied on the chance-constrained model, which allows the model to adapt to changes in the mine by updating the mean and variance of the uncertain parameters. The real-time allocation approach is implemented on a mine with a simplified haulage configuration. The results of two scenarios illustrate and compare the effectiveness use of the number and truck size obtained with and without considering the chance-constrained programming approach and the real-time hauling framework [8].

Sousa Bastos (2010) presents a hybrid method, Genetic Time Dependent Markov Decision Process (G-TiMDP) which is a combination of Genetic Algorithm and Time Dependent Markov Decision Process. The objective is to maximize tonnage production over the shift. The proposed model is simulated by SimEvent for each truck type based on dependent states that represent queues with different sizes at shovels and also uncertain parameters, such as stochastic path selection and Gaussian-based truck travelling times that present in the truck dispatching model [22].

2.6 Summary and remarks

A number of different methods used to study truck-and-shovel systems is covered in the literature review. Some of these methods rely on empirical rules and some are highly mathematical model, requiring significant computational effort. Most of them ignore the stochastic equipment behaviour and environmental changes in an open-pit mine. None of these methods comprehensively is able to consider all aspects of truck-and-shovel systems. This is because a
truck-and-shovel system is complex as a result of its stochastic nature and significant number of interactions between elements.

Table 1 summarizes the areas covered by the publications of the thesis. The results in the publications provide new knowledge about the effectiveness of different dispatching strategies by introducing a realistic stochastic production simulation model, which takes the main uncertainties of an actual open-pit mine into account as well as the equipment age levels. Details of the overall approach and new research findings are discussed in Chapters 3 and 4.

**Table 1.** The classification of the publications based on the literature review.

<table>
<thead>
<tr>
<th>Publication</th>
<th>Truck dispatching strategies</th>
<th>Heuristic truck dispatching methods</th>
<th>Mathematical programming methods</th>
<th>Simulation methods</th>
<th>Other stochastic methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>Publication 1</td>
<td>x</td>
<td>x</td>
<td></td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Publication 2</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Publications 3-4</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
</tbody>
</table>
3. Truck dispatching modelling

Previous research studies have presented different approaches to improve the operation of truck-and-shovel systems [4], [12], [20]–[46]. However, most of them assume that all trucks and shovels have the same operating performances or ignore the stochastic nature of the truck-and-shovel operations, while in reality each machine has its own reliability, availability, and maintainability.

This chapter discusses the proposed model based on two different approaches of a truck-and-shovel system in actual open-pit mines. The first approach is a simulation method, which consists of two models. The first model in Publication 1 determines the required number of trucks and reveals bottlenecks in a truck haulage system. The second model in Publication 2 analyzes the effects on productivity by continuously dispatching trucks in the open-pit mine under the most used heuristic truck dispatching methods. These two models consider main uncertain parameters in the mine operations.

The second approach combines mathematical programming and simulation. Two models are considered in this approach. The first model proposed in Publication 3 is based on differences in the match factor. The optimal boundary fleet is optimized by fixing the production target to ensure the necessary number and type of trucks. Simulation is used to allocate trucks based on different heuristic truck dispatching methods in conjunction with the match factor for different heterogeneous fleet types. The second model in Publication 4 generates a close to optimal maintenance schedule for different truck age levels, in which trucks are assigned to shovels based on different heuristic truck dispatching methods. These two models take into account the stochastic equipment behaviour and uncertain parameters in the operations.

The following sections explain general details of these two approaches and summarize the modelling framework methods in the publications.

3.1 A simulation method

3.1.1 Basic modelling assumptions

In this thesis, the following basic assumptions are made in the simulation models. Publication 1, the payload of single-trailer and double-trailer trucks is assumed to be 70 tonnes and 120 tonnes. Publications 2-4 relate to the actual fleet allocation with a single material type, especially the extraction of overburden. All trucks start operation at the parking area near the processing plant
at the start of the shift and park there at the end of the shift. All shovels and
the dumping point are able to serve only one truck at a time. Moreover, the
mine haul roads are designed to provide two-way traffic for the trucks. There-
fore, more than one truck can travel along different roads. Trucks are allowed
to overtake each other along the roads. The operating costs of trucks and shov-
els rely on the historical actual operation costs in the mine. The simulation
model is performed for two operational types. The first is the ideal operation,
in which trucks and shovels run over a daily 24-hour period without any rest.
The second is the operation under an unexpected event, such as the break-
down of the truck or shovel. The broken trucks or shovels are not considered
for assignment until they become operational again.

3.1.2 Input data set components

One of the most important aspects in the simulation models is the input data
because it affects reliable results can be produced as well as how much of the
real system can be represented in the simulation model. The input data are
very difficult to generalize for a model to be universally applicable because
naturally each mine has its own unique topography and multiple types of
trucks and shovels to operate within different policies. However, the basic
events in a cyclic operation of trucks and shovels are similar as shown in Fig. 2.
They are defined as follows.

![Figure 2. A cyclic operating event of truck and shovel. (Reproduced from Publication 3)](image)

**Travelling** refers to the time the empty truck travels to a shovel at the loading
point area.

**Waiting** refers to the time the truck waits at a shovel. On the other hand (in
terms of shovels), it refers to the time from the moment when the previous
truck leaves the loading point area until the moment the next truck takes the
position for loading.

**Spotting** refers to the time the truck positions itself for loading.

**Loading** in terms of trucks refers to the time the shovel loads the material in
the truck. In terms of shovels, it refers to the time between the moment when
the first material is loaded into the truck, and the moment when the truck
leaves the loading point.

**Hauling** refers to the time the truck hauls to a dump point.

**Queuing** refers to the time the truck waits at the dump point.
*Backing* refers to the time the truck spends on taking the position for dumping.

*Tipping* refers to the time the truck dumps the material.

The statistical data sets gathered from the mine are the inputs of the discrete event simulation model. First, the cyclic operation time of trucks and shovels is observed and collected using a GPS system. The collected data is sufficient to allow statistical analysis. After this, the distributions of the cyclic operation time of trucks and shovels are analyzed to find a suitable parametric distribution. A log-normal distribution is chosen because it fits to the empirical distribution of event times better than many other parametric distributions, such as the exponential distribution and weibull distribution. The fitting is based on the sample mean and the sample variance calculated from the corresponding data set. The implementation of the proposed model is carried out using MATLAB® [93].

### 3.1.3 General structure of the simulation model

The proposed conceptual simulation model is presented in Fig. 3. The starting point is the analysis of collected data. The data variables are calculated and converted into input defined sets. The selected trucks are assigned to the loading points based on differently defined objective functions in each publication 1-4. The simulation model is run for one thousand replications to calculate the lower bound for the production, which is exceeded with 95% probability under the assumption that the model is correctly specified.

![Figure 3. The conceptual model.](image-url)
The simulation was first tested by using the re-sampling from the real activity time data and the fitted log-normal distribution. The results obtained from the re-sampling are almost identical to the results obtained from the fitted log-normal distribution, which confirms that the log-normal model is sufficiently accurate for modelling activity times, in order to obtain realistic results.

The current time of all trucks and shovels are assigned to be zero at the beginning of the simulation. Each truck and shovel has its current time updated with the simulated sequence activity. After that the trucks and shovels are sorted in ascending order by their current time. The trucks and shovels are matched based on the chosen truck dispatching strategies and heuristic truck dispatching methods.

### 3.2 A mathematical programming method

An actual open-pit mine currently uses the simplex algorithm to dispatch trucks to shovels, which considers a set of optimal paths between shovels and the waste dump. The actual strategy not only tries to satisfy the linear programming requirement to minimize the total cost but it also actively minimizes the shovel idle time. However, the actual production of the mine in each month is relatively low compared to the equipment capacity. The problem is solved by the two new different specific simulation-optimization modelling frameworks as presented below.

#### 3.2.1 Match factor for different heterogeneous fleet types model

Match factor is a significant tool for determining an appropriate fleet size of trucks and shovels, especially during the equipment selection phase, so that the truck fleet productivity would match that of the shovel fleet. However, when the fleet is already selected, the match factor can be used to estimate the relative efficiency of the fleet. This thesis discusses overall efficiency of the fleets including a heterogeneous truck fleet, a heterogeneous shovel fleet, heterogeneous truck and shovel fleets, and optimal boundary of fleets by measuring match factor and modelling the truck dispatching approaches.

To obtain accurate individual times of travelling and hauling in each different heterogeneous match factor, the operation would have to be observed at both load and dump ends, which is not easy to accomplish. A collective of travel and haul times in a heterogeneous shovel fleet and optimal boundary of fleets is assumed by using average travelling and hauling distances, and average uphill/downhill velocity of each truck type. Other assumptions considered in building the simulation model are similar as mentioned in Section 3.1. The experimental simulation is tested by using these assumed parameters. The fitted model yields similar result as the actual production of the mine. The following assumptions are the basis of the mathematical programming model developed for each decision scenario.
A heterogeneous truck fleet refers to the case where there are different types of trucks in the fleet, while the shovels remain uniform in type. The match factor ($MF_i$) is illustrated by equation (1) [46].

$$MF_i = \frac{\left(\sum_{i \in X} nt_i\right)\left(\sum_{i \in X} (nt,tl_i)\right)}{ns \sum_{i \in X} (nt,tc_i)},$$

where $nt_i$ is the number of trucks of type $i \in X$ ($X$ is the set of all truck types), $tl_i$ is the time required for loading truck type $i$ with shovel, $ns$ is the number of shovels, and $tc_i$ is the cycle time for truck type $i$.

A heterogeneous shovel fleet refers to the situation where only one type of truck operates in the fleet, while shovels are of different types. The match factor ($MF_j$) is addressed in equation (2) [46].

$$MF_j = \frac{\left(\sum_{i \in X} nt_i\right)lcm(ul)}{\sum_{j \in Y} \left(\frac{lcm(ul)}{ul_j}\right)tc},$$

where $lcm(ul)$ is the least common multiple of unique loading times for all shovels of type $j$, $ul_j$ is the cycle time of the shovel type $j$ when working with one truck type, $ns$ is the number of shovels of type $j \in Y$ ($Y$ is the set of all shovel types), and $tc$ is the average cycle time for all trucks in the current period.

Heterogeneous truck and shovel fleets refer to the case of multiple types of trucks and shovels operates in the fleet. The ratio of match factor ($MF_{ij}$) is presented in equation (3) [46].

$$MF_{ij} = \frac{\left(\sum_{i \in X} nt_i\right)\left[\left(\sum_{j \in Y} nt_i\right)lcm(ul)\right]}{\sum_{j \in Y} \left(\frac{lcm(ul)}{ul_j}\right)\sum_{i \in X} (nt,tc_i)},$$

where $lcm(ul)$ is the least common multiple of all truck loading times for shovel type $j$, $lcm(ul_j)$ is the least common multiple of the cycle time of the shovel type $j$ when working with a truck type $i$, and $ul_j$ is the cycle time of the shovel $j$ when working with truck type $i$.

Optimal boundary of heterogeneous truck and shovel fleets refers to 18 decision scenarios in Publication 3. Each scenario is composed of a different number and type of trucks. However, the number and type of shovels remains the same for all scenarios.

The objective function of each heterogeneous fleet type is to maximize the production for the fleet in the mining operation [31], [44], which is applied to truck dispatching system as follows:

$$\text{Max} \sum_{i \in X} \sum_{j \in Y} VT_{i,j} R_{i,j}$$

with the constraint conditions:
Truck dispatching modelling

\[
\sum_{i \in X} \sum_{j \in Y} VT_{[i,j]} R_{[i,j]} \leq VS_j \quad \forall j \in Y
\]  
(5)

\[
\sum_{i \in X} \sum_{j \in Y} VT_{[i,j]} O_i \geq P \quad \forall i \in X
\]  
(6)

\[
\sum_{i \in X} \sum_{j \in Y} R_{[i,j]} \leq 1
\]  
(7)

\[
\sum_{i \in X} \sum_{j \in Y} R_{[i,j]} = 0 \quad \text{if } i = i' \text{ with } i \in X
\]  
(8)

\[
\sum_{i \in X} \sum_{j \in Y} R_{[i,j]} = 0 \quad \text{if } j = j' \text{ with } j' \in Y
\]  
(9)

\[
R_{[i,j]} = \begin{cases} 1 \text{ if truck } i \text{ is assigned to shovel } j \\ 0 \text{ otherwise} \end{cases}
\]  
(10)

where \( VT_{[i,j]} \) is the volume of truck \( i \) on the selected shovel \( j \) in bank cubic metre (bcm); \( R_{[i,j]} \) is binary which indicates the possible shovels where the truck could be sent; \( VS_j \) is the total volume of shovel \( j \) when it has completed loading of the assigned truck over the shift in bcm; \( O_i \) is the analysis number of trips of each type of trucks in one month; and \( P \) is the production requirement per month in bcm.

The meaning of each constraint is as follows. Constraint (5) ensures that the production of truck associated to the shovel \( j \) should not exceed the total volume of the shovel when completed loading. Constraint (6) enforces that the total production should be equal to or greater than the production requirement. Constraint (7) avoids the duplications, once truck \( i \) is assigned to shovel \( j \), it cannot be assigned to another shovel. Constraint (8) is activated when truck \( i \) is temporarily inactive, and it is deactivated when truck \( i' \) returns to operation. Constraint (9) is activated when shovel \( j' \) fails, and it is deactivated when shovel \( j' \) returns to operation. Constraint (10) is a binary decision variable representing assignment of truck \( i \) to shovel \( j \) based on truck selection criteria. The truck selection criteria rely on heuristic truck dispatching methods, which are applied to one of the truck dispatching strategies. These criteria are listed below.

**Minimizing Shovel Waiting Time (MSWT):** The selected trucks are assigned to the shovels that are expected to have the longest idle time:

\[
d = \arg \max_j \{ \max_i \{ t_j - ts_j, 0 \} \},
\]  
(11)

where \( d \) is the shovel for which the truck is assigned, \( t_j \) is the expected truck travel time from the dispatching point to the shovel and \( ts_j \) is the time for the shovel to complete loading all the trucks in the queue, including the one being loaded and those that are en route to this shovel, but have not yet reached it. When the waiting time \( t_j - ts_j \) is zero, it means that the truck has been positioned and is ready for loading at the same time as the shovel has finished loading the previous truck. If the waiting time is positive, it corresponds to the shovel waiting time for this truck. The negative waiting time means that the truck has arrived at the shovel, which is still loading another truck.
where $t_j = \frac{d_{-t_i}}{v_{ad_{-t_i}}} + (b_i \cdot t_s_{-i})$, $d_{-t_i}$ is the simulated travelling distance, $v_{ad_{-t_i}}$ is the expected velocity, where $v_{ad_{-t_i}} = \frac{1}{2} (v_{u_{-t_i}} + v_{d_{-t_i}})$, $v_{u_{-t_i}}$ is the average uphill velocity, $v_{d_{-t_i}}$ is average downhill velocity, $b_i$ is the simulated indicator, where $b_i = (1, p_i)$, $p_i$ is the probability of spotting and backing in a cyclic operation of each truck type, $t_{-s_{-i}}$ is the simulated spotting time.

Minimizing Truck Cycle Time (MTCT): The selected trucks are assigned to the shovel that allows the shortest truck cycle time. The decision making criterion for assigning the truck is

$$d = \arg \min_j \{ c_j \}, \quad (12)$$

where $c_j$ is defined as the truck cycle-time for shovel $j$, $c_j = t_j + t_{s_j} + t_{r_j}$, $t_j$ is the expected time of the assigned truck hauls its load from shovel $j$ to the waste dump and tipping, where $t_{r_j} = \frac{h_{-t_i}}{v_{u_{-t_i}}} + (b_i \cdot t_{-b_i})$, $h_{-t_i}$ is the simulated hauling distance of truck type $i$, and $t_{-b_i}$ is the simulated backing time.

Minimizing Truck Waiting Time (MTWT): The assignment of the selected trucks is to the shovel in which the loading operation starts first. The decision-making criterion is as follows:

$$d = \arg \min_j \{ \max_j \{ t_j, t_{s_j} \} \}, \quad (13)$$

Minimizing Shovel Saturation and Coverage (MSC): The first few trucks with the smallest expected time are selected for assignment to the shovel at equal time intervals to keep the shovel non-idle. The decision making criterion for assigning a truck is

$$d = \arg \min_j \{ t_{j} - t_{s_{-j}} \}, \quad (14)$$

3.2.2 Age-based maintenance model

As mentioned before, the proposed solutions are mostly maximizing productivity for the fleet. However, inactive time of trucks and shovels is one of the most important events that this study aims to shorten. To reduce inactive time of trucks and shovels, maintenance plays a crucial role as it directly influences the level of operational availability and the production.

The simulation of overburden production under the operational availability is developed based on the four models in Publication 4. The first model is the ideal approach, assuming all trucks, irrespective of age, have identical performance levels and 100% availability. The second model is the original approach in which the specific events, such as inactive times, preventive, and corrective maintenance hours of different truck age levels are considered. The third model is the traditional approach following the interval range of operational availability, 85-90% [32]. The last model is the optimal approach, which is evaluated by fixing the monthly production by 10% above the average plan production.
All the proposed four models are relied on the truck selection criteria, the \textit{m-trucks-for-n-shovels} with MTCT. The extensive empirical data, such as the basic events in a cyclic operation time of truck and shovel are collected by the GPS system from January to December, 2014 in the actual mine. Moreover, the preventive and corrective maintenance hours are inferred from the historical data based on the equipment age levels. The truck fleet contains two different truck age levels: when a truck age is between 50,000 and 90,000 hours, it is allocated to level 1, and when it is less than 50,000 hours, it is allocated to level 2. Table 2 presents the maintenance, breakdown, and operating costs as dollars per hour for the truck types at two age levels. This means that the maintenance cost increases as the age of the truck increases.

**Table 2. The comparison cost of truck age levels.**

<table>
<thead>
<tr>
<th>The comparison cost of truck age levels (USD/h)</th>
<th>Truck age level 1</th>
<th>Truck age level 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Small</td>
<td>Large</td>
</tr>
<tr>
<td>Average maintenance cost</td>
<td>24</td>
<td>38</td>
</tr>
<tr>
<td>Average breakdown cost</td>
<td>40</td>
<td>80</td>
</tr>
<tr>
<td>Operating cost</td>
<td>90</td>
<td>130</td>
</tr>
</tbody>
</table>

### 3.3 Summary and remarks

In summary, this chapter has presented the different specific simulation and optimization models to allocate available trucks for maximizing productivity. It is measured by the total number of trips that each truck can perform. Each proposed model copes with uncertainties, such as hauling distance, truck velocity, truck cycle time, loading time of matched truck and shovel, and inactive time of trucks and shovels, associated with the real mine operations. The modelling framework methods in the publications are summarized in Table 3.

**Table 3. The classification of the publications based on the framework methods.**

<table>
<thead>
<tr>
<th>Publication</th>
<th>Truck dispatching strategies</th>
<th>Heuristic truck dispatching methods</th>
<th>Mathematical programming methods</th>
<th>Specific addition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Publication 1</td>
<td></td>
<td></td>
<td></td>
<td>Discrete event simulation</td>
</tr>
<tr>
<td>Publication 2</td>
<td>The \textit{1-truck-for-n-shovels, the m-trucks-for-1-shovel, and the m-trucks-for-n-shovels}</td>
<td>MSWT, MTCT, MTWT, MSC</td>
<td></td>
<td>Discrete event simulation</td>
</tr>
<tr>
<td>Publication 3</td>
<td>The \textit{m-trucks-for-n-shovels}</td>
<td>MSWT, MTCT, MTWT, MSC</td>
<td>Maximizing productivity</td>
<td>Heterogeneous fleet types and the optimal boundary model</td>
</tr>
<tr>
<td>Publication 4</td>
<td>The \textit{1-truck-for-n-shovels, the m-trucks-for-1-shovel, and the m-trucks-for-n-shovels}</td>
<td>MSWT, MTCT</td>
<td>Fixing the production</td>
<td>Operational availability</td>
</tr>
</tbody>
</table>
4. Case study and discussion of results

This chapter summarizes and discusses the results obtained in the publications. The main results are related to the simulation and optimization models based on the collected data from the actual open-pit mines in East Kalimantan, Indonesia.

4.1 Case studies

4.1.1 A case study of truck coal haulage route system

The study of the truck coal haulage route system is carried out at PT. Trubaindo Coal Mining in East Kalimantan, Indonesia as shown in Fig. 4. The main focus in this study is trucks are loaded at the mine stockyard, then weighed for information on coal quantity before being hauled to the port stockyard, and the coal dumped in the hopper. Thereafter, trucks return to the loading area for the next load. The distance between the mine and the port stockyard is 40 km. About 25,000 tonnes of coal is loaded daily using many different contractors with heterogeneous capabilities. The fleet consists of 9 double-trailers (120 tonnes), 5 double-trailers (90 tonnes), 20 single-trailers (70 tonnes), 10 single-trailers (80 tonnes), and 15 conventional trucks (30 tonnes).

The observed data of the heterogeneous truck fleet was collected by a tailor-made GPS tracking system. The collected data covered the time period between January 4 and August 24, 2010, over a daily 24-hour period which included two different shifts. The payload and number of trucks in this study are assumed to be 38 single-trailers (70 tonnes) and 25 double-trailers (120 tonnes).
4.1.2 A case study of truck-and-shovel system

Extensive empirical data was collected between January and December, 2014, through the GPS system from the actual open-pit mine, PT. Kitadin Tandung Mayang in East Kalimantan, Indonesia (Fig. 5). The production of mine is approximately three million tonnes of coal per annum with a total movement of overburden of fifty million bcm using a fleet of 115 machines. The overburden extraction fleet contains mixed truck types (32 of size 23 bcm and 36 of size 41.5 bcm) and mixed shovel types (16 of size 7 m³ and 4 of size 14 m³). In the case study presented in this thesis, a 50,000-hour range is used. This means that a truck age is between 50,000 and 90,000 hours, it is allocated to level 1, and when it is less than 50,000 hours, it is allocated to level 2. There are 18 small and 16 large trucks at level 1, and 14 small and 20 large trucks at level 2.

The operation starts when a truck receives a dispatching order and travels to the assigned shovel. After that, the overburden is loaded onto the truck and the truck hauls the overburden to the dump point and dumps it. The truck waits for a new dispatching order. This is a daily cyclic operation, which operates under three shifts.
4.2 Determining a number of trucks

4.2.1 A truck coal haulage route system

Statistical data sets gathered from the mine in Section 4.1.1 are sufficient to produce significant results. The major events in the cyclic operation of the truck coal haulage route are loading, weighting, and full/empty truck travelling. These are selected events for both single-trailer and double-trailer trucks, applied in the discrete event simulation model in Publication 1. The simulation shows that the average duration of each event could be lowered by 20% from the observed data, the lower average duration reflecting an improvement in the event. Table 4 presents the improved number of trips and capacities of the coal haulage system, in which full/empty-truck travelling times yield significantly increasing capacity by approximately 10% for both truck types, while loading and weighting events slightly affect the coal haulage capacity. If such an improvement can be achieved, then the number of single-trailer trucks in the system can be reduced from 38 trucks to 34 trucks at a capacity of 20,000 tonnes per day.

Table 4. Coal haulage capacity and the number of trips at improved events. (Reproduced from Publication 1)

<table>
<thead>
<tr>
<th>Truck types</th>
<th>Double-trailer trucks</th>
<th>Single-trailer trucks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduced average duration</td>
<td>-20% 0%</td>
<td>-20% 0%</td>
</tr>
<tr>
<td>Daily capacity</td>
<td>No. of trips</td>
<td>Tonnes</td>
</tr>
<tr>
<td>Loading</td>
<td>173</td>
<td>20,760</td>
</tr>
<tr>
<td>Weighting</td>
<td>180</td>
<td>21,600</td>
</tr>
<tr>
<td>Full/empty truck travelling</td>
<td>197</td>
<td>23,640</td>
</tr>
</tbody>
</table>
4.2.2 A truck-and-shovel system

The 18 different scenarios in Publication 3 are generated using one class of the heuristic truck dispatching methods, MTCT. Each scenario carries out a simulation with the same input parameters as used for the month of October 2014, collected from the GPS system in the actual open-pit mine of Section 4.1.2, except the travelling and hauling times which are calculated based on the fitted model. The 18 decision scenarios start from scenario S1 with 68 small trucks to scenario S18 with 68 large trucks, continuing to increase stepwise with 4 large trucks and decrease stepwise by 4 small trucks. The number and type of shovels in each scenario remain the same as used in the actual mine. The main objective is to maximize the productivity while placing a different number of trucks based on their types. The simulated results of the proposed model in each scenario are presented in Table 5. These scenarios indicate that the operating cost under the ideal operation increases when the number of large trucks increases, as shown in Fig. 6(a). Moreover, the average overburden in all scenarios from S1 to S18 decreases gradually towards 15% when the event of truck and shovel breakdown is considered, see Table 5. Fig. 6(b) shows the match factor ratio in each scenario exceeds 1.0, which indicates that the trucks are arriving faster than shovels are able to serve. Under these circumstances, the trucks are on queue and the overall fleet is slightly over-trucked.

Table 5. The simulated results of 18 decision scenarios. (Reproduced from Publication 3)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Small trucks (unit)</th>
<th>Large trucks (unit)</th>
<th>Operating cost under the ideal operation (1x10^3 USD/month)</th>
<th>Overburden production^1 under the ideal operation (1x10^3 bcm)</th>
<th>Overburden production under the breakdown event of truck or shovel (1x10^3 bcm)</th>
<th>A match factor ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>68</td>
<td>0</td>
<td>7,545</td>
<td>2,691</td>
<td>2,537</td>
<td>1.143</td>
</tr>
<tr>
<td>2</td>
<td>64</td>
<td>4</td>
<td>7,660</td>
<td>2,837</td>
<td>2,358</td>
<td>1.153</td>
</tr>
<tr>
<td>3</td>
<td>60</td>
<td>8</td>
<td>7,776</td>
<td>2,585</td>
<td>2,110</td>
<td>1.163</td>
</tr>
<tr>
<td>4</td>
<td>56</td>
<td>12</td>
<td>7,891</td>
<td>2,340</td>
<td>1,910</td>
<td>1.173</td>
</tr>
<tr>
<td>5</td>
<td>52</td>
<td>16</td>
<td>8,006</td>
<td>2,118</td>
<td>1,675</td>
<td>1.184</td>
</tr>
<tr>
<td>6</td>
<td>48</td>
<td>20</td>
<td>8,121</td>
<td>1,872</td>
<td>1,454</td>
<td>1.195</td>
</tr>
<tr>
<td>7</td>
<td>44</td>
<td>24</td>
<td>8,236</td>
<td>1,987</td>
<td>1,555</td>
<td>1.205</td>
</tr>
<tr>
<td>8</td>
<td>40</td>
<td>28</td>
<td>8,352</td>
<td>2,146</td>
<td>1,693</td>
<td>1.216</td>
</tr>
<tr>
<td>9</td>
<td>36</td>
<td>32</td>
<td>8,467</td>
<td>2,281</td>
<td>1,831</td>
<td>1.228</td>
</tr>
<tr>
<td>10</td>
<td>32</td>
<td>36</td>
<td>8,582</td>
<td>2,433</td>
<td>1,999</td>
<td>1.239</td>
</tr>
<tr>
<td>11</td>
<td>28</td>
<td>40</td>
<td>8,697</td>
<td>2,608</td>
<td>2,165</td>
<td>1.251</td>
</tr>
<tr>
<td>12</td>
<td>24</td>
<td>44</td>
<td>8,812</td>
<td>2,768</td>
<td>2,343</td>
<td>1.263</td>
</tr>
<tr>
<td>13</td>
<td>20</td>
<td>48</td>
<td>8,928</td>
<td>2,982</td>
<td>2,541</td>
<td>1.275</td>
</tr>
<tr>
<td>14</td>
<td>16</td>
<td>52</td>
<td>9,043</td>
<td>3,379</td>
<td>2,928</td>
<td>1.287</td>
</tr>
<tr>
<td>15</td>
<td>12</td>
<td>56</td>
<td>9,158</td>
<td>3,731</td>
<td>3,299</td>
<td>1.300</td>
</tr>
<tr>
<td>16</td>
<td>8</td>
<td>60</td>
<td>9,273</td>
<td>4,157</td>
<td>3,685</td>
<td>1.312</td>
</tr>
<tr>
<td>17</td>
<td>4</td>
<td>64</td>
<td>9,388</td>
<td>4,571</td>
<td>4,088</td>
<td>1.326</td>
</tr>
<tr>
<td>18</td>
<td>0</td>
<td>68</td>
<td>9,504</td>
<td>4,706</td>
<td>4,474</td>
<td>1.339</td>
</tr>
</tbody>
</table>

^1 The actual overburden production is 1,261,861 bcm and the plan is 1,678,208 bcm
In the mine operation under consideration, the mine haul roads are designed to provide two-way traffic for the trucks. More than one truck can travel along different roads, so trucks are allowed to overtake each other along the roads. However, in reality fast trucks can be delayed behind slower trucks when they travel along the same road, which is known as truck bunching. The true effect of bunching, however, remains elusive. Mixed fleets may exacerbate bunching caused by payload variance. For this reason, only scenarios S7-S12 are considered. The bunching effects of this range of scenarios should resemble the original decomposition of the truck fleet closely enough.

Fig. 7 (a) shows the comparison of simulated results of overburden production and operating cost based on (i) the simulation and optimization model (MTCT and Operating cost) and (ii) the specific model (OMTCT and OOperating cost). The results show that the simulated model (MTCT line) increases the production by 4% when increasing the number of large trucks by two and decreasing the number of small trucks by two, see Table 6.
Case study and discussion of results

Figure 7. (a) The comparison of simulated results of overburden production and operating cost based on the simulation and optimization model (MTCT and Operating cost) and specific model (OMTCT and OOperating cost) under the ideal operation, and (b) the comparison of match factor and productivity ratio based on the simulation and optimization model (Match Factor and Productivity ratio) and the specific model (OMatch Factor and OProductivity ratio) under the ideal operation. (Reproduced from Publication 3)

Table 6. The results of the simulation and optimization model. (Reproduced from Publication 3)

<table>
<thead>
<tr>
<th>Truck (unit)</th>
<th>MTCT 10^3 bcm</th>
<th>MTCT 95% 10^3 bcm</th>
<th>Operating cost 10^3 USD/month</th>
<th>Match factor</th>
<th>Productivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small, 26</td>
<td>2,075</td>
<td>1,705</td>
<td>8,294</td>
<td>1.130</td>
<td>0.250</td>
</tr>
<tr>
<td>Large</td>
<td>2,154</td>
<td>1,765</td>
<td>8,352</td>
<td>1.134</td>
<td>0.258</td>
</tr>
<tr>
<td>Small, 30</td>
<td>2,202</td>
<td>1,877</td>
<td>8,409</td>
<td>1.137</td>
<td>0.262</td>
</tr>
<tr>
<td>Large</td>
<td>2,245</td>
<td>1,818</td>
<td>8,467</td>
<td>1.140</td>
<td>0.265</td>
</tr>
<tr>
<td>Small, 32</td>
<td>2,339</td>
<td>1,896</td>
<td>8,524</td>
<td>1.144</td>
<td>0.274</td>
</tr>
<tr>
<td>Large</td>
<td>2,422</td>
<td>2,012</td>
<td>8,582</td>
<td>1.147</td>
<td>0.282</td>
</tr>
<tr>
<td>Small, 34</td>
<td>2,523</td>
<td>2,076</td>
<td>8,640</td>
<td>1.150</td>
<td>0.292</td>
</tr>
<tr>
<td>Large</td>
<td>2,595</td>
<td>2,174</td>
<td>8,697</td>
<td>1.154</td>
<td>0.298</td>
</tr>
<tr>
<td>Small, 36</td>
<td>2,678</td>
<td>2,256</td>
<td>8,755</td>
<td>1.157</td>
<td>0.306</td>
</tr>
</tbody>
</table>

On the other hand, the specific model (OMTCT line) is simulated by fixing the production to 10% above the target plan with respect to the fleet decomposi-
tion. The results are presented in Table 7. It shows that the scenario of 22 small trucks and 36 large trucks has the potential to be useful for the actual mine operation, where the productivity ratio of the specific model (OProductivity ratio line) equals to 1. Using this approach, a substantial cost saving of trucks results in 532,800 USD per month or 6.29% can be achieved. Moreover, the match factor results from the specific model (OMatch Factor line), decreases when the production is out of the target range, see Fig. 7 (b).

<table>
<thead>
<tr>
<th>Truck (unit)</th>
<th>42</th>
<th>38</th>
<th>36</th>
<th>34</th>
<th>30</th>
<th>26</th>
<th>22</th>
<th>20</th>
<th>18</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small, 24</td>
<td>1,860</td>
<td>1,821</td>
<td>1,865</td>
<td>1,910</td>
<td>1,904</td>
<td>1,877</td>
<td>1,886</td>
<td>1,869</td>
<td>1,826</td>
</tr>
<tr>
<td>Large</td>
<td>OMTCT (1x10³ bcm)</td>
<td>1,860</td>
<td>1,821</td>
<td>1,865</td>
<td>1,910</td>
<td>1,904</td>
<td>1,877</td>
<td>1,886</td>
<td>1,869</td>
</tr>
<tr>
<td>Small, 26</td>
<td>1,528</td>
<td>1,468</td>
<td>1,496</td>
<td>1,526</td>
<td>1,532</td>
<td>1,545</td>
<td>1,536</td>
<td>1,516</td>
<td>1,507</td>
</tr>
<tr>
<td>Large</td>
<td>OMTCT 95% (1x10³ bcm)</td>
<td>1,528</td>
<td>1,468</td>
<td>1,496</td>
<td>1,526</td>
<td>1,532</td>
<td>1,545</td>
<td>1,536</td>
<td>1,516</td>
</tr>
<tr>
<td>Small, 28</td>
<td>1,710</td>
<td>1,695</td>
<td>1,730</td>
<td>1,770</td>
<td>1,770</td>
<td>1,750</td>
<td>1,760</td>
<td>1,740</td>
<td>1,710</td>
</tr>
<tr>
<td>Large</td>
<td>Operating cost (1x10³ USD/ month)</td>
<td>1,710</td>
<td>1,695</td>
<td>1,730</td>
<td>1,770</td>
<td>1,770</td>
<td>1,750</td>
<td>1,760</td>
<td>1,740</td>
</tr>
<tr>
<td>Small, 30</td>
<td>0.229</td>
<td>0.227</td>
<td>0.231</td>
<td>0.234</td>
<td>0.236</td>
<td>0.235</td>
<td>0.238</td>
<td>0.234</td>
<td>0.227</td>
</tr>
<tr>
<td>Large</td>
<td>OMatch factor</td>
<td>0.229</td>
<td>0.227</td>
<td>0.231</td>
<td>0.234</td>
<td>0.236</td>
<td>0.235</td>
<td>0.238</td>
<td>0.234</td>
</tr>
<tr>
<td>Small, 32</td>
<td>0.229</td>
<td>0.227</td>
<td>0.231</td>
<td>0.234</td>
<td>0.236</td>
<td>0.235</td>
<td>0.238</td>
<td>0.234</td>
<td>0.227</td>
</tr>
<tr>
<td>Large</td>
<td>OProductivity</td>
<td>0.229</td>
<td>0.227</td>
<td>0.231</td>
<td>0.234</td>
<td>0.236</td>
<td>0.235</td>
<td>0.238</td>
<td>0.234</td>
</tr>
</tbody>
</table>

4.3 Evaluating production

4.3.1 Dispatching behaviour

The simulation study in Publication 2 demonstrates the effect of changing truck dispatching strategies in conjunction with the heuristic truck dispatching methods in the actual open-pit mine of Section 4.1.2, based on the input parameters which were collected through the GPS system between June and October 2014. Table 8 illustrates the results of different simulation models. The m-trucks-for-n-shovels is clearly the best allocation approach compared to the 1-truck-for-n-shovels and the m-trucks-for-1-shovel, even when the ideal operation (scenario 1) and unexpected event (scenario 2) are considered.

The choice of the heuristic truck dispatching method has a significant influence on the production based on different truck dispatching approaches, see Table 8. For example, MSC method, which is the best method for the m-trucks-for-n-shovels approach, is inefficient when the 1-truck-for-n-shovels approach is used. MTWT and MSWT method yield higher production than other methods in each month for the 1-truck-for-n-shovels approach. However, MSWT method is about 6% lower in production than others when operating with the m-trucks-for-n-shovels approach.
Additionally, the simulation study in Publication 4 determines the results of two models based on the input parameters which were collected through the GPS system in the actual mine of Section 4.1.2 for one year, 2014. Model I represents the ideal operation, which does not consider the inactive times of different truck age levels. Model II takes these characteristics into account. Figs. 8 and 9 present the total production values of two models based on three unique truck dispatching systems. These systems are the 1-truck-for-n-shovels with MSWT, the m-trucks-for-1-shovel, and the m-trucks-for-n-shovels with MTCT.

![Figure 8](image)

**Figure 8.** The simulated results of overburden production under the ideal operation (Model I). (Reproduced from Publication 4)

Fig. 8 illustrates the simulated results of the ideal operation, assuming that all trucks, irrespective of age, have identical performance level and 100% availability. The m-trucks-for-1-shovel obtains similar result as the actual production, while the 1-truck-for-n-shovels with MSWT yields 25% higher result than the actual production. The m-trucks-for-n-shovels with MTCT achieves the highest production, which is 55% higher compared to the actual production. The figure also shows the level, above which 95% of the simulated production figure line, that is, the production is more than this with 95% probability.
However, the production in each truck dispatching system decreases gradually by 38% when the breakdowns are considered in the simulation model. Fig. 9 shows the simulated results of the 1-truck-for-n-shovels with MSWT and the m-trucks-for-1-shovel, which are 37% and 39% lower than the actual production. However, the m-trucks-for-n-shovels with MTCT yields significantly higher production even when unpredictable events are included in the model, see Table 9.

Table 9. The comparison of Model I and Model II based on the index production (%). (Reproduced from Publication 4)

<table>
<thead>
<tr>
<th>Month</th>
<th>The 1-truck-for-n-shovels</th>
<th>The m-trucks-for-1-shovel</th>
<th>The m-trucks-for-n-shovels</th>
<th>Plan</th>
<th>Actual</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Model I</td>
<td>Model II</td>
<td>Model I</td>
<td>Model II</td>
<td>Model I</td>
</tr>
<tr>
<td>Jan</td>
<td>155</td>
<td>91</td>
<td>115</td>
<td>77</td>
<td>265</td>
</tr>
<tr>
<td>Feb</td>
<td>148</td>
<td>91</td>
<td>111</td>
<td>79</td>
<td>257</td>
</tr>
<tr>
<td>Mar</td>
<td>166</td>
<td>102</td>
<td>124</td>
<td>86</td>
<td>290</td>
</tr>
<tr>
<td>Apr</td>
<td>92</td>
<td>43</td>
<td>64</td>
<td>34</td>
<td>140</td>
</tr>
<tr>
<td>May</td>
<td>79</td>
<td>39</td>
<td>58</td>
<td>32</td>
<td>127</td>
</tr>
<tr>
<td>Jun</td>
<td>85</td>
<td>40</td>
<td>67</td>
<td>35</td>
<td>148</td>
</tr>
<tr>
<td>Jul</td>
<td>89</td>
<td>41</td>
<td>71</td>
<td>36</td>
<td>156</td>
</tr>
<tr>
<td>Aug</td>
<td>95</td>
<td>43</td>
<td>75</td>
<td>37</td>
<td>166</td>
</tr>
<tr>
<td>Sep</td>
<td>94</td>
<td>42</td>
<td>74</td>
<td>36</td>
<td>164</td>
</tr>
<tr>
<td>Oct</td>
<td>101</td>
<td>44</td>
<td>79</td>
<td>37</td>
<td>176</td>
</tr>
<tr>
<td>Nov</td>
<td>75</td>
<td>35</td>
<td>55</td>
<td>32</td>
<td>118</td>
</tr>
<tr>
<td>Dec</td>
<td>83</td>
<td>39</td>
<td>58</td>
<td>33</td>
<td>126</td>
</tr>
</tbody>
</table>

4.3.2 Match factor behaviour

The differences between match factors are investigated in three heterogeneous fleet types, a heterogeneous truck fleet, a heterogeneous shovel fleet, and a fleet comprising both heterogeneous truck and shovel resources. A stochastic simulation study is carried out with a classic truck dispatching strategy and
heuristic truck dispatching methods under the ideal operation and breakdown event (Publication 3). The results are presented in Table 10.

Table 10: The results of average production (in $1\times10^3$ bcm) based on three heterogeneous fleet types.

<table>
<thead>
<tr>
<th></th>
<th>A heterogeneous truck fleet</th>
<th>A heterogeneous shovel fleet</th>
<th>Heterogeneous truck and shovel fleets</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Small shovel</td>
<td>Large shovel</td>
<td>Small truck</td>
</tr>
<tr>
<td>MSWT</td>
<td>Ideal operation</td>
<td>2,095</td>
<td>2,354</td>
</tr>
<tr>
<td></td>
<td>Breakdown event</td>
<td>1,680</td>
<td>1,877</td>
</tr>
<tr>
<td>MTCT</td>
<td>Ideal operation</td>
<td>2,131</td>
<td>2,155</td>
</tr>
<tr>
<td></td>
<td>Breakdown event</td>
<td>1,696</td>
<td>1,722</td>
</tr>
<tr>
<td>MTWT</td>
<td>Ideal operation</td>
<td>2,110</td>
<td>2,149</td>
</tr>
<tr>
<td></td>
<td>Breakdown event</td>
<td>1,688</td>
<td>1,719</td>
</tr>
<tr>
<td>MSC</td>
<td>Ideal operation</td>
<td>2,115</td>
<td>2,158</td>
</tr>
<tr>
<td></td>
<td>Breakdown event</td>
<td>1,690</td>
<td>1,721</td>
</tr>
<tr>
<td>A match factor ratio</td>
<td>Plan</td>
<td>1.147</td>
<td>1.147</td>
</tr>
<tr>
<td></td>
<td>Actual</td>
<td>1.147</td>
<td>1.147</td>
</tr>
<tr>
<td>Operating cost under</td>
<td>Ideal operation</td>
<td>8,107</td>
<td>10,483</td>
</tr>
<tr>
<td></td>
<td>(1x10^3 USD/month)</td>
<td>(MSWT)</td>
<td>(MTCT)</td>
</tr>
<tr>
<td>Average productivity</td>
<td>(MTCT)</td>
<td>0.263</td>
<td>0.225</td>
</tr>
<tr>
<td>under the ideal</td>
<td>(MSWT)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>operation</td>
<td>(MTCT)</td>
<td>(MTCT)</td>
</tr>
</tbody>
</table>

The number of trucks and shovels in a heterogeneous truck fleet and a heterogeneous shovel fleet used in the simulation models is the same as operated in an actual open-pit mine of Section 4.1.2, except the types are changed based on the fleet type.

Table 10 shows the simulated results of overburden production of a heterogeneous truck fleet with small shovel type under the ideal operation yields similar results in each heuristic truck dispatching method. However, when changing the type of shovel to be large, the simulated result of MSWT yields a high production increase of 12.34%, while for MTCT, MTWT, and MSC the production increases by 1.66%. On the other hand, under the breakdown event, MSWT leads to 27% lower production compared to the ideal operations. The production decreases due to the fact that the broken trucks or shovels will not be considered for assignment until they become operational again.

The simulated results of overburden production with a heterogeneous shovel fleet with small truck type based on MTCT, MTWT, and MSC, are equivalent and yield equal production, while the production of MSWT is about 10% lower, see Table 10. Moreover, the simulated results of a heterogeneous shovel fleet with large truck type also indicate that use of MSWT results in 17% lower production than that of MTCT, MTWT, and MSC. The change of truck type to larger trucks has a major impact on MTCT, MTWT, and MSC, increasing the simulated production by 100%, while for MSWT the increase is 96%. The main
reason for the inefficient result of MSWT is that the method always assigns a truck to the shovel that has been waiting the longest. Since the match factor ratios of a heterogeneous shovel fleet with small/large truck type illustrate that the overall fleets are slightly over-trucked, the probability that a shovel will wait is too low.

Heterogeneous truck and shovel fleets contain mixed truck types and mixed shovel types as operated in the actual mine (Section 4.1.2). The design of this model yields the results of match factor ratio in each month (June-October) exceeding 1.0, as 1.106, 1.066, 1.139, 1.185, and 1.239 respectively. This indicates that the trucks are arriving faster than the shovels are able to serve. Under these circumstances, the trucks are on queue and being over-trucked. The production of MTCT, MTWT, and MSC is equivalent, while MSWT is 7% lower production, see Table 10. Moreover, the production in each heuristic truck dispatching method decreases gradually by 25%, when the breakdown of truck or shovel is considered.

An extension of the simulation model is derived by reducing the number of trucks based on their types in the fleet by 10%, and in this case the resulting match factor ratios from June to October are 0.976, 0.941, 1.006, 1.046, and 1.094 respectively (Table 10). These ratios are close to the theoretically perfect mach of 1.0, which yield good results in terms of overall efficiency and productivity of the fleet. The production in each heuristic truck dispatching method under the ideal operation is close to the plan. However, it is lower than the real fleet model under the breakdown event of a truck or of a shovel by 7%.

4.3.3 Age-based maintenance behaviour

The proposed four models in Publication 4 are relied on the truck selection criteria, the m-trucks-for-n-shovels with MTCT. The extensive empirical data, such as the basic events in a cyclic operation time of truck and shovel are collected in the actual mine (Section 4.1.2). Moreover, the preventive and corrective maintenance hours are inferred from the historical data based on the equipment age levels.

The first model is the ideal approach, assuming all trucks, irrespective of age, have identical performance levels and 100% availability. The second model is the original approach in which the specific events, such as inactive times, preventive, and corrective maintenance hours of different truck age levels are considered. The third model is the traditional approach following the interval range of operational availability. In this case, 85% and 90% are selected and applied to truck age level 1 and 2. The total maintenance time per month of truck age level 1 and 2 is 108 and 72 hours. The last model is the optimal approach, which is evaluated by fixing the monthly production by 10% above the average plan production². The operational availability of trucks in age level 1 and level 2 is 65% and 70%. The preventive and corrective maintenance ratio in the mine operation under consideration is 7:3. As a result, the preventive and corrective maintenance schedules for level 1 are 151.2 hours and 64.8

²Average plan production is 1,422,548 bcm; Average actual production is 1,044,509 bcm
hours per month. On the other hand, for the truck age level 2, these figures are 176.4 hours and 75.6 hours per month. Fig. 10 shows the simulated results of overburden production under the operational availability based on the four models. The reliability, availability, and maintainability characteristics play a crucial role in the production of the fleet for entire year.

![Figure 10. The simulated results of overburden production under the operational availability. (Reproduced from Publication 4)](image)

The original approach yields the average production to be 16.25% higher than the average plan, while the traditional approach results in 34.68% higher production. The total cost of each approach is calculated using the maintenance, breakdown, and operating costs, which provided in Table 2. The optimal approach performs the unit cost saving for individual truck age levels as presented in Table 11.

**Table 11.** The comparison cost (in 1x10^3 USD/year) of the simulated approaches. (Reproduced from Publication 4)

<table>
<thead>
<tr>
<th></th>
<th>Ideal operation</th>
<th>Original case</th>
<th>Traditional approach</th>
<th>Optimal approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maintenance cost of truck age levels</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Large 1</td>
<td>890</td>
<td>984</td>
<td>2,298</td>
<td></td>
</tr>
<tr>
<td>Small 1</td>
<td>247</td>
<td>276</td>
<td>829</td>
<td></td>
</tr>
<tr>
<td>Large 2</td>
<td>377</td>
<td>435</td>
<td>1,016</td>
<td></td>
</tr>
<tr>
<td>Small 2</td>
<td>454</td>
<td>311</td>
<td>933</td>
<td></td>
</tr>
<tr>
<td>Breakdown cost</td>
<td>46</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total maintenance and breakdown costs</td>
<td>2,016</td>
<td>2,007</td>
<td>5,076</td>
<td></td>
</tr>
<tr>
<td>Total operating cost</td>
<td>65,318</td>
<td>49,256</td>
<td>48,988</td>
<td>22,861</td>
</tr>
<tr>
<td>Average cost of the fleet</td>
<td>5.443</td>
<td>4.272</td>
<td>4.249</td>
<td>2.328</td>
</tr>
<tr>
<td>(1x10^3 USD/month)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average Production</td>
<td>2,389</td>
<td>1,698</td>
<td>2,177</td>
<td>1,606</td>
</tr>
<tr>
<td>(1x10^3 bcm/month)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average productivity</td>
<td>0.439</td>
<td>0.398</td>
<td>0.512</td>
<td>0.690</td>
</tr>
</tbody>
</table>
4.4 Discussion

The thesis addresses one of the primary problems in an open-pit mine: efficient matching trucks and shovels. In other words, the aim is to determine the required number of trucks and shovels as well as their types to make the best match in order to satisfy the production target. This problem is investigated using different simulation and optimization models, which contain the behaviours of dispatching strategy, match factor, and age-based maintenance under the ideal operation and breakdown event.

The choice of the heuristic truck dispatching method has a significant influence on the performance of the mine. Operationally, the match factor ratio in the actual mine exceeds 1.0, which is over-trucked. With such a criterion, the corresponding dispatching method, MSWT always assigns a truck to the shovel that has been waiting the longest. This situation does not produce efficient result since the probability that a shovel will wait is slightly low. Conversely, MTCT, MTWT, and MSC yield higher production.

The simulation results reveal remarkable differences in production figures under different heterogeneous fleet types, including a heterogeneous shovel fleet, a heterogeneous truck fleet, and heterogeneous truck and shovel fleets. As an example of a heterogeneous shovel fleet, the production of MTCT, MTWT, and MSC increases dramatically by 100% when changing the size of trucks to be large, while for MSWT the increase is 96%. On the other hand, in the case of a heterogeneous truck fleet, changing to the large shovel type increases the production by 10% if MSWT method is used, while using other heuristic truck dispatching methods the production is increased by 2%. As a result, increasing equipment capacity also has an impact on the production.

A heterogeneous truck and shovel fleets type is the real fleet model, which is used in the actual open-pit mine operation. The results of match factor ratio in each month exceed 1.0, which indicate that the trucks are arriving faster than shovels are able to serve. Under these circumstances, the trucks are on queue. An extension of the simulation model is derived by reducing the number of trucks based on their types by 10%, which yields better results in terms of overall efficiency and productivity of the fleet.

Additionally, the 18 decision scenarios illustrate the simulated results of overburden production with a different number and type of trucks. The number of 22 small trucks and 36 large trucks under the ideal operation yields a good result. The production is above target plan by 10% and the substantial cost reduction is 6%. However, in reality each truck has its own reliability, availability, and maintainability. These characteristics play a crucial role in the production and operating costs. Therefore, it is better to have buffer trucks, or an input parameter of scheduled maintenance must be included.

As the input data for the simulation and optimization models varies based on the collected data, and naturally each mine is unique in its topography and in its operations. However, the collected data over a one-year period is sufficient to produce statistically significant results. The selected months allow observation of the significant effects from the weather during the operation. June and July fall in the season of heavy rains with an average rainfall of 200 mm on 14
days totalling 49 hours per month. August, September, and October fall in the season of moderate rains with an average rainfall of 113 mm on 10 days totalling 25 hours per month. Heavy rainfall has an effect on operations making truck travel more difficult and leading to more equipment breakdowns than during the dry season.

4.5 Summary and remarks

In this chapter, the results of the proposed simulation and optimization models are presented. The proposed models in Publications 1-4 are able to cope with the main uncertainties associated with truck and shovel operations in the actual open-pit mines. Table 12 presents the publication results based on different objectives and scope of work in the thesis.

Publication 1 introduces a tailor-made low cost GPS tracking system and examines the benefits achieved by applying the system at a coal hauling operation. The simulation results show that the improved cycle time allows decreasing the required number of trucks, while maintaining a particular haulage capacity. Moreover, the main findings in Publication 3 provide evidence that the match factor is able to determine limits for an appropriate fleet size, when the equipment selection phase occurs. On the other hand, the match factor can be used to estimate the relative efficiency of the fleet when the fleet is already selected and in place. However, the match factor cannot be used alone for the fleet optimization. The choice of truck dispatching strategies and heuristic truck dispatching methods in Publications 2-4 plays a crucial role in the assignments of trucks under the ideal operation and breakdown event. To reduce the truck and shovel breakdown, a maintenance schedule is necessary as it directly influences the operational availability. A close to optimal preventive and corrective maintenance schedule in Publication 4 is proposed for different truck age levels. This effective maintenance schedule leads to the annual cost saving for the fleet.

Table 12. The publication results align with the objectives and scope of the thesis.

<table>
<thead>
<tr>
<th>Objectives</th>
<th>Publication</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. To reveal bottlenecks in a truck haulage system and study the possibility of reducing truck cycle times.</td>
<td>x</td>
</tr>
<tr>
<td>2. To analyze the behaviour of dispatching strategy in an open-pit mine in conjunction with different heuristic truck dispatching methods.</td>
<td>x x</td>
</tr>
<tr>
<td>3. To determine the necessary number and type of trucks and shovels to meet the production target. This objective is achieved by evaluating different scenarios based on the choice of truck dispatching strategies and heuristic truck dispatching methods. Each scenario has different number and type of trucks and shovels.</td>
<td>x</td>
</tr>
<tr>
<td>4. To design a close to optimal scheduled maintenance for different truck age levels.</td>
<td>x</td>
</tr>
</tbody>
</table>
5. Conclusions

This chapter contains the thesis contributions and recommendations for future work.

5.1 Contributions

Operationally, the stochastic nature of truck-and-shovel in open-pit mines composes of three causes. First, the pickup and delivery points settle on the same locations during a long period of time, which generally corresponds to a shift of 8 or 12 hours. The cyclic event time of each truck is really short 12-18 minutes compared to the length of the shift and the timing demands at each pickup point are frequently fast, approximately 2-3 minutes. Second, the raw material is highly variable and encumbered with estimation error because the operation is in the midst of coal and overburden, which are not well characterized. Third, there are uncertainties associated with truck-and-shovel operations, such as the varying topography of the pit, a network of haul routes, weather conditions, road conditions, visibility, and the variability in the status of operating equipment. These three causes directly influence the production of mines.

Previous research in the context of truck-and-shovel systems has presented different objectives based on 5 classification approaches to improve the operations. The approaches are truck dispatching strategies, heuristic truck dispatching methods, mathematical programming methods, simulation methods, and other stochastic methods. However, most approaches ignore the stochastic nature of truck-and-shovel operations or assume that all trucks and shovels have the same operating performances. This thesis utilizes some of the new possibilities enabled by the previous approaches.

The proposed models in this thesis offer the following significant contributions to the body of knowledge on truck-and-shovel systems. First, a reliable data input modelling and a tailor-made low cost GPS tracking system are implemented at a coal hauling operation. The comparison of time in each cyclic activity or event of truck is specified based on start zone and end zone contour of a mine map.

Second, a new knowledge about the effectiveness of different dispatching strategies and heuristic truck dispatching methods is presented. These are the first to take main uncertainties of an actual mine into account. The uncertain-
ties include hauling distance, truck velocity, truck cycle time, loading time of matched truck and shovel, inactive time of truck and shovel, and equipment age levels. It is reported for the first time that the choice of the heuristic truck dispatching method has a significant influence on the mine performance, and simulated results reveal remarkable differences in production figures under different strategies.

Third is a pioneering effort to develop simulation models with different aspects of truck-and-shovel operations under the ideal operation and under random failure events. These models contribute significantly to the body knowledge on a match factor ratio. It is a decision tool for determining the required number of trucks and shovels as well as their types, to make the best matches between them. Moreover, the match factor ratio is applicable for improving the truck cycle time in order to gain maximal efficiency from an existing fleet, and to specify limits for an appropriate fleet size from an equipment selection phase.

Fourth is a novel truck dispatching simulation model based on reliability, availability, and maintainability characteristics for each truck age level. The proposed model considers the maintenance cost variation with truck age along with the production requirements. The model provides an alternative option for maintenance scheduling in a fleet which contains trucks of different ages.

5.2 Recommendations

Even though, the proposed simulation models in this thesis have provided pioneering efforts to analyze and improve the truck-and-shovel system. There is a need for continued investigation into using the simulation models in this context. The following recommendations are addressed for further research. First, the dispatching problem in this thesis focuses on the fleet allocation with a single material type, especially the extraction of overburden. To deal with the problem comprehensively, the simulation model should be extended to quantity and quality of coal by including several options for loading and dumping which contain stockpiles and crushers. Moreover, coal blending is of major interest to fleet allocation for maximizing cash flow. Second, the velocity of trucks and the hauling distances use in the two models, a heterogeneous shovel fleet and optimal boundary of heterogeneous truck and shovel fleets are assumed based on the fitted model and the average uphill/downhill of haul roads. To deal with this limitation and make the results more accurate, it needs to consider the haul road profiles and different velocities in each segment of haul roads. Third, the total costs of the fleet in each forecasting operational availability approach is calculated using only three costs, which are the maintenance, breakdown, and operating costs. To make the cost model more precise, one needs to take indirect costs of not operating certain equipment into account.
References


[44] N. Cetin, Open-pit truck/shovel haulage system simulation, Thesis of doctor of philosophy in the department of mining engineering, The graduate school of


