A Decision Support System and Cost-Performance Analysis for Dust Control at Open-Pit Coal Mines

Von der Fakultät für Georessourcen und Materialtechnik der Rheinisch-Westfälischen Technischen Hochschule Aachen

zur Erlangung des akademischen Grades eines Doktors der Ingenieurwissenschaften

genehmigte Dissertation
vorgelegt von M.Sc.

Ismet Özdemir

aus Ankara, Türkei

Berichter: Univ.-Prof. Dr.-Ing. Dipl.-Wirt. Ing. Per Nicolai Martens
Univ.-Prof. Dr.-Ing. Christian Niemann-Delius


Diese Dissertation ist auf den Internetseiten der Hochschulbibliothek online verfügbar
Acknowledgments

The work presented in this thesis has been carried out within the framework of the “Research Association Mining and Environment in Vietnam” (RAME) project and during my employment as a research assistant at the Institute of Mining Engineering I (BBK I), RWTH Aachen University. I wish to gratefully acknowledge the German Federal Ministry of Education and Research (BMBF) for their financial support to the RAME project.

I would like to express my deepest gratitude to Professor Dr.-Ing. Dipl.-Wirt.Ing. Per Nicolai Martens, my adviser and head of BBK I, for giving me with the opportunity to complete my PhD under his supervision. His valuable support and immense guidance made this work possible. I am also sincerely grateful to Univ.-Prof. Dr.-Ing. Christian Niemann-Delius for accepting being my second PhD adviser immediately and reviewing my thesis with his deep knowledge on mine dust control.

Special thanks go to Dr. Tobias Katz for his scholarly inputs and consistent encouragement during my research. This thesis was enriched significantly through his insightful comments.

All the RAME project partners, engineers and scientists from Brenk Systemplannung and CBM also deserve my sincerest thanks. Without their friendly assistance and collaboration, I could not complete my research. I especially would like to thank to Arne Förster, research assistant at BBK I and co-worker in the RAME project, for the stimulating discussions and the technical support in the field measurements. I also acknowledge the help given by the managers and engineers of the VINACOMIN and the Nui Beo Coal Company in organization of the field work in Ha Long, Vietnam.

I should not forget to acknowledge the past and present members of BBK I for providing a great work environment and all the fun we have had in the last four years. In particular, I am grateful to Rene Randaxhe for his both professional and personal support and guidance.

Lastly, I would like to thank my grandparents Mesut and Havva Esatoğlu for all their unconditional love and support in all my pursuits. And most of all, I must express my gratitude to my loving, encouraging, patient and wise wife Bengi whose faithful support during all these years is so appreciated. Thank you.
Abstract

Fugitive dust emissions from mining activities can have severe health and environmental impacts unless adequately controlled. Designing proper mine dust control strategies requires evaluation of two main aspects: dust emission levels and cost-effectiveness of control methods.

These aspects can be adequately evaluated by integrating location- and activity-specific dust emission factors, reduction factors and the cost parameters of control methods. This thesis presents a decision support system (Dust-DSS) that is capable of estimating open-pit coal mine dust emissions and the cost-performance of dust control methods on the basis of these specific parameters. Additionally, this thesis investigates the dust emission levels from different mining activities and the limits of applicability of prominent dust control methods.

The DSS integrates dust emission factors of mining activities, reduction factors and the cost parameters of dust control methods designed for a typical open-pit hard coal mine, the NBCC mining site at Ha Long (Vietnam). The emission factors were derived using data obtained from real-time dust emission measurements at the NBCC site. Similarly, the reduction factors of the dust control methods were developed by either analyzing data from the real-time measurements or reviewing the relevant literature. Finally, the cost parameters of these dust control methods (e.g., operational constants, unit equipment and material costs) were determined on the basis of the observations at the NBCC mining site and actual market prices.

The developed Dust-DSS includes a guide module, i.e., best practice guide (BPG) and a computational module. The BPG is a text-based document that presents background information for envisaging mine dust control approaches. The computational module provides a platform to calculate emission levels from different mining activities and cost-performance of related control methods. This module was built by incorporating location- and activity-specific dust emission factors, reduction factors and the cost parameters of control methods determined within the scope of this thesis.

Predictive Dust-DSS scenarios were developed and simulated in order to identify major mine dust sources and applicability limits of different dust control methods. The scenario simulations revealed that overburden haulage and wind erosion are
the major dust sources for the investigated open-pit coal mining operations. Their impact varies according to the critical parameters, i.e., road length for overburden haulage and exposed area for wind erosion. Moreover, the simulation results showed that these parameters, as well as the interest rate and the project duration determine the feasibility of the dust control methods.

To sum up, the dust emission and reduction factors presented for the mining site investigated in this thesis can be applied for other mining operations with comparable mining and dust control conditions. Furthermore, the Dust-DSS based on these factors can be employed to design cost-effective dust control strategies for any active or planned open-pit coal mining operation.

The work presented in this thesis has been completed within the framework of the “Research Association Mining and Environment in Vietnam” (RAME) that aims to develop and implement measures as well as to carry out capacity building to address environmental impacts of hard coal mining in Vietnam.
Diffuse Staubemissionen aus Bergbauprozessen können massive ökologische und gesundheitliche Auswirkungen hervorrufen, sofern keine Staubminderungsmaßnahmen ergriffen werden. Die Entwicklung geeigneter Staubminderungsverfahren erfordert die Bewertung von hauptsächlich zwei Aspekten: die Höhe der Staubemissionen und die Kosteneffektivität der Minderungsmaßnahmen.


Das entwickelte Staub-DSS besteht aus einem anwendungsorientierten Modul, Best Practice Guide (BPG), und einem Rechenmodul. Der BPG ist ein textbasiertes Dokument, welches Hintergrundinformationen zur Herangehensweise von Staubminderungen im übertägigen Bergbau liefert. Auf der anderen Seite bietet das

Um die wesentlichen Staubquellen von Bergbauprozessen zu identifizieren und die Grenzen der Anwendbarkeit der verschiedenen Methoden zu bestimmen, wurden vorhersehbare Staub-DSS-Szenarien entwickelt und simuliert. Die Simulationen der Szenarien ergaben, dass der Abraumtransport und die Winderosion als zentrale Staubquellen für die untersuchten Steinkohlentagebaue ermittelt werden konnten. Die Auswirkungen der Staubquellen hängen von den kritischen Parametern, d.h. Straßenlänge für Abraumtransport und freiliegende Fläche für die Winderosion ab. Darüber hinaus haben die Simulationsergebnisse gezeigt, dass diese Parameter sowie der Zinssatz und die Projektdauer, die Machbarkeit der Staubminderungsmaßnahmen bestimmen.

Zusammenfassend können die hier dargestellten Ergebnisse der Staubemissionen und Reduktionsfaktoren für andere Bergwerksbetriebe mit vergleichbaren Abbau und Staubminderungsbedingungen angewendet werden. Außerdem kann das Staub-DSS auf Grundlage der beiden Faktoren als kosteneffektive Staubminderungsstrategie für aktive oder geplante Kohlentagebaue eingesetzt werden.

# TABLE OF CONTENTS

**ACKNOWLEDGMENTS** ........................................................................................................................................... I

**ABSTRACT** ....................................................................................................................................................... III

**ZUSAMMENFASSUNG** ........................................................................................................................................... V

**TABLE OF CONTENTS** ......................................................................................................................................... VII

**CHAPTER 1. INTRODUCTION** ................................................................................................................................. 1

1.1. Background and Motivation ............................................................................................................................. 1

1.2. Aims and Objectives ......................................................................................................................................... 8

1.3. Contributions ................................................................................................................................................... 9

1.4. Structure of Thesis ....................................................................................................................................... 10

**CHAPTER 2. LITERATURE REVIEW** .................................................................................................................. 12

2.1. Mine Dust Emission Factors ......................................................................................................................... 12

2.2. Mine Dust Reduction Factors ...................................................................................................................... 16

2.3. Decision Support Systems ........................................................................................................................... 17

**CHAPTER 3. DESCRIPTION OF PROJECT AREA** .............................................................................................. 21

3.1. Economic Importance of Mining .................................................................................................................. 21

3.2. Geology and Mining .................................................................................................................................. 21

3.3. Climate......................................................................................................................................................... 23

3.4. Environmental Sensitivity .......................................................................................................................... 25

**CHAPTER 4. METHODOLOGY** ............................................................................................................................. 27

4.1. Development of Mine Dust Emission Factors, Reduction Factors and Dust Control Cost Parameterization ........................................................................................................................................... 28

4.1.1. Description of Real-Time Measurement Equipment ............................................................................. 29

4.1.2. Mine Dust Emission Factors Development ............................................................................................ 31

4.1.2.1. Identification of Dust-generating Mining Activities and Influencing Parameters ........................ 31

4.1.2.2. Conducting Real-time Dust Emission Measurements ................................................................... 32

4.1.2.3. Dispersion Modeling and Statistical Analysis for Emission Factors Development .................. 40

4.1.3. Mine Dust Control Reduction Factors Development ........................................................................... 42

4.1.3.1. Identification of Adapted and Alternative Dust Control Methods .................................................... 43

4.1.3.2. Identification of Primary Mine Dust Sources .................................................................................. 44

4.1.3.3. Conducting Real-time Dust Control Performance Measurements ............................................. 45

4.1.3.4. Mine Dust Reduction Factors Development ................................................................................... 49

4.1.4. Mine Dust Control – Cost Parameterization ......................................................................................... 51

4.2. Development of Mine Dust Control Decision Support System (Dust-DSS) and Scenario Simulation .................................................................................................................................................. 53

4.2.1. Conceptual DSS ....................................................................................................................................... 57

4.2.2. Description of DSS Building Platforms ................................................................................................. 59

4.2.2.1. Description of DSS Computational Module Building Platform ....................................................... 59
4.2.2.2. Description of DSS Guide Module Building Platform ...................................................... 60
4.2.3. Development of DSS ........................................................................................................... 60
4.2.3.1. Development of DSS Computational Module ................................................................. 60
4.2.3.2. Development of DSS Guide Module (BPG) ................................................................. 71
4.2.3.3. DSS Verification and Validation ..................................................................................... 71
4.2.4. DSS Scenario Simulation ...................................................................................................... 72
4.2.4.1. Reference Scenario ........................................................................................................ 74
4.2.4.2. Overburden Haulage and Wind Erosion Scenarios ......................................................... 75

CHAPTER 5. RESULTS....................................................................................................................... 77
5.1. Proposed Mine Dust Emission Factors, Reduction Factors and Dust Control Cost Parameters 77
5.1.1. Proposed Mine Dust Emission Factors ................................................................................ 77
5.1.1.1. Identified Dust-generating Activities and Influencing Parameters .................................. 77
5.1.1.2. Results of Real-time Dust Emission Measurements ....................................................... 79
5.1.1.3. Results of Dispersion Modeling and Statistical Analysis – Emission Factors ................. 80
5.1.2. Proposed Mine Dust Reduction Factors .............................................................................. 81
5.1.2.1. Identified Adapted and Alternative Dust Control Methods ............................................. 81
5.1.2.2. Identified Primary Mine Dust Sources ............................................................................ 82
5.1.2.3. Results of Real-time Dust Control Performance Measurements ................................... 83
5.1.2.4. Results of Mine Dust Reduction Factors Development .................................................. 83
5.1.3. Proposed Mine Dust Control Cost Parameters ..................................................................... 87

5.2. Developed Decision Support System and Scenario Simulation ............................................. 90
5.2.1. Developed Mine Dust Control Decision Support System (Dust-DSS) ................................ 90
5.2.1.1. DSS Computational Module ......................................................................................... 90
5.2.1.2. DSS Guide Module (BPG) .......................................................................................... 95
5.2.1.3. DSS Verification and Validation Results ......................................................................... 97
5.2.2. DSS Scenario Simulation Results ...................................................................................... 98
5.2.2.1. Simulation Results of Reference Scenario ...................................................................... 98
5.2.2.2. Simulation Results of Overburden haulage and Wind Erosion Scenarios ....................... 102

CHAPTER 6. DISCUSSION ................................................................................................................. 110
6.1. Mine Dust Emission Factors, Reduction Factors and Dust Control Cost Parameters .......... 110
6.1.1. Mine Dust Emission Factors ............................................................................................. 110
6.1.1.1. Overburden Haulage – Emission Factors ..................................................................... 111
6.1.1.2. Overburden Dumping – Emission Factors ...................................................................... 113
6.1.1.3. Wind Erosion – Emission Factors .................................................................................. 113
6.1.2. Mine Dust Control – Reduction Factors ............................................................................ 115
6.1.2.1. Primary Mine Dust Sources ......................................................................................... 115
6.1.2.2. Overburden Haulage – Reduction Factors for Control Methods .................................... 118
6.1.2.3. Overburden Dumping – Reduction Factors for Control Methods .................................. 120
6.1.2.4. Wind Erosion – Reduction Factors for Control Methods ............................................... 121
6.1.3. Mine Dust Control – Cost Parameters .............................................................................. 122
CHAPTER 1. INTRODUCTION

1.1. Background and Motivation

Coal is a primary energy resource that supplies almost 30% of the world’s total energy demands. Coal-fired power plants generate more than 40% of the world’s electricity. Furthermore, coal-based electricity and hence coal consumption at the global level is expected to escalate in upcoming decades. In fact, the International Energy Agency (IEA) anticipates approximately a 20% increase in coal production from 2009 to 2035 in the New Policies Scenario and 60% in the Current Policies Scenario. On the other hand, coal supply costs have risen as a result of higher mining costs at less easy-to-mine and/or more distant locations, changing mining tax regimes, as well as additional cost pressures by more stringent environmental, health and safety legislation on mining (IEA, 2011; IEA, 2013). Besides, environmental and health problems of coal mining continue to be a public concern, as coal remains to be a primary fuel for energy generation. One of the severe environmental and health impacts of coal mining is dust emission, which can negatively affect local and regional air quality and workers’ health.

Air quality is determined by measuring ambient concentrations of pollutants. US Environmental Protection Agency (USEPA) defines six principal air pollutants that are particulate matter (PM), ozone ($O_3$), carbon monoxide (CO), nitrogen dioxide ($NO_2$), sulfur dioxide ($SO_2$) and lead (Pb) (USEPA, 1990). As suggested in other studies, particulate matter (PM) or dust is the major air pollutant caused by hard rock mining and coal mining (Desautels, 1997; Ghose, 2004; Donnelly, et al., 2011). Moreover, Ghose and Majee (2000) stated that surface coal mining has higher detrimental impact on environment than underground coal mining. They also claimed that level of dust emissions from coal mining operations has increased considerably in India from 1995/1996 to 2000 due to the shift from underground mining to surface mining and the large scale mechanization. In another study (Singh, 2008), air pollution from surface coal mines was found to be much higher than underground mines, as the former impact both the mining area and its surroundings.

Substantial dust generation in surface coal mining operations was also confirmed by Donnelly, et al. (2011). In their benchmark report, they assessed the dust emissions in about 57 surface and underground coal mines in the Greater Metropolitan Region.
(GMR) in New South Wales (NSW), Australia. They explained that underground mines emit less dust than surface mines because of a limited amount of overburden removal and the execution of key dust-generating activities below ground. This conclusion was also verified by the dust emission levels and rankings provided for the investigated mines in GMR, as the majority of the surface mines were ranked higher than underground mines.

Dust emission levels and rankings for individual coal mining activities were also listed by Donnelly, et al. (2011). Accordingly, it was affirmed that mine trucks travelling on unpaved haul roads is the primary emission source followed by wind erosion. In another study from Australia (Environment Australia, 1998), transportation on haulage roads was also designated as the primary dust source in surface coal mines based on data obtained from the NSW State Pollution Control Commission. Additionally, a study focusing on the dust emissions in surface coal mines in the northern part of Colombia highlighted the contribution of transportation on unpaved roads and wind erosion together with coal and overburden handling to the total mine dust emission (Huertas, Dumar, & Huertas, 2012). Furthermore, coal preparation and transportation activities (Chaulya, et al., 2002; Ghose, 2004), and additionally wind erosion (Ghose, 2004), were reported as the major sources of dust emissions for the studied surface coal mines in India.

In addition to the air quality impact of dust emissions from coal mining, occupational health effects from dust exposure in coal mines have been widely discussed in the literature. The US National Institute for Occupational Safety and Health (NIOSH) reviewed the studies on occupational health effects associated with exposures to respirable coal mine dust in 1995 (NIOSH, 1995). Later, NIOSH provided a supplementary review of information pertaining to these health effects published from 1995 to 2011 (NIOSH, 2011). As stated in these studies, exposure to coal mine dust and crystalline silica dust due to mining operations causes severe respiratory diseases, including coal workers’ pneumoconiosis (CWP), chronic obstructive pulmonary disease (COPD) and silicosis.

The risk of surface coal miners (particularly drill crew members) developing pneumoconiosis was first revealed in US mines (Banks, Bauer, Castellan, & Lapp, 1983). This risk was also identified among surface coal mine workers in the UK (Love, et al., 1997). The latter work also indicated the direct correlation between the
dust exposure concentration and the risk of CWP. Additionally, the effect of tenure in surface coal mining jobs on the prevalence of CWP among US national coal workers was shown in a later study (CDC, 2003). Within this context, Love, et al. (1997) recommended increased dust control measures in surface coal mine operations to limit mine dust exposure and its associated health impacts.

The latest NIOSH review (NIOSH, 2011) also presented that CWP prevalence, which had been declining for some time, has recently begun rising in US coal mines according to federal surveillance data. Furthermore, this review argued that the actual shifting of coal mining from more productive seams to thinner coal seams is likely to induce an increased risk of silicosis in the future. Therefore, NIOSH highlighted the need for efforts to reduce exposure to both coal mine dust and crystalline silica within coal mining operations.

Mining activities are generally subject to the prevalent environmental and health regulations on account of their adverse impacts on air quality and workers' health. These regulations are revised with regard to changing national or international pollution reduction targets over time and thus new regulations propose updated and tightened emission standards. For instance, the European Union (EU) has introduced reduced threshold values for PM concentrations in ambient air and has suggested target values and long-term objectives in the “Directive on Ambient Air Quality and Cleaner Air for Europe” (European Union, 2008). Another example is that NIOSH advised lower dust exposure limits for respirable coal mine dust, enhanced medical surveillance and other improvements for reducing dust exposure on the basis of evidences regarding its adverse health effects (NIOSH, 1995). A recent study by IEA (2011) argued that complying with such increasingly stringent environmental, health and safety legislation is one of the causes for the increasing cost of coal mining. From the same IEA study, an analysis of the average coal production costs of major state-owned enterprises in Shanxi province, China, confirmed this interpretation. From 2000 to 2009, production costs have broadly tripled since, among other reasons, levies and taxes were introduced or increased, mostly aimed at mitigating the environmental impacts of mining.

There have been also numerous studies investigating the external (indirect) costs for compensating for the environmental and health effects caused by coal mining, e.g., the costs of air pollution and human injuries. The studies reviewed in this thesis
evaluated dust or PM emissions as one of the stimulators for the external costs of coal mining (Sevenster, Croezen, van Valkengoed, Markowska, & Dönszelmann, 2008; Yushi, Hong, & Fuqiang, 2008; Epstein, et al., 2011; Blignaut, Koch, Riekert, Inglesi-Lotz, & Nkambule, 2011).

The severity of the dust emission problem in coal mining is based on its environmental and health impacts and relevant internal and external costs, which are explained above. Ecologically and economically balanced solutions to the coal mine dust problem therefore require the development of cost-effective management strategies. However, as described in the best practice booklet for mine dust control published by Environment Australia, defining a strategy for responding to the dust problem at all stages of mining operations is already a challenging task for mining companies. This includes the identification of mine dust sources, estimating dust levels, evaluating potential environmental and health effects and assigning the incorporation of control measures (Environment Australia, 1998). Furthermore, a detailed report on the principles of dust management in extractive industries suggests that a standardized site-specific dust management plan should start with the identification of both dust sources and receptors (AEA, 2011). In this regard, estimation of mine dust emission levels is a prerequisite for the assessment of air quality impact and the introduction of appropriate dust control methods (Chakraborty, et al., 2002; Ghose, 2004).

Dust or PM emissions are measured in different size ranges such as Total Suspended Particulate (TSP with aerodynamic diameter ($d_a < 57 \mu m$)), PM10 (PM with $d_a < 10 \mu m$) and PM2.5 (PM with $d_a < 2.5 \mu m$). TSP can be measured by standard high-volume samplers, which often have an effective cut-off point of 30 \mu m aerodynamic diameter. Therefore, Suspended Particulate (SP or PM30 with $d_a < 30 \mu m$) is generally regarded as the appropriate equivalent of TSP (USEPA, 1995a).

Dust emissions can be quantitatively predicted by emission factors defined for the different size ranges described above. Several emissions factors for different mining activities developed by various researchers have been proposed. An elaborate literature review of dust emission factors suggested for the most intense mine dust sources (i.e., haulage activity and wind erosion) and for an additional source (i.e., overburden dumping) for comparison purposes is given in Section 2.1.
In general, emission factors are derived by averaging available data and considered to reflect long-term averages of all the same category sources. Therefore, these factors are prone to uncertainty and may misrepresent the individual sources (AEA, 2011). On this subject, Ghose (2004) stated that emission factors developed for one mining site may yield misleading results for another mining site due to the site-specific nature of dust. In a comprehensive study on mine dust emission factors, USEPA compiled the factors developed for western surface mines and thus suggested these factors for any of the surface coal mines located in the western US (USEPA, 1998a). With regard to these widely accepted emission factors introduced by USEPA, Chakraborty, et al. (2002) questioned their accordance with coal mines in India and argued that these emission factors cannot be applicable for the estimation of emission levels in Indian mines since geological, mining and microclimatic conditions are different in India than in the United States. Overall, as noted in a recent study, the validity of the previously developed emission factors in any given coal mining operation is limited to the conditions prevailing during the time they were developed (Huertas, Dumar, & Huertas, 2012). For this reason, closer-to-reality predictions of the dust emission levels arising from mining activities necessitate the development of location- and activity-specific emission factors. Effective dust control approaches can be designed on the basis of such reliable emission assessments.

Besides mine dust emission factors, a number of mine dust control methods and corresponding reduction factors are presented in the literature. A review of the literature on the control methods proposed for major mine dust sources, i.e., haulage activity and wind erosion, and for the additional activity of overburden dumping, as well as the corresponding reduction factors pertaining to these methods are presented in Section 2.2.

The literature review on mine dust control methods revealed that a wide range of reduction factors was submitted by different authors for the same or similar methods due to varying measurement conditions such as target particle size and the application rate of the tested method. As an example, water spraying, which is the most common control method applied for dust from haulage activity, can be given. There have been many studies focusing on the effectiveness, i.e., reduction factor, of water spraying for dust emissions from transportation on haulage roads. In a USEPA report (USEPA, 1983), emission decreases were suggested for TSP as 95%
at 0.5 hour and 55% at 4.4 hours after application of water spraying at a rate of 0.13 gal/yd² (ca. 0.6 L/m²). Additionally, the Midwest Research Institute (MIR) estimated 72% and 74% control effectiveness for PM10 and TSP, respectively, over a three-hour period after 0.46 gal/yd² (ca. 2.1 L/m²) water spraying (USEPA, 2006a). Another study proposed that an effective watering period ranges from 0.5 hours up to 12 hours with an overall effectiveness of 40% (Foley, Cropley, & Giummarra, 1996). Later, a handbook on fugitive dust emissions (Countess Environmental, 2006) postulated that the control effectiveness for water spraying varied between 10% and 74%, whereas a more recent study by the National Pollutant Inventory (NPI) for Mining (Environment Australia, 2012) recommended 50% and 75% of dust control effectiveness for watering levels of 2 L/m²·h and >2 L/m²·h, respectively. These variations in reduction factors documented in the literature indicate that application of these factors in any particular mining operation may lead to improper evaluations of dust control performances. In this context, development of location- and activity-specific reduction factors can provide accurate performance estimates and consequently selection of appropriate dust control methods.

As stated above, location- and activity-specific emissions and reduction factors can improve the prediction of mine dust emission levels and the effectiveness of possible measures; however, mine dust control decisions remain a complex task. The difficulty with these decisions stems from the complexity and variety of dust generation mechanisms and corresponding control methods. Mine operators must decide on the simultaneous implementation of control methods for different dust sources (NIOSH, 2003). For this purpose, several institutions have published guidelines for the effective control of dust from mining and mineral handling processes (Environment Australia, 1998; NIOSH, 2003; Countess Environmental, 2006; AEA, 2011; NIOSH, 2012).

Studies have also been conducted on dust emissions particularly arising from coal mining. Donnell, et al. (2011) provided best practices for controlling particle emissions from coal mining activities in the Greater Metropolitan Region (GMR) in New South Wales (NSW), Australia. Another recent study from Australia, the National Pollutant Inventory (NPI) for Mining, described the controlled and uncontrolled emission estimation techniques for coal mining operations (Environment Australia, 2012).
Although it is possible to define dust control practices in mining from a general perspective on the basis of the above mentioned studies, there is no “one-size-fits-all” dust management approach. Mine operators should therefore design dust control strategies that adjust the temporal and spatial variability of emission mechanisms, as well as the cost-performance of control methods in a mining area. Furthermore, the selection of dust control methods should be made during the mine planning phase because reacting after dust emission problems occur is often difficult, impractical or costly (Environment Australia, 1998).

At this point, decision support systems (DSS), which are computer-based tools for facilitating the assessment of complex tasks and assisting in making appropriate decisions, can be applied.

The concept of DSS was introduced by Gorry and Scott Morton (Gorry & Scott Morton, 1971) on the basis of Simon’s description of decision processes (Simon, 1960) and Anthony’s taxonomy for managerial activity (Anthony, 1965). A literature review of DSS is provided in Section 2.3. McIntosh, et al. (2011) proposed that the necessity for deriving new environmental policies and management approaches for complicated environmental problems identified in the late twentieth and early twenty-first centuries has led to the development of environmental DSS, or EDSS. Accordingly, a large variety of DSS have been developed to aid the decision making process in terms of the management of environmental problems. However, no studies presenting a specific DSS designed for evaluating dust emission levels from different sources and the cost-effectiveness of corresponding control methods in mining operations were found during the literature review (see Section 2.3).

To sum up, as introduced in the previous paragraphs, dust emissions from surface coal mines may cause various adverse environmental and health impacts. An appropriate evaluation of emission levels and cost-performance of dust control methods requires the identification of site-specific emissions, their reduction, as well as cost factors. Moreover, designing, evaluating and choosing dust control strategies is in most cases an unstructured decision making issue due to the complexity and variety of mine dust sources and potential control methods. As a result, decision support systems based on location- and activity-specific dust emission factors, reduction factors and the cost parameters of control methods can assist in the development of cost-effective mine dust management options.
1.2. Aims and Objectives

This thesis has three main aims:

- to demonstrate the importance of location- and activity-specific mine dust emission and reduction factors in mine dust management decisions;
- to develop, on the basis of these location- and activity-specific factors, a dust control decision support system (Dust-DSS) that enables accurate evaluation of dust emission levels and cost-performance of possible control options, and correspondingly assists in designing cost-effective dust control approaches for open-pit coal mining operations;
- to investigate and identify mine dust emission levels and the limits of the applicability of different dust control methods in terms of their costs and performances through DSS scenario simulations.

These research aims were addressed within the framework of the Research Association Mining and Environment in Vietnam (RAME) and RAME sub-project IV: “Dust Mitigation and Monitoring”. A description of the project area is provided in CHAPTER 3.

As noted in Section 1.1, haulage activity and wind erosion are indicated as the primary dust sources for surface coal mines. Therefore these activities and overburden dumping as an additional activity for comparison purposes will be particularly focused on in this thesis. In this context, in order to achieve the aims mentioned above, the following objectives are set for this thesis:

- to present location- and activity-specific mine dust emission factors for overburden haulage, wind erosion and overburden dumping under Vietnamese conditions;
- to present location- and activity-specific reduction factors for the dust control methods proposed for overburden haulage, wind erosion and overburden dumping under Vietnamese conditions;
- to determine the cost parameters for proposed mine dust control methods;
- to develop a DSS computational module that integrates emission and reduction factors, as well as cost parameters;
Introduction

- to define the techniques and the technologies for successful mine dust control within a Best Practice Guide (BPG) (the DSS guide module); to verify and validate the developed DSS;
- to design predictive DSS scenarios based on the mining and environmental conditions of the project area;
- to perform DSS scenario simulations within varying mining and cost-performance boundary conditions;
- to assess the DSS scenario simulation results in terms of dust emissions from individual activities and total costs, as well as the cost-effectiveness of different dust control methods.

1.3. Contributions

This thesis presents new dust emission factors for selected mining activities, namely, overburden haulage, wind erosion and overburden dumping, as well as reduction factors for dust control methods relevant to these activities under Vietnamese conditions, which have not been previously investigated. These factors may also be applicable for surface mines that have similar mining, geological and climatic characteristics, and that apply comparable control techniques. In this way, emission levels and possible control performances at such mining locations can be precisely evaluated through the application of these emission and reduction factors. Moreover, the methodological approach followed in this thesis for deriving these factors can be adapted for the development of analogous factors for further mining activities and/or at other mining areas.

The DSS developed within the scope of this thesis can be applied to investigate cost-effective dust control approaches for any active or planned open-pit coal mining operation. Designing mine dust management strategies based on the developed DSS can therefore lead to reduced costs and lower environmental and health impacts. This will in turn result in lower mining and coal supply costs, as well as lower external costs due to coal mining.

Additionally, the scenarios that were assessed within the DSS point out the specific cost and performance parameters that should be taken into account while formulating an adequate dust control approach. Besides, the scenario simulation
Results provide a new perspective for the evaluation of costs and cost-effectiveness of the examined mine dust control methods.

In conclusion, this thesis contributes to the existing literature on dust emission and reduction (control) factors, as well as to the methodologies for developing these factors. Furthermore, by incorporating these factors with the control cost accounting, the developed DSS advances the assessment techniques of dust control strategies. Finally, this thesis enhances the knowledge pertaining to the application boundaries of the investigated dust control methods.

1.4. Structure of Thesis

The main structure of this thesis consists of seven chapters as illustrated in Figure 1. CHAPTER 2 presents the results of an extensive literature review on dust emission and reduction factors, as well as decision support systems.

CHAPTER 3 describes the RAME project area by providing its mining, geological and environmental conditions.

CHAPTER 4 documents the emission measurement equipment, measurement design and data analysis for the development of the mine dust emission and reduction factors, and describes the dust control cost parameterization. This chapter also documents the methodology for dust control DSS development, DSS verification and validation, as well as the development and simulation of the DSS scenarios.

CHAPTER 5 presents the results obtained from measurements taken at the project area, the dust emission factors for selected source activities (i.e., overburden haulage, wind erosion and overburden dumping) and the reduction factors for corresponding dust control methods. Additionally, this chapter includes insight to these control methods and the limits of their applicability. The context of the developed DSS and the results of DSS scenario simulations are also presented in this chapter.

CHAPTER 6 provides the interpretation of the key results given in CHAPTER 5 in light of the literature review in CHAPTER 2. Moreover, CHAPTER 6 also discusses the coherence of these results in terms of the aims of the thesis.
CHAPTER 7 concludes this thesis with an extensive overview of the research results, presents the limitations encountered during the research and includes recommendations for further research.

**Figure 1.** Thesis structure
CHAPTER 2. LITERATURE REVIEW

This chapter presents the primary results of the literature review pertaining to the research topics addressed in this thesis, starting in the first section with the dust emission factors for the major mine dust sources in surface coal mining, i.e., overburden haulage and wind erosion (as noted in Section 1.1), and as well as for overburden dumping. An overview of the reduction factors for the dust control methods proposed for these activities is provided in the second section. This is followed by a comprehensive review of the literature regarding decision support systems.

2.1. Mine Dust Emission Factors

A dust emission factor numerically represents the amount of dust particles emitted from a source activity in terms of the parameters influencing the emission rate. These influencing parameters can be divided into three categories: (i) measure of source activity; (ii) properties of the material being disturbed; (iii) climatic parameters (USEPA, 1998b).

Numerous studies are available in the literature that focus on the development of dust emission factors for surface coal mining operations in the US (Cowherd, Axetell, Guenther, & Jutze, 1974; Axetell J. K., 1978; Axetell & Cowherd, 1984; Muleski G. E., 1991; Muleski, Garmen, & Cowherd, 1994). The US Environmental Protection Agency (USEPA) conducted a comprehensive study on the subject and compiled emission factors for different industries within a document referred to as AP-42. The first version of AP-42, Section 11.9, which is devoted to the emission factors for dust sources at western US surface coal mines, was drafted in 1983; the latest version was published in 1998 (USEPA, 1998a; USEPA, 1998b). Other sections of AP-42 also includes additional emission factors for activities related to mining such as haulage on unpaved roads (USEPA, 2006a) and wind erosion (USEPA, 2006c).

Environment Australia has published emission estimation technique manuals for various industrial activities in Australia. Two of these manuals (Environment Australia, 2000; Environment Australia, 2012) describe the estimation techniques for emissions associated with mining activities. The corresponding emission factors recommended in these manuals for mining were mostly drawn from the USEPA AP-42 study mentioned above. In addition, different authors investigated the dust
emission factors for surface coal mining operations in India (Chakraborty, et al., 2002; Chaulya, et al., 2002; Chaulya, 2004; Ghose, 2004; Ghose, 2007). Furthermore, in a recent study, Böhner (2014) quantified the emissions arising from the major dust sources at industrial rocks and minerals quarries and pits in Germany.

As explained in Section 1.1 of this thesis, location- and activity-specific emission factors can provide for the better prediction of mine dust emission levels. Therefore, the RAME sub-project IV: “Dust Mitigation and Monitoring” focuses on the emission factors for the mining activities identified at the project area, the NBCC coal mine in Ha Long, Vietnam. Among these mining activities, the emission factors for primary dust-generating activities (overburden haulage and wind erosion), as well as an additional activity (overburden dumping) under Vietnamese conditions will specifically be addressed in this thesis. Accordingly, from the preceding literature, the emission factors suggested by Chakraborty, et al. (2002) and those in the different sections of the USEPA AP-42 document (USEPA, 2006a; 2006b; 2006c) will be used as references for comparing the emission factors proposed in this thesis.

USEPA (2006a) recommended a size-specific emission factor equation for haulage activity on unpaved roads as given in Eq. 1:

\[
E = k \times \left( \frac{s}{12} \right)^a \times \left( \frac{W}{3} \right)^b
\]

**Eq. 1**

where \(k, a\) and \(b\) are empirical constants for the stated aerodynamic particle sizes (PM2.5, PM10 and PM30) and:

- \(E\) = size-specific emission factor (lb/VMT)
- \(s\) = surface material silt content (%)
- \(W\) = mean vehicle weight (tonnes)

It should be noted here that PM30, or SP, is generally used as a surrogate for TSP (USEPA, 1995a), as previously noted in Section 1.1.
Chakraborty, et al. (2002) defined the SP (PM30) emission rate for transportation on haul roads as shown in Eq. 2:

\[
E = \left(\frac{100 - m}{m}\right)^{0.8} \times \left(\frac{s}{100 - s}\right)^{0.1} \times u^{0.3} \times [2663 + 0.1(v + fc)]10^{-6} \tag{Eq. 2}
\]

where:

- \( E \) = emission rate (g/s*m)
- \( m \) = moisture content of haul road dust (%)
- \( s \) = silt content of haul road dust (%)
- \( u \) = wind speed (m/s)
- \( v \) = average vehicle speed (m/s)
- \( f \) = frequency of vehicle movement (no/h)
- \( c \) = capacity of dumpers (tonnes)

The emission factor given by USEPA (2006c) for particulate emissions generated by the wind erosion of exposed material is illustrated in Eq. 3. The erosion potential \( P \) in Eq. 3) is described by Eq. 4:

\[
E = k \sum_{i=1}^{N} P_i \tag{Eq. 3}
\]

\[
P = 58(u^* - u_t^*)^2 + 25(u^* - u_t^*)
\]

\[
P = 0 \ (u^* \leq u_t^*) \tag{Eq. 4}
\]

where \( k \) is the particle size multiplier defined for PM2.5, PM10, PM15 and PM30 and:

- \( E \) = emission factor (g/m²)
- \( N \) = number of disturbances per year (365 for a surface disturbed daily)
- \( P \) = erosion potential (g/m²)
- \( u^* \) = friction velocity (m/s)
- \( u_t \) = threshold friction velocity (m/s)

As an example, the threshold friction velocity \( (u_t) \) for overburden material was determined by the field measurements as 1.02 m/s (USEPA, 2006c).
The emission rate defined by Chakraborty, et al. (2002) for wind erosion from exposed overburden dumps in terms of SP (PM30) is given below (Eq. 5):

\[
E = \left(\frac{100 - m}{m}\right)^{0.2} \times \left(\frac{s}{100 - s}\right)^{0.1} \times \left(\frac{u}{2.6 + 120u}\right) \times \left(\frac{a}{0.2 + 276.5a}\right) \tag{Eq. 5}
\]

where:

- \(E\) = emission rate (g/s*m²)
- \(m\) = moisture content of dump material (%)
- \(s\) = silt content of dump material (%)
- \(u\) = wind speed (m/s)
- \(a\) = area of active dump (km²)

USEPA (2006b) correlated the dust emission due to dumping activity with the mean wind speed and material moisture content as shown in Eq. 6:

\[
E = 0.0016k \times \left(\frac{U}{2.2}\right)^{1.3} \div \left(\frac{M}{2}\right)^{1.4} \tag{Eq. 6}
\]

where \(k\) is the multiplier for PM2.5, PM5, PM10, PM15 and PM30 and:

- \(E\) = emission factor (kg/Mg)
- \(U\) = mean wind speed (m/s)
- \(M\) = material moisture content (%)

On the other hand, Chakraborty, et al. (2002) defined the SP (PM30) emission rate for overburden dumping (unloading) as follows (Eq. 7):

\[
E = 1.76h^{0.5}\left(\frac{100 - m}{m}\right)^{0.2} \times \left(\frac{s}{100 - s}\right)^2 \times u^{0.8} \times (cy)^{0.1} \tag{Eq. 7}
\]

where:

- \(E\) = emission rate (g/s)
- \(m\) = moisture content of unloading material (%)
- \(s\) = silt content of unloading material (%)
- \(u\) = wind speed (m/s)
- \(h\) = drop height (m)
- \(c\) = capacity of unloader (tonnes)
- \(y\) = frequency of unloading (no/hour)
2.2. Mine Dust Reduction Factors

A reduction factor (i.e., control effectiveness) of a dust control method is the percentage ratio of the amount of emission controlled (reduced) to the amount of uncontrolled emission. In the literature, a wide range of mine dust control methods and respective reduction factors have been provided.

In a handbook on fugitive dust emissions from major sources within different industries including coal mining, Countess Environmental (2006) compiled dust control measures for these sources and their effectiveness. A recent NIOSH study summarized the best dust control techniques for mining and mineral processing activities and the effectiveness of these techniques (NIOSH, 2012). In another recent work, Environmental Australia (2012) provided emission reductions for control methods proposed for various mining operations.

During the literature review on dust reduction factors, a study focusing on overall fugitive dust emission control (USEPA, 1992) and a study conducted for dust sources at iron and steel plants (USEPA, 1983) were also evaluated. The recommended control techniques and corresponding reduction factors in these studies for haulage on unpaved roads and wind erosion were found to also be applicable to mining areas.

Since mine haul roads are the primary dust sources at coal mines, particular attention was given to the control of dust emission from haul roads during the literature review. The effectiveness of dust control methods for unpaved haul roads were discussed in different sections of the USEPA AP-42 document (USEPA, 1998c; 2006a). Additionally, Thompson and Visser (2007) assessed the control effectiveness of dust palliatives on surface mine haul roads. A study by Reed and Organiscak (2005) regarding dust exposure to mine truck drivers also specified several dust control practices and their effectiveness. General studies on road dust control were also found in the literature. For example, Muleski and Cowherd (1987) analyzed the dust control effectiveness of chemical suppressants on unpaved roads. Other examples are two extensive studies on various measures for controlling road dust and their effectiveness (Foley, Cropley, & Giummarra, 1996; Watson, et al., 1996). The reduction factors, i.e., the control
effectiveness presented in these studies are considered viable for the control methods proposed for overburden haulage within the scope of this thesis.

The dust control methods for overburden haulage, wind erosion and overburden dumping and their respective reduction factors suggested in the literature are shown in Appendix C.

2.3. Decision Support Systems

Decision support systems (DSS) are computer-aided systems that support complex decision making by assisting in the organization of information (Sage, 1991; Sauter, 1997). The evolution of DSS since their first phase of development in the 1970s has previously been discussed in detail by various authors including Courtney (2001) and Shim, et al. (2002).

The DSS concept was first defined in the work of Gorry and Scott Morton (1971) on management information systems. The authors proposed a two-dimensional framework by combining the categories of managerial activities described by Anthony (1965) with the decision types defined by Simon (1960). Anthony (1965) divided managerial activities into strategic planning, management control and operational control, and argued that each category represents different information requirements. Simon (1960), on the other hand, classified the decisions according to their mechanisms as programmed (repetitive and routine) and non-programmed (novel, ill-structured and consequential) decisions.

Within their framework, Gorry and Scott Morton (1971) expanded Simon’s classification as structured, semi-structured and unstructured decisions. In order to explain this classification, they referred to problem solving, i.e., decision, phases as defined by Simon (1960): intelligence (necessity for a decision), design (development of possible solutions) and choice (selection of the best solution). Accordingly, Gorry and Scott Morton (1971) classified the structured decision problems as problems in which all of these three phases, i.e., intelligence, design and choice, are defined. Furthermore, they described DSS as computer-based tools that deal with semi-structured or unstructured problems where at least one of these phases is ill-structured (Gorry & Scott Morton, 1971). This definition for DSS was confirmed by several later authors (Bonczek, Holsapple, & Whinston, 1981; Sprague & Carlson, 1982; Sage, 1991; Courtney, 2001; Shim, et al., 2002).
McIntosh, et al. (2011) explained that the different types of decisions, i.e., structured, semi-structured and unstructured, can also be identified using the three point spectrum provided by Pidd (2009). In this spectrum, decisions are ranged according to the complexity of problem formulation and solution as (1) puzzles (both formulation and solution are agreed upon); (2) problems (formulation is agreed upon and solution is arguable); (3) messes (both formulation and solution are arguable). Accordingly, McIntosh, et al. concluded that DSS provide support for either semi-structured decisions with agreeable formulation but arguable solution, as well as for unstructured decisions with arguable formulation and solution.

DSS is a type of computer-based information systems (CBIS) that are used for the improvement of operations, management and decision making. Eom (2001) proposed that DSS have become an important subset of CBIS since the 1970s. Sauter (1997) described four possible information systems along a continuum from management information systems (MIS) through decision support systems (DSS), executive information systems (EIS) to expert systems (ES). In addition to these systems, Eom (2001) specified artificial neural networks (ANN) as the latest addition to CBIS.

Sprague and Carlson (1982) and later also Sage (1991) defined the primary components of DSS as database management systems (DBMS), model-based management systems (MBMS) and dialog generation and management systems (DGMS). DBMS are the tools for creating, managing and storing input data to DSS (Eom, 2001), whereas MBMS enable the decision maker to explore the decision making environment through the use of models based on algorithms and protocols (Sage, 1991). Additionally, DGMS, i.e., the user-interface, is designed to provide users with gateways for transmitting their inputs to and for acquiring outputs from DMBS and MBMS (Sage, 1991; Eom, 2001). In addition to these three components of DSS, Sauter (1997) stated a fourth component, that is, mail or message management systems (MMS), which provide supplementary sources of data, modeling, or general help in the decision making process.

Integration of the aforementioned subsystems of DSS, i.e., MBMS, DBMS and DGMS, requires an appropriate design approach. In general, a system development life cycle (SDLC) approach, which includes different hierarchical phases, has been widely employed for building computer-based systems. However, alternative
approaches have also been proposed by authors, since there is no accepted procedure for dividing systems projects into the phases of SDLC (Watson, Watson, Singh, & Holmes, 1995). In particular, the SDLC approach is incompatible with DSS development due to the unstructured (Moore & Chang, 1980) or fuzzy (Sauter, 1997) nature of DSS problems. Prototyping, iterative design and heuristic design are some examples of alternatives to SDLC (Watson, Watson, Singh, & Holmes, 1995). Additionally, Sage (1991) suggested a seven-phase DSS design methodology on the basis of representations, operations, memory aids and controls (ROMC) analysis defined by Sprague and Carlson (1982). Sauter (1997) provided another methodology that differs from the SDLC approach by providing a detailed account of the required information and information types for a DSS design. Later, Marakas (1999) proposed another method, the DSS development process (DDP), which enables a unique approach for each DSS design project. This method will be employed in this thesis for the development of the Dust-DSS.

English, et al. (1999) comprehensively described the need for tools to aid environmental decision making and listed air-quality control as one of the 10 clusters of environmental decisions. More specifically, McIntosh, et al. (2011) explained the development of environmental DSS or EDSS as a result of searching for solutions to the complex and extended environmental issues of the past number of decades. In their study focusing on challenges and recommending best practices in the development of EDSS, a range of EDSS representing various land and water related decision contexts was reviewed. Additionally, a comprehensive evaluation of exemplary EDSS available in the US can be found in a report prepared by Sullivan (2002).

Regarding air-quality control, numerous DSS especially for urban air pollution are presented in the literature (Fedra & Haurie, 1999; Bohler, Karatzas, Peinel, Rose, & San Jose, 2002; Fincher & Stave, 2007; Elbir, et al., 2010). However, to date, no literature has been found on DSS for mine dust control that will be researched in this thesis. Nonetheless, there are studies that have focused on the cost and performance of mine dust control. Vizayakumar and Mohapatra (2002) studied the health and environmental impacts of emissions from coal mining including particulate emissions and built a system dynamics model for evaluating alternative control policies. Additionally, in more specific studies, models were developed for the
performance and economic evaluation of dust control approaches, i.e., water spraying and application of chemicals, for unpaved mine haul roads (Thompson & Visser, 2002; 2007). Moreover, the handbook by Countess Environmental (2006) and the report by Donnelly, et al. (2011) provided cost figures and a cost-effectiveness analysis for different dust control options. However, it is noted in these studies that their results were based on generalized assumptions and that actual cost-effectiveness values need to be evaluated for site-specific conditions.
CHAPTER 3. DESCRIPTION OF PROJECT AREA

The “Research Association Mining and Environment in Vietnam” (RAME) project focuses on developing and adapting environmental concepts as well as carrying out capacity building for the hard coal mining industry in Vietnam. For this purpose, RAME has carried out joint research projects funded by the German Ministry of Education and Research (BMBF) in close cooperation with the Vietnam National Coal Mineral Industries Group (VINACOMIN). The research described in this thesis was conducted as a part of RAME sub-project IV: “Dust Mitigation and Monitoring”, in which fugitive dust emission problems at open-pit coal mines are addressed. The project site chosen was the open-pit coal mines operated by the Nui Beo Coal Joint Stock Company (NBCC) in Ha Long, located in Quang Ninh Province in Northern Vietnam.

3.1. Economic Importance of Mining

Hard coal mining is one of the core industries in Quang Ninh Province, as it provides most of the total hard coal production in Vietnam (Sinh, 1998; USGS, 2009). The NBCC, one of the group companies of VINACOMIN, runs open-pit coal mining operations in Ha Long where the country’s largest coal reserve lies.

VINACOMIN operates 95% of the coal mines in Quang Ninh Province. The estimated coal reserves in the region are approximately 10.5 bn t (USGS, 2009). Accordingly, this province contributes the majority of the total coal production of Vietnam and the mining industry is the largest employer in the province (Sinh, 1998).

Furthermore, the growing energy demand in Vietnam due to the country’s incremental economic development, with annual rates of 7% to 8% in recent years, requires an increase in domestic coal production (Nhan & Ha-Duong, 2009). Moreover, it is expected that coal will be the dominant fuel for electricity generation in Vietnam from 2015 to 2030 (Nhan & Ha-Duong, 2009). Thus, coal mining contributes to the energy security and the socio-economic development of Vietnam (Chinh & Gheewala, 2008).

3.2. Geology and Mining

Ha Long is geologically located within the 200 km long anthracite Quang Yen basin which constitutes the bulk of Vietnam’s coal reserves. This high energy anthracite
reserves is high in quality with its high calorific value (7000 to 8600 kcal/kg) and low ash and sulfur (3% to 7% ash, 0.2% to 1.2% S) contents (Kušnir, 2000). The coal reserves in this basin mined by the NBCC are found within the lower subformation (T3n-r hg1) of the Hon Gai formation. The subformation is composed of alternating strata of conglomerate, gritstone, sandstone, siltstone, clay shale, coaly shale and coal seams with a total thickness ranging from 1500 m to 1700 m (DPGM, 2001).

Figure 2 shows a map of the NBCC mining area. As shown in this figure, the NBCC operates two open-pit mines in Ha Long. The individual thickness of the coal seam at the NBCC mines varies from 7 m to 50 m. The dip angle of the coal seam is on average about 30°.

Figure 2. Map of NBCC mining area (BBK I, 2013a)
Hard coal production, overburden removal rates and the corresponding stripping ratios of the NBCC from 2003 to 2011 are shown in Figure 3. As can be seen in this figure, the coal production of NBCC was 5.1 Mt in 2009, 5.3 Mt in 2010 and 4.7 Mt in 2011. The amount of overburden removed for the same years were 21.5 Mm$^3$, 20.8 Mm$^3$ and 21.5 Mm$^3$. The average stripping ratio at the NBCC mines between 2003 and 2011 was recorded as 5.4 m$^3$/t (BBK I, 2013a).

![Figure 3. Production development of NBCC from 2003 to 2011](image)

The mining method employed by the NBCC is conventional truck and shovel operation, working in two open pits (see Figure 2). Drilling and blasting is applied in overburden removal. The overburden material is then either transported to the Chinh Bac dumping site or backfilled into the mined sections of the open pits. Raw coal is transported to the coal preparation plants within the mining site for pre-treatment. Subsequently, the coal is hauled by trucks to the VINACOMIN-owned coal washing plant adjacent to My Con Cua Harbor. The main haulage roads in the mining area and the road to the harbor are also shown in Figure 2.

### 3.3. Climate

Ha Long has a typical tropical monsoon climate divided into two seasons: a cool and dry season between November and April and a hot and rainy season between
May and October. The short-term average meteorological data for the years 2010 and 2011, obtained from the Bai Chay meteorological station in Ha Long are given in Table 1. Additionally, this table summarizes the number of wet days (at least 0.254 mm of precipitation) estimated based on the assumption proposed by USEPA (1998b; 2006a).

<table>
<thead>
<tr>
<th>Meteorological Info</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total precipitation</td>
<td>mm</td>
<td>72</td>
<td>13</td>
<td>33</td>
<td>81</td>
<td>198</td>
<td>316</td>
<td>247</td>
<td>447</td>
<td>336</td>
<td>64</td>
<td>6</td>
</tr>
<tr>
<td>No of wet days (&gt;0.254 mm)</td>
<td>day</td>
<td>8</td>
<td>8</td>
<td>10</td>
<td>12</td>
<td>11</td>
<td>16</td>
<td>16</td>
<td>23</td>
<td>17</td>
<td>8</td>
<td>4</td>
</tr>
<tr>
<td>Average wind speed</td>
<td>m/s</td>
<td>2.4</td>
<td>2.1</td>
<td>2.3</td>
<td>1.8</td>
<td>2.2</td>
<td>2.3</td>
<td>2.5</td>
<td>2.2</td>
<td>2.4</td>
<td>3.0</td>
<td>2.4</td>
</tr>
<tr>
<td>Average temperature</td>
<td>°C</td>
<td>15.1</td>
<td>17.8</td>
<td>18.5</td>
<td>22.5</td>
<td>26.7</td>
<td>29.1</td>
<td>29.4</td>
<td>27.9</td>
<td>27.5</td>
<td>24.7</td>
<td>22.5</td>
</tr>
<tr>
<td>Average humidity</td>
<td>%</td>
<td>81</td>
<td>87</td>
<td>84</td>
<td>88</td>
<td>85</td>
<td>84</td>
<td>83</td>
<td>87</td>
<td>84</td>
<td>77</td>
<td>76</td>
</tr>
<tr>
<td>Average daily solar radiation</td>
<td>kWh/m²/d</td>
<td>1.8</td>
<td>2.3</td>
<td>1.8</td>
<td>2.7</td>
<td>4.0</td>
<td>4.9</td>
<td>5.7</td>
<td>4.3</td>
<td>4.2</td>
<td>3.6</td>
<td>3.7</td>
</tr>
<tr>
<td>Dominant wind direction 2010</td>
<td>-</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>NNW</td>
<td>N</td>
<td>N</td>
<td>NE</td>
<td>NE</td>
<td>N</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>Dominant wind direction 2011</td>
<td>-</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>NE</td>
<td>N</td>
<td>N</td>
<td>NNE</td>
<td>NE</td>
<td>SSE</td>
<td>N</td>
<td>N</td>
</tr>
</tbody>
</table>

As shown in Table 1, significant differences can be observed between total precipitation, average number of heavy rainy days, temperature and daily solar radiation levels measured in Ha Long during the dry and wet seasons. The maximum precipitation, 447 mm, was seen in August, whereas the minimum precipitation was received as 6 mm in November. Correspondingly, the highest number of wet days was estimated at 23 days in August, whilst only four days were classified as wet days in November and December.

As mentioned above, the air temperature in Ha Long is very high during the rainy season. The average temperature reached its highest in July with 29.4°C, and
dropped down to 15.1°C in January. Similarly, the daily solar radiation level is typically high during the rainy season and decreases in the dry season. The highest and lowest solar radiations were recorded as 5.7 kWh/m²/d in July and as 1.8 kWh/m²/d in January and March, respectively. There were minor or no variations in average wind speed, average humidity and dominant wind direction data based on seasonal changes.

3.4. Environmental Sensitivity
The NBCC mining site is located in an environmentally sensitive area, as it is less than 3 km away from the Ha Long Bay UNESCO World Heritage Site. This heritage site is renowned for its outstanding scenic beauty composed of numerous caves and extraordinary geomorphological structures, instilling it with significant biological value (IUCN/WCMC, 2000). Vietnam’s first national park, Cat Ba Island National Park, can also be found in the same area, adjacent to this World Heritage Site. The park has a unique ecosystem and high species richness and is therefore recognized as a high priority for global conservation (WB, 2005). Ha Long recently became a center of tourism due to both its remarkable natural scenery and its wide range of biodiversity.

The mining activities in Ha Long have substantial environmental impacts on local natural resources, i.e., the Ha Long Bay UNESCO World Heritage Site and Cat Ba National Park. The operations of the NBCC also cause a variety of environmental effects, primarily due to mine dust emissions, mine water discharges and waste rock dump slope stability issues.

In the NBCC mining area, fugitive mine dust is generated by coal production and overburden handling activities, as well as by wind erosion. Coal extraction, haulage and preparation are considered to be the most intense dust sources in the coal production chain. In addition, the significant dust-generating activities related to overburden handling are overburden removal, haulage and dumping. Overall, the primary dust sources at the NBCC mining area are overburden truck haulage and wind erosion since they cause 54% and 34% of the total dust generation at the mining area, respectively (BBK I, 2013b). The current dust control methods applied in the NBCC area can be considered insufficient; however these can be optimized (Martens, Katz, Özdemir, Förster, & Fuchsschwanz, 2013).
Mine water discharge can be stimulated by high rainfall intensity over a mining area. The rainy season in Ha Long, which has above average precipitation levels, lasts from May to October, as described in Section 3.3. The monthly average precipitation can be more than 300 to 400 mm during this season (see Table 1). The high level of precipitation in Ha Long increases mine water discharge levels. Particularly at dumping sites in the NBCC mining area, surface run-off, water infiltration and seepage can be observed. There is neither a water drainage system nor a water treatment facility present at the site for controlling the mine water. According to the results of the water sampling conducted in August 2008 at two open-pit lakes and the mine-water collection dam, the pH values of the mine water lie between 2.7 and 7.6, and the water is therefore classified as high-acidic/extreme metal (Ahmad, 2013).

Stability is one of the major prerequisites for the successful rehabilitation of waste rock dump (WRD) areas. Unless adequately treated, WRD stabilization problems can also induce other environmental impacts like erosion, settlement and contaminated mine water. The current dumping method employed at the Chin Bac waste rock dump in the NBCC mining area is sidehill dumping. At some locations of this dump site, dumping heights (i.e., bench heights) of up to 50 m with a slope angle of 27° can be observed. At other locations, varying dumping heights between 10 m and 20 m and with slope angles ranging from 30° to 40° can be found. As a result of side-hill dumping, the above mentioned problems can be observed at the mining site. However, the layered dumping method designed within the framework of the RAME project offers significant potential for controlling these impacts. This method proposes reduced dumping heights (4 m) and increased slope angles (45°), and eventually a higher factor of safety (FoS) (Martens, Pateiro Fernandez, Ahmad, Fuchsschwanz, & Deissmann, 2009; Ahmad, 2013; Martens, Katz, Özdemir, Förster, & Fuchsschwanz, 2013).
CHAPTER 4. METHODOLOGY

Evaluation of fugitive mine dust generation and its control can be considered a mine-specific issue for the majority of mining activities. Site-specific characteristics, which are mining conditions, local climate and geology, determine the emission levels of individual mine dust sources. Additionally, the performance of any mine dust control method depends on both these site-specific conditions, as well as the application variations of said method. In addition, various control methods are available for a single mine dust source, and each method has different effectiveness levels and cost drivers. Therefore, the primary subject of this thesis, i.e., development of mine dust control decision support system (Dust-DSS), is based on in-detail identification of location- and activity-specific mine dust emission factors, reduction factors of dust control methods and the cost parameters of these methods.

The location- and activity-specific parameters and the Dust-DSS were developed and implemented for the chosen open-pit coal mine of the Nui Beo Coal Company (NBCC), located in Ha Long, Vietnam, within the scope of the RAME sub-project IV: “Dust Mitigation and Monitoring”.

The thesis methodology is illustrated in the form of a flowchart in Figure 4. As indicated, first, site-specific emission factors for the identified dust-generating mining activities (i.e., dust sources) were derived at the NBCC mining area. Second, the reduction factors were estimated as a performance measure of proposed dust control methods, which were grouped as the methods adapted at the NBCC mining area and the alternatives to these methods. Concurrently, the cost driving parameters for these control methods were identified and valued. Following on, a mine dust control DSS was developed based on emission factors, reduction factors and the cost parameters of the control methods. Finally, DSS scenarios were designed and simulated in order to evaluate the emission levels of different mining activities, as well as the costs and applicability limits of selected dust control methods. Details of the methodological approach are provided in the following sections.
4.1. Development of Mine Dust Emission Factors, Reduction Factors and Dust Control Cost Parameterization

In order to estimate mine dust emission factors, first, the site-specific dust emission sources (i.e., mining activities) at the NBCC mining area and the parameters influencing dust emission were determined (see Figure 4). Following on, real-time dust emission measurements were conducted. Finally, based on the measurement data, mine dust emission factors were estimated by means of dispersion modeling and subsequent statistical analysis.

The computer-based dispersion modeling and following statistical analysis were performed within the scope of the RAME sub-project IV: “Dust Mitigation and Monitoring”. The results (mine dust emission factors) for the selected mining activities (overburden haulage, overburden dumping and wind erosion) are presented in Table 6 in Section 5.1.1.3 of this thesis.

Mine dust control methods were grouped as adapted and alternative methods (see Figure 4). The dust reduction factors of the methods adapted at the NBCC mining area were estimated based on real-time dust control performance measurements.
These measurements were targeted to quantify the parameters influencing dust control and were followed by dispersion modeling and statistical analysis. For alternative methods, the control performances were adapted from existing literature (see Appendix C).

Cost parameters for the proposed dust control methods were determined according to previous studies, e.g., CostMine’s “Mine and Mill Equipment Costs Estimator’s Guide” (CostMine, 2009; 2012), and cost information from local statistical institutes (Landesregierung NRW, 2012) and suppliers.

4.1.1. Description of Real-Time Measurement Equipment

The methodological approach for the development of mine dust emission and reduction factors are similar as both involve real-time emission measurements. During these measurements, individual dust sources at the NBCC mining area and adapted dust control methods were focused on with respect to the emission (particulate matter, PM) concentration levels according to varying mining and dust control conditions.

There are two fundamental methods for PM concentration measurement: the gravimetric method and optical counting. PM concentration is determined in units of PM mass per volume of air using the gravimetric method, whereas optical counting provides concentrations in particle per volume of air.

The real-time emission measurements at the NBCC mining area were targeted in order to measure fluctuating PM levels according to constantly varying measures of the source activities and/or the application levels of dust control methods. In standard gravimetric methods, PM concentrations are determined by the ratio of collected particles on a filter medium to the volume of air passed through the filter. Therefore, gravimetric methods can only provide average dust concentration levels for long-term intervals that are equal to the filter change periods. For this reason, mobile optical counting devices, which measure dust concentrations for short-term intervals, were selected for the measurements at the NBCC mining area. Moreover, as suggested by Klenk (2011), mobile optical measurement of PM concentrations is appropriate for the identification of airborne dust particles in larger areas and in the case of more diffuse sources. Consequently, mobile optical aerosol spectrometers
Methodology

(Grimm, Models 1.107 and 1.109) were used in the real-time emission measurements.

Grimm aerosol spectrometers are capable of measuring both the particle concentration in particle per liter of air volume and the mass concentration in µg per m³ of air volume by using standardized dust mass fraction according to the EN 481 standard. The measuring principle of the spectrometer is the optical light scattering of single particles, using a semiconductor laser as light source. The 1.107 model can simultaneously measure particles at PM1, MP2.5 and PM10, whereas the 1.109 model possess 31 particle size channels and can detect particles between 0.25 µm and 32 µm. The spectrometers can measure in intervals from six seconds up to 60 minutes and all measuring results are stored in the devices’ memory card, for later transmission to an external PC (GRIMM, 2009).

Six aerosol spectrometers, one a 1.107 model and five 1.109 models, were utilized for real-time measurements. The spectrometers were sensitive to humidity and it was not always possible to employ all six during the measurements, due to the high humidity conditions at the mining area. The 1.109 model spectrometers were attached and used on field tripods (Figure 5), whereas the 1.107 model spectrometer was employed within its outdoor housing.

Figure 5. A: Spectrometer on a tripod; B: Spectrometer (GRIMM, 2009); C: USA on a pneumatic mast
Wind conditions, i.e., wind speed and direction, were measured during the real-time measurements using an ultrasonic anemometer (USA), type USA-1 (METEK). This portable anemometer enabled exact local wind monitoring at the measurement locations. The USA system applies ultrasonic pulses along three non-coplanar ray paths for measuring wind speed and wind direction, or alternatively, the three orthogonal wind components x, y, z (METEK, 2005). As can be seen in Figure 5, the USA was operated on a pneumatic mast in order to ensure the appropriate measurement height.

4.1.2. Mine Dust Emission Factors Development

Estimation of fugitive dust emission levels from individual mining activities is important for evaluating the impact of each activity on air quality and for further designing activity-specific dust control methods. Fugitive mine dust emissions can be quantitatively determined using emission factors which are based on the parameters influencing dust generation.

Mine dust emission factors for the NBCC mining area were developed using a stepwise approach as illustrated in Figure 4. First, the dust-generating mining activities at the NBCC mining area and the parameters influencing the dust emission for each mining activity were identified. Based on this information, real-time dust emission measurements were designed and conducted between October 2010 and November 2012. The measurement data were analyzed by dispersion modeling and subsequent statistical analysis of modeling outcomes, which eventually provided the site-specific emission factors.

4.1.2.1. Identification of Dust-generating Mining Activities and Influencing Parameters

Identification of Dust-generating Mining Activities

In order to derive site-specific dust emission factors, as a first step, dust-generating mining activities and the parameters influencing dust generation were identified through on-site observations, meetings with the NBCC representatives and a literature search. These dust-generating activities were subdivided as coal production and overburden handling related activities, because coal and overburden material have different physical characteristics and therefore different dispersion mechanisms when emitted as dust.
A flowchart listing all identified dust-generating mining activities (i.e., dust sources) within coal production and overburden handling activity groups, as well as wind erosion as an additional dust source at the NBCC mining area is illustrated in Figure 15 in Section 5.1.1.1 of this thesis. Within the scope of RAME sub-project IV, the mining activities listed in this figure were taken into consideration for further analysis. Among these activities, this thesis focused specifically on overburden haulage, overburden dumping and wind erosion.

**Identification of Influencing Parameters**

A dust emission factor relates the emission rate of an activity to the parameters influencing the emission and reflects the relative significances of these parameters to the quantity of the emission. The influencing parameters can be categorized as: (i) measure of source activity; (ii) properties of the material being disturbed; (iii) climatic parameters (USEPA, 1998b). Accordingly, the parameters influencing the dust emissions were identified for each dust-generating mining activity at the NBCC mining area, grouped under these three categories and separately measured during the real-time dust emission measurements. The influencing parameters considered for the activities focused on within this thesis (i.e., overburden haulage, overburden dumping and wind erosion) are given both in Table 2 in the following section and in Table 5 in Section 5.1.1.1.

**4.1.2.2. Conducting Real-time Dust Emission Measurements**

The real-time dust emission measurements aimed to determine both the PM emission concentrations generated by mining activities, as well as the scalar quantities of the parameters influencing emissions.

Quantification of fugitive dust emissions generated by individual mining activities is usually a difficult task due to various parameters influencing the emission rate and the physical limitations of the measurements, such as the mobility of sources and interference with other sources. Therefore, detailed standardization of dust emission measurements for individual dust sources is not always suitable and modifications regarding the source properties are required. However, from a general perspective, emission measurements can be classified as direct and indirect measurements (VDI, 2005).
In direct measurements, the emission source strengths are determined by measuring the dust concentration at the point of transition from the source into the ambient air. On the other hand, indirect measurements aim to estimate the emissions from immission (i.e., ambient air pollution) levels in terms of dust concentration using reverse calculations.

Direct measurement practices require accessible and stationary sources for accurate emission quantification. The direct methods are therefore difficult to apply for the quantification of transshipment processes and wind erosion, despite being the most reliable methods for determining emissions (VDI, 2005; 2010). Consequently, the emission levels of dust sources at the NBCC mining area were quantified using indirect measurement practices.

The procedures for indirect measurements can be conceived in two different measurement setups: the upwind-downwind method and measurement around the source (VDI, 2010). An alternative indirect measurement method is exposure profiling featuring particulate concentration measurements over an effective cross section of dust plume (Cowherd, Axetell, Guenther, & Jutze, 1974). However, this method was impractical for application at the NBCC mining area, as it requires several dust samplers installed in a vertical profile at different heights and predetermined source conditions, such as regulated traffic.

A common method for wind erosion measurements is the wind tunnel method, based on emission measurements under controlled velocities (Countess Environmental, 2006). Despite its reliability, this method was not considered at the NBCC mining area, as the construction of a wind tunnel over the investigated open surfaces was not feasible. Alternatively, a standardized method for the determination of dust precipitation, i.e., the Bergerhoff method, can be applied for wind erosion quantification (VDI, 1996). However, this method was not chosen, since its measurement requirements, e.g., a long-term measurement period (ca. 30 days), could not be met at the NBCC mining area.

Consequently, for the activities studied within the scope of this thesis, the upwind-downwind method was adapted for overburden haulage and overburden dumping, whereas wind erosion was measured at several points within the investigated areas.
The upwind-downwind method essentially requires the measurement of dust concentrations up and downwind of an emission source, as well as wind conditions at the source location. This method has long been utilized in previous studies for the quantification of various fugitive dust sources at construction sites, agricultural lands and mining areas (Kolnsberg, 1976; Axetell & Cowherd, 1984; Watson, Chow, & Pace, 2000; Countess, et al., 2001; Chaulya, et al., 2002; Chakraborty, et al., 2002; Watson, et al., 2011). In this measurement method, the difference between the emissions measured at the upwind and downwind locations represents the net emissions from the sources.

The real-time dust emission measurements for overburden haulage activity were completed from October 2011 to November 2010. A photograph taken on the measurement day of 2010-11-04 and a sketch of the measurement setup are shown in Figure 6.

As shown in Figure 6, six aerosol spectrometers and one USA were used for the overburden haulage emission measurements within the upwind-downwind setup. Five of the spectrometers were installed in two rows downwind of the haulage roads for the quantification of particulate immissions from haulage activities. The sixth spectrometer was placed upwind of the roads for the evaluation of background particulate concentrations. The positions of the upwind (uw) and downwind (dw) spectrometers, and the USA are shown both in the photograph taken on the measurement day of 2010-11-04, as well as in the sketch of the measurement setup in Figure 6.

The haulage activity measurements involved immission quantifications by different truck classes according to the type and condition of haul roads. Consequently, dumping trucks (capacity from ca. 12.3 t to 21.9 t), off-highway trucks (capacity of 55.0 t and 56.2 t) and articulated dump trucks (capacity of 32.5 t and 37.0 t) were investigated on main and side roads, as well as under dry and wet road conditions.
The dust emission due to overburden dumping activity was quantified on the basis of the measurements implemented from November 2011 to December 2011. During these measurements, four aerosol spectrometers and one USA were placed within a customized upwind-downwind measurement setup. Three of the spectrometers were installed in a row at the edge of the dumping level for determination of particulate matter immissions downwind of the dumping points. The background particulate concentrations upwind of the dumping points were evaluated by the fourth spectrometer, which was placed below the dumping level. The USA was positioned on the dumping level for the real-time wind condition measurements. Figure 7 shows
a photograph of the measurement setup (position of upwind (uw) and downwind (dw) spectrometers and USA) and its schematic illustration for the measurement taken on 2011-12-03.

![Image of measurement setup](image)

**Figure 7.** Real-time dust emission measurement setup for overburden dumping on 2011-12-03

For the real-time measurements, dust generation due to dumping activities was considered as an integrated emission caused by trucks approaching the dumping point, actual dumping activity and truck departure from the dumping point. Therefore,
the time required for each step and the total duration of a complete cycle were recorded. Additionally, the measurements for dumping activity focused on dust emission levels from different types of trucks at varying dumping heights. These measurements were conducted for dumping trucks (average capacity of 26700 kg) and off-highway trucks (average capacity of 56700 kg) at the dumping heights and slope angles varied approximately from 7 m to 40 m and from 33° to 42°, respectively.

Real-time wind erosion measurements were conducted using four aerosol spectrometers and one USA from November 2011 to December 2011. In these measurements, immission levels were determined at several points within the investigated areas. A photograph showing the measurement on 2011-12-21 and a sketch of the measurement setup for the same day is shown in Figure 8.

During the real-time measurements for overburden haulage, overburden dumping and wind erosion at the NBCC mining area, the 1.109 model spectrometers were used for particle counting in 31 size channels within a range of 0.25 µm to 32.0 µm, while the 1.107 model was used for the quantification of dust mass concentrations only in PM1, PM2.5 and PM10 fractions. The output interval of the spectrometers and the USA were selected as six seconds in order to collect representative data for short intervals. The USA was installed at suitable points downwind of the source activities for recording the local wind conditions at the measurement areas.
The parameters influencing dust generation were also determined during the real-time measurements (listed in Table 2). The methodologies and sources used to quantify these parameters are also given in this table.
Table 2. Measurement methods for parameters influencing dust emission (overburden haulage, overburden dumping and wind erosion)

<table>
<thead>
<tr>
<th>Mining Activity / Dust Source</th>
<th>Influencing Parameter</th>
<th>Measurement Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overburden haulage</td>
<td>Truck type</td>
<td>Visual observation</td>
</tr>
<tr>
<td></td>
<td>Truck weight</td>
<td>Suppliers' catalogues</td>
</tr>
<tr>
<td></td>
<td>Truck speed</td>
<td>Travel time measurement using a stopwatch within a certain road span</td>
</tr>
<tr>
<td></td>
<td>Road surface thickness</td>
<td>Measuring the thickness of loose surface material and the depths of truck tire prints</td>
</tr>
<tr>
<td>Overburden dumping</td>
<td>Truck type</td>
<td>Visual observation</td>
</tr>
<tr>
<td></td>
<td>Dump weight</td>
<td>Estimation based on number of shovels required to fill the trucks and capacities of loader shovels</td>
</tr>
<tr>
<td></td>
<td>Dumping height and slope angle</td>
<td>Optical hand clinometer (BGI, 1995)</td>
</tr>
<tr>
<td></td>
<td>Dumping duration, truck approaching &amp; departure duration</td>
<td>Time measurement using a stopwatch</td>
</tr>
<tr>
<td></td>
<td>Dust propensity</td>
<td>Visual observation (1 = lowest, 5 = highest)</td>
</tr>
<tr>
<td>Wind erosion</td>
<td>Surface area</td>
<td>GPS measurement</td>
</tr>
<tr>
<td></td>
<td>Vegetation density and vegetation height</td>
<td>Metering</td>
</tr>
<tr>
<td></td>
<td>Surface roughness</td>
<td>Visual observation (0.5 to 1.0, where 1.0 is for a smooth surface)</td>
</tr>
<tr>
<td>Overall</td>
<td>Particle size distribution, silt content and moisture content</td>
<td>Overburden (for dumping) or surface (for haulage and wind erosion) material sampling (grid or random sampling) and consequent laboratory testing (TCVN 4198:1995, 1995; TCVN 4196:1995, 1995)</td>
</tr>
<tr>
<td></td>
<td>Climatic parameters</td>
<td>USA and spectrometers</td>
</tr>
</tbody>
</table>

For example, as shown in Table 2, road surface material (loose surface material on haul roads) was collected by either grid or random sampling (when grid sampling was not applicable due to heavy traffic during measurements). The collected samples were then analyzed for particle size distribution, silt content and moisture content according to Vietnamese standards (TCVN 4198:1995, 1995; TCVN 4196:1995, 1995) by a soil laboratory. As another example, the road surface thickness was determined by measuring both the thickness of loose surface material and the depths of truck tire prints. As a final example, mean dump weights for different type of trucks used for overburden haulage at the NBCC mining area.
(i.e., off-highway trucks, dumping trucks and articulated dump trucks) were estimated based on the average number of shovels required to fill each truck type and approximate capacities of loader shovels. The number of shovels was counted at the overburden loading locations and shovel capacities were obtained from the loader operators. The average dump weight estimated for the off-highway trucks (56.7 t) were slightly larger than the dump capacities suggested by the suppliers (55.0 t and 56.2 t). On the other hand, a single overall average dump weight was estimated for other types of trucks as 26.7 t. Considering that the articulated trucks are rarely employed for overburden haulage and dumping, this average was inconsistent with the recommended truck capacities for dumping trucks (12.3 t to 12.8 t) and for the articulated dump trucks (32.5 t and 37.0 t).

Exemplary sets of dust immission levels recorded in terms of mass concentrations during the real-time measurements for overburden haulage, overburden dumping and wind erosion are presented in Appendix A-1. Additionally, a summary of the measurement results for the parameters influencing the dust emissions from these sources is provided in Appendix A-2.

Other mining activities that are included in overburden handling (i.e., drilling, blasting and loading) and in the coal production chain (from loosening to haulage to the coal washing plant) were not studied as part of this thesis, but were investigated in detail within the framework of RAME sub-project IV. Accordingly, similar indirect measurement strategies were followed for these activities. A varying number of spectrometers, from three to six and a USA were employed during the real-time measurements conducted for these mine dust sources. In addition, the parameters influencing the emission levels of these activities were also quantified via in situ measurements and laboratory tests. The details concerning the measurements for these mine dust sources are presented in the RAME sub-project IV: “Dust Mitigation and Monitoring” Final Report (BBK I, 2013b).

4.1.2.3. Dispersion Modeling and Statistical Analysis for Emission Factors Development

Subsequent to the real-time measurements at the NBCC mining area, the dust emissions generated by the source activities were estimated by computer-based dispersion models within the extent of RAME sub-project project IV.
For haulage activity, the AUSTAL2000 dispersion model was used for calculating emissions due to truck movement on mine haul roads. AUSTAL2000 is a Lagrangian particle model for simulating the atmospheric dispersion of substances (Janicke Consulting, 2011). AUSTAL2000 was developed based on the LASAT model (Lagrangian Simulation of Aerosol Transport), which computes the transport of trace substances in the atmosphere.

The dispersion modeling for truck transportation on mine haul roads was performed as part of RAME sub-project IV. As described in the project’s final report (BBK I, 2013b), haulage activity was considered to be a line dust source and the source strength recalculations in the AUSTAL2000 model provided the emission level generated by transportation activities on haulage roads. In this step, the difference between immission measurements and the background concentrations determined by dispersion modeling with backward particle trajectories provided the additional load caused by haulage roads.

The emissions generated by overburden dumping and wind erosion were calculated using LASAT model simulations as previously presented in the RAME sub-project IV Final Report (BBK I, 2013b). These simulations were based on the dispersion and transport of a representative sample of tracer particles (Janicke Consulting, 2010). In the modeling approaches, atmospheric conditions and the spatial locations of dust sources, as well as the measurement points, were incorporated into conceptual site models.

In order to calculate the dumping activity dust emission, a theoretical emission rate was assigned to the dumping locations in the LASAT model. These locations were defined as area sources that included truck movements immediately before and after the actual dumping activity. The difference between the estimated immissions for the measurement points using the LASAT model runs and the real-time dust concentration measurements provided the calibration factors for each model simulation. These factors, alongside the measured upwind concentrations were then used to calculate the emission levels at dumping locations.

Similar to the overburden activity, wind erosion was calculated by taking into account the calibration factors based on the variation between real-time measurements and the immissions predicted by LASAT models. In this case, wind erosion was
considered as an area source and the influence of upwind concentrations were not considered for the evaluation.

The source emissions calculated by dispersion modeling were analyzed on the basis of the source activity rates in order to develop dust emission factors. For truck haulage activity, dust emission factors were developed in units of grams of PM10 per truck per kilometer (g PM10/km*truck) for wet and dry road conditions depending on the mine truck and haul road types. The overburden dumping emission factor was averaged as the amount of PM30 in grams generated by a tonne of material being dumped (g PM30/t). In addition, the emission factor of wind erosion was quantified in terms of grams of PM30 generated by the size of the area subjected to wind erosion within one hour (g PM30/m²*h).

The estimated mine dust emission factors for overburden haulage, dumping and wind erosion are presented in Table 6 in Section 5.1.1.3 of this thesis. A complete list of emission factors determined within the RAME project for the dust-generating activities at the NBCC open-pit coal mining area can be found in the RAME sub-project IV Final Report (BBK I, 2013b) and here in Appendix B.

4.1.3. Mine Dust Control – Reduction Factors Development

Successful mine dust control management necessitates detailed identification of dust sources and relevant control methods. The effectiveness, i.e., performance of these control methods are defined by the dust reduction factors designated by the type and level of control, as well as the local conditions such as mining characteristics or climate. Therefore, determination of the location- and activity-specific dust reduction factors is necessary for the reliable performance assessment of mine dust control methods.

In order to develop the site-specific reduction factors for the NBCC mining area, first, the dust control methods adapted at the area and the alternative methods were determined (see Figure 4). Following on, the adapted and alternative control methods were separated into two groups as direct and indirect methods with respect to their application requirements. Finally, the reduction factors of the adapted methods were estimated by dispersion modeling and further statistical analysis based on the data obtained from the real-time measurements. For the alternative
methods, the reduction factors were approximated according to values given in the literature.

4.1.3.1. Identification of Adapted and Alternative Dust Control Methods

The dust control methods adapted at the NBCC mining area and their alternatives were determined via observations made at the area, feedback from the NBCC representatives and by consulting the literature review (see Appendix C).

The proposed dust control methods were classified as direct and indirect control methods according to their application principles. The direct methods involved equipment and materials used for dust emission reduction, whereas indirect methods targeted emission prevention via the modification of mining activities. For instance, water spraying is applied at the NBCC mining area against dust emissions from truck traffic on haul roads. This approach is considered a direct method, as it essentially involves water trucks for dust suppression and water as a dust suppressant. On the other hand, indirect control methods require neither equipment nor material for dust control; for example, regulating driving patterns – which is suggested as an alternative dust control method for the NBCC mining area – is classified as an indirect control method for dust generation during overburden haulage. This method includes only the application of driving precautions, such as reducing truck speed (see Appendix C) and keeping adequate distances between trucks (Reed & Organiscak, 2005).

As a general observation, primarily wet dust control methods using untreated mine water as a medium are employed at the NBCC mining area. Mine haul roads, the major dust source of the area, are sprayed by water trucks at irregular intervals (Figure 9). The untreated water is acidic in nature and has devastated the interior pumping systems of these water trucks. Therefore, the watering is done using gravitational forces and with low outlet pressures. Wind erosion is another important dust source at the mining area and is mainly controlled by vegetation. However, vegetation is not applicable at the overburden storage areas, due to steep slope angles (>37°) and high slope heights (up to 50 m) (Ahmad, 2013). Coal preparation plants also serve as significant dust sources within the NBCC mining area. For dust suppression during coal processing, water spraying systems, which are only placed
at the product discharge points, are used. However, these sprays are not present at screens, crushers and belt conveyor transfer points, or at stock areas.

Figure 9. Haulage truck (left) and water truck (right) operating at the NBCC mining area

Alternatives to the dust control methods applied at the NBCC mining area were also determined. For this step, the methods applicable at the mining area were reviewed and selected from numerous dust control methods reported in the literature (see Appendix C) as well as on the basis of on-site observations and feedbacks received from the NBCC site engineers. The control methods identified for overburden haulage, dumping and wind erosion are listed in Table 7 in Section 5.1.2.1 of this thesis.

4.1.3.2. Identification of Primary Mine Dust Sources

The dust emission levels of individual mining activities were taken into consideration for designing the dust control performance measurements that would help to identify and focus on the primary mine dust sources. The average daily dust emissions from each mining activity and the total daily dust emission level at the NBCC area was estimated based on the site-specific emission factors. Accordingly, the primary dust-generating activity was specified as overburden haulage, which constituted 54% of the total daily dust emission at the NBCC mining area (see Figure 16 in Section 5.1.2.2 of this thesis). Therefore, among the mine dust sources focused on within this thesis, dust control performance measurements were implemented only for overburden haulage.
The performances of the control methods associated with overburden dumping and wind erosion were determined on the basis of the data obtained from the previous real-time measurements that were conducted for the development of emission factors. Additionally, the reduction factors of the control methods, for which there were no measurement data (e.g., road paving for haulage and chemical wetting for wind erosion), were estimated according to data found in the literature.

4.1.3.3. Conducting Real-time Dust Control Performance Measurements

The real-time dust control performance measurements included quantification of immission concentrations generated by mining activities according to the predefined application conditions of the control methods. Performance of a dust control method can be expressed using a reduction factor, which is the percentage reduction in dust generation as a result of the application of said method. Therefore, immission concentrations caused by source activities in controlled and uncontrolled conditions were monitored during the dust control performance measurements.

Dust control performance measurements were only conducted for overburden haulage activity, as explained in the previous section. These measurements were targeted to differentiate between dust reduction levels with respect to the application level of the tested control method. In this context, the existing dust control method applied for overburden haulage, i.e., water spraying, was investigated in terms of immission levels resulting from haulage activity according to various water spraying rates. Finally, the actual reduction maintained and the potential reduction levels to be achieved by water spraying was distinguished on the basis of these immission levels, as well as varying water spraying rates.

The dust control performance measurements for overburden haulage were carried out in November 2012. For these measurements, an indirect measurement approach was applied due to its feasibility for mining environments as already discussed in Section 4.1.2.2. These indirect measurements were conducted with three 1.109 model spectrometers, one 1.107 model spectrometer and one USA. In Figure 10, the positions of the upwind (uw) and downwind (dw) spectrometers and USA for the measurement date of 2012-11-02 is shown.
Analogous to the real-time emission measurements (see Section 4.1.2.2), for the dust control performance measurements, the 1.109 model spectrometers were used for particle counting from 0.25 µm to 32.0 µm in 31 size channels, whilst the model 1.107 measured dust mass fractions of PM1, PM2.5 and PM10. The output interval
of the spectrometers and the USA were assigned as six seconds and the USA was installed downwind of the test road.

During the performance measurements for water spraying on haulage roads, the immission levels by haulage activity were measured according to varying water spraying rates. As explained in Section 4.1.3.1, the pumping systems of the water trucks used at the NBCC mining area are defective and thus, watering is done by gravitational forces. Consequently, the capacity of water trucks, watering distances and truck speeds determine the watering amount. The water tank capacity of each truck employed at the NBCC site and the average truck speed are about 10200 L and 19 km/h, respectively. It was calculated that one truck can spray a distance of 8 km with a watering span of 3.4 m before refilling. Accordingly, the average watering amount at the NBCC mining area was estimated at 0.38 L/m². The spraying intervals of water trucks varied from 30 minutes to several hours. Based on these observations, the watering rate assigned by the water truck speed was considered as the performance evaluation criterion for the real-time measurements implemented for water spraying.

In order to estimate the influence of the watering rate on the control of dust emission from haulage activity, the actual (0.38 L/m²) and improved (0.50 L/m²) watering amounts were tested over approximately four-hour measurement durations. The dust immission levels under these watering amounts with varying watering intervals from 10 minutes to two hours were quantified. These immission levels were then evaluated through dispersion modeling and statistical analysis (see next section) to develop reduction factors for water spraying under different application conditions. In Figure 11, the influence of water spraying with 0.50 L/m² after four minutes (left) and 35 minutes (right) on the dust generation due to haulage activity is shown.

In the real-time performance measurements, the parameters influencing the performance of water spraying were also quantified. These parameters and the measurement methods used to quantify them are listed in Table 3.
Figure 11. Dust generation on haulage road after watering during the real-time dust control performance measurements for water spraying on 2012-11-01

Table 3. Measurement methods for parameters influencing the dust control performance of water spraying for overburden haulage

<table>
<thead>
<tr>
<th>Dust Control Performance Parameter</th>
<th>Measurement Method</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Measure of source activity</strong></td>
<td>Truck type</td>
</tr>
<tr>
<td><strong>Control conditions</strong></td>
<td>Watering amount</td>
</tr>
<tr>
<td></td>
<td>Watering interval</td>
</tr>
<tr>
<td><strong>Properties of the material being disturbed</strong></td>
<td>Particle size distribution, silt content and moisture content</td>
</tr>
<tr>
<td><strong>Climatic parameters</strong></td>
<td>Wind speed and direction, temperature, humidity, air pressure</td>
</tr>
</tbody>
</table>

A representative measurement result of dust immission levels in terms of mass concentrations from overburden haulage activity under varying watering rates is provided in Appendix (2). In addition, the parameters influencing the dust control performance determined during the real-time measurements is presented in Appendix A-4.

The individual dust emission levels from other mining activities considered under overburden handling (i.e., overburden drilling, blasting and loading) were at limited levels. Therefore, for the dust control methods associated with these activities, no performance measurements were implemented. However, reduction factors for these methods were also obtained as described in the following section, Section 4.1.3.4.
On the other hand, additional real-time performance measurements for several dust-generating points at the NBCC coal preparation plants were applied within the scope of RAME sub-project IV. The reduction factors developed based on these measurements for the dust control methods applied at the coal preparation plants are presented in the sub-project IV Final Report (BBK I, 2013b).

4.1.3.4. Mine Dust Reduction Factors Development

The reduction factors for the dust control methods corresponding to the mine dust sources at the NBCC mining area were estimated on the basis of the real-time dust control performance measurements, previous emission measurements and literature review.

The methodological approaches for determining the reduction factors of the control methods for the emission sources studied in this thesis, i.e., overburden haulage, dumping and wind erosion, are described below. The estimated reduction factors for these activities are presented in Appendix C.

Overburden Haulage—Reduction Factors for Control Methods

As already noted, water spraying is the only dust control method adapted for haulage activity at the NBCC mining area, and its reduction factor was estimated subsequent to real-time performance measurements (see Section 4.1.3.3). The reduction factors of alternative methods considered for haulage activity were obtained from previous studies. These adapted and alternative methods are listed in Table 7 in Section 5.1.2.1.

The real-time performance measurements for the water spraying method were performed under the actual watering amount applied at the NBCC, 0.38 L/m², and the improved amount of 0.50 L/m² obtained according to different watering intervals. The obtained immission levels from haulage activity under these two rates over time were analyzed within RAME sub-project IV using LASAT model simulations.

In the LASAT models, the spatial locations of the haulage road and the measurement points, as well as the atmospheric conditions were defined within a conceptual site model. A theoretical emission was assigned at the source area (haul road); and the model simulations computed immissions at the measurement points. A comparison of the computed and measured immissions was used to
determine the calibration factors. Based on these factors, the overburden haulage emissions during the dust control performance measurements were estimated.

The emission levels calculated for overburden haulage according to actual and improved watering rates at different watering intervals were then analyzed in this thesis. The percentage reductions in these emission levels at certain time points after watering at two different amounts (i.e., 0.38 and 0.50 L/m²) were calculated. By linear interpolation of these two sets of reduction factors, a third theoretical set of reduction factor for the watering amount of 0.60 L/m² under varying watering durations was approximated. The developed reduction factors for water spraying at different amounts are presented in Section 5.1.2.4.

**Overburden Dumping – Reduction Factors for Control Methods**

The data obtained from the real-time emission measurements was utilized for the development of dust reduction factors for the control methods applied against dust generation from overburden dumping. As described in Section 4.1.3.1, the overburden storage areas, where the dumping activities take place, have steep slope angles (>37°) and high slope (dumping) heights (up to 50 m). Therefore, the current design of the dumping sites at the NBCC mining area induces several environmental and stabilization problems. In order to eliminate these problems, layered dumping at a height of 4 m is suggested as a more reliable dumping practice within the framework of the RAME project (Ahmad, 2013).

In addition, dust generation due to dumping at the NBCC mining area can be significantly reduced by lowering the dumping heights down to 4 m. It is noted in Section 4.1.2.2 that the influence of dumping heights on the dust emission at dumping operations had been investigated throughout the real-time emission measurements. The calculated direct relationship between the dumping emission level and the dumping height was used as the basis for deriving the emission reduction factor related to dumping height reduction. At this step, the average dumping height observed during the real-time measurements (21.31 m) was used as a reference height and a corresponding emission for an exemplary dumping activity at this height was estimated. Similarly, a second emission at the layered dumping height (4 m) was calculated and the percentage difference between these two
hypothetical emissions provided the emission reduction factor for dumping height reduction. The results are presented in Section 5.1.2.4.

As a second dust control method for overburden dumping, the watering dumping layer was taken into consideration. Dumping layers are randomly watered with water trucks employed at the NBCC mining area in order to reduce dustiness at the dumping locations. As explained previously, the dust emissions from dumping activities were considered as the total emissions from the dumping cycle, including the truck approaching the dumping point, actual dumping activity and truck departure from the dumping point. The visual dust propensity values for these different processes were postulated as their individual emission shares. Accordingly, the percentages for truck approach and departure within the total dumping dust emission were obtained. By accepting that the dust generated due to truck movements can be mitigated by the reduction factor estimated for watering in haulage activity, the reduction factor for watering dumping layer was calculated. This factor is described in Section 5.1.2.4.

Wind Erosion – Reduction Factors for Control Methods

The emission data obtained from the real-time measurements, which was used for emission factor development, was insufficient for analyzing the reduction potential of the dust control methods applied against wind erosion at the NBCC mining area. Moreover, no additional measurements concerning the performances of these control methods were conducted, due to the limited time period for the emission measurements at the mining area. Consequently, the dust reduction factors for the primary wind erosion control methods were compiled after reviewing the relevant literature and are presented in Appendix (1).

4.1.4. Mine Dust Control – Cost Parameterization

The dust control methods studied within this thesis were categorized as direct and indirect methods (see Section 4.1.3.1). The direct methods aim dust control by the application of palliative or suppression mediums, such as water or chemicals, whereas the indirect methods provide emission prevention through operational measures.

The overall costs of the direct control methods were divided into capital and operational costs, based on overhead (e.g., equipment, material or personnel) costs.
The capital cost of a dust control method included expenditures for the installation or the first time application of said method. The corresponding operational costs comprised the expenses related to the operation and maintenance of the control method.

It was impossible to gather reliable cost data on mining operations in Vietnam’s closed political system. Therefore, the unit overhead cost parameters and their values for the direct mine dust control methods were compiled from foreign sources (see (5)) and defined in EUR (€). The majority of the unit cost parameters were adapted from the CostMine’s “Mine and Mill Equipment Costs Estimator's Guide” (CostMine, 2009; 2012) at an exchange rate of 1.33 USD ($) per EUR (€).

The unit costs for water, electricity and fuel were assigned according to the data obtained from local statistical institutes or market research. For example, the unit water cost was determined with respect to the water abstraction charges defined in the draft law publicized by the State Government of North-Rhine Westphalia, Germany in October 2012 (Landesregierung NRW, 2012). In order to estimate the other unit costs for materials (e.g., chemicals used) and equipment (e.g., spray systems), corresponding suppliers were consulted.

The overhead rates represented the utilization levels of equipment, material and personnel required for the implementation of a dust control method. Although these parameters are site- or application-specific, they were quantified relative to the standard applications.

The indirect dust control methods required no capital investment for purchasing new equipment or installing a new system and consequently, had no operational costs. These methods only involved operational precautions, which imply the adjustment of mining practices and may cause indirect costs. These costs are certainly mine-specific, due to the variety of possible modifications applicable within the mining workflow. Therefore, they were defined using a single parameter as “indirect cost” and valued as zero within this thesis.

The cost parameters determined for the water spraying method, which was used to reduce dust emissions from overburden haulage activity, are listed in Section 5.1.3 as an example. In addition, the cost parameters of the alternative dust control methods considered for haulage activity are presented in (5).
4.2. Development of Mine Dust Control Decision Support System (Dust-DSS) and Scenario Simulation

As a primary part of this thesis, a mine dust control decision support system (Dust-DSS), which aims to find ecologically and economically balanced solutions for controlling open-pit coal mine dust emissions, was developed. This DSS was designed on the basis of the RAME project results obtained at the NBCC mining area. The system comprises a guide module, i.e., best practice guide (BPG), and a computational module. The BPG includes standardized and proven dust control measures for open-pit coal mines, whereas the computational module focuses on the quantification of the environmental and economic dimensions of these control measures.

A basic version of the computational component of the DSS was built as a dust control cost-performance model in Microsoft Excel. Afterwards, this version was extended and reorganized, and the final version of the Excel-based DSS computational module was achieved.

On the basis of the Excel version, the computational component of the DSS presented and applied in this thesis was developed using a system dynamic modeling platform, Vensim Software (Ventana Systems, Inc.). This Vensim version in a dynamic structure enabled the DSS parameters to be non-linear over time and the dust emission and reduction calculations to be global within time and space. Additionally, by converting the Excel-based DSS into Vensim, the simulation capacity of the Dust-DSS was expanded.

Apart from the Vensim version presented in this thesis, an analogue version of the Dust-DSS as a web application was created as one of the objectives of the RAME sub-project IV. For this purpose, the DSS parameters and equations were migrated into a MySQL database in order to create the computational module of the web-based DSS. PHP software (server-side scripting language) was used to implement the web application.

The DSS guide module, BPG, was developed using a Wiki-application (Wikimedia Foundation, Inc.) as a web application, too. On the web-based version of the DSS, links to the BPG were added to the computational module. Further details about the
web version of the DSS are presented in the RAME sub-project IV final report (BBK I, 2013b).

After reviewing the DSS development approaches in the literature (see CHAPTER 2), the DSS development process (DDP) proposed by Marakas (1999) was chosen and adapted as the method for the development of the Dust-DSS (see Figure 12).

As depicted in Figure 12, the DSS development process was completed in two steps as building the conceptual system and the working system. The process was initiated by a problem diagnosis at which point uncertainty in determination of site-specific mine dust control approaches at the open-pit coal mining operations was comprehended.

Subsequently, the DSS objective was identified as the generation of a platform that enables the user (i.e., mine managers and environmental officers) to design effective and economic dust control approaches for open-pit coal mining operations under recognized site-specific conditions (i.e., mining, climatic and dust control conditions).

At the next step, the DSS requirements, i.e., functional, interface and coordination requirements, were determined. The functional requirements define the capacity of the DSS to deal with the information useful to the solution of the problem addressed by the DSS (Marakas, 1999). Accordingly, the DSS functional requirements were identified as:

- providing background information to the user on mine dust emission and control; and
- calculating mine dust emissions and the cost-effectiveness of dust control methods based on the location- and activity-specific parameters that are the emission factors of mining activities and the reduction factors and the cost parameters of dust control methods.
The DSS interface requirements focus on the interaction between the DSS and the user (Marakas, 1999). Within this respect, it was specified that the DSS would have two separate modules: (i) a guide module; (ii) a computational module. The guide module (Best Practice Guide - BPG) was intended to provide background information on the application and performance of the considered dust control measures. The computational module was conceived to estimate dust emissions from mining activities and the cost-effectiveness of corresponding dust control methods.

Additionally, it was decided that the computational module would include separate views for:

- introducing the overall site-specific information required for estimation of the mine dust emission levels and the cost-performance of dust control methods;
- defining the activity rates and emission factors of each mining activity identified for the NBCC mining operation (see Figure 15 in Section 5.1.1.1) and for estimating the individual emission levels;

- defining the cost and performance parameters (reduction factors) and for estimating the cost-effectiveness of the mine dust control methods proposed for each mining activity;

- presenting the overall DSS results.

The coordination requirements of DSS implied the integration of different DSS parts; the sequence of decision making; and the facilitation of access to information relevant to DSS problems (Marakas, 1999). Accordingly, it was envisaged that hyperlinks to the DSS guide module would be added within the DSS computational module in order to achieve the coordination between these modules. Moreover, the additional links would connect the separate views of the DSS computational module listed above. The decision making process would start by introducing overall site-specific information, continue with the simultaneous emission and cost-performance calculations, and end with the evaluation of the DSS results. The calculation results would then be stored for further analysis and comparison of the mine dust emission levels and the costs and performances of dust control methods.

Based on the functional, interface and coordination requirements, the conceptual DSS, which includes the computational and guide modules, was designed. As mentioned above, the computational module was conceived to perform dust emission calculations based on the emission factors and cost-effectiveness estimations for corresponding dust control methods regarding to the reduction factors and cost parameters. Considering the time dependency of these factors and parameters, especially the cost parameters, the computational component of the DSS was required to be combined in a dynamic structure and developed with the aforementioned modeling tool, Vensim Software (Ventana Systems, Inc.). The guide module (BPG) was envisaged to be built on Wiki-application (Wikimedia Foundation, Inc.).

The working DSS was then constructed in a second step on the basis of the conceptual model (see Figure 13 in Section 4.2.1). At this step, the computational module was generated in Vensim through iterative design based on the determined
model parameters and expansion of the refined structures. Besides, the BPG was generated as a text-based web page.

After a complete working Dust-DSS was achieved, the computational module was verified and validated with respect to mine dust generation and control specifications observed at the NBCC mining area and data obtained from the literature. At the final step, i.e., incremental adaptation, the DSS was completed with the final refinement of the activities of the previous steps.

The validated DSS was utilized to analyze the mine dust emission levels and the applicability limits of various mine dust control methods. For this purpose, different dust emission and control scenarios referring to the mining and environmental conditions at the NBCC mining area were developed. The influences of the critical scenario uncertainties on the emission levels and the cost-effectiveness of the proposed control methods were investigated via sensitivity analyses.

### 4.2.1. Conceptual DSS

The mine dust control decision support system (Dust-DSS) was conceived according to the methodology described in the previous section. In this respect, the DSS was built on the site-specific dust emission factors defined for the mining activities at the NBCC area and the reduction factors and the cost parameters of the corresponding control methods. A decision flow diagram of the conceptual DSS is presented in Figure 13. As shown in this figure, the DSS includes a guide module, i.e., Best Practice Guide (BPG) and a computational module.

The BPG is a text based document and comprises background information on mine dust generation, its environmental, health and social effects, the monitoring techniques thereof, dispersion modeling principles, dust control methods and a legislative framework pertaining to air quality and occupational health and safety. Within the DSS decision flow, the BPG provides supporting knowledge for the definition of the mine dust sources and for the selection of appropriate control methods (see Figure 13).
Figure 13. Decision flow diagram of conceptual DSS

The DSS computational module consists of simultaneously running environmental target and cost sub-modules as shown in Figure 13. The environmental target sub-module is based on emission factors corresponding to distinct mine dust sources and the reduction factors of selected dust control methods. As illustrated in Figure 13, this module computes the total emission (TE) according to the emission factors, as well as defined mining and local conditions, such as the operation rate of the dust-generating activities or the local precipitation.

Concurrent to the total emission (TE) calculation, the combined reduction (CR) provided by the selected control methods was estimated in accordance to their assigned dust emission reduction factors. As described in Figure 13, the combined
reduction was then compared with the environmental target (ET), which is the overall dust reduction level intended by the system user.

When the combined reduction (CR) is less than the user defined environmental target (ET), the selected control methods will not meet the target (see Figure 13). In this case, the selected methods need to be replaced or improved until they assure the desired combined reduction, i.e., a reduction higher than the environmental target.

Simultaneously, the cost sub-module of the DSS calculates the total cost of the selected control methods and compares it with the user defined dust control budget. The selected control methods maintaining the environmental target are defined as feasible if the overall control cost meets the budget. Otherwise, the methods are revised or alternative methods are selected in order to find the option remaining within dust control budget boundaries (see Figure 13).

The dust reduction target in the DSS model was defined as a fixed user-defined target in terms of combined reduction. Therefore, the DSS system was considered as least-cost analysis of dust control projects.

4.2.2. Description of DSS Building Platforms

4.2.2.1. Description of DSS Computational Module Building Platform

The computational module of the dust control DSS was built using Vensim Software (Ventana Systems, Inc.), a modeling tool for dynamic systems that enables visual model conceptualization, documentation, simulation, analyzing model simulation results and optimization (Ventana Systems, Inc., 2007).

Dynamic systems are constructed in Vensim by defining the system variables, their values or equations and the connections among them. Three types of variables, i.e., constants, auxiliaries and levels can be generated in Vensim. Variables with initial fixed values are defined as constants, whereas auxiliaries are the dynamic variables computed from other variables at a given model time. Additionally, the levels are the variables with initial values that change over model time by accumulating or integrated rates (Ventana Systems, Inc., 2007).

The system variables can be defined within visually separated views when the designed model is large (numerous variables exists) and when comprehension of the
model is not clear into a single view. These multiple views split the model into different sectors that might be devoted to discrete model functions. The links between multiple views are maintained by the shadow variables, which are the visual representations of the existing variables defined in one of the model views (Ventana Systems, Inc., 2007).

To sum up, the DSS computational module was built on the Vensim platform, as it provided the essential requirements for designing a time-dependent model.

4.2.2.2. Description of DSS Guide Module Building Platform

The DSS guide module (BPG) was developed using Wiki software (Wikimedia Foundation, Inc.). This application provides a platform to the user for creating and editing web pages on web servers (Wikimedia Foundation, 2013). Therefore, documentation of complex issues and procedures, which require continuous updating, can be provided properly through Wiki software. As a result, a Wiki platform was selected as a tool for compiling the dust control BPG as it allows for editing information in response to recent changes within the industry, following the updated information instantaneously and tracking the changes in the BPG from any place via an Internet connection.

4.2.3. Development of DSS

4.2.3.1. Development of DSS Computational Module

The DSS computational module was developed by translating the conceptual model (see Figure 13 in Section 4.2.1) into a dynamic model. As previously described, the emission factors of the mine dust sources and the reduction factors and the cost parameters of the corresponding control methods constituted the basis of the DSS computational module. These parameters were defined within the DSS for individual mining activities and the various control methods related to these activities.

Several thousands of DSS parameters were incorporated into ca. 40 separate Vensim model views. For each mining activity, the calculation modules for total emissions and combined reductions were constructed within different model views (interfaces) from the cost calculation modules of the control methods. Two additional views for the parameters associated with the mining and local conditions, as well as
for the overall results were created. As previously mentioned, the links between separate views were maintained via the shadow variables.

The model duration was adjusted to 50 years. The time step, which helped to increase the model's accuracy, was selected as one month. This was considered the smallest period for which a significant change in the model was likely.

The DSS model views were grouped as an initial view called “Project Info”, dust emission and control performance views, dust control cost views and a final view labeled “Overall Results”; these are described below.

**Project Info View**

General operating parameters of the mining activities defined in the DSS, local conditions as well as meteorological data, were introduced within the first model view, i.e., “Project Info” view. The variables placed in this view provided an introduction to mine dust control projects and a basis for further dust control calculations made in other views. The variables of the “Project Info” view and its structure is illustrated in Figure 19 in Section 5.2.1.1.

**Dust Emission and Control Performance Views**

A separate model view was built for each mining activity included within the Dust-DSS. The emission factors for these mining activities, their activity rates and the reduction factors of the control methods were embedded into the dust emission-control views.

The emission factors, which were determined for all the identified mine dust sources at the NBCC mining area and designated in the DSS, are provided in Appendix B. The dust control methods for the mine dust sources focused on in this thesis, i.e., overburden haulage, wind erosion and overburden dumping, and their respective reduction factors used in the DSS are compiled in Appendix C.
Based on these parameters, the total emissions generated by mining activities can be calculated by the equation proposed by USEPA (1995b) as:

\[ E = A \times EF \times \left(1 - \frac{ER}{100}\right) \]  

**Eq. 8**

where:

- \( E \) = emission generated (kg)
- \( A \) = activity rate (unit: depends on mining activity)
- \( EF \) = emission factor (kg/activity rate)
- \( ER \) = overall emission reduction effectiveness (%)

This equation (Eq. 8) was adopted in the Dust-DSS for the calculation of emission levels from the defined mining activities. Clearly, by neglecting the \( ER \), the emission levels – without application of dust control methods – could be estimated. These uncontrolled emission levels were denoted as emission levels without mitigation \( (E_{wom}) \) in the DSS. A sample \( E_{wom} \) calculation for a haulage activity is shown in Example Box 1.

**Example Box 1. Calculation of emission without mitigation \( (E_{wom}) \)**

Uncontrolled PM10 emission (PM10 emission without mitigation) per hour caused by a single truck (average speed = 10 km/h) hauling overburden on a dry main road can be calculated as described below.

The PM10 emission factor \( (EF) \) suggested in this thesis for haulage activity on a dry main road is listed in Table 6 in Section 5.1.1.3:

\[ EF = 880 \text{ g/truck } \times \text{ km} \]

Given this emission factor, the activity rate \( (A) \) will be a function of the number of trucks using this road, the average truck speed and the duration of the activity:

\[ A = 1 \text{ truck } \times 10 \text{ km/h } \times 1 \text{ h} = 10 \text{ truck } \times \text{ km} \]

Accordingly, for this activity, total PM10 emission without mitigation \( (E_{wom}) \) was calculated using Eq. 8 as follows:

\[ E_{wom} = 10 \text{ truck } \times \text{ km} \times 880 \text{ g/truck } \times \text{ km} = 8880 \text{ g} = 8.8 \text{ kg} \]

The overall emission reduction effectiveness \( (ER \text{ in } \%) \) given in Eq. 8 reflects the performance of the dust control methods. This parameter was introduced as a reduction factor \( (RF \text{ in } \%) \) in the Dust-DSS.
When multiple control methods are selected for the same dust source, their overall performance is defined by a combined reduction. Accordingly, Eq. 9 was used in the Dust-DSS in order to calculate a “Combined Reduction Factor”.

\[
CRF = 100 \times \left[ 1 - \prod_{m} \left( 1 - \left( \frac{RF_m}{100} \right) \right) \right]
\]

Eq. 9

where:

\[
CRF = \text{combined reduction factor (\%)}
\]

\[
RF_m = \text{reduction factor of an individual dust control method (\%)}
\]

\[
m = \text{control method indices (-)}
\]

Example Box 2 shows a sample calculation for a combined reduction factor for two dust control methods simultaneously applied for a haulage activity.

<table>
<thead>
<tr>
<th>Example Box 2. Calculation of combined reduction factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuing the truck haulage example given in Example Box 1, if two dust control methods, e.g., water spraying and regulating driving pattern, are applied simultaneously, their combined reduction factor can be calculated as described below.</td>
</tr>
<tr>
<td>The reduction factors ((RF)) of these control methods are provided in Appendix C-1:</td>
</tr>
<tr>
<td>(RF_1 = 70%) (for water spraying)</td>
</tr>
<tr>
<td>(RF_2 = 42%) (for regulating driving pattern)</td>
</tr>
<tr>
<td>Based on these reduction factors, the combined reduction factor ((CRF)) was calculated using Eq. 9 as follows:</td>
</tr>
<tr>
<td>(CRF = 100 \times \left[ 1 - \left( 1 - \left( \frac{70}{100} \right) \right) \times \left( 1 - \left( \frac{42}{100} \right) \right) \right] = 82.6%)</td>
</tr>
</tbody>
</table>

The mine dust emissions can naturally be mitigated by precipitation. Therefore, in addition to the emission factors and activity rates defined for mining activities and the reduction factors of dust control methods, precipitation level is another key parameter driving the emission quantity generated by a mine dust source.

USEPA simplified the relation between the emission amount and the precipitation level for some surface coal mining operations, i.e., scrapers in travel mode, general traffic and haul trucks (USEPA, 1998b), as well as for unpaved roads (USEPA, 1998c; 2006a). In these studies, it is proposed that annual average emissions are
inversely correlated with the number of wet days per year on which precipitation is more than 0.254 mm (0.01 inches). This assumption about the emission estimation for unpaved roads is also suggested by Environment Australia (1998) in its best practice booklet for dust control and later by the Western Regional Air Partnership (WRAP) in its fugitive dust handbook (Countess Environmental, 2006). Moreover, the National Pollutant Inventory (NPI), which includes techniques for estimating emissions in mining operations in Australia, employs USEPA’s assumption about wind erosion from active coal stockpiles (Environment Australia, 2012). Consequently, this assumption was extended and applied in the DSS for all mine dust sources at open-pit coal mining operations. It was adjusted in the mine dust emission calculations using the DSS computational module, so that when precipitation was higher than 0.254 mm/day, natural dust control occurred and no additional control approach was required.

The number of holidays, when there was no mining activity and hence no dust generation due to mining, were also accounted for in the DSS. The averages of high precipitation days, i.e., heavy rainy days and the number of holidays were designated on a monthly basis in accordance with the time step (one month) selected for the DSS model. As a result, the equation given by USEPA in terms of yearly emissions (USEPA, 2006a) was modified and the equation below was adapted into the DSS for emission with natural mitigation ($E_{wnm}$):

$$E_{wnm} = E \times \left( \frac{30 - \text{No emission days}}{30} \right)$$

Eq. 10

where:

- $E_{wnm} = \text{emission with natural mitigation (kg)}$
- $E = \text{emission generated – potential (kg)}$

The summation of heavy rainy days and the number of holidays provided no emission days per month. However, clearly, for the estimation of wind erosion, only the heavy rainy days were accounted for, since wind erosion took place independently from the holidays.
The emission levels of the mining activities after mitigation \((E_{am})\) were determined in the DSS using an equation (Eq. 11) derived on the basis of Eq. 1, Eq. 2 and Eq. 3.

\[
E_{am} = A \times EF \times \left(1 - \frac{CRF}{100}\right) \times \left(\frac{30 - No \ emission \ days}{30}\right)
\]

where:

- \(E_{am}\) = emission after mitigation (kg)
- \(A\) = activity rate (unit: depends on mining activity)
- \(EF\) = emission factor (kg/activity rate)
- \(CRF\) = combined reduction factor (%)

Eq. 11 correlates the dust emission and control parameters of each mining activity and its complementary control methods. An example showing how this equation is used for the calculation of emission after mitigation is presented in Example Box 3.

**Example Box 3. Calculation of emission after mitigation**

In this example, the haulage activity described in Example Box 1 is considered for one month. Accordingly, PM10 emission (after mitigation) by a single truck (average speed = 10 km/h) hauling overburden on a dry main road can be calculated as described below. The monthly operating time for a haul truck is assumed as 480 hours.

The PM10 emission factor \((EF)\) suggested in this thesis for haulage activity on dry main road is listed in Table 6 in Section 5.1.1.3.

\(EF = 880 \ g/truck \times km\)

Given this emission factor, the activity rate \((A)\) is calculated to be:

\(A = 1 \ truck \times 10 \ km/h \times 480 \ h/month = 4800 \ truck \times km\)

When water spraying and regulating driving pattern are applied simultaneously in order to mitigate the dust emission from this activity, their combined reduction factor \((CRF)\) will be 82.6% as estimated in Example Box 2. Assuming no emission days per month as eight days, total PM10 emission per month after mitigation \((E_{am})\) is calculated by using Eq. 11 as follows:

\[
E_{am} = 4800 \ truck \times km \times 880 \ g/truck \times km \times \left(1 - \frac{82.6}{100}\right) \times \left(\frac{30 - 8}{30}\right)
\]

\[
E_{am} = 538982 \ g = 539 \ kg
\]
Considering that the same dust-generating mining activity (e.g., overburden haulage) may be performed at different locations (e.g., on different roads) in a mining area at the same time, five as a reasonable number of source locations (e.g., roads for haulage activity) were defined for each mining activity in the dust emission-control views. Therefore, for example, five identical dust emission-control calculation sets for the overburden haulage activity were incorporated into the DSS. Consequently, it was possible to define up to five haulage roads within the mining area with distinctive parameters influencing the dust emission and/or control methods.

As a final step, for each mining activity defined in the DSS, overall dust emission and combined reduction calculations were embedded within their separate dust emission and control performance views. To illustrate this, model structure for overburden haulage is shown in Figure 20 in Section 5.2.1.1.

**Dust Control Cost Views**

The dust control cost views included the cost parameters identified for the proposed control methods. These parameters were based on the unit costs of equipment, materials and/or personnel required for implementation of the methods and divided as capital and monthly operational costs for direct control methods. The costs of indirect control methods were represented by constants on a monthly basis and valued as zero.

The DSS computational module was primarily designed for the evaluation of the costs of mine dust control projects and their control effectiveness. Aggregation of these costs and benefits over time is required for cost-effectiveness analysis and further decisions, especially pertaining to long-term mine dust control projects.

Stermole and Stermole (1996) summarized that net present value (NPV) and interest rate of return (IRR) analyses are the two most widely used cost evaluation techniques among individuals, companies and government organizations. Similarly, a survey conducted in Canada yielded results indicating that the majority of the large firms prefer NPV and IRR as investment decision making tools (Bennouna, Meredith, & Marchant, 2010). In another study, these two analyses were defined as two equivalent ways for assessing the commercial viability of a project (Perman, Ma, McGilvray, & Common, 2003).
NPV and IRR are regarded as discounted cash flow analysis methods and they are based on the time value concept (Stermole & Stermole, 1996; Ehrhardt & Brigham, 2009; Bennouna, Meredith, & Marchant, 2010). Additionally, in environmental studies, discounting method is often applied for the evaluation of future costs and benefits (Goulder & Stavins, 2002).

The NPV of a project is the net cash flow of the project in present values (see Eq. 12), whereas the IRR method estimates the internal rate that provides a net cash flow equal to zero.

$$NPV = \sum_{t=0}^{T} \frac{N_t}{(1 + i)^t}$$  \hspace{1cm} \text{Eq. 12}

where:

- $NPV = \text{net present value (currency)}$
- $N_t = \text{net cash flow at time } t \text{ (currency)}$
- $i = \text{interest rate (\%)}$
- $T = \text{project lifetime (time)}$

The DSS model developed in this thesis aimed at estimating the total costs of the proposed dust control strategies. Additionally, in general, the IRR method may generate multiple solutions for varying cash flows, which is also possible for many of the control methods considered in the DSS model. Therefore, the DSS computational module was designed to calculate the NPV of the dust control projects, instead of the IRR. In addition, the nominal cost calculations of the studied dust control methods were implemented into the DSS.

Overall dust control costs in nominal and present values were evaluated in terms of capital and operational expenditures in the DSS. These cost components and the total costs were directly related to the dust control project duration as illustrated in Eq. 13 to Eq. 15.

$$CC_N = CC \times \left(\frac{PD}{SL}\right)$$  \hspace{1cm} \text{Eq. 13}

$$OC_N = OC \times PD$$  \hspace{1cm} \text{Eq. 14}
\[ TC_N = CC_N + OC_N \]  

Eq. 15

where:

- \( CC_N \) = nominal capital cost (€)
- \( OC_N \) = nominal operational cost (€)
- \( TC_N \) = nominal total cost (€)
- \( CC \) = capital cost, initial investment required for dust control project (€)
- \( OC \) = operational cost of control system (€/month)
- \( PD \) = project duration (month)
- \( SL \) = system lifetime, acceptable service life or re-application time (month)

Similarly, the present value of capital cost (\( CC_{PV} \), see Eq. 16) and operational cost (\( OC_{PV} \), see Eq. 17) and the total cost - present value (\( TC_{PV} \), see Eq. 18) were calculated as follows:

\[ CC_{PV} = \sum_{t=0}^{PD/SL} \frac{CC}{(1 + i)^{(t \times SL)}} \]  

Eq. 16

\[ OC_{PV} = \sum_{t=0}^{PD} \frac{OC}{(1 + i)^t} \]  

Eq. 17

\[ TC_{PV} = CC_{PV} + OC_{PV} \]  

Eq. 18

where:

- \( CC_{PV} \) = present value of capital cost (€)
- \( OC_{PV} \) = present value of operational cost (€)
- \( TC_{PV} \) = present value of total cost (€)
- \( CC \) = capital cost (€)
- \( OC \) = operational cost (€/month)
- \( PD \) = project duration (month)
- \( SL \) = system lifetime (month)
- \( i \) = interest rate (%)
- \( t \) = project time (month)
For further assessment of the dust control alternatives regarding their costs and performances, the cost-effectiveness ratio ($CER$) and cost-reduction ratio ($CRR$) calculations were also added to the model as described in Eq. 19 and Eq. 20:

\[ CER = \frac{TC_{pv}}{(E_{am} - E_{wnm})} \]  
\[ Eq. 19 \]

where:

$CER$ = cost-effectiveness ratio (€/kg)

$TC_{pv}$ = present value of total cost (€)

$E_{am}$ = emission after mitigation (kg)

$E_{wnm}$ = emission with natural mitigation (kg)

\[ CRR = \frac{TC_{pv}}{RF \ or \ CRF} \]  
\[ Eq. 20 \]

where:

$CRR$ = cost-reduction ratio (€/%)  

$TC_{pv}$ = present value of total cost (€)

$RF$ = reduction factor (%), if a single control method is applied

$CRF$ = combined reduction factor (%), if multiple control methods are applied

The $CER$ explains the level of dust control expenditures per the quantity of mitigated dust and is given in €/kg. $CRR$ simply represents the amount of control expenditures per percentage of dust reduction (€/%). Lower $CER$ and $CRR$ demonstrate higher cost-effectiveness and cost-reduction of the corresponding control method, respectively.

An exemplary dust control cost view constructed for the water spraying method and applied for overburden haulage activity is shown in Figure 21 in Section 5.2.1.1.

**Overall Results Views**

The final model views, namely “Dust Control Overall Performance” and “Dust Control Overall Cost” were created to summarize the model outcomes. In these model views, the total emissions generated by the defined mining activities before and after the implementation of the control methods, the overall combined reduction attained by these methods and their total costs, and the overall cost-effectiveness evaluations were included.
In the “Dust Control Overall Performance” view, the total sums of the emissions from selected mine dust sources in terms of emissions without mitigation ($E_{wom}$, see Eq. 8), with natural mitigation ($E_{wnm}$, see Eq. 10) and after mitigation ($E_{am}$, see Eq. 11) were computed.

The overall combined reduction ($OCR$) achieved by application of a single or a set of dust control method(s) for various mine dust sources were also included in the control performance view. This overall reduction was expressed as the weighted average of the combined reduction factor ($CRF$) values and was added into the DSS using Eq. 21.

$$OCR = \frac{\sum_m (E_m \times CRF_m)}{\sum_m E_m} \tag{Eq. 21}$$

where:

- $OCR$ = overall combined reduction (%)
- $m$ = indices of the emission sources and their designated control methods
- $E_m$ = emission level of the $m$th dust source without mitigation, $E_{wom}$ (kg)
- $CRF_m$ = combined reduction factor achieved for the $m$th dust source (%)

The overall mine dust control project costs were concluded within the “Dust Control Overall Cost” view. In this view, the summations of the total nominal cost ($TNC$) and the total cost - present value ($TC_{PV}$) of the selected control methods are provided. The latter is calculated as the overall total cost - present value ($OTC_{PV}$) and compared with the user defined dust control project budget in order to evaluate the feasibility of the selected control methods.

Furthermore, in this final model view, the overall cost-effectiveness ratio ($OCER$) of the dust control projects was also computed with regard to Eq. 22 developed on the basis of Eq. 19. The final parameter embedded into the “Dust Control Overall Cost” view was the overall cost-reduction ratio ($OCRR$), which was defined by combining Eq. 20 and Eq. 21 into Eq. 23.

$$OCER = \frac{OTC_{PV}}{(OE_{am} - OE_{wnm})} \tag{Eq. 22}$$
where:

\[ OCER = \frac{OTC_{PV}}{OCR} \]

\[ OCRR = \frac{OCT_{PV}}{OCR} \]

\[ OE_{am} = \text{overall emission after mitigation (kg)} \]

\[ OE_{wnm} = \text{overall emission with natural mitigation (kg)} \]

\[ OCR = \text{overall combined reduction (kg)} \]

As an example, Figure 22 and Figure 23 in Section 5.2.1.1 show the overall results of views created for overburden handling activities and wind erosion.

4.2.3.2. Development of DSS Guide Module (BPG)

The definition of best practices for dust control varies over time due to technological improvements and changes in the legal framework. Therefore, the DSS guide module (BPG) was developed on a Wiki-application in order to allow users to edit the BPG according to recent developments within the industry.

Within the BPG, the procedures, techniques and technologies for successful mine dust control were described. While preparing the guide, the specific mining conditions at the open-pit coal mines in Vietnam were additionally considered. Furthermore, the mine dust emission factors that were developed through on-site measurement at the NBCC mining area were also included in the guide.

4.2.3.3. DSS Verification and Validation

DSS was verified in order to ensure that the conceptual model as defined by Davis (1992) or the agreed specifications and assumptions on the model as noted by Carson (2002) were accurately adapted into the DSS. For this purpose, the consistency of the DSS computational module with the conceptual DSS was examined via self-assessment.

Firstly, the relationships among the system components illustrated in the DSS flow diagram (Figure 13 in Section 4.2.1) were checked within the Vensim model in which these causal connections were represented by arrows. At this step, the causes and uses of the important model variables, e.g., water spraying cost for haulage, were
also analyzed using the “Tree Diagram” tool of Vensim. Secondly, the specified
equations between variables were verified using the Vensim “Equation Editor”.

The validation tests for dynamic models were summarized by Sterman (2000).
Among these tests, the following were selected according to their coherence with the
DSS objectives and used to validate the accuracy of the DSS computational module:

- Dimensional consistency test: units of variables defined in the model were
  validated using the “Units Check” tool of Vensim.

- Extreme conditions test: extreme values were assigned for certain
  parameters, e.g., 30 days per month for the number of heavy rainy days, in
  order to assess the model performance within utmost limits.

- Reproduction test: the ability of the model to reflect the performance of real
  systems was validated by observing the influence of changes in the selected
  constants, e.g., road length and on the dynamic variables, e.g., required
  number of trucks for water spraying.

- Sensitivity analysis test: the effects of variations in the critical parameters on
  model outputs were examined using sensitivity simulations in Vensim.

The results of the DSS verification and validation tests are provided in
Section 5.2.1.3.

**4.2.4. DSS Scenario Simulation**

After the Dust-DSS was verified and validated, predictive scenarios based on the
mining and environmental conditions at the NBCC mining area were designed.
These scenarios were then simulated within the DSS with the aim of investigating
the total and individual mine dust emission levels and the applicability limits of the
proposed dust control methods. The simulations were performed on a dataset
representing the actual NBCC system conditions and their variations.

The mining conditions, which comprised applied mining methods, the primary mining
components and dimensions, as well as environmental conditions, were determined
using on-site observations, meetings with the NBCC representatives and additional
desk studies. The local short-term meteorological data (Table 1 in Section 3.3) was
obtained from the Bai Chay meteorological station in Ha Long (Bai Chay
Meteorological Station, 2012).
As the methodology for scenario development and simulation, approaches described in existing studies were adapted (Schoemaker, 1995; Mahmoud, et al., 2009). Accordingly, a stepwise approach, as illustrated in Table 4, was employed and three scenarios, namely, the reference scenario, the overburden haulage scenario and the wind erosion scenario, were designed.

Each step of the scenario development and simulation was converged after iterations of the proposed step-wise approach described in Table 4 until plausible, internally consistent and coherent scenarios were achieved.
As an example, the critical uncertainties for the reference scenario were identified as road length and wind erosion area after evaluating the emission levels estimated as simulation results.

4.2.4.1. Reference Scenario

The reference scenario was developed according to the operational sequence in the NBCC mining area. This scenario was aimed at emission level estimations for different mine dust sources and the identification of the primary dust sources under given conditions over a 20-years period (see Table 4 in the previous section). The flowchart for the reference scenario is presented in Figure 14.

![Reference Scenario Flow](image)

Overburden haulage and wind erosion have already been indicated as the major dust sources at open-pit coal mines in previous studies as stated in Section 1.1. Therefore, these activities, as well as an additional activity (i.e., overburden dumping) for comparison purposes were particularly studied in this thesis. Accordingly, in order to focus on these dust sources, only the overburden handling
activities and wind erosion were included in the reference scenario as it is presented in Table 4 and depicted in the scenario flowchart in Figure 14.

It was proposed that the results of the reference scenario would assist mine managers and environmental officers in their mine dust control decisions under varying conditions. Accordingly, the reference scenario concept was developed to involve the key assumptions and data, as well as critical uncertainties (see Table 4). The mine dust emission levels, which were specified as the key decision factor in this scenario, was designated by the assumptions and data about mining conditions, the emission factors and the climatic conditions. The values assigned to these scenario parameters are listed in Appendix E-2. Furthermore, even if the individual and total mine haulage road lengths and the total size of the areas subjected to wind erosion were quantified accurately for the NBCC mining operation; these parameters were selected as the critical uncertainties (see Table 4). This was because they were assumed to vary from one mining site to another and because their variations significantly influence the total mine dust emission levels.

Once the concept behind the reference scenario had been identified, the scenario was analyzed through simulations within the Dust-DSS. In this step, the simulation outputs were examined to evaluate the consistency of the scenario and its variations. Additionally, sensitivity analyses were conducted in order to assess how the changes in the critical uncertainties affected the simulation results. For this purpose, gradual variations in the road length from 1 km to 50 km and in the wind erosion area from 0.1 km$^2$ to 5 km$^2$ were separately simulated.

Finally, the scenario assessment step provided an interpretation of the reference scenario simulation outputs, as explained in Table 4 (see previous section). These simulation results are presented in Section 5.2.2.1.

### 4.2.4.2. Overburden Haulage and Wind Erosion Scenarios

The main dust sources within the operational flowchart given for overburden handling and wind erosion at the NBCC mining area (see Figure 14) were determined as overburden haulage activity and wind erosion (see Section 5.2.2.1). Consequently, by following the methodology described in Table 4 given in Section 4.2.4, two additional scenarios for these mine dust sources were developed.
The overburden haulage and wind erosion scenarios were targeted to determine the applicability limits of the control methods proposed for these mine dust sources over a time horizon of 30 years. In this context, these individual scenarios involved dust emission generation due to overburden haulage and wind erosion, as well as the application of corresponding dust control methods.

These individual scenarios were also aimed at helping mine managers and environmental officers in their mine dust control decisions. The key assumptions and data as well as the critical uncertainties considered for these scenarios are listed in Table 4. The road length and the wind erosion area, as already explained for the reference scenario, may differ from one mining site to another; and these differences can result in significant variations in the total mine dust emission levels. Therefore, these parameters were identified as critical uncertainties for the respective scenarios. Additionally, the interest rate and the project time were taken into consideration as other critical uncertainties for both scenarios since they are the main factors driving the mine dust control costs. The key decision factors for the overburden haulage and wind erosion scenarios were determined as the project time, the mine dust emission levels and the cost-performance of the selected dust control methods.

The simulations of the individual scenarios were conducted with the Dust-DSS and the simulation outputs were evaluated for their consistency. Moreover, the influences of critical uncertainties (i.e., interest rate, project time, road length and wind erosion area) on the model outputs were examined using sensitivity analyses. At this point, sub-scenarios of the individual scenarios were developed by assuming stepwise changes in these uncertain parameters. Appendix E-3 includes these assumptions and data for the overburden haulage and wind erosion scenarios, as well as their sub-scenarios. The simulation results of these individual scenarios and the sensitivity analyses for the critical uncertainties are provided in Section 5.2.2.2.
CHAPTER 5. RESULTS

The results obtained from the real-time dust emission and control performance measurements at the NBCC mining area, i.e., dust emission and reduction factors, are presented in the first section of this chapter. Furthermore, the selected dust control methods for the mining area and their cost parameters are provided. In the subsequent section, the decision support system (Dust-DSS), which was developed based on the dust emission and reduction factors and the dust control cost parameters, is described. The outcomes of the DSS scenario simulations are also given in this final section.

5.1. Proposed Mine Dust Emission Factors, Reduction Factors and Dust Control Cost Parameters

This section presents the parameters required for quantification of the mine dust emission levels and cost-performance evaluation of the corresponding dust control methods. First, the site-specific emission factors for the dust sources at the NBCC mining area and then the reduction factors developed for the control methods associated with these dust sources are presented. Finally, the cost parameters designated for these control methods are given at the end of this section.

5.1.1. Proposed Mine Dust Emission Factors

5.1.1.1. Identified Dust-generating Activities and Influencing Parameters

Identified Dust-generating Mining Activities

The dust-generating activities identified at the NBCC mining area were divided into coal production and overburden handling activity chains. This was because the different materials (i.e., coal and overburden material) handled in each chain had different physical characteristics and dispersion mechanisms. The mining activities, i.e., dust sources, involved in these chains are shown in a flowchart in Figure 15. Additionally, wind erosion, which cannot be allocated specifically to one of the process chains mentioned above, was included in this chart, as it is a considerable dust source for the majority of mining operations. As an individual study focus, overburden haulage, overburden dumping and wind erosion (shown in bold italic in Figure 15) were examined in the further steps of this thesis.
Identified Influencing Parameters

Following identification of the dust-generating activities at the NBCC mining area, the parameters influencing the mine dust emissions were determined. The influencing parameters for the activities focused on within this thesis, i.e., overburden haulage, overburden dumping and wind erosion, are listed in Table 5.
Table 5. Parameters influencing dust emission (overburden haulage, overburden dumping and wind erosion)

<table>
<thead>
<tr>
<th>Mining Activity / Dust Source</th>
<th>Measure of Source Activity</th>
<th>Properties of the Material being Disturbed</th>
<th>Climatic Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overburden haulage</td>
<td>1. Truck type</td>
<td>1. Particle size distribution</td>
<td>1. Wind speed and direction</td>
</tr>
<tr>
<td></td>
<td>2. Truck weight (empty and loaded)</td>
<td>2. Silt content</td>
<td>2. Temperature</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4. Road surface load</td>
<td>4. Air pressure</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5. Road surface thickness</td>
<td></td>
</tr>
<tr>
<td>Overburden dumping</td>
<td>1. Truck type</td>
<td>1. Particle size distribution</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2. Dump weight</td>
<td>2. Silt content</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3. Dumping height</td>
<td>3. Moisture content</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4. Slope angle</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>5. Dumping duration</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>6. Truck approaching &amp; departure duration</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>7. Dust propensity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wind erosion</td>
<td>1. Surface area</td>
<td>1. Particle size distribution</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2. Vegetation density</td>
<td>2. Silt content</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3. Vegetation height</td>
<td>3. Moisture content</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4. Surface roughness</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

5.1.1.2. Results of Real-time Dust Emission Measurements

Real-time dust emission measurements were conducted to evaluate both the dust immission levels from the mining activities and the parameters influencing the dust emissions at the NBCC mining area. The detailed descriptions of the measurements for overburden haulage, overburden dumping and wind erosion are given in Section 4.1.2.2.

The immission levels due to mine dust sources were quantified using several aerosol spectrometers in the real-time measurements. Exemplary mass concentrations recorded with the spectrometers are concluded in the Final Report of RAME sub-project IV: “Dust Mitigation and Monitoring” (BBK I, 2013b). In Appendix A-1, representative dust mass concentration profiles over time obtained during the real-time measurements for overburden haulage, overburden dumping and wind erosion are illustrated. Additionally, the emission influencing parameters (see Table 5 in the
previous section) quantified during the real-time measurements are provided in Appendix A-2.

5.1.1.3. Results of Dispersion Modeling and Statistical Analysis – Emission Factors

Mine dust emission factors for the major dust sources at the NBCC mining area (see Figure 15 in Section 5.1.1.1) were developed using real-time measurements, followed by dust dispersion modeling and an analysis of model simulation results as described in Section 4.1.2. The emission factors derived for the activities focused within the scope of this thesis, i.e., overburden haulage, overburden dumping and wind erosion, were previously introduced in the RAME sub-project IV Final Report (BBK I, 2013b) and are presented here in Table 6.

The truck haulage emission factors were classified in terms of road types and conditions. Accordingly, the factors listed in Table 6 for main/side roads with dry/wet road conditions were obtained. These emission factors were suggested for both coal and overburden material haulage and estimated in unit of grams of PM10 per truck per kilometer (g/truck*km).

The emission factor for overburden dumping (see Table 6) was quantified as the ratio of PM30 (SP or TSP) generation to the amount of material dumped (g/t), whereas the emission factor for wind erosion at the NBCC mining area was derived in terms of grams of PM30 (SP or TSP) per area in square meter per hour (g/m$^2$*h).

Table 6. Dust emission factors for haulage, overburden dumping and wind erosion (BBK I, 2013b)

<table>
<thead>
<tr>
<th>Mining Activity / Dust Source</th>
<th>Dust Emission Factor</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Truck haulage</td>
<td></td>
<td></td>
</tr>
<tr>
<td>on dry main road</td>
<td>880</td>
<td>g PM10/km*truck</td>
</tr>
<tr>
<td>on wet main road</td>
<td>524</td>
<td></td>
</tr>
<tr>
<td>on dry side road</td>
<td>1124</td>
<td></td>
</tr>
<tr>
<td>on wet side road</td>
<td>392</td>
<td></td>
</tr>
<tr>
<td>Overburden dumping</td>
<td>0.225</td>
<td>g PM30/t</td>
</tr>
<tr>
<td>Wind erosion</td>
<td>0.198</td>
<td>g PM30/m$^2$*h</td>
</tr>
</tbody>
</table>

The dust emission factors of the other mining activities defined for the NBCC mine were calculated within the extent of the RAME project. These emission factors of the
mining activities including overburden drilling, blasting, loading and coal production are provided both in the RAME sub-project IV Final Report (BBK I, 2013b) and in Appendix B of the present thesis. In the end, the emission factors derived for all these mining activities were accommodated in the Dust-DSS as described in Section 4.2.3.

5.1.2. Proposed Mine Dust Reduction Factors

5.1.2.1. Identified Adapted and Alternative Dust Control Methods

The adapted and alternative dust control methods for the NBCC mining area were classified as direct and indirect methods with respect to their implementation features as described in Section 4.1.3.1. The control methods proposed for overburden haulage, dumping and wind erosion are listed in Table 7.

Table 7. Mine dust control methods (haulage, overburden dumping and wind erosion)

<table>
<thead>
<tr>
<th>Mining Activity / Dust Source</th>
<th>Dust Control Methods</th>
<th>Method Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overburden haulage</td>
<td>Road surface treatment</td>
<td>Water spraying</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Application of surface agents</td>
</tr>
<tr>
<td></td>
<td>Road condition improvement</td>
<td>Road paving/sealing</td>
</tr>
<tr>
<td></td>
<td>Regulating driving pattern</td>
<td></td>
</tr>
<tr>
<td>Overburden dumping</td>
<td>Wind prevention combined with water sprays</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Truck mounted fog cannon</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Watering dump level surface</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Reducing dumping height</td>
<td></td>
</tr>
<tr>
<td>Wind erosion</td>
<td>Areal stabilization</td>
<td>Vegetative cover</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Water exposure</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mulching</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Surface agents</td>
<td>Chemical wetting</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Crusting</td>
</tr>
<tr>
<td></td>
<td>Peripheral stabilization</td>
<td>Plantation wind breaks</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Artificial wind barriers</td>
</tr>
</tbody>
</table>
5.1.2.2. Identified Primary Mine Dust Sources

The emission levels of the individual dust sources at the NBCC mining area were calculated prior to the real-time dust control performance measurements. This calculation was made on the basis of the emission factors derived for the NBCC operation and the rate of the dust-generating activities. Accordingly, daily emissions of the individual mining activities and their proportions within the total dust emission at the mining area were computed. The pie chart in Figure 16 illustrates these individual shares of the activities within overall dust generation at the mining area. Consequently, overburden truck haulage had the highest portion (approximately 54%) of the overall daily dust emission. This was followed by wind erosion, which constituted almost 34% of the overall emission. The emission level of overburden dumping was limited and generated less than 0.1% of the overall emission. The result table given in Appendix B presents the daily dust emissions by the individual mining activities, the overall daily dust emission and the ratios of the individual emissions to the overall emission for the NBCC mining area.

Emissions from mining activities were calculated by assigning the daily measures of these activities to the related emission factors. In these calculations, the annual overburden and coal productions at the NBCC operation in 2011, which were 21.48 Mm$^3$ and 5.15 Mt, respectively, and the number of working shifts (960) for the same year were used (BBK I, 2013a).
Considering the emission sources studied within this thesis, dust generation due to overburden haulage was estimated for 22 main and two side roads with a total length of 24.5 km. The dust emissions from overburden dumping were calculated for eight dumping locations with a total dumping rate of 40500 tonnes/shift. Daily wind erosion level at the NBCC mining area was determined for the total size of the open surfaces within the mining area as equaling $4.51 \text{ km}^2$. For the emission calculations, the emission factors suggested for haulage on the dry main road, overburden dumping and wind erosion (see Table 6) were used.

### 5.1.2.3. Results of Real-time Dust Control Performance Measurements

Real-time dust control performance measurements were conducted only for the water spraying method applied for haulage activity as explained in Section 4.1.3.3. In these measurements, the immission levels from the haulage activity under varying water spraying rates were investigated together with the parameters influencing the dust control performance.

The immission levels were recorded in terms of dust mass concentration with several aerosol spectrometers during the real-time dust control performance measurements. An exemplary mass concentration profile associated with the specific watering rates over the measurement period is given in Appendix (1). Additionally, the parameters influencing the control performance of water spraying, which were also quantified during these measurements, are summarized in Appendix A-4.

### 5.1.2.4. Results of Mine Dust Reduction Factors Development

The dust reduction factors of the control methods adapted at the NBCC mining area were determined through dispersion modeling and further statistical analysis, as well as through the literature review. In the following, the reduction factors of the dust control methods adapted for overburden haulage, dumping and wind erosion at the NBCC mining area are presented. The other control methods proposed for these mine dust sources and their respective reduction factors have been compiled in Appendix C.

As described in Section 4.2.3.1, the reduction factors of all the dust control methods proposed for the NBCC mining operation were transferred into the Dust-DSS as performance parameters.
Overburden Haulage – Reduction Factors for Control Methods

The suggested control methods for dust generation due to overburden haulage are listed in Table 7 in Section 5.1.2.1. Among these methods, water spraying, which is categorized as a direct adapted method in this table, is the control approach employed at the NBCC mining area for dust suppression on the haul roads. Therefore, the performance measurements for water spraying were implemented in order to designate the dust reduction factor that needed to be achieved by this method. The reduction factors proposed for the other control methods given in Table 7 were compiled via the literature review and are summarized in Appendix C-1.

As described in detail in Section 4.1.3.3, during the real-time performance measurements for water spraying, the actual watering amount at the NBCC mining area (0.38 L/m²), as well as an improved amount (0.50 L/m²) were tested. Consequently, two empirical reduction factors for these rates over varying watering durations were developed by dispersion modeling and subsequent statistical analysis.

A third theoretical reduction factor for a watering amount of 0.60 L/m² was estimated by linear interpolation of the empirical factors determined for the actual (0.38 L/m²) and improved (0.50 L/m²) amounts. The results are graphically represented in Figure 17. The targeted dust control level for the haulage activity, which was assumed as 70% for the NBCC mining area, is also shown in the graph.

As it is shown in Figure 17, the actual watering amount, i.e., 0.38 L/m², demonstrated a dust reduction varying between 27% and 53% for corresponding durations of 45 minutes and 10 minutes after watering. Although the improved amount of 0.50 L/m² provided higher reduction potential than the actual amount, it failed to reach the target control level. It should be noted here that the reduction factors for 0.50 L/m² watering at times 30, 40 and 45 minutes were approximated by interpolation of the empirical factors calculated for the preceding and succeeding times. The reduction level of 0.50 L/m² watering reached its maximum, 60%, 10 minutes after watering and decreased to 53% within 45 minutes.

On the other hand, the theoretical watering amount of 0.60 L/m² yielded an estimated reduction of 74% for the first 10 minutes after implementation. Moreover,
watering with this amount at 30-minute intervals theoretically achieved the target
dust control, assumed as 70%, for the haulage activities at the NBCC mining area.

As a result, the optimum watering rate at the NBCC mining area was approximated
as 1.20 L/m²*h.

![Figure 17. Dust reduction factor (%) for water spraying vs. time after water spraying (min)](image)

**Overburden Dumping – Reduction Factors for Control Methods**

The reduction factors for the control methods proposed for overburden dumping
were determined by analyzing real-time emission measurements data and reviewing
previous studies. The control methods applied at the NBCC mining area, reducing
dumping height and watering dumping layer, were investigated on the basis of the
emission measurements data. Appendix C-2 provides a table showing the reduction
factors for dust control methods proposed in the literature for overburden dumping
activity.

The overburden storage areas in the NBCC mining area cause several
environmental and stabilization problems due to steep slope angles (>37°) and high
dumping heights rising up to 50 m. Therefore, it was suggested to apply layered
dumping method for the storage of overburden material and to reduce the dumping
heights down to 4 m within the framework of the RAME project (Ahmad, 2013). In
this respect, for the real-time emission measurements, the influence of dumping
heights on the dust emission at dumping operations was examined. On the basis of these measurements, the graph below (Figure 18) presenting the dust reduction factors according to the dumping heights was obtained. For this estimation, the average dumping height observed during the real-time measurements, 21.31 m, was taken as a reference value.

![Figure 18. Dust reduction factor (%) for reducing dumping height vs. dumping height (m)](image)

The graph in Figure 18 shows that reducing the dumping height from the average 21.31 m to the layered dumping height of 4 m at the NBCC overburden storage areas was able to provide a dust reduction of 57%.

The dust emission from dumping activities was quantified as representing the total dust generation by trucks approaching the dumping point, actual dumping activity and departure from the dumping point. It was accepted that the second control method for dumping activities, watering dumping layer, could mitigate dust generation due to truck approach and departure. Based on the visual dust propensity levels observed during the real-time measurements, the total share of truck approach and departure within dust emission levels due to dumping was estimated at 18%, whereas actual dumping represented 82% emission as a whole. Taking into account that the reduction level of watering for dust generation by truck haulage was suggested as 70% (see Figure 17), the overall reduction level for the watering dumping layer was estimated to be approximately 13%.
Wind Erosion – Reduction Factors for Control Methods

In the NBCC mining area, vegetation is the main control method applied against wind erosion (see Section 4.1.3.1). The dust reduction factors for this control method and the alternative methods were collected by reviewing the literature and are presented in Appendix (1).

5.1.3. Proposed Mine Dust Control Cost Parameters

The mine dust control methods studied within this thesis are classified as direct and indirect methods as it pertains to their application principles (see Section 4.1.3).

The overall costs of the direct methods are represented by capital and operational costs including overheads, i.e., equipment, material and personnel costs. These overhead cost parameters and their unit costs were obtained by examining numerous sources (see Section 4.1.4).

The indirect control methods, as already described in Section 4.1.4, included only those regulations established within mining practices for reducing the level of dust generation. These methods incurred no capital or operational expenditures for control system installations or applications and therefore their cost parameters were valued as zero.

As an example, the cost parameters determined for the control methods proposed for truck haulage are listed in (1). The parameters for the water spraying method are also listed in Table 8. The cost parameters given in Table 8 are grouped as constant and dynamic variables. The constant variables \(C1\) to \(C5\), \(C9\) to \(C11\), \(O1\); and \(O3\) to \(O7\) have fixed, pre-defined and site- or application-specific values. These parameters were quantified with respect to the mining conditions at the NBCC mining area. However, the dynamic cost variables, which are highlighted in bold in the table, were estimated based on constant and/or other dynamic variables. Eq. 24 describes how “watering rate”, one of the dynamic cost variables for the water spraying method, relates to the pre-defined constants.
Table 8. Cost parameters of water spraying proposed for haulage activity

<table>
<thead>
<tr>
<th>Control Method: Road Surface Treatment – Water Spraying</th>
<th>Unit</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduction factor</td>
<td>70 %</td>
<td>NBCC measurements</td>
</tr>
</tbody>
</table>

**Cost calculation**

1. **Capital cost**

<table>
<thead>
<tr>
<th>C1</th>
<th>Truck capacity</th>
<th>Unit</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>26500 L</td>
<td>(CostMine, 2012; BBK I, 2013a)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>C2</th>
<th>Truck operating time per day</th>
<th>h</th>
<th>(BBK I, 2013a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C3</td>
<td>Truck cycle length</td>
<td>km</td>
<td>(BBK I, 2013a)</td>
</tr>
<tr>
<td>C4</td>
<td>Truck cycle time</td>
<td>min</td>
<td>(BBK I, 2013a)</td>
</tr>
<tr>
<td>C5</td>
<td>Truck watering span (fraction)</td>
<td>Half span/width</td>
<td>(BBK I, 2013a)</td>
</tr>
<tr>
<td>C6</td>
<td>Truck watering span (in meter)</td>
<td>m</td>
<td>(BBK I, 2013a)</td>
</tr>
<tr>
<td></td>
<td>Watering rate</td>
<td>1.2 L/m²*h</td>
<td>(BBK I, 2013a)</td>
</tr>
<tr>
<td>C7</td>
<td>Required number of trucks</td>
<td>3 truck</td>
<td>(BBK I, 2013a)</td>
</tr>
<tr>
<td>C9</td>
<td>Truck cost</td>
<td>240000</td>
<td>(CostMine, 2012; BBK I, 2013a)</td>
</tr>
<tr>
<td>C10</td>
<td>Truck lifetime</td>
<td>114 month</td>
<td>(CostMine, 2012; BBK I, 2013a)</td>
</tr>
<tr>
<td>C11</td>
<td>Installation of ancillaries (filling stations etc.)</td>
<td>176000 €</td>
<td>(CostMine, 2012; BBK I, 2013a)</td>
</tr>
</tbody>
</table>

2. **Operational cost**

| O1 | Unit water cost | 0.045 €/m³ | (Landesregierung NRW, 2012) |
| O2 | Water requirement | 85179 L/h | (BBK I, 2013a) |
| O3 | Unit fuel cost   | 0.891 €/L | (EUROPIA, 2012; BBK I, 2013a) |
| O4 | Fuel requirement | 40 L/truck*h | (CostMine, 2012; BBK I, 2013a) |
| O5 | Total driver salary per truck | 4260 €/truck*month | (CostMine, 2012; BBK I, 2013a) |
| O6 | Maintenance cost  | 7085 €/truck*month | (CostMine, 2012; BBK I, 2013a) |
| O7 | Operation cost of ancillaries | 2640 €/month | (CostMine, 2012; BBK I, 2013a) |

\[
Watering\ rate\ (C7) = \frac{C1}{C3 \times 1000 \times C6 \times \frac{C4}{60}}
\]

Eq. 24

where:

- \(C7\) = watering rate (L/m²*h)
- \(C1\) = truck capacity (L)
- \(C3\) = truck cycle length (km)
- \(C6\) = truck watering span (m)
- \(C4\) = truck cycle time (min)
Amount of watering trucks required ("required number of trucks") for achieving the target water rate is another dynamic variable and is estimated for the given road size as follows:

\[
\text{Required number of trucks (C8)} = \left( \frac{\text{Road size (m}^2) \times C7 \times 24}{C1 \times \frac{60}{C4} \times C2} \right) \quad \text{Eq. 25}
\]

where:

- \( C8 \) = required number of trucks (truck)
- \( C7 \) = watering rate (L/m² h)
- \( C1 \) = truck capacity (L)
- \( C4 \) = truck cycle time (min)
- \( C2 \) = truck operating time per day (h)

The amount of water to be sprayed per hour, "water requirement", is also a dynamic variable and calculated by multiplying the watering rate with the road size as shown in the below equation:

\[
\text{Water requirement (O2)} = C7 \times \text{Road size (m}^2) \quad \text{Eq. 26}
\]

where:

- \( O2 \) = water requirement (L/h)
- \( C7 \) = watering rate (L/m² h)

The road size stated in Eq. 25 and Eq. 26 is another dynamic parameter that is a function of the road length (m) and the road width (m). These parameters were defined as the emission calculation parameters and were thus not included within the cost parameters of control methods for haulage activity. The average road width at the NBCC mining area (12 m) and a hypothetical road length (6000 m = 6 km) were used for the exemplary cost parameters given in Table 8. The water trucks employed at the NBCC mine are capable of spraying one half of the road. Accordingly, “truck watering span (in meter)” (6 m) was calculated on the basis of the pre-defined road width (12 m) and “truck watering span (fraction)” that was set as “half”.

According to above, the cost parameters of the entire set of control methods proposed for the NBCC mining operation were included within the cost calculation module of the Dust-DSS, as outlined in Section 5.2.1 below.
5.2. Developed Decision Support System and Scenario Simulation

The primary result of this thesis, the mine dust control decision support system (Dust-DSS), is introduced in this section. Accordingly, the computational and guide modules of the DSS and its verification and validation results are presented in the following. At the end of the section, the simulation outcomes of the DSS scenarios are provided.

5.2.1. Developed Mine Dust Control Decision Support System (Dust-DSS)

5.2.1.1. DSS Computational Module

The Vensim model developed as the DSS computational module includes multiple separate views dedicated to different tasks as explained below. These model views comprise an opening view, labeled “Project Info”, dust emission and control evaluation views labeled “Dust Emission and Control Performance” and “Dust Control Cost”, as well as result views, namely “Overall Results”.

Project Info View

“Project Info” is the opening view of the DSS computational module and it includes the overall site-specific information required for estimation of the mine dust emission levels and control cost-performances. These can be grouped as the mining parameters (e.g., working hours), the local conditions (e.g., yearly interest rate) and the meteorological data (e.g., number of heavy rainy days). The structure of this view is illustrated in Figure 19.
Dust Emission and Control Performance Views

The “Dust Emission and Control Performance” views include the mine dust emission factors, the operation rates of the mining activities and the reduction factors of the proposed dust control methods. Separate views were created in the Vensim model for each dust-generating mining activity.

An exemplary model structure for overburden haulage is provided in Figure 20. As depicted in this figure, the dust emission parameters including the emission factor (marked “1”) and operational measures (marked “2”) were introduced in this view for emission level calculations without the application of any control method, i.e., emission without mitigation (marked “3”).
The overburden haulage view (see Figure 20) also shows the influence of the mining and the climatic conditions, i.e., working hours per shift and day and no emission days per month (marked “4”) on dust emissions with natural mitigation. Since these parameters were previously introduced in the “Project Info” view, they were defined as shadow variables in this view. Consequently, they provide a link between these two separate model views.

Finally, the dust control options proposed for overburden haulage activity were included in this exemplary view (marked “5”). In conjunction with their start and end
Results

Results

results and reduction factors, the combined reduction (marked “6”) was designated. The emission levels after mitigation (marked “7”) were defined as a function of the combined reduction and the dust emissions with natural mitigation.

Dust Control Cost Views

The overall cost calculations of the dust control methods were embedded in the Vensim model “Dust Control Cost” views. In parallel with the “Dust Emission and Control Performance” views, 17 separate views were created for the cost evaluation of the control methods proposed for each mining activity. The overhead cost parameters of the control methods and their unit costs were defined within these views.

As an example, the dust control cost view of the water spraying method proposed for overburden haulage activity is given in Figure 21. Numerous dynamic and constant cost variables are present in this model’s structure for control cost calculations. For instance, a dynamic cost variable, watering rate (marked “1” in Figure 21), was defined on the basis of the constants: truck capacity, truck cycle length and time and truck watering span (see also Eq. 24 in Section 5.1.3). Water requirement (marked “2”) is another dynamic variable and estimated in terms of the watering rate and the size of the road (marked “3”) as shown in Eq. 26 in Section 5.1.3. The latter is a shadow variable and thus the link between this view and the corresponding dust emission and control performance view of overburden haulage (see Figure 20).

The nominal cost calculation of water spraying method (marked “4”) was designed on the basis of various capital and operational cost parameters such as water requirement (marked “2”), as shown in Figure 21. Similarly, the net present value (NPV) of dust control cost (marked “5”) was designated by the same cost parameters and in addition, monthly interest rate (marked “6”). The monthly interest rate was initially introduced in the “Project Info” view and added as a shadow variable in this view.
Overall Results Views

The overall results of the model are presented within two separate views as “Dust Control Overall Performance” and “Dust Control Overall Cost”. The overall result views for overburden handling activities and wind erosion are shown in Figure 22 and Figure 23. The former consists of the calculations for the total mine dust emission generated by the defined sources (marked “1” in Figure 22), the reduced level of the total emission with natural mitigation (marked “2”) and after mitigation (marked “3”). Additionally, this view includes the overall combined dust reduction
factor attained by the defined control methods (not shown in Figure 22). Furthermore, the “Dust Control Overall Cost” view summarizes the estimated costs of the mine dust control projects in nominal and present values (marked “1” and “2” in Figure 23).

Figure 22. Dust-DSS on Vensim: the “Dust Control Overall Performance” view

Figure 23. Dust-DSS on Vensim: the “Dust Control Overall Cost” view

5.2.1.2. DSS Guide Module (BPG)

The DSS guide module - Best Practice Guide (BPG), which is available online for the authorized users of the RAME project, was developed on a Wiki platform. An
exemplary web page for the “Introduction” chapter of the BPG is shown in Figure 24. In this figure, the content list of the BPG is also found as a side-menu.

The BPG includes seven chapters as listed in its side-menu (see Figure 24). In the first two chapters, background information on mine dust generation and its environmental, health and social effects and scope are given, and the aim and design of mine dust monitoring are introduced. In the following chapter, the principles for dust dispersion modeling and its application in mine dust control are described. The emission factors suggested for various mine dust sources are listed in the next chapter. The scope and aim of mine dust control (mitigation), background information on control methods, their design and selection criteria and how to evaluate the performance of dust control are described in the next chapter. This is followed by a chapter presenting the legislative framework on air quality and occupational health and safety in Vietnam and the EU. The final chapter of the BPG includes definitions for the terms relevant to dust control and monitoring.
5.2.1.3. DSS Verification and Validation Results

The consistency between the developed and conceptual DSSs was examined by the model verification techniques described in Section 4.2.3.3. As an example for verification of the relationships among the system components, a tree diagram showing the causes (up to two depths) of the variable “Truck Haulage: Water Spraying Cost NPV” is given in Figure 25. The tree diagram shows the system components (up to selected depths) that cause the considered variable to change.

![Tree Diagram](image)

**Figure 25.** Causes tree diagram of “Truck Haulage: Water Spraying Cost NPV”

The DSS model was also validated according to the test methods listed in Section 4.2.3.3. An exemplary result for the Vensim sensitivity analysis of the water spraying control cost in net present value (NPV, M€) regarding the unit fuel cost (€/L) is graphically illustrated in Figure 26. In this analysis, the influence of fuel cost variations between 0.5 €/L and 1.5 €/L over a 360-month (30-year) period on the water spraying cost was calculated. As this figure demonstrates, the total dust control cost after 30 years changed from approximately 5 M€ to 7.5 M€ as it concerned the corresponding fuel cost variations.
5.2.2. DSS Scenario Simulation Results

The predictive scenarios with reference to the NBCC mining conditions were simulated in order to determine the mine dust emission levels and the applicability limits of the proposed dust control methods. Two groups of scenarios, the reference scenario and the individual scenarios, were developed and simulated by following the methodology explained in Section 4.2.4. The simulation results are presented in the below sections. These results are interpreted and discussed in Section 6.2.2.

5.2.2.1. Simulation Results of Reference Scenario

The reference scenario simulations revealed two main outcomes: (1) the primary mine dust sources as it concerned emission levels; (2) the effect of critical uncertainties on the simulation results.

The mine dust emission levels were estimated on the basis of the Dust-DSS simulation database including the assumptions and data about mining conditions, emission factors and climatic conditions (see Appendix E-1 and Appendix E-2). Accordingly, the dust emissions generated by individual mining activities throughout
the scenario time of 20 years were calculated. The proportions of the dust emission levels for each mine dust source evaluated within the reference scenario, i.e., overburden handling activities and wind erosion, are shown in Figure 27. Overburden haulage had the highest share with 57% whereas wind erosion constituted around 42% and other overburden handling activities generated only 1.6% of the total dust emission. It should be noted that, in the reference scenario, the total road length and the wind erosion area were assigned as 24.5 km and 4.51 km², respectively (see Appendix E-2).

![Figure 27](image-url)

Figure 27. Percentage shares (%) of the dust sources included in the reference scenario

(1) The emission from overburden haulage was estimated in PM10 whereas the emissions from other activities were estimated in PM30.

The influence of the critical uncertain parameters (i.e., road length and wind erosion area) on the total mine dust emission levels were estimated through sensitivity analyses. The ratios of these total emissions to the total emission estimated for a one-km road network are presented as dimensionless index emission levels in Figure 28. Moreover, the percentage shares of each mine dust source within the total emission also varied by alternating road length, as illustrated in Figure 29.
Step-wise changes in the wind erosion area also affected the total mine dust emission levels. The reflection of these area increments from 0.1 km$^2$ to 5 km$^2$ in total emissions pertaining to the reference area of 0.1 km$^2$ is displayed as
dimensionless index emission levels in Figure 30. Varying wind erosion areas also influenced the ratios of emissions from different dust sources to the total emission level as shown in Figure 31.

**Figure 30.** Index emission levels (-) for varying wind erosion areas (km$^2$) estimated for the reference scenario

**Figure 31.** Percentage shares (%) of the mine dust sources included in the reference scenario for varying wind erosion areas (km$^2$)
5.2.2.2. Simulation Results of Overburden haulage and Wind Erosion Scenarios

The simulation results of the reference scenario showed that overburden haulage was the primary mine dust source of overburden handling activities, followed by wind erosion. Therefore, separate scenarios for these dust sources, including the application of proposed control methods, were developed and simulated within the Dust-DSS. These simulations were targeted to investigate how the changes in critical uncertainties affect the dust emission levels and the dust control cost-performance. In the following, the results of these sensitivity simulations are presented.

Overburden Haulage Scenarios

For the dust emission and control analysis of overburden haulage activity, in total, 10 scenarios ("OH1" to "OH10") were developed. Sensitivity analyses for the cost-performance of dust control methods proposed for overburden haulage were conducted through simulations of these scenarios in the Dust-DSS. As it is presented in Appendix E-3, the first five scenarios ("OH1" to "OH5") focused on the cost-performance of these methods using a hypothetical activity including 58 haulage trucks on an 18-km road network. In these scenarios, water spraying, application of surface agents and road paving methods were investigated regarding their cost development over time. For this purpose, the net present values (NPV) of these dust control alternatives were estimated for 30 years (360 months) with yearly interest rates (IR) from 1% to 5% assigned in the scenarios from "OH1" to "OH5", respectively.

Figure 32 shows a graph for the total costs in NPV computed via scenario simulations for each control method over time. In this graph, the uppermost cost lines of each control method represent the results of scenario "OH1", where the interest rate was set as 1%. As is shown, the total costs over time declined in conjunction with incremental interest rates. Thus, the lowest control costs in NPV were calculated for a 5% interest rate assigned to scenario "OH5".

For further cost-performance assessment of the dust control methods considered for overburden haulage, the cost-effectiveness ratio (CER) and the cost-reduction ratio (CRR) of these methods were also computed for scenarios "OH1" to "OH5". The
CER and CRR curves for water spraying, the application of surface agents and road paving methods over time are illustrated in Figure 33 and Figure 34, respectively. These graphs were plotted for scenario “OH5”, for which a 5% yearly interest rate was assumed.

**Figure 32.** Total costs (NPV, M€) of the dust control methods proposed for overburden haulage over time (month)

**Figure 33.** Cost-effectiveness ratio (CER, €/kg) of the dust control methods proposed for overburden haulage over time (month) estimated in the scenario “OH5” (IR-yearly=5%)
Figure 34. Cost-reduction ratio (CRR, €/%) of the dust control methods proposed for overburden haulage over time (month) estimated in the scenario “OH5” (IR-yearly=5%)

The scenarios, “OH6” to “OH10”, were developed for sensitivity analyses of the dust control costs with respect to varying road lengths (1 km to 50 km). Individual control costs in the NPV of water spraying, application of surface agents and road paving over time were calculated using simulations of these scenarios in the Dust-DSS. In these simulations, a 5% yearly interest rate was selected, as given in the scenario conditions presented in Appendix E-3.

The total costs calculated by the simulations of the scenarios “OH6” to “OH10” showed a similar pattern to the total cost graph of the scenario “OH5”, shown in Figure 32. Therefore, for ease of presentation of the simulation results of these scenarios, only the time points (month) at which the cost of an individual control method exceeded the costs of other methods were determined. In Section 6.2.3, these intersection times, once the costs of water spraying and the application of surface agents became higher than the road paving cost for the scenarios “OH6” to “OH10” are presented in Table 13 and discussed.

**Wind Erosion Scenario**

The cost-performances of the dust control methods proposed for wind erosion was evaluated through the simulation of 12 scenarios (“WE1” to “WE12”). Overall, seven control methods were analyzed in four groups: (1) ground covering methods (crop and grass vegetation); (2) application of surface agents (chemical wetting and
crusting); (3) water exposure; (4) peripheral methods (installation of wind barrier and wind break). Different yearly interest rates or wind erosion areas were defined in each scenario for the cost-performance sensitivity analyses (see Appendix E-3).

The first five scenarios ("WE1" to "WE5") involved varying interest rates (IR) between 1% and 5%. The total dust control costs in NPV for the scenarios "WE1" (IR = 1%), "WE3" (IR = 3%) and "WE5" (IR = 5%) are illustrated in Figure 35, Figure 36 and Figure 37, respectively. The wind erosion control methods were also examined regarding to their cost-effectiveness ratios (CER) and cost reduction ratios (CRR) via simulations of the scenarios "WE1" to "WE5". The CER and CRR graphs obtained for the scenario "WE5" are shown in Figure 38, Figure 39 and Figure 40.

Influence of wind erosion area on the dust control cost was determined through simulations of the scenarios "WE6" to "WE12". Different area sizes from 0.1 km² to 5 km² were assigned in these scenarios and the costs of proposed control methods were estimated accordingly. As stated in Appendix E-3, 5% yearly interest rate was selected in these scenarios. The simulation results for scenarios "WE6", "WE10" and "WE12" are illustrated in Figure 41, Figure 42 and Figure 43, respectively.

![Figure 35](image-url)  
**Figure 35.** Total costs (NPV, M€) of the dust control methods proposed for wind erosion over time (month) estimated in the scenario "WE1" (IR-yearly=1%)
Figure 36. Total costs (NPV, M€) of the dust control methods proposed for wind erosion over time (month) estimated in the scenario “WE3” (IR-yearly=3%)

Figure 37. Total costs (NPV, M€) of the dust control methods proposed for wind erosion over time (month) estimated in the scenario “WE5” (IR-yearly=5%)
Figure 38. Cost-effectiveness Ratio (CER, €/kg) of the dust control methods proposed for wind erosion over time (0 to 120 months) estimated in the scenario “WE5” (IR-yearly=5%)
Figure 40. Cost-reduction ratio (CRR, €%) of the dust control methods proposed for wind erosion over time (month) estimated in the scenario “WE5” (IR-yearly=5%)

Figure 41. Total costs (NPV, M€) of the dust control methods proposed for wind erosion over time (month) estimated in the scenario “WE6” (area=0.1 km²)
Figure 42. Total costs (NPV, M€) of the dust control methods proposed for wind erosion over time (month) estimated in the scenario “WE10” (area=2 km²).

Figure 43. Total costs (NPV, M€) of the dust control methods proposed for wind erosion over time (month) estimated in the scenario “WE12” (area=5 km²).
CHAPTER 6. Discussion

The first section of this chapter provides an interpretation of the mine dust emission and reduction factors, as well as the cost parameters of the dust control methods proposed in this thesis with respect to previous studies. The second section discusses the developed Dust-DSS and the implications of the DSS scenario simulation results.

6.1. Mine Dust Emission Factors, Reduction Factors and Dust Control Cost Parameters

The first two parts of this section reviews the mine dust emission factors suggested for the NBCC mining area and the reduction factors estimated for the proposed mine dust control methods. These factors are compared with the literature values and evaluated accordingly. The final part focuses on the validity of the dust control cost parameters determined for the proposed methods.

6.1.1. Mine Dust Emission Factors

The location- and activity-specific emission factors developed within the scope of the RAME sub-project IV and presented in this thesis (listed in Table 6 in Section 5.1.1.3) were compared with the factors and rates suggested by Chakraborty, et al. (2002) and USEPA (2006a; 2006b; 2006c). The emission equations suggested for haulage, dumping and wind erosion in these studies have already been provided in Section 2.1. For ease of comparison, these primary equations from the previous studies were converted to comparative emission factors in identical units to factors presented in this thesis. At this step, the primary equations were solved by assigning the average emission parameters (e.g., activity rates and climatic conditions) obtained during the real-time measurements at the NBCC mining area (see Appendix F). The dust emission factors presented in this thesis and comparative factors are summarized in Table 9.
Table 9. Developed and comparative dust emission factors

<table>
<thead>
<tr>
<th>Mining Activity / Dust Source</th>
<th>Emission Factors</th>
<th>Comparative Emission Factors</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Truck haulage</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>on dry main road</td>
<td>880$^{(1)}$</td>
<td>1250$^{(2)}$</td>
<td>g PM10/km*truck</td>
</tr>
<tr>
<td>on wet main road</td>
<td>524$^{(1)}$</td>
<td>4006$^{(3)}$</td>
<td>g PM30/km*truck</td>
</tr>
<tr>
<td>on dry side road</td>
<td>1124$^{(1)}$</td>
<td>1473$^{(4)}$</td>
<td>g PM10/km*truck</td>
</tr>
<tr>
<td>on wet side road</td>
<td>392$^{(1)}$</td>
<td>2.046$^{(6)}$</td>
<td>g PM30/t</td>
</tr>
<tr>
<td>Overburden dumping</td>
<td>0.225</td>
<td>0.454$^{(6)}$</td>
<td>g PM30/t</td>
</tr>
<tr>
<td>Wind erosion</td>
<td>0.198</td>
<td>0$^{(7)}$</td>
<td>g PM30/m²*h</td>
</tr>
</tbody>
</table>

(1) In g PM10/km*truck
(2) In g PM10/km*truck, based on a reference study (USEPA, 2006a)
(3) In g PM30/km*truck, based on a reference study (USEPA, 2006a)
(4) In g PM30/km*truck, on dry road, based on a reference study (Chakraborty, et al., 2002)
(5) In g PM30/km*truck, on wet road, based on a reference study (Chakraborty, et al., 2002)
(6) Based on a reference study (USEPA, 2006b)
(7) Based on a reference study (USEPA, 1998a)
(8) Based on a reference study (Chakraborty, et al., 2002)

6.1.1.1. Overburden Haulage – Emission Factors

The truck haulage emission factors presented in this thesis were developed in unit of grams of PM10 per truck per kilometer travelled (g/truck*km). These factors were evaluated in terms of the comparative emission factors (see Table 9) converted (as shown in Appendix F-1) from the emission equations provided by Chakraborty, et al. (2002) and USEPA (2006a).

The USEPA emission equation (see Eq. 1 in Section 2.1) was suggested for unpaved road conditions and as independent from the road type (main or side road). The range of the road surface moisture content during USEPA tests conducted for developing this primary emission equation was reported as ranging from 0.03% to 13% (USEPA, 2006a). Therefore, the road condition for the derived comparative emission factors was considered as dry (see Appendix F-1).

As shown in Table 9, the comparative emission factor derived for PM10 (1250 g/truck*km) by the USEPA equation almost matches the emission factors presented in this thesis, which are 880 grams of PM10 for dry main road and 1124 grams of PM10 for dry side road. However, the emission levels computed by the comparative USEPA factors and the emission factors suggested in this thesis may vary.
significantly for large scale mining operations, as shown in Example Box 4. This indicates that location- and activity-specific mine dust emission factors can provide more precise estimates of dust emission levels than the factors derived under different mining, geological and climatic conditions.

Example Box 4. Calculation of emission with different emission factors

A sample calculation of PM10 emission by a single haulage truck is given in Example Box 1. Continuing the same example, PM10 emission per day caused by 20 trucks (average speed = 10 km/h) is calculated with different emission factors in this example. Daily operating time for haul trucks is assumed as 16 hours. The PM10 emission factors \( EF \) suggested in this thesis for haulage activity are given above in Table 9.

\[
EF_1 = 880 \, g/truck \cdot km = 0.880 \, kg/truck \cdot km \text{ (on dry main road)}
\]

\[
EF_2 = 1124 \, g/truck \cdot km = 1.124 \, kg/truck \cdot km \text{ (on dry side road)}
\]

The comparative emission factor derived for PM10 on the basis of the USEPA equation (USEPA, 2006a) is also presented in Table 9.

\[
EF_3 = 1250 \, g/truck \cdot km = 1.250 \, kg/truck \cdot km \text{ (on dry road)}
\]

The activity rate \( A \) is calculated to be:

\[
A = 20 \, truck \times 10 \, km/h \times 16 \, h = 3200 \, truck \cdot km
\]

Accordingly, for this activity, total PM10 emission without mitigation \( E_{wom} \) is calculated with different emission factors \( EF_1, EF_2 \) and \( EF_3 \) by using Eq. 8 as follows:

\[
E_{wom,1} = 3200 \, truck \cdot km \times 0.88 \, kg/truck \cdot km = 2816 \, kg
\]

\[
E_{wom,2} = 3200 \, truck \cdot km \times 1.124 \, kg/truck \cdot km = 3597 \, kg
\]

\[
E_{wom,3} = 3200 \, truck \cdot km \times 1.250 \, kg/truck \cdot km = 4000 \, kg
\]

As a result, total PM10 emission amounts computed with \( EF_1 \) and \( EF_3 \) for this activity diverge by \( 1184 \, kg \) per day. This difference in emission calculation with \( EF_2 \) and \( EF_3 \) is \( 403 \, kg \) per day.

Chakraborty, et al. (2002) provided an equation for SP (PM30) emission from for haul roads, and again independent from the road type (see Eq. 2 in Section 2.1). The comparative factor derived based on this primary equation for dry haul roads (1473 g PM30/truck*km, see Table 9) is higher than the emission factors proposed in this thesis (880 g PM10/truck*km and 1124 g PM10/truck*km). This can be explained as a result of the difference between the aerodynamic size ranges (PM10 and PM30).
of these emission factors, since higher emission levels can naturally be expected for
the larger size range (PM30). On the contrary, the second comparative factor (317
g/truck*km, for wet haul roads) was lower than the presented emission factors for
PM10 in this thesis, 392 g/truck*km and 524 g/truck*km.

6.1.1.2. Overburden Dumping – Emission Factors

The dust emission factor suggested in this thesis for overburden dumping activity is
given in grams of PM30 (SP or TSP) per tonne of material dumped (g/t) (see Table
9). This emission factor is incompatible with the comparative factors derived (as
explained in Appendix F-2) from the emission equations suggested by
USEPA (2006b) and Chakraborty, et al. (2002).

It should be noted that the USEPA equation (see Eq. 6 in Section 2.1) used in this
thesis is suggested for the dust emissions from aggregate handling and storage
piles, and does not represent the overburden dumping activity completely.
Nevertheless, for the PM30 (SP or TSP) particle range, solution of the USEPA
equation led to a comparative emission factor of 0.454 g/t, whereas the equation of
Chakraborty, et al. (see Eq. 7 in Section 2.1) was converted as 2.046 g/t (see Table
9).

Obviously, the proposed emission factor in this thesis (0.225 g/t) differs greatly from
the comparative literature values (0.454 g/t and 2.046 g/t). The literature values also
differ considerably from each other, because they had been developed for specific
mining locations. These results demonstrate that reliable mine dust emission
estimates require the identification of location- and activity-specific emission factors.
Otherwise, calculations based on other available emission factors may lead to
incompatible results varying by several orders of magnitude.

6.1.1.3. Wind Erosion – Emission Factors

In this thesis, the wind erosion factor is proposed as 0.198 grams of PM30 (SP or
TSP) per the area size in square meters per hour (g/m²*h) (see Table 9). This value
was assessed by comparing the wind erosion estimation procedure introduced by
USEPA (2006c) and the emission rate provided by Chakraborty, et al. (2002).

As described in Section 2.1, the USEPA estimation procedure (see Eq. 3 and Eq. 4)
requires the calculation of erosion potential as a function of threshold friction velocity
(u_i) and friction velocity (u*). When the latter is lower than the former, the wind erosion potential is assumed to be zero. Accordingly, the comparative emission factor (see Table 9) was estimated at zero with the USEPA procedure on the basis of data gained from real-time measurements at the NBCC mining area (shown in Appendix F-3).

On the other hand, the equation of Chakraborty, et al. (2002) (see Eq. 5 in Section 2.1) delivered a comparative emission factor of 0.177 g/m²*h in PM30 (SP or TSP), which is almost at the same level with the factor suggested in this thesis, i.e., 0.198 g/m²*h (see Table 9). Although, these factors compute an approximately equivalent amount of wind erosion on small-scale areas over short time periods, wind erosion levels under extended conditions substantially differ from each other as shown in Example Box 5. This supports the inference made previously concerning the overburden haulage and dumping activities, i.e., that the location- and activity-specific mine dust emission factors yield more accurate emission results than the factors developed for other mining operations.

---

**Example Box 5. Calculation of wind erosion with different emission factor**

Wind erosion in PM30 over a 0.5 km² exposed area per day is calculated with different emission factors in this example.

The emission factor suggested in this thesis (EF₁) and the comparative factor derived from the equation of Chakraborty, et al. (2002) (EF₂) for wind erosion can be given in kg PM30 emission as follows:

\[
EF_1 = 198 \text{ kg} / \text{km}^2 \cdot \text{h (see Table 9 above)}
\]

\[
EF_2 = 177 \text{ kg} / \text{km}^2 \cdot \text{h (see Table 9 above)}
\]

The activity rate (A) is calculated to be:

\[
A = 0.5 \text{ km}^2 \times 24 \text{ h} = 12 \text{ km}^2 \cdot \text{h}
\]

Accordingly, total wind erosion (PM30) without mitigation (E_wom) is calculated with these emission factors (EF₁ and EF₂) by using Eq. 8 as follows:

\[
E_{wom,1} = 12 \text{ km}^2 \cdot \text{h} \times 198 \text{ kg} / \text{km}^2 \cdot \text{h} = 2376 \text{ kg}
\]

\[
E_{wom,2} = 12 \text{ km}^2 \cdot \text{h} \times 177 \text{ kg} / \text{km}^2 \cdot \text{h} = 2124 \text{ kg}
\]

As a result, the difference between the wind erosion level estimates by EF₁ and EF₂ is 252 kg PM30 per day.
6.1.2. Mine Dust Control – Reduction Factors

The mine dust control methods studied in this thesis for the emissions from overburden haulage, dumping and wind erosion at the NBCC mining area are compiled in Appendix C. The reduction factors of these control methods were developed by evaluating data obtained from the real-time dust control performance and emission measurements, as well as from previous studies (see also Appendix C). The different factors obtained for the same control methods were assessed with respect to their relevance to the NBCC mining area; and a single reduction factor for each control method was approximated. These average reduction factors were then assigned as the performance parameters of the dust control methods into the Dust-DSS developed within the scope of this thesis.

Prior to the real-time dust control performance measurements, the primary mine dust sources for the NBCC operation were determined as shown in Figure 16 in Section 5.1.2.2. In the following sections, the identified primary mine dust sources and the dust reduction factors suggested in this thesis are discussed by comparing them with the values presented in the literature.

6.1.2.1. Primary Mine Dust Sources

The individual emission levels of the mine dust sources identified at the NBCC mining area were calculated on the basis of the activity rates of these sources and the derived emission factors for the NBCC operation. The dust emission levels and corresponding percentage shares of each dust source within the total daily emission level are presented as a pie chart in Figure 16 in Section 5.1.2.2 and in tabular form in Appendix B.

Overburden truck haulage, which constitutes almost 54% of the total mine dust emission, is specified as the primary dust-generating activity at the NBCC mining area. Together with coal trucking, the total haulage activity within the mining area accounts for approximately 63.3% of the total emission. Wind erosion is determined as the second highest dust source with a 33.9% contribution to the total mine dust emission. These estimates were compared with data from previous studies in Table 10.
Table 10. Shares (%) of mining activities in total mine dust emission

<table>
<thead>
<tr>
<th>Mining Activity / Dust Source</th>
<th>Share in Total Dust Emission (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NBCC (Donnelly, et al., 2011)</td>
</tr>
<tr>
<td></td>
<td>(Environment Australia, 1998)</td>
</tr>
<tr>
<td></td>
<td>(Huertas, Dumar, &amp; Huertas, 2012)</td>
</tr>
<tr>
<td></td>
<td>(Ghose, 2004)</td>
</tr>
<tr>
<td>Truck haulage (overburden and coal)</td>
<td>63.3(1)</td>
</tr>
<tr>
<td>Wind erosion</td>
<td>33.9(1)</td>
</tr>
</tbody>
</table>

(1) The emission from overburden and coal truck haulage was estimated in PM10 whereas the emission from wind erosion was estimated in PM30.
(2) In TSP
(3) In PM10
(4) In PM2.5
(5) Independent of particle size

Donnelly, et al. (2011) investigated the TSP, PM10 and PM2.5 emissions from different coal mining activities at approximately 57 open-cut and underground coal mines in the Greater Metropolitan Region (GMR) in New South Wales (NSW), Australia. Accordingly, they identified that wheel generated dust, mainly due to trucks travelling on unpaved haul roads, as well as wind erosion of overburden dumps as the primary emission sources for different particle size ranges (see Table 10). The proportions of wind erosion given in Table 10 are the overall proportions of different wind erosion sources (i.e., wind erosion of overburden dumps, exposed areas and coal stockpiles) provided individually in the reference study (Donnelly, et al., 2011).

Another study conducted in Australia (Environment Australia, 1998) presented the shares of various surface coal mining activities in total mine dust emission according to data obtained from the NSW State Pollution Control Commission. In this study, the material transportation on haul roads was proposed as the major contributor to mine dust emission with 42% (independent of particle size) in both truck-shovel and dragline operations (see Table 10). However the contribution of wind erosion (exposed areas) was given as only 6% and 7% in truck-shovel and dragline operations, respectively, and ranked below other mining activities (e.g., topsoil removal or dragline operation).

In addition to the studies mentioned above, Huertas, Dumar and Huertas (2012) investigated the dust emission levels at surface coal mines in the northern part of Colombia. In their study, material transportation over unpaved roads was identified
as the highest TSP emission source with a 34% share (see Table 10). They ranked the TSP emissions from coal handling (29% share) and wind erosion (28% share, see Table 10) below that of transportation. In the same study, quite different results were delivered for PM10 emissions. In this case, 52% of the total PM10 emissions in the monitored mining areas were estimated as being the result of overburden handling, 25% due to transportation (see Table 10) and 16% due to coal handling.

There have been other studies proposing different dust emission rankings for the individual surface coal mining activities. Chaulya, et al. (2002) investigated several surface coal mining sites in India and reported coal preparation plants and transportation activities as the highest dust emission sources in those sites. Similarly, dust emission level estimates presented in another study for a surface coal mining operation in India proposed coal size reduction (coal preparation) as the major dust-generating mining activity, followed by wind erosion and material transportation on haul roads (Ghose, 2004). In this study, dust emissions by coal size reduction, wind erosion and transportation (overburden and coal) were calculated as 6812.5 kg/d, 1569.2 kg/d and 492.3 kg/d, respectively. These emission levels are equivalent to the corresponding emission proportions of 72.7%, 16.8% and 5.3% within the estimated total mine dust generation, i.e., 9366.7 kg/d (see Table 10).

The contributions of different mining activities to the total mine dust emission estimated in this thesis for the NBCC mining area differ somewhat from those proposed for other coal mining locations examined in the studies referenced in Table 10. This may have been due to the possible variations in emission influencing parameters (e.g., mining conditions and climatic conditions), as well as the emission factors assigned to the mine dust emission calculations in these studies. It should also be noted that the dust emission factors employed for the NBCC haulage activity represent only PM10 generation; and haulage emissions will definitely constitute a higher proportion than the suggested 63.3% within the total mine dust emission if TSP emission levels were considered.

The emission proportions provided by Donnelly, et al. (2011) were based on the total emissions by numerous dust-generating activities included in open-cut and underground mining operations. Additionally, the prevailing mining conditions for dust emission levels, e.g., haul road length and wind erosion area, were not stated in
the study of Donnelly, et al. (2011) or in the handbook of Environmental Australia (1998), and were most likely different from the NBCC conditions.

In the work of Huertas, Dumar and Huertas (2012), the average total overburden (pit and dump) and coal (stock) areas (areas exposed to wind erosion) in the investigated mining operations was given as 3.09 km$^2$, whereas the wind erosion area was determined as 4.51 km$^2$ for the NBCC mining area studied in this thesis. Moreover, the physical properties, e.g., moisture content or silt content of the disturbed material and the emission factors defined for the mining activities in their work are entirely different than those employed in the emission calculations in this thesis.

Other research (Chaulya, et al., 2002; Ghose, 2004) were also conducted under different mining and environmental conditions. For example, Ghose (2004) reported the total haul length for overburden and coal transportation as 1.2 km, while the total area exposed to wind erosion was 6.73 km$^2$ for the mine studied in this instance. On the other hand, the length of the road network and the wind erosion area at the NBCC mining area were determined as 24.5 km and 4.51 km$^2$, respectively. Additionally, the selected emission factor equations by Ghose and the factors proposed in this thesis for the estimation of individual mine dust emission levels were widely disparate.

To sum up, it is clear that the emission levels of individual mine dust sources and their importance within the overall mine dust emission are strongly dependent on the specific mining conditions. Nonetheless, it is safe to conclude that haulage activity and wind erosion are the major dust sources at surface coal mines.

6.1.2.2. Overburden Haulage – Reduction Factors for Control Methods

The reduction factor of the water spraying method applied at the NBCC mining area was estimated at 70% by analyzing the real-time performance measurements data. As explained in detail in Section 5.1.2.4, this reduction factor will be achieved with a watering amount of 0.60 L/m$^2$ at 30-minute watering intervals. Accordingly, the optimum watering rate for the NBCC haul roads was suggested as being 1.20 L/m$^2$*h. The factors proposed for the alternative dust control methods for haulage activity were compiled through a literature review (see Appendix C-1). In the following, the water spraying reduction factor derived for the NBCC operation is
assessed in comparison with the factors suggested in previous studies (Foley, Cropley, & Giummarra, 1996; USEPA, 1998c; Countess Environmental, 2006; Environment Australia, 2012). These factors have previously been summarized in Section 1.1 and are also listed in tabular form in Appendix C-1.

The estimated dust reduction factor in this thesis (70%) for water spraying on haul roads is within the range of previously proposed factors except for that indicated by Foley, et al. (1996) (40%). However, this low reduction level was likely suggested due to the extended watering intervals of up to 12 hours considered in their study. Therefore, the estimated reduction factor (70%) was also compared with previous studies according to the required watering rate of 1.20 L/m²·h.

The watering rates given by USEPA (1998c) can be converted as 0.69 L/m²·h for 74% and 1.18 L/m²·h for 95% reductions (see Appendix C-1). Despite its relatively high value, the conceived watering rate of the NBCC mining site (1.20 L/m²·h) can apparently not provide a dust reduction as high as that suggested by the USEPA study. On the other hand, the NBCC watering rate is much lower than the rates (2 L/m²·h and >2 L/m²·h) reported in the NPI document (Environment Australia, 2012). Nevertheless, the NBCC rate enables a coherent reduction factor (70%) when measured against the reductions indicated in this reference study (50% and 75%). Another study postulated, without mentioning any watering rate, that the water spraying reduction varies from 10% to 74% (Countess Environmental, 2006).

It is clear that uneven reduction factors for the water spraying method are recommended in different studies even when comparable watering rates are proposed. This is because, in addition to the watering rates, the effectiveness of the water spraying method depends on vehicle parameters, as well as on climatic conditions (Countess Environmental, 2006). Moreover, varying activity parameters (e.g., traffic volume) and road conditions (e.g., surface roughness) were probably present for each reference study. Therefore, it can be stated that reliable evaluation of dust control performance requires determination of the parameters influencing the effectiveness of the control methods, as well as identification of location- and activity-specific reduction factors.
6.1.2.3. Overburden Dumping – Reduction Factors for Control Methods

The reduction factors of the dust control methods focused on in this thesis for overburden dumping (i.e., reducing dumping height and watering dumping layer methods) were estimated by analyzing the real-time emission measurements data as explained in Section 5.1.2.4. The reduction factors of other control methods proposed for overburden dumping were referenced from the literature (see Appendix C-2).

No previously published relevant value was available to use as a reference for evaluation of the reduction factor derived in this thesis for the watering dumping layer method. However, the reduction factor proposed for reducing the dumping height method was compared with the dust control levels derived according to the emission equation provided by Chakraborty, et al. (2002) for overburden unloading activities (see Section 2.1).

The graph in Figure 44 illustrates the dust reduction factors with respect to the dumping heights determined by both evaluating the NBCC measurements and the equation provided by Chakraborty, et al. (2002).

Figure 44. Dust reduction factor (%) for reducing dumping height vs. dumping height (m)

As already mentioned in Section 5.1.2.4, reducing the average dumping height of 21.31 m at the NBCC mining area to the recommended layered dumping height of
4 m will provide a 57% dust reduction. Therefore, the average dumping height (21.31 m) was taken as the reference point with zero reduction (see Figure 44). The emission levels provided by the equation of Chakraborty, et al. (2002) were calculated according to the parameters measured during the real-time measurements for overburden dumping at the NBCC mining area (see Table 11).

Table 11. Averages of the parameters measured during the real-time measurements for overburden dumping

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture content of unloading material</td>
<td>5.35 %</td>
</tr>
<tr>
<td>Silt content of unloading material</td>
<td>7.65 %</td>
</tr>
<tr>
<td>Wind speed</td>
<td>2.85 m/s</td>
</tr>
<tr>
<td>Drop height</td>
<td>21.31 m</td>
</tr>
<tr>
<td>Capacity of unloader</td>
<td>41.70 t</td>
</tr>
<tr>
<td>Frequency of unloading</td>
<td>29.00 no./h</td>
</tr>
</tbody>
</table>

As is shown in Figure 44, the line representing the estimated dust reduction levels based on the real-time measurements (“NBCC Dumping”) matches well with the reduction levels derived by the equation of Chakraborty, et al. (2002) (“Chakraborty Dumping”). This result indicates the consistency of the dust reduction factor developed for the reducing dumping height method at the NBCC mining area. Furthermore, this shows that mining and dust control conditions drive dust control effectiveness, and thus promotes the importance of location- and activity-specific reduction factors for precise dust control performance estimates.

6.1.2.4. Wind Erosion – Reduction Factors for Control Methods

As explained in Section 4.1.3.4, the reduction factors of the dust control methods proposed for wind erosion were collected by conducting a literature review (see Appendix (1)).

Although the referenced studies listed in Appendix (1) possess different reduction levels for the same dust control methods considered for wind erosion, these variations fall within a comparable range. For example, the control factors recommended for vegetative ground cover, which is one of the most widely-used control measures against wind erosion, can be given. In a report prepared for
USEPA, the dust control level of vegetative cover was suggested as being 70% (USEPA, 1983). Another USEPA analysis proposed a 5% to 95% dust reduction for vegetation depending on plant type (USEPA, 1992). In a more recent study, the Western Regional Air Partnership’s (WRAP) Fugitive Dust Handbook, a higher reduction factor of 90% was recommended for crop vegetation (Countess Environmental, 2006).

As stated in the USEPA analysis (USEPA, 1992), plant type is important for wind erosion control, because some types, such as grasses, provide dense and complete cover, and consequently higher dust reduction. In addition, Lyon and Smith (2010) concluded that emission quantity decreases with an increasing percentage of ground cover. In their study, a table showing the effect of soil cover (from 0% to 100%) on relative soil loss reduction (from 0% to 99%) compared to bare soil was also presented. In conclusion, two different reduction factors for vegetative ground cover against wind erosion (30% for grassing and 90% for cropping) were assumed for the NBCC mining area by considering the data observed in the literature (see Appendix (1)).

6.1.3. Mine Dust Control – Cost Parameters

The dust control methods studied in this thesis were grouped into direct and indirect methods as explained in Section 4.1.3. The capital and operational cost parameters for the direct methods were classified as constant and dynamic variables as illustrated by the exemplary set of parameters for the water spraying method listed in Table 8 in Section 5.1.3.

The cost parameters assigned to the direct mine dust control methods were assigned in accordance with the NBCC mining conditions. For example, the watering rate (1.2 L/m²*h) designated for the water spraying method (see Table 8).

( ) was the rate recommended for the NBCC water trucks in order to maintain a 70% dust reduction as indicated in Section 5.1.2.4. As another example, average water truck speed can be noted. This was estimated at 18.5 km/h based on truck cycle length (8 km) and cycle time (28 min), and by assuming a two-minute truck filling time. This approximate speed was slightly over the water truck speed observed on-site (16.2 km/h), and below the vehicular speed limit (20 km/h) at the NBCC mining area.
On the other hand, unit costs were identified according to the market conditions in the Eurozone because collecting complete cost data from a closed political system, such as that of Vietnam, was impossible. Therefore, the unit costs of the mine dust control methods did not reflect the conditions at the NBCC mining area. In this respect, different and presumably lower cost levels than those provided in this thesis can be expected.

The second group of dust control methods was defined as indirect methods, which involved only modifications in the mining operations in terms of dust emission control. As mentioned in Section 4.1.3.1, these methods require no expenditures for the installation or application of dust control systems. However, such modifications in mining operations, e.g., reducing dumping height in order to mitigate dust emission from overburden dumping, may cause indirect costs. Despite this, the costs of indirect dust control methods were valued as zero, since estimation of these indirect costs compatible with any mining condition is a challenging task and beyond the aim of this thesis.

6.2. Decision Support System and Scenario Simulation

6.2.1. Mine Dust Control Decision Support System (Dust-DSS)

The mine dust control decision support system (Dust-DSS) developed within the scope of this thesis is described in Section 5.2.1. The sections below discuss the competence of the computational and guide modules of the DSS. Additionally, the accuracy of the DSS is evaluated with respect to the DSS verification and validation results in the end of this section.

6.2.1.1. DSS Computational Module

The “Dust Emission and Control Performance” and “Dust Control Cost” views constitute the main part of the DSS computational module. In these views, the mine dust emission levels with and without the application of control methods and the overall cost and performance of the selected control methods are calculated.

An exemplary DSS model view of dust emission and control performance calculation for overburden haulage is shown in Figure 20 in Section 5.2.1.1. Additionally, the cost calculation model view of the water spraying method proposed for overburden haulage activity is shown in Figure 21 in the same section. As can be seen in these
figures, the DSS computational module incorporates the mine dust emission and reduction factors, as well as the cost parameters of the dust control methods proposed for open-pit mining operations. The casual behaviors among these system parameters are explicitly shown by the arrows in these detailed model structures.

The “Dust Emission and Control Performance” and “Dust Control Cost” views for the other control methods proposed for the considered mine dust sources were built in similar fashion to the model views described above for overburden haulage. In conclusion, the DSS computational module provides a platform for the accurate evaluation of mine dust emission levels and cost-performance of dust control methods.

6.2.1.2. DSS Guide Module (BPG)

As described in Section 5.2.1.2 and illustrated in Figure 24, the DSS guide module - Best Practice Guide (BPG) - includes several chapters that approaches the mine dust issue from various perspectives.

Previous studies applying a range of different scopes have aimed at providing guidance for dust control at mining areas. Environment Australia published a booklet including best practices in dust management in mining (Environment Australia, 1998). In addition to the scope of the BPG developed within this thesis, some case studies demonstrating the application of best dust management approaches across Australia are presented in this booklet. The National Institute for Occupational Safety and Health (NIOSH) also delivered a handbook describing the effective methods for controlling the dust emissions from mining and tunneling operations (NIOSH, 2003). Later, Countess Environmental prepared the WRAP Fugitive Dust Handbook addressing the control of dust generation at various sources (Countess Environmental, 2006). Apart from the dust control methods described in similar studies, this handbook also covers dust emission estimation methodologies, as well as regulatory aspects and cost-effectiveness calculation techniques. NIOSH published another guidebook on best practices for dust control in coal mining in order to reduce worker exposure to respirable coal and silica dust (NIOSH, 2010). Dust control in longwall and continuous mining operations and at surface mines are described in this guidebook. More recently, NIOSH provided a handbook focusing particularly on dust control in mining and in processing of minerals (NIOSH, 2012).
Compared to the previous studies described above, the BPG developed within this thesis incorporates dust control methods and other important mine dust management aspects, such as monitoring and modeling, which are not discussed or discussed only briefly in these studies. However, the previous examples provide dust control methods for both surface and underground mining operations, whereas the BPG focuses only on the dust problem at open-pit coal mines. Moreover, some distinctive information on dust control can be found in other studies; for example, the best management principles demonstrated in real cases included in Environment Australia’s booklet (Environment Australia, 1998) or the sample cost-effectiveness calculations given in the WRAP Fugitive Dust Handbook (Countess Environmental, 2006). Nonetheless, the BPG was conceived as the guide module of the Dust-DSS and its primary aim is to assist the DSS users in designing their mine dust control strategy. Although, the scope of the BPG is limited to the DSS requirements, its content is elaborated on the basis of the DSS components.

To sum up, it can be deduced that the BPG is capable of providing sufficient background information concerning proper dust management in open-pit coal mine operations.

6.2.1.3. DSS Verification and Validation

The DSS developed in this thesis was verified to the degree that the conceptual model effectively adapted to the DSS as described in Section 5.2.1.3. On the basis of the analysis of the system structure presented in the same section (e.g., the causes tree diagram in Figure 25), it was confirmed that the developed DSS matched the specifications of the conceptual model.

The tests applied for the DSS validation are listed in Section 4.2.3.3. As an example, a graph displaying the result of the sensitivity analysis test for the water spraying cost according to the unit fuel cost is given in Figure 26 in Section 5.2.1.3. This reference variable, the unit fuel cost, was identified as one of the critical parameters within the DSS model by knowing that fuel prices vary significantly according to location and operation. As can be observed from this graph, the water spraying cost in the net present value (NPV) ranged between approximately 5 M€ and 7.5 M€ for fuel cost variations from 0.5 €/L to 1.5 €/L over a 30-year period. This clearly shows the effect of deviations in unit fuel costs on the water spraying costs estimated by the
DSS. Similar sensitivity analysis tests proved the robustness of the DSS results to significant changes in critical parameters.

As a result of the sensitivity and other dynamic model tests suggested in Section 4.2.3.3, the developed DSS was validated. Accordingly, it is envisaged that the Dust-DSS can assist in making decisions and planning for dust control at other active or planned mining operations employing similar mining practices.

6.2.2. Decision Support System Scenario Simulation

The predictive scenarios pertaining to the NBCC mining conditions were simulated by the DSS in order to determine the approximate mine dust emission levels and the applicability limits of the proposed dust control methods. Two groups of scenarios, the reference and individual scenarios, were developed and simulated by following the methodology explained in Section 4.2.4. The results of scenario simulations are discussed in the following sections.

6.2.2.1. Reference Scenario

In the reference scenario, only the overburden handling activities and wind erosion were included as mentioned in Section 4.2.4.1. The scenario simulation results are presented in Section 5.2.2.1. As a first result, the proportions of dust emission levels of each mining activity within the total mine dust emission over the scenario duration of 20 years are depicted in a pie chart in Figure 27 (Section 5.2.2.1). As can be seen in this figure, overburden haulage constituted the largest portion at 57%, while wind erosion caused 42% of the total emission.

The contributions of overburden haulage and wind erosion to the total dust generation estimated in the reference scenario were compared with a previous study (Donnelly, et al., 2011). In this study, the TSP emission levels of 26 different coal production and overburden handling activities within the average total TSP emission (155.8 kt/y) are presented. However, the majority of these activities was not taken into account within the reference scenario, since it focused only on overburden handling activities and wind erosion. Therefore, only the TSP emission data provided for wheel generated dust, wind erosion due to overburden and exposed areas, trucks (dumping overburden), blasting, loaders (overburden) and drilling activities in the study of Donnelly, et al. (2011) were analyzed. The individual shares of these
selected activities were recalculated with respect to their average total TSP emission (127.6 kt/y).

The share of the wheel generated dust, which was reported as 52.4%, was recalculated as 64% in proportion to its average TSP emission (81.6 kt/y). This recalculated proportion represents both coal and overburden haulage activities, independent from the haul road lengths. However, the reference scenario provided emission levels of only overburden haulage on a road network with a predefined total length of 24.5 km (see Appendix E-2). Therefore, it can be suggested that the estimated share for overburden haulage through the reference scenario simulation (57%) is at a comparable level with the recalculated reference proportion (64%).

The proportion of the total wind erosion (32.6 kt/y) due to overburden and exposed areas was estimated at 25.6% within the total TSP emission of the selected mining activities (127.6 kt/y) on the basis of data presented by Donnelly, et al. (2011). This share is considerably lower than the wind erosion share (42%) estimated via the simulation of the DSS reference scenario. However, the average wind erosion area for the studied mines was not provided by Donnelly, et al. (2011), whereas it was defined as 4.51 km$^2$ in the reference scenario. Considering that the area is the primary driving factor for the wind erosion level, the wind erosion share calculated by the reference scenario simulations can be deemed reliable.

Figure 28 to Figure 31 in Section 5.2.2.1 illustrates the influence of haul road length and wind erosion area, which were defined as the critical uncertain parameters, on the total mine dust emission levels.

The index emission levels shown in Figure 28 represent the ratio of total daily mine dust emissions according to varying road lengths to the total daily emission with a reference road length of 1 km. As shown in this figure, the dimensionless index of total emission including an overburden haulage activity on a 50-km road network was estimated at 2.14 (-). In other words, increasing the road length from 1 km to 50 km only doubled the total mine dust emission. This limited increase in index emissions occurred as a result of the high level of wind erosion in the reference scenario. However, the percentage distribution of the emission levels of different mine dust sources according to the varying road lengths provided a better overview for the significance of the critical uncertain parameters in mine dust emission.
calculations (Figure 29). The proportion of dust emission from a one-km road network within the total emission was estimated at 18%, while this was 62% for a road network extended to 50 km.

Similarly, the total mine dust emission including wind erosion from a 5-km$^2$ area was calculated as being only 1.76 times higher than the one with a wind erosion area of 0.1 km$^2$ (Figure 30), due to the dominance of overburden haulage within the total mine dust emission. Even more interesting, the proportion of wind erosion within the total emission varied between 1.5% and 44% for areas from 0.1 km$^2$ to 5 km$^2$, respectively (Figure 31).

As a result, it can be deduced that critical emission parameters such as the wind erosion area and the road length undoubtedly influence the emission levels and the significance of individual mine dust sources.

6.2.3. Overburden Haulage and Wind Erosion Scenarios

In total, 10 overburden haulage (“OH1” to “OH10”) and 12 wind erosion (“WE1” to “WE12”) scenarios were simulated using the Dust-DSS. The simulation results of the dust control costs, cost-effectiveness ratios (CER) and cost-reduction ratios (CRR) under varying uncertainties, i.e., interest rates, road lengths and wind erosion areas, are presented in Section 5.2.2.2. The results are discussed in the following parts in order to evaluate the influence of these critical uncertainties on dust control costs and cost-performance.

Overburden Haulage Scenarios

The dust control methods (i.e., water spraying, application of surface agents and road paving) proposed for haulage activity were investigated in terms of their cost-effectiveness through simulations of the first five overburden haulage scenarios (“OH1” to “OH5”).

The simulation results providing the total cost of each dust control method in NPV over time are graphically illustrated in Figure 32 in Section 5.2.2.2. According to this graph, water spraying was determined as the most expensive dust control method for the scenario duration of 30 years (360 months). For the same period, applying surface agents and road paving indicated the second highest and the lowest costs, respectively. As expected, the dust control costs in NPV decreased with increasing
yearly interest rates (IR) from 1% to 5%. The graph in Figure 32 also reveals that the cost of dust control with surface agents was estimated to always be less than the cost of water spraying. Moreover, in the long term, road paving provided lower total costs than both methods. For an explicit comparison of the costs of selected control methods, the intersection points of the cost lines shown in Figure 32 are provided in Table 12 below.

Table 12. Intersection points (month) of total cost (NPV, in Figure 32) and CER and CRR (in Figure 33 and Figure 34) graphs of dust control methods in scenarios “OH1” to “OH5”

<table>
<thead>
<tr>
<th>Scenario / Graph</th>
<th>Water Spraying Cost</th>
<th>Surface Agent Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Road Paving Cost</td>
<td>Road Paving Cost</td>
</tr>
<tr>
<td></td>
<td>(month)</td>
<td>(month)</td>
</tr>
<tr>
<td>Scenario “OH1” / NPV</td>
<td>48</td>
<td>115</td>
</tr>
<tr>
<td>Scenario “OH2” / NPV</td>
<td>49</td>
<td>115</td>
</tr>
<tr>
<td>Scenario “OH3” / NPV</td>
<td>50</td>
<td>116</td>
</tr>
<tr>
<td>Scenario “OH4” / NPV</td>
<td>51</td>
<td>124</td>
</tr>
<tr>
<td>Scenario “OH5” / NPV</td>
<td>52</td>
<td>132</td>
</tr>
<tr>
<td>Scenario “OH5” / CER</td>
<td>36</td>
<td>98</td>
</tr>
<tr>
<td>Scenario “OH5” / CRR</td>
<td>36</td>
<td>98</td>
</tr>
</tbody>
</table>

As can be seen in Table 12, the cost lines of water spraying and road paving methods met at time points varying from 48 to 52 months, due to the different interest rates assigned in the scenarios “OH1” to “OH5”. This implies that, under the defined scenario conditions, road paving is a more feasible option than water spraying for periods longer than approximately four years. Consequently, compared to water spraying, road paving can be recommended as a practical dust control method for permanent mine haul roads and semi-permanent roads that remain unchanged for at least four years.

The costs estimated for the application of surface agents exceeded the road paving costs between 115 and 132 months, depending on the selected interest rate (see Table 12). This implies that road paving is a more favorable option than application of surface agents in terms of dust control costs for permanent roads and semi-permanent roads operated for longer than 10 years.
It should also be noted that road paving, which is characterized by high capital cost, became a more feasible measure than both water spraying and application of surface agents at later time points and with increasing interest rates (and vice versa), since these methods entail high operational costs.

In addition to their overall costs, dust control methods were also assessed with respect to their cost-effectiveness ratios (CER) and cost-reduction ratios (CRR). The results obtained for an interest rate at 5% are illustrated in Figure 33 and Figure 34 in Section 5.2.2.2 and in Table 12 above. Both the CRR and CER of water spraying developed higher than those estimated for road paving after 36 months (three years). Besides, the ratios of application for surface agents exceeded the ratios of road paving at the simulation time of 98 months (ca. eight years). As can be seen, these intersection times were attained earlier in comparison to those observed for the total costs of the control methods. This was because the reduction factor assigned for road paving (90%) was greater than the factors for water spraying and application of surface agents, which both equaled 70%. Finally, the cost-performance assessment also supports road paving as being more feasible over somewhat longer durations than other selected dust control methods, in other words, for permanent and semi-permanent roads. It can be concluded that, compared to paving, water spraying and application of surface agents are viable alternatives for temporary mine haul roads operated for a length of mostly three and eight years, respectively.

The other overburden haulage scenarios, “OH6” to “OH10”, analyzed how sensitive the dust control costs were to varying road lengths (1 km to 50 km). The dust control costs estimated in these scenarios with a 5% yearly interest rate showed similar trends as those observed in the scenario “OH5”. As a result, water spraying resulted in the highest dust control cost over 30 years, followed by application of surface agents. Once again, road paving indicated the lowest cost at the end of this simulation period. The intersection points of these costs in NPV are listed in Table 13 below.
Table 13. Intersection points (month) of total cost (NPV) of dust control methods in scenarios “OH6” to “OH10”

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Water Spraying Cost – Road Paving Cost (month)</th>
<th>Surface Agent Cost – Road Paving Cost (month)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario “OH6”</td>
<td>5</td>
<td>132</td>
</tr>
<tr>
<td>Scenario “OH7”</td>
<td>45</td>
<td>132</td>
</tr>
<tr>
<td>Scenario “OH8”</td>
<td>48</td>
<td>132</td>
</tr>
<tr>
<td>Scenario “OH9”</td>
<td>51</td>
<td>132</td>
</tr>
<tr>
<td>Scenario “OH10”</td>
<td>55</td>
<td>132</td>
</tr>
</tbody>
</table>

The results provided in Table 13 suggest that road paving is a more economical dust control method than water spraying both for relatively longer durations and permanent and semi-permanent mine haul roads. As presented in this table, water spraying cost was estimated to be lower than road paving cost for the first five months in scenario “OH6”, in which the road length was chosen as 1 km. For longer road lengths, as defined in the subsequent scenarios, increased durations, i.e., intersection times were determined. For example, the water spraying cost exceeded the cost of paving for a 10-km road network at the 48th month in the scenario “OH8”. This intersection time was calculated as 55 months for a road length of 50 km in the scenario “OH10”.

The simulation results of the scenarios “OH6” to “OH10” further suggest that, in comparison to water spraying, road paving turns into a cost-effective method at earlier times for relatively shorter haul road lengths. This correlation is explicit when the intersection time estimated in scenario “OH6”, five months, is compared to the result of scenario “OH7”, 45 months. However, the differences between these time points are less obvious among scenarios “OH7” to “OH10”, in which longer haul roads than in scenario “OH6” were simulated (see Appendix E-3). There were two reasons for this tendency. First, in the scenario simulations, the operational cost of water spraying was dominant within its overall costs and was developed with a greater rate than its capital cost when the haul road length was increased. Second, different from water spraying, road paving capital cost, which was proportional to the road length, was the largest cost component within the paving total cost and its operational cost showed only a limited increase for extended road lengths. These two reasons yielded minor differences for the intersection times, which converged to
a range between 45 and 55 months in the scenarios “OH7” to “OH10”. Thus, it can be interpreted that road paving, with regard to the scenario conditions, is a more economical dust control method than water spraying after approximately four years for mine haul roads longer than 5 km.

When the simulation results of scenarios “OH6” to “OH10” were compared with respect to the costs of the application of surface agents and road paving, it was observed that the cost lines of both methods intersected at the same time point (132 months, ca. 11 years) in each scenario. As expected, this result equals the intersection point obtained in scenario “OH5”, since a 5% yearly interest rate was assumed in all these scenarios (“OH5” to “OH10”). This result was accounted for by the cost parameters of both dust control methods proportional to the road length. Consequently, gradual increases in the road length escalated the dust control costs of both methods with the same magnitude in the scenario simulations.

Although the simulation results of scenarios “OH6” to “OH10” imply that the cost development trends for both the application of surface agents, as well as road paving methods are the same for any given haul road length, this conclusion may not be valid. Within the Dust-DSS, the capital and operational cost parameters of these dust control methods were defined as constants in terms of road size (€/m²). However, the unit costs for these methods, especially for the application of surface agents, can be expected to vary with road length. Therefore, this comparison indicates a deficiency in the DSS model for reflecting the influence of a critical uncertainty, i.e., haul road length, on the unit costs of the dust control methods. Nonetheless, it is safe to say that road paving is a more feasible dust control method under the given scenario conditions than the application of surface agents in the case of longer durations, e.g., more than 11 years.

As a result, the total costs and cost-performances of different dust control methods proposed for overburden haulage were assessed through the simulation of 10 overburden haulage scenarios (“OH1” to “OH10”) within the Dust-DSS. These simulations revealed the limits of the applicability of these control methods according to varying interest rates and road lengths.
Wind Erosion Scenario

The effect of interest rate on the cost of dust control methods proposed for wind erosion was analyzed using simulations of the scenarios “WE1” to “WE5”. The cost development curves of these dust control methods attained in the scenarios “WE1”, “WE3” and “WE5” are presented in Figure 35 to Figure 37 in Section 5.2.2.2. In order to provide a better interpretation of these graphs, the intersection points essential for the cost comparison of the proposed control methods are presented in Table 14 below. The cost estimates in NPV for areal and peripheral stabilization methods under different yearly interest rates are discussed hereinafter.

Table 14. Intersection points (month) of total cost graphs (NPV, in Figure 35, Figure 36 and Figure 37) of dust control methods in scenarios "WE1" to "WE12"

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario &quot;WE1&quot;</td>
<td>22</td>
<td>66</td>
<td>43</td>
<td>145</td>
<td>31</td>
<td>109</td>
<td>169-181 &amp; 346-361</td>
</tr>
<tr>
<td>Scenario &quot;WE3&quot;</td>
<td>22</td>
<td>70</td>
<td>43</td>
<td>166</td>
<td>31</td>
<td>121</td>
<td>n/a</td>
</tr>
<tr>
<td>Scenario &quot;WE5&quot;</td>
<td>23</td>
<td>72</td>
<td>46</td>
<td>199</td>
<td>37</td>
<td>133</td>
<td>n/a</td>
</tr>
<tr>
<td>Scenario &quot;WE6&quot;</td>
<td>25</td>
<td>77</td>
<td>46</td>
<td>199</td>
<td>37</td>
<td>133</td>
<td>n/a</td>
</tr>
<tr>
<td>Scenario &quot;WE10&quot;</td>
<td>20</td>
<td>71</td>
<td>46</td>
<td>199</td>
<td>37</td>
<td>133</td>
<td>n/a</td>
</tr>
<tr>
<td>Scenario &quot;WE12&quot;</td>
<td>14</td>
<td>61</td>
<td>46</td>
<td>199</td>
<td>37</td>
<td>133</td>
<td>n/a</td>
</tr>
</tbody>
</table>

Water exposure was identified as the most expensive areal dust control method for wind erosion over the simulation period of 360 months (30 years). In the scenarios “WE1”, “WE3” and “WE5”, the dust control costs of this method exceeded grassing costs at around 22 months as shown in Table 14. Subsequently, water exposure costs developed further and became higher than cropping costs at around 70 months. Additionally, water exposure always possessed higher costs than chemical wetting and crusting methods except for the first and second months. Therefore, the estimated dust control costs indicate that water exposure is a
short-term cost-effective solution; however, grassing and cropping are more feasible for dust control durations longer than approximately two and six years, respectively.

Compared to the application of surface agents, i.e., chemical wetting and crusting, vegetation methods are also more favorable in the long term. In the scenarios “WE1” to “WE5”, cropping became more economical than both chemical wetting after 145 to 199 months (ca. 14 years) and crusting after 109 to 133 months (ca. 10 years) (see Table 14). Similarly, the application costs of these surface agents exceeded grassing costs at times between 31 and 46 months (ca. three years). It should also be noted here that the establishment of vegetation comprising native flora species ensures a permanent and self-sustaining measure. Therefore, vegetation for wind erosion provides longer measures than other areal dust control methods even after mining ceases.

Another cost comparison was made between plantation wind breaks and artificial wind barriers, which are defined as peripheral stabilization methods. Wind breaks always resulted in less costs than wind barriers except for negligible durations (< 15 months) after the time points 169 and 346 months in the scenario “WE1”.

The simulation results for the scenarios “WE1” to “WE5” revealed that variations in the yearly interest rate did not significantly affect the cost trends of wind erosion control methods. However, as expected, the methods with high operational costs, especially those defined as the areal dust control methods (i.e., water exposure, chemical wetting and crusting), were found feasible for longer durations at higher interest rates. The application costs of these control methods exceeded the costs of the methods with high capital costs (i.e., cropping and grassing) at later time points as the interest rate increased.

The simulation results of the scenario “WE5” were also evaluated with regards to the cost-effectiveness ratios (CER) and cost-reduction ratios (CRR) estimated for a 5% yearly interest rate. The CER and CRR curves of the wind erosion control methods developed for the scenario “WE5” are illustrated in Figure 38 to Figure 40 in Section 5.2.2.2. For a better comparison of the cost development lines drawn in these figures, their intersection points are listed in Table 15 below.

As shown in Table 15, among the areal stabilization methods, water exposure was less favorable than cropping after 32 months (ca. three years), as well as grassing
after 47 months (ca. four years). These turning points were different than those estimated for dust control costs, due to the influence of the reduction factors. Distinctive reduction factors were assigned for each dust control method as 50% for water exposure, 30% for grassing and 90% for cropping. Nonetheless, the CER and CRR graphs confirmed the above conclusion made on the basis of the dust control costs that water exposure should only be considered as a short-term solution and that grassing and cropping are more feasible for long-term control.

Table 15. Intersection points (month) of CER and CRR graphs (in Figure 38, Figure 39 and Figure 40) of dust control methods in scenario “WE5”

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>CER</td>
<td>47</td>
<td>32</td>
<td>n/a</td>
<td>199</td>
<td>n/a</td>
<td>151</td>
<td>88</td>
</tr>
<tr>
<td>CRR</td>
<td>47</td>
<td>32</td>
<td>n/a</td>
<td>199</td>
<td>n/a</td>
<td>151</td>
<td>88</td>
</tr>
</tbody>
</table>

Furthermore, with respect to the CRR and CER curves, chemical wetting was a better choice than cropping up to the time point of 199 months (see Table 15). This turning point occurred at the same time in the previous dust control cost comparison for scenario “WE5” (see Table 14) because both control methods had equal reduction factors (90%). However, the intersection point of crusting and cropping curves in the CRR and CER graphs (151 months) was reached 18 months after that in the dust control cost graph of scenario “WE5” (133 months). This was because of a slight difference between the reduction factors of crusting (95%) and cropping (90%). Therefore, as previously interpreted from the dust control cost curves, the cost-performance evaluation suggests that cropping provides a more feasible wind erosion control than application of surface agents, chemical wetting and crusting over extended durations.

The CRR and CER graphs also revealed that grassing was not a preferable option in comparison to crusting and chemical wetting for any time scale. This corresponded to the lower reduction factor for grassing (30%) against both crusting (90%) and chemical wetting (95%). However, as Lyon and Smith (2010) suggested, increasing the percentage of surface vegetation cover lessens the wind erosion. Accordingly, by supposing that the percentage of grassing cover increases over time, this method
presumably provides higher wind erosion reduction at further time points. It can be concluded that the cost-performance ratios (CRR and CER) for the grassing method had been underestimated in the scenario simulations by assigning a constant reduction factor (30%) for this method over time.

The cost-performance evaluation for the peripheral control methods for wind erosion yielded a different conclusion than the dust control cost analysis. Wind barrier installation showed better cost-performance (less CRR and CER) than wind break plantation after 88 months (see Table 15). This resulted because of the different reduction factors selected for these methods (60% for wind barrier and 30% for wind break).

On the other hand, as Charman (2001) and later Presley and Tatarko (2009) stated, the width, height and porosity of the wind barrier or break determine the degree of protection, i.e., dust reduction. Additionally, Brandle and Finch (1991) noted that the effectiveness of a wind break depends on its structure: height, density, number of rows, species composition, length, orientation and continuity. Consequently, reduction factors higher than 30% proposed for wind break plantation can be achieved naturally as plants grow over time or through narrow planting. In these cases, this method may provide better CRR and CER compared with those for wind barrier installation. Moreover, as previously suggested for areal vegetation, wind break plantation, especially those made up of native species, represents long-term and self-sustaining protection. Hence, from an environmental point of view, wind break plantation presents a more preferable option than artificial wind barriers.

Simulations of the wind erosion scenarios “WE6” to “WE12” focused on the influence of wind erosion area variations from 0.1 km$^2$ to 5 km$^2$ on dust control costs. These scenarios were run with a 5% yearly interest rate; and the corresponding results for scenarios “WE6”, “WE10” and “WE12” are graphically illustrated in Figure 41 to Figure 43 in Section 5.2.2.2. The cost intersection points of these scenarios are also provided in Table 14 above.

When the dust control costs of areal methods were compared, water exposure had the highest overall costs in the scenarios “WE6” to “WE12”. Although this method possessed relatively low costs at the start of the simulation time, its costs increased gradually over time and exceeded the costs of cropping and grassing methods.
When larger wind erosion areas were simulated, these cost intersections were observed at earlier times as shown in Table 14.

In the scenario “WE6”, in which a 0.1-km$^2$ area was simulated, the water exposure cost exceeded the cost of grassing and cropping at 25 and 77 months, respectively. These time points were estimated at 14 months for grassing and 61 months for cropping for an area of 5 km$^2$ assigned in scenario “WE12”. Therefore, water exposure can be considered a cost-effective measure for only limited durations and for relatively small areas.

Increasing the wind erosion area did not change the intersection times for the cost curves of cropping and grassing with those of application of surface agents (see Table 14). Grassing had lower dust control costs than crusting after 37 months and chemical wetting after 46 months in the scenarios “WE6” to “WE12”. Similarly, the costs of crusting and later chemical wetting methods exceeded cropping costs at 133 and 199 months. The reason for this was that the capital and operational cost parameters of these control methods were determined as constants and as a function of the wind erosion area (€/m$^2$). Although this was a reasonable assumption, it indicates the insensitivity of these cost parameters to the changes in the wind erosion area.

Peripheral dust control methods, wind breaks and wind barriers showed no intersection in the simulation results of scenarios “WE6” to “WE12”. The most prominent result of these simulations was that the peripheral methods, among all the other proposed wind erosion control methods, ended up having the highest control costs in scenario “WE6”. The smallest area (0.1 km$^2$) was selected in this scenario and for larger areas, as in the example of scenarios “WE10” and “WE12”, peripheral dust control methods had relatively lower costs compared to other methods. Therefore, it can be argued that wind barriers always possess lower control costs than wind breaks for any area size and that these peripheral wind erosion control methods are therefore preferable in larger areas when compared to areal methods.

To sum up, in total, 12 wind erosion scenarios (“WE1” to “WE12”) were simulated in the Dust-DSS under varying critical uncertainties, i.e., interest rate and wind erosion area. The simulation results provided a better understanding of the applicability limits of various wind erosion control methods as they relate to these uncertainties.
CHAPTER 7. CONCLUSION AND FUTURE WORK

7.1. Summary of the Thesis

The aim of this thesis was to develop a mine dust control DSS (Dust-DSS) that combines dust emission estimation with cost-performance evaluation of control methods for open-pit coal mining operations. To achieve this, the mining activities at the NBCC mine, which is the study area of RAME sub-project IV: “Dust Mitigation and Monitoring”, located in Ha Long, Vietnam, was investigated. Accordingly, mine dust emission factors and reduction factors of the corresponding control methods were developed for a typical open-pit coal mine. In addition to these location- and activity-specific dust emission and reduction factors, cost parameters of the selected dust control methods were determined and integrated into the DSS. The thesis also aimed at evaluating the requirements of these site-specific factors in designing effective dust control approaches and identifying the applicability limits of different dust control methods. These aims were addressed specifically by dust emission calculations and DSS scenario simulations based on the NBCC mining conditions.

As indicated in Section 1.1, haulage activity and wind erosion are the primary dust sources at surface coal mines. Therefore, within the scope of this thesis, dust emissions from these activities and an additional activity (i.e., overburden dumping) were focused on. The emission factors of these mine dust sources were developed through analysis of the data obtained from real-time measurements conducted at the NBCC mining area. These factors were evaluated and discussed by comparing them with emission factors and rates presented in the literature (Chakraborty, et al., 2002; USEPA, 2006a; 2006b; 2006c). It was conceived that emission calculations, especially for large-scale mining activities and based on the factors suggested in this, varied significantly from those made by the factors noted in the literature. Furthermore, emission calculations using the factors from the literature also differed considerably from each other, because these factors were proposed for specific mining locations. These findings indicate that location- and activity-specific mine dust emission factors can yield more reliable emission estimates than the factors defined for different mining areas. Additionally, it is envisaged that the emission factors proposed in this thesis will be applicable to surface mining operations having similar
mining practices (e.g., mine equipment size), geological properties (e.g., silt content of the material handled) and climatic conditions (e.g., local wind speed).

The emission factors developed for the mining activities at the NBCC mining site and the rates of these activities were applied in order to determine the individual emission levels of each activity. Accordingly, overburden haulage was identified as the primary mine dust source, as has already been suggested by other studies for different surface coal mining operations (Environment Australia, 1998; Donnelly, et al., 2011; Huertas, Dumar, & Huertas, 2012). The emission estimates in this thesis also affirmed wind erosion as another substantial mine dust source at surface coal mines, as revealed in previous studies (Donnelly, et al., 2011; Huertas, Dumar, & Huertas, 2012).

The reduction factors of the mine dust control methods studied in this thesis were obtained by analyzing data from real-time dust control performance and dust emission measurements, as well as by reviewing the factors provided in the literature (see Appendix C). The reduction factors estimated for overburden haulage in this thesis also differed from these literature factors, due to varying measurement conditions (e.g., source characteristics), the application rates of control methods (e.g., water spraying rate) and/or climatic conditions (e.g., local wind speed). This confirmed the necessity for location- and activity-specific reduction factors for accurate dust control performance evaluation in mining operations. It is also considered that the reduction factors developed in this study for dust control methods will be valid for other mining locations under analogous application conditions, mining features and climatic characteristics.

In this thesis, mine dust control methods requiring capital investment and operational costs were classified as direct methods, whereas methods involving only modifications in mining activities, and hence no financial investment, were labeled indirect methods. The cost parameters of the direct methods were divided into capital and operational costs, and quantified by making site observations and reviewing various sources (see (5)). Additionally, the application of indirect dust control methods may give rise to external costs, due to modifications being made in the mining activities. However, developing a technique applicable for the calculation of these external costs for any given mining condition was not the subject
of this thesis. Therefore, the application costs for the indirect dust control methods considered in this thesis were valued as zero.

The emission factors proposed for the open-pit coal mining activities and the reduction factors and cost parameters of the related control methods constituted the basis of the mine dust control DSS (Dust-DSS) developed in this thesis. The Dust-DSS is capable of estimating the dust emission levels and cost-performances of possible control approaches for open-pit coal mining operations. Thus, the DSS can assist in designing cost-effective dust control strategies for active or planned open-pit coal mining projects.

The Dust-DSS was applied to investigate and identify the individual dust emission levels of different mining activities and the application boundaries of the related dust control methods. At this point, the predictive DSS scenarios, i.e., the reference scenario and the overburden haulage and wind erosion scenarios were designed according to the mining and environmental conditions of the project area, the NBCC mining area. These scenarios were then simulated in order to assess how the varying critical uncertainties, i.e., decisive mining conditions and cost parameters, influenced the emission levels of individual mining activities and the costs and performances of proposed dust control methods. The DSS scenarios were clearly not aimed at calculating the exact costs of the simulated dust control options.

The reference scenario included emission calculations for only the overburden handling activities and wind erosion as described in Section 4.2.4.1. The scenario simulations revealed: (1) that haulage and wind erosion were the primary mine dust sources; second; (2) that the dust emission levels and the significance of individual mine dust sources were highly dependent on the critical parameters, i.e., road length (km) for haulage and the exposed area (km$^2$) for wind erosion. Based on these results, it is recommended that decision makers need to place an emphasis on these two particular mine dust sources when designing effective dust control strategies.

Simulations of the overburden haulage and wind erosion scenarios were evaluated in terms of their costs, cost-effectiveness ratios (CER) and the cost-reduction ratios (CRR) of selected control methods under varying interest rates (%), road lengths (km) and wind erosion areas (km$^2$) over a time frame of 30 years. The
simulation results showed that these critical parameters and additionally, the project duration (month) determined the eligibility of dust control methods. This demonstrates the necessity of considering these site-specific factors when designing mine dust control strategies.

### 7.2. Research Limitations

Some research limitations arose during the completion of this thesis due to time constraints and the research design.

The emission factors provided in both this thesis and the RAME sub-project IV Final Report (BBK I, 2013b) represents only the ratio of generated emission amount to the source activity rate. The effects of parameters influencing dust emission levels, which were quantified during the real-time measurements, were not evaluated during the development of the emission factors due to time constraints. Accurate assessment of the relative significance of each influencing parameter requires a set of controlled experiments, which is a time-consuming practice and was therefore not possible within the scope of the RAME project. This can be explored in future work aiming to develop mine dust emission factor equations for the study area, based on the influencing parameters and their relative significance to the quantity of emissions.

Another limitation concerning the emission factors was their particle size ranges. The factor for overburden haulage was given in grams of PM10, whereas those for overburden dumping and wind erosion were estimated in grams of PM30 (SP or TSP). This was a result of changes occurring in the research design during the project’s time frame. In a future study, it is possible to develop emission factors in various size ranges, e.g., PM1, PM2.5, PM10 or PM30, which was beyond the scope of this thesis.

The Dust-DSS presented in this thesis integrates the dust emission factors of various mining activities, the reduction factors of the corresponding dust control methods and their cost parameters as considered for open-pit coal mining operations. However, the emission and reduction factors were developed for Vietnamese mining conditions, whilst the cost parameters were identified for market conditions in the Eurozone, since gathering reliable cost data from within Vietnam was unfeasible. Therefore, the costs of mine dust control methods calculated by the DSS scenario
simulations are only valid within the Eurozone. However, this is an acceptable limitation, as this thesis clearly did not aim at estimating exact dust control costs, but rather the applicability limits of the examined control approaches. Nonetheless, the developed DSS is capable of calculating the dust emission levels and the costs and performances of the control methods for a given open-pit coal mining operation when accurate (i.e., location- and activity-specific) emission and dust control factors and unit costs are assigned.

7.3. Future Work

Future work can both extend the research provided in this thesis and address the research limitations described in the previous section.

Additional real-time controlled emission measurements, in which every emission influencing parameter is held constant except for a single parameter, can be conducted for the mining activities studied in this thesis. These measurements would deliver reliable data for evaluating the relative significance of each influencing parameter in terms of dust emissions from those activities. Accordingly, development of dust emission factor equations for the studied mining activities on the basis of these evaluations can be the focus of future research. Furthermore, the data obtained from the real-time measurements conducted within the scope of this thesis can be extended by these additional measurements in order to analyze the dust emission levels from individual activities in different particle size ranges, e.g., PM1, PM2.5, PM10 or PM30.

Validation of the emission and reduction factors developed in this thesis at similar mining areas, as well as under similar geological and climatic conditions can be another focus for future research. This will increase the reliability of these factors and provide better insight into the effects of location- and activity-specific characteristics.

Another worthwhile future research possibility is the development of analogous emission and reduction factors for other mining activities, e.g., dragline excavation, as well as at other mining locations by following the methodological approach described in this thesis. These further factors can then be used for extension of the Dust-DSS presented in this thesis.

Finally, the developed Dust-DSS can be applied to other open-pit coal mining operations in order to investigate the limits of the applicability of the dust control
methods under different mining conditions. This would broaden the general knowledge of the costs and performances of mine dust control methods.
REFERENCES


Countess, R., Barnard, W., Claiborn, C., Gilette, D., Latimer, D., Pace, T., & Watson, J. (2001). *Methodology for estimating fugitive windblown and mechanically resuspended road dust emissions applicable for regional scale air quality modeling, Prepared for Western Governors' Association*. Westlake Village, CA, US.


References


Appendix A. Summary of Real-time Measurements Results

A-1. Dust Emission Measurements – Immission Levels


Figure A-2. Exemplary dust mass concentration profile over time obtained during the real-time dust emission measurement for overburden dumping activity with the Aerosol Spectrometer AS 9G 50 on 2011-12-03.
A-2. Dust Emission Measurements – Emission Influencing Parameters

Table A-1. Summary of the dust emission influencing parameters for overburden haulage

<table>
<thead>
<tr>
<th>Influencing Parameter</th>
<th>Measurement Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measure of source activity</td>
<td></td>
</tr>
<tr>
<td>Truck type</td>
<td>• Off-highway trucks (Caterpillar 773 B/E/F, Komatsu HD465);</td>
</tr>
<tr>
<td></td>
<td>• Dump trucks (CAMC HN3250G4D, Howo Sinotruk 371,</td>
</tr>
<tr>
<td></td>
<td>Hyundai HD270, Kamaz 320 Turboloader, Scania P340,</td>
</tr>
<tr>
<td></td>
<td>Volvo FM 380 / FM400);</td>
</tr>
<tr>
<td></td>
<td>• Articulated trucks (Volvo A35D, Volvo A40D)</td>
</tr>
<tr>
<td>Truck weight</td>
<td>Varies between 13.9 and 46.5 tonnes depending on truck type</td>
</tr>
<tr>
<td>Truck speed</td>
<td>Average speed of 19.3 km/h</td>
</tr>
<tr>
<td>Properties of the material being disturbed</td>
<td></td>
</tr>
<tr>
<td>Particle size distribution, silt content(1)</td>
<td>• Gravel (&gt;2 mm): average of 25.7%</td>
</tr>
<tr>
<td></td>
<td>• Sand (0.05 mm - 2 mm): average of 41.7%</td>
</tr>
<tr>
<td></td>
<td>• Silt (0.005 mm – 0.05 mm): average of 13.2%</td>
</tr>
<tr>
<td></td>
<td>• Clay (&lt;0.005 mm): Average of 19.4%</td>
</tr>
<tr>
<td>Moisture content(2)</td>
<td>Average of 5.4% for dry road surface, 28.0% for wet road surface</td>
</tr>
<tr>
<td>Road surface thickness</td>
<td>0.5 to 4 cm.</td>
</tr>
<tr>
<td>Climatic parameters</td>
<td></td>
</tr>
<tr>
<td>Wind speed and direction</td>
<td>Average speed of 2.9 m/s and direction 187°</td>
</tr>
<tr>
<td>Temperature</td>
<td>23.6°</td>
</tr>
<tr>
<td>Humidity</td>
<td>79%</td>
</tr>
<tr>
<td>Air pressure</td>
<td>Not analyzed</td>
</tr>
</tbody>
</table>

(1) Particle size distribution was determined according to the Vietnamese standard TVCN: 4198, where grain size of silt particles is graded between 0.005 to 0.05 mm (TCVN 4198:1995, 1995).
(2) Moisture content was determined according to the Vietnamese standard TVCN: 4196 (TCVN 4196:1995, 1995).
### Table A-2. Summary of the dust emission influencing parameters for overburden dumping

<table>
<thead>
<tr>
<th>Influencing Parameter</th>
<th>Measurement Data</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Measure of source activity</strong></td>
<td></td>
</tr>
</tbody>
</table>
| Truck type                           | • Off-highway trucks (Caterpillar 773 B/E/F, Komatsu HD465);
|                                       | • Dump trucks (CAMC HN3250G4D, Howo Sinotruk 371);
|                                       | • Articulated trucks (Volvo A35D, Volvo A40D)                                                                                                                                                         |
| Dump weight                          | Average 56.7 tonnes for off-highway trucks and 26.7 tonnes for dumping and articulated trucks                                                                                                       |
| Dumping height and slope angle       | Average height of 21.3 m and angle of 36.3°                                                                                                     |
| Dumping duration, truck approaching & departure duration | Average dumping duration of 15 sec., approaching duration of 29 sec., departure duration of 15 sec.                                                                                                  |
| Dust propensity                      | 82% of dust due to dumping 18% of dust due to approaching/departure                                                                             |
| **Properties of the material being disturbed** |                                                                                                                                                   |
| Particle size distribution, silt content<sup>(1)</sup> | • Gravel (>2 mm): average of 52.3%  
|                                       | • Sand (0.05 mm - 2 mm): average of 32.7%  
|                                       | • Silt (0.005 mm – 0.05 mm): average of 8.0%  
|                                       | • Clay (<0.005 mm): average of 7.0%   |
| Moisture content                     | Average of 5.4%                                                                                                                                      |
| **Climatic parameters**              |                                                                                                                                                   |
| Wind speed and direction             | Average speed of 2.9 m/s and direction 187°                                                                                                         |
| Temperature, humidity, air pressure  | Not analyzed                                                                                                                                                                                     |

<sup>(1)</sup> Particle size distribution was determined according to the Vietnamese standard TVCN: 4198, where grain size of silt particles is graded between 0.005 to 0.05 mm (TCVN 4198:1995, 1995).

<sup>(2)</sup> Moisture content was determined according to the Vietnamese standard TVCN: 4196 (TCVN 4196:1995, 1995).

### Table A-3. Summary of the dust emission influencing parameters for wind erosion

<table>
<thead>
<tr>
<th>Influencing Parameter</th>
<th>Measurement Data</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Measure of source activity</strong></td>
<td></td>
</tr>
<tr>
<td>Surface area</td>
<td>Average of 19,675 m&lt;sup&gt;2&lt;/sup&gt;</td>
</tr>
</tbody>
</table>
| Vegetation density and vegetation height | Vegetation density from 0% to 45%  
|                                       | Vegetation height from 0 m to 1 m                                                                                                                  |
| Surface roughness                    | Smooth surface for no-vegetation, roughness is not available for vegetated areas.                                                                     |
| **Properties of the material being disturbed** |                                                                                                                                                   |
| Particle size distribution, silt content<sup>(1)</sup> | • Gravel (>2 mm): average of 53.0%  
|                                       | • Sand (0.05 mm - 2 mm): average of 32.8%  
|                                       | • Silt (0.005 mm – 0.05 mm): average of 6.7%  
|                                       | • Clay (<0.005 mm): average of 7.5%   |
| Moisture content                     | Average of 1.5%                                                                                                                                      |
| **Climatic parameters**              |                                                                                                                                                   |
| Wind speed and direction             | Average speed of 2.6 m/s and direction 183°                                                                                                         |
| Temperature, humidity, air pressure  | Not analyzed                                                                                                                                                                                     |

<sup>(1)</sup> Particle size distribution was determined according to the Vietnamese standard TVCN: 4198:1995, where grain size of silt particles is graded between 0.005 to 0.05 mm (TCVN 4198:1995, 1995).

<sup>(2)</sup> Moisture content was determined according to the Vietnamese standard TVCN: 4196 (TCVN 4196:1995, 1995).


A-3. Dust Control Performance Measurements – Immission Levels

![Exemplary dust mass concentration profile over time obtained during the real-time dust control performance measurement for overburden haulage activity with the Aerosol Spectrometer AS 9G 49 on 2012-11-02](image)

Figure A-4. Exemplary dust mass concentration profile over time obtained during the real-time dust control performance measurement for overburden haulage activity with the Aerosol Spectrometer AS 9G 49 on 2012-11-02

A-4. Dust Control Performance Measurements – Performance Influencing Parameters

Table A-4. Summary of the parameters influencing the dust control performance of water spraying for overburden haulage

<table>
<thead>
<tr>
<th>Parameter Influencing Dust Control Performance</th>
<th>Measurement Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measure of source activity</td>
<td>Truck type</td>
</tr>
<tr>
<td>Dust control conditions</td>
<td>Watering amount(1)</td>
</tr>
<tr>
<td></td>
<td>0.38 L/m² and 0.50 L/m²</td>
</tr>
<tr>
<td></td>
<td>Watering interval</td>
</tr>
<tr>
<td></td>
<td>Varies between 10 minutes and 2 hours</td>
</tr>
<tr>
<td>Properties of the material being disturbed</td>
<td>Particle size distribution, silt content(2)</td>
</tr>
<tr>
<td></td>
<td>• Gravel (&gt;2 mm): average of 21.1%</td>
</tr>
<tr>
<td></td>
<td>• Sand (0.05 mm - 2 mm): average of 51.4%</td>
</tr>
<tr>
<td></td>
<td>• Silt (0.005 mm – 0.05 mm): average of 14.1%</td>
</tr>
<tr>
<td></td>
<td>• Clay (&lt;0.005 mm): average of 13.4%</td>
</tr>
<tr>
<td></td>
<td>Moisture content(3)</td>
</tr>
<tr>
<td></td>
<td>Minimum of 2.2% and maximum of 19.0% depending on watering rate</td>
</tr>
<tr>
<td>Climatic parameters</td>
<td>Wind speed and direction, temperature, humidity, air pressure</td>
</tr>
<tr>
<td></td>
<td>Not analyzed</td>
</tr>
</tbody>
</table>

(1) Calculated based on measured water truck speeds.
(2) Particle size distribution was determined according to the Vietnamese standard TVCN: 4198, where grain size of silt particles is graded between 0.005 to 0.05 mm (TCVN 4198:1995, 1995).
(3) Moisture content was determined according to the Vietnamese standard TVCN: 4196 (TCVN 4196:1995, 1995).
### Table A-5. Mine dust emission factors and daily emission levels estimated for the NBCC mining area

<table>
<thead>
<tr>
<th>Mining Activity / Dust Source</th>
<th>Dust Emission Factor</th>
<th>Unit</th>
<th>Dust Emission Rate - per Activity</th>
<th>Unit</th>
<th>Activity Rate - at NBCC</th>
<th>Unit</th>
<th>Daily Dust Emission - at NBCC</th>
<th>Unit</th>
<th>Share in Total Dust Emission (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OB drilling</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case 1 (Atlas Copco DML)</td>
<td>26.17</td>
<td>g/m</td>
<td>0.355</td>
<td>g/s</td>
<td>159.4</td>
<td>m/day</td>
<td>200</td>
<td>kg/day</td>
<td>0.32</td>
</tr>
<tr>
<td>Case 2 (Atlas Copco DM 45E)</td>
<td>320.67</td>
<td>g/m</td>
<td>3.810</td>
<td>g/s</td>
<td>159.4</td>
<td>m/day</td>
<td>200</td>
<td>kg/day</td>
<td>0.32</td>
</tr>
<tr>
<td>Case 3 (SBSH-250MNA-32)</td>
<td>1279.8</td>
<td>g/m</td>
<td>8.509</td>
<td>g/s</td>
<td>112.5</td>
<td>m/day</td>
<td>200</td>
<td>kg/day</td>
<td>0.32</td>
</tr>
<tr>
<td>OB blasting</td>
<td>0.53</td>
<td>g/t</td>
<td>3432.313</td>
<td>g/s</td>
<td>-</td>
<td></td>
<td>41</td>
<td>kg/day</td>
<td>0.06</td>
</tr>
<tr>
<td>Overburden (OB) handling</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case 1 (Hydr. Excv. - CAT)</td>
<td>3.93</td>
<td>g/t</td>
<td>0.800</td>
<td>g/s</td>
<td>34638</td>
<td>t/day</td>
<td>369</td>
<td>kg/day</td>
<td>0.58</td>
</tr>
<tr>
<td>Case 2 (Hydr. Excv. - Howo)</td>
<td>3.78</td>
<td>g/t</td>
<td>0.670</td>
<td>g/s</td>
<td>57960</td>
<td>t/day</td>
<td>369</td>
<td>kg/day</td>
<td>0.58</td>
</tr>
<tr>
<td>Case 3 (Chain Excv. - CAT)</td>
<td>4.70</td>
<td>g/t</td>
<td>0.810</td>
<td>g/s</td>
<td>28898</td>
<td>t/day</td>
<td>369</td>
<td>kg/day</td>
<td>0.58</td>
</tr>
<tr>
<td>OB truck haulage (on dry main road)</td>
<td>880</td>
<td>g/km/truck</td>
<td>4.816</td>
<td>g/s/truck</td>
<td>18960.0</td>
<td>km*truck/day</td>
<td>16685</td>
<td>kg/day</td>
<td>26.38</td>
</tr>
<tr>
<td>OB truck haulage (on wet main road)</td>
<td>524</td>
<td>g/km/truck</td>
<td>2.867</td>
<td>g/s/truck</td>
<td>-</td>
<td></td>
<td>369</td>
<td>kg/day</td>
<td>0.58</td>
</tr>
<tr>
<td>OB truck haulage (on dry side road)</td>
<td>1124</td>
<td>g/km/truck</td>
<td>6.151</td>
<td>g/s/truck</td>
<td>15471.3</td>
<td>km*truck/day</td>
<td>17390</td>
<td>kg/day</td>
<td>27.49</td>
</tr>
<tr>
<td>OB truck haulage (on wet side road)</td>
<td>392</td>
<td>g/km/truck</td>
<td>2.145</td>
<td>g/s/truck</td>
<td>-</td>
<td></td>
<td>369</td>
<td>kg/day</td>
<td>0.58</td>
</tr>
<tr>
<td>OB dumping</td>
<td>0.225</td>
<td>g/t</td>
<td>0.123</td>
<td>g/s</td>
<td>121496.3</td>
<td>t/day</td>
<td>27</td>
<td>kg/day</td>
<td>0.04</td>
</tr>
<tr>
<td>Coal production</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coal loading</td>
<td>5.37</td>
<td>g/t</td>
<td>0.350</td>
<td>g/s</td>
<td>86.4</td>
<td>t/day</td>
<td>86</td>
<td>kg/day</td>
<td>0.14</td>
</tr>
<tr>
<td>Coal truck Haulage (on dry main road)</td>
<td>880</td>
<td>g/km/truck</td>
<td>4.816</td>
<td>g/s/truck</td>
<td>3244.3</td>
<td>km*truck/day</td>
<td>2855</td>
<td>kg/day</td>
<td>4.51</td>
</tr>
<tr>
<td>Coal truck Haulage (on wet main road)</td>
<td>524</td>
<td>g/km/truck</td>
<td>2.867</td>
<td>g/s/truck</td>
<td>-</td>
<td></td>
<td>369</td>
<td>kg/day</td>
<td>0.58</td>
</tr>
<tr>
<td>Coal truck Haulage (on dry side road)</td>
<td>1124</td>
<td>g/km/truck</td>
<td>6.151</td>
<td>g/s/truck</td>
<td>2758.0</td>
<td>km*truck/day</td>
<td>3100</td>
<td>kg/day</td>
<td>4.90</td>
</tr>
<tr>
<td>Coal truck Haulage (on wet side road)</td>
<td>392</td>
<td>g/km/truck</td>
<td>2.145</td>
<td>g/s/truck</td>
<td>-</td>
<td></td>
<td>369</td>
<td>kg/day</td>
<td>0.58</td>
</tr>
<tr>
<td>Coal unloading</td>
<td>0.15</td>
<td>g/t</td>
<td>0.022</td>
<td>g/s</td>
<td>16093.8</td>
<td>t/day</td>
<td>2</td>
<td>kg/day</td>
<td>0.00</td>
</tr>
<tr>
<td>Charging the processing plant</td>
<td>52.80</td>
<td>g/t</td>
<td>1.540</td>
<td>g/s</td>
<td>16093.8</td>
<td>t/day</td>
<td>850</td>
<td>kg/day</td>
<td>1.34</td>
</tr>
<tr>
<td>Coal processing (screening sieve)</td>
<td>1.20</td>
<td>g/t</td>
<td>0.035</td>
<td>g/s</td>
<td>11909.4</td>
<td>t/day</td>
<td>14</td>
<td>kg/day</td>
<td>0.02</td>
</tr>
<tr>
<td>Coal processing (crusher)</td>
<td>9.00</td>
<td>g/t</td>
<td>0.095</td>
<td>g/s</td>
<td>4184.4</td>
<td>t/day</td>
<td>38</td>
<td>kg/day</td>
<td>0.06</td>
</tr>
<tr>
<td>Coal dropping</td>
<td>4.50</td>
<td>g/t</td>
<td>0.128</td>
<td>g/s</td>
<td>16093.8</td>
<td>t/day</td>
<td>72</td>
<td>kg/day</td>
<td>0.11</td>
</tr>
<tr>
<td>Processed coal loading</td>
<td>5.37</td>
<td>g/t</td>
<td>0.350</td>
<td>g/s</td>
<td>16093.8</td>
<td>t/day</td>
<td>86</td>
<td>kg/day</td>
<td>0.14</td>
</tr>
<tr>
<td>Wind erosion</td>
<td>0.198</td>
<td>g/m²*h</td>
<td>n/a</td>
<td>g/s</td>
<td>4.51</td>
<td>km²</td>
<td>21432</td>
<td>kg/day</td>
<td>33.89</td>
</tr>
</tbody>
</table>
Appendix C. Mine Dust Control Methods – Reduction Factors

C-1. Dust Control Methods for Haulage – Reduction Factors

Table A-6. Reduction factors for the dust control methods proposed for dust generation due to haulage activity and assigned reduction factors in the DSS

<table>
<thead>
<tr>
<th>Control Method</th>
<th>Reduction Factor (%)</th>
<th>Reduction Factor (%) Assigned in DSS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Road surface treatment</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water spraying</td>
<td>70(^{(1)}) (BBK I, 2013a) (see Section 5.1.2.4)</td>
<td>70</td>
</tr>
<tr>
<td></td>
<td>40(^{(2)}) (Foley, Cropley, &amp; Giummarra, 1996)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>72 and 74(^{(3)}) (USEPA, 1998c)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>55 or 95(^{(4)}) (USEPA, 1983)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10 to 74(^{(2)}) (Countess Environmental, 2006)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>50 or 75(^{(5)}) (Environment Australia, 2012)</td>
<td></td>
</tr>
<tr>
<td><strong>Application of surface agents</strong></td>
<td>See Table A-7</td>
<td>70</td>
</tr>
<tr>
<td><strong>Road condition improvement</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Paving/sealing</td>
<td>95 to 100 (Foley, Cropley, &amp; Giummarra, 1996)</td>
<td>90</td>
</tr>
<tr>
<td></td>
<td>100 (Reed &amp; Organiscak, 2005)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>&gt;90 (Countess Environmental, 2006)</td>
<td></td>
</tr>
<tr>
<td><strong>Regulating driving pattern</strong></td>
<td>40 to 75(^{(6)}) 50 to 85(^{(7)}) (Foley, Cropley, &amp; Giummarra, 1996)</td>
<td>42</td>
</tr>
<tr>
<td></td>
<td>42 or 58(^{(8)}) (Watson, et al., 1996)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>44(^{(9)}) (Countess Environmental, 2006)</td>
<td></td>
</tr>
</tbody>
</table>

(1) For watering rate: 1.2 L/m\(^2\)*h.
(2) No condition is defined.
(3) 72% for PM10 and 74% for TSP after over 3 hours of 0.46 gal/yd\(^2\) (ca. 2.08 L/m\(^2\)) watering.
(4) 55% for TSP after 4.4 hours of 0.13 gal/yd\(^2\) (ca. 0.59 L/m\(^2\)) watering, 95% for TSP after 0.5 hours of 0.13 gal/yd\(^2\) (ca. 0.59 L/m\(^2\)) watering.
(5) 50% for watering level: 2 L/m\(^2\)*h, 75% for watering level >2 L/m\(^2\)*h.
(6) For speed reduction from 75 to 50 km/h.
(7) For speed reduction from 65 to 30 km/h.
(8) 42% for speed reduction from 25 to 10 mph (ca. 40 to 16 km/h) and 58% for speed reduction from 25 to 15 mph (ca 40 to 24 km/h).
(9) For vehicle speed limit: 25 mph (ca. 40 km/h).
Table A-7. Reduction factors for the surface agents proposed for dust generation due to haulage activity

<table>
<thead>
<tr>
<th>Surface Agent</th>
<th>Reduction Factor (%)</th>
<th>Comment</th>
<th>Reference Study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Any</td>
<td>40 to 80</td>
<td>-</td>
<td>(Foley, Cropley, &amp; Giummarra, 1996)</td>
</tr>
<tr>
<td>Petroleum resins</td>
<td>0 to 80</td>
<td>Depending on the total volume (per unit area) of petroleum resin concentrate applied</td>
<td>(USEPA, 1998c)</td>
</tr>
<tr>
<td>Any</td>
<td>84</td>
<td>-</td>
<td>(Countess Environmental, 2006)</td>
</tr>
<tr>
<td>Surfactants</td>
<td>33 to 50</td>
<td>Given as extension the time between watering</td>
<td></td>
</tr>
<tr>
<td>Salts</td>
<td>95&lt;sup&gt;(1)&lt;/sup&gt; 82&lt;sup&gt;(2)&lt;/sup&gt; 14&lt;sup&gt;(3)&lt;/sup&gt;</td>
<td>(1) For magnesium chloride up to 22 days after application (2) For calcium chloride 2 weeks after application (3) For calcium chloride 7 weeks after application</td>
<td>(NIOSH, 2012)</td>
</tr>
<tr>
<td>Petroleum resins</td>
<td>70&lt;sup&gt;(4)&lt;/sup&gt; 4 to 38&lt;sup&gt;(5)&lt;/sup&gt;</td>
<td>(4) Up to 21 days after application (5) During 4-week period after application</td>
<td></td>
</tr>
<tr>
<td>Polymers</td>
<td>74 to 81&lt;sup&gt;(6)&lt;/sup&gt; 13 to 14&lt;sup&gt;(7)&lt;/sup&gt;</td>
<td>(6) Up to 4 weeks after application (7) After 5 weeks of application</td>
<td></td>
</tr>
<tr>
<td>Adhesives</td>
<td>50 to 63&lt;sup&gt;(8)&lt;/sup&gt; 31 to 45&lt;sup&gt;(9)&lt;/sup&gt;</td>
<td>(8) Up to 4 weeks after application (9) Nothing specified</td>
<td></td>
</tr>
</tbody>
</table>

C-2. Dust Control Methods for Dumping – Reduction Factors

Table A-8. Reduction factors for the dust control methods proposed for dust generation due to overburden dumping activity and assigned reduction factors in the DSS

<table>
<thead>
<tr>
<th>Control Method</th>
<th>Reduction Factor (%)</th>
<th>Reduction Factor (%) Assigned in DSS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reducing dumping height</td>
<td>7 to 63&lt;sup&gt;(1)&lt;/sup&gt;</td>
<td>57</td>
</tr>
<tr>
<td>Watering dump top-surface</td>
<td>13</td>
<td>13</td>
</tr>
<tr>
<td>Usage of fog cannons</td>
<td>&lt;95</td>
<td>90</td>
</tr>
<tr>
<td>Installation of roofed sheds (or wind fences) combined with water sprays</td>
<td>85 or 95&lt;sup&gt;(2)&lt;/sup&gt;</td>
<td>95</td>
</tr>
</tbody>
</table>

<sup>(1)</sup> 7% reduction for reducing dumping height by 10% and 63% reduction for reducing dumping height by 90%.
<sup>(2)</sup> 85% reduction for wind fences and 95% reduction for roofed sheds.
## C-3. Dust Control Methods for Wind Erosion – Reduction Factors

Table A-9. Reduction factors for the dust control methods proposed for dust generation due to wind erosion and assigned reduction factors in the DSS

<table>
<thead>
<tr>
<th>Control Method</th>
<th>Reduction Factor (%)</th>
<th>Reduction Factor (%) Assigned in DSS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Areal surface stabilization</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vegetative ground cover</td>
<td>70</td>
<td>(USEPA, 1983)</td>
</tr>
<tr>
<td></td>
<td>90</td>
<td>(Countess Environmental, 2006)</td>
</tr>
<tr>
<td></td>
<td>5 to 99</td>
<td>(USEPA, 1992)</td>
</tr>
<tr>
<td></td>
<td>0 to 99&lt;sup&gt;(1)&lt;/sup&gt;</td>
<td>(Lyon &amp; Smith, 2010)</td>
</tr>
<tr>
<td>Water exposure</td>
<td>50</td>
<td>(Donnelly, et al., 2011)</td>
</tr>
<tr>
<td></td>
<td>90</td>
<td>(Countess Environmental, 2006)</td>
</tr>
<tr>
<td>Mulching</td>
<td>20 to 40&lt;sup&gt;(2)&lt;/sup&gt;</td>
<td>(Countess Environmental, 2006)</td>
</tr>
<tr>
<td>Surface agents</td>
<td>70 to 84</td>
<td>(Donnelly, et al., 2011)</td>
</tr>
<tr>
<td></td>
<td>85</td>
<td>(Countess Environmental, 2006)</td>
</tr>
<tr>
<td></td>
<td>89.6&lt;sup&gt;(3)&lt;/sup&gt;</td>
<td>(USEPA, 1992)</td>
</tr>
<tr>
<td><strong>Peripheral surface stabilization</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plantation wind breaks</td>
<td>30</td>
<td>(Donnelly, et al., 2011)</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>(Countess Environmental, 2006)</td>
</tr>
<tr>
<td></td>
<td>0 to 88</td>
<td>(USEPA, 1992)</td>
</tr>
<tr>
<td>Artificial wind barriers</td>
<td>75 to 80</td>
<td>(Donnelly, et al., 2011)</td>
</tr>
<tr>
<td></td>
<td>4 to 88</td>
<td>(Countess Environmental, 2006)</td>
</tr>
<tr>
<td></td>
<td>0 to 88</td>
<td>(USEPA, 1992)</td>
</tr>
</tbody>
</table>

<sup>(1)</sup> Reduction factor increases with the ground cover (0 to 100%)

<sup>(2)</sup> 30% reduction for grassing and 90% reduction for cropping

<sup>(3)</sup> Proposed for agricultural wind erosion

<sup>(4)</sup> Proposed for a latex binder

<sup>(5)</sup> 90% reduction for chemical wetting and 95% reduction for crusting
Appendix D. Mine Dust Control Methods – Cost Parameters

Table A-10. Cost parameters of water spraying proposed for haulage activity

<table>
<thead>
<tr>
<th>Control Method: Road Surface Treatment – Water Spraying</th>
<th>Unit</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduction factor</td>
<td>70 %</td>
<td>(BBK I, 2013a)</td>
</tr>
</tbody>
</table>

Cost calculation

1. Capital cost

<table>
<thead>
<tr>
<th>Unit</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Truck capacity 26500 L</td>
<td>(CostMine, 2012; BBK I, 2013a)</td>
</tr>
<tr>
<td>Truck operating time per day 16 h</td>
<td>(BBK I, 2013a)</td>
</tr>
<tr>
<td>Truck cycle length 8 km</td>
<td>(BBK I, 2013a)</td>
</tr>
<tr>
<td>Truck cycle time 28 min</td>
<td>(BBK I, 2013a)</td>
</tr>
<tr>
<td>Truck watering span Half span/width</td>
<td>(BBK I, 2013a)</td>
</tr>
<tr>
<td>Truck watering span 6 m</td>
<td>(BBK I, 2013a)</td>
</tr>
<tr>
<td>Watering rate 1.2 L/m²*h</td>
<td>(BBK I, 2013a)</td>
</tr>
<tr>
<td>Required number of trucks 3 truck</td>
<td>(BBK I, 2013a)</td>
</tr>
<tr>
<td>Truck cost 240000 €</td>
<td>(CostMine, 2012; BBK I, 2013a)</td>
</tr>
<tr>
<td>Truck lifetime 114 month</td>
<td>(CostMine, 2012; BBK I, 2013a)</td>
</tr>
<tr>
<td>Installation of ancillaries (filling stations etc.) 176000 €</td>
<td>(CostMine, 2012; BBK I, 2013a)</td>
</tr>
</tbody>
</table>

2. Operational cost

<table>
<thead>
<tr>
<th>Unit</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit water cost 0.045 €/m³</td>
<td>(Landesregierung NRW, 2012)</td>
</tr>
<tr>
<td>Water requirement 85179 L/h</td>
<td>(BBK I, 2013a)</td>
</tr>
<tr>
<td>Unit fuel cost 0.891 €/L</td>
<td>(EUROPIA, 2012; BBK I, 2013a)</td>
</tr>
<tr>
<td>Fuel requirement 40 L/truck*h</td>
<td>(CostMine, 2012; BBK I, 2013a)</td>
</tr>
<tr>
<td>Total driver salary per truck 4260 €/truck*month</td>
<td>(CostMine, 2012; BBK I, 2013a)</td>
</tr>
<tr>
<td>Maintenance cost 7085 €/truck*month</td>
<td>(CostMine, 2012; BBK I, 2013a)</td>
</tr>
<tr>
<td>Operation cost of ancillaries 2640 €/month</td>
<td>(CostMine, 2012; BBK I, 2013a)</td>
</tr>
</tbody>
</table>
### Table A-11. Cost parameters of application of surface agents proposed for haulage activity

<table>
<thead>
<tr>
<th>Control Method: Road Surface Treatment – Application of Surface Agents</th>
<th>Unit</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduction factor</td>
<td>70</td>
<td>%</td>
</tr>
</tbody>
</table>

**Cost calculation**

1. **Capital cost**
   - Equipment cost (truck, spray etc.) | 4.29 | €/m² | (CostMine, 2012; BBK I, 2013a) |
   - Equipment lifetime | 114 | month | (CostMine, 2012; BBK I, 2013a) |
   - Installation of ancillaries (filling stations etc.) | 0.41 | €/m² | (CostMine, 2012; BBK I, 2013a) |

2. **Operational cost**
   - Required surface agent per application | 0.00021 | kg/m² | (CMRI, 2011; BBK I, 2013a) |
   - Re-application period | 1 | day | (CMRI, 2011; BBK I, 2013a) |
   - Surface agent cost | 17.97 | €/kg | (CMRI, 2011; BBK I, 2013a) |
   - Unit water cost | 0.045 | €/m³ | (Landesregierung NRW, 2012) |
   - Water requirement | 9.72 | L/m² | (CMRI, 2011; BBK I, 2013a) |
   - Cost per application | 0.004 | €/m² | (CostMine, 2012; BBK I, 2013a) |
   - Equipment operation/maintenance cost | 0.26 | €/m²/month | (CostMine, 2012; BBK I, 2013a) |
   - Operation cost of ancillaries | 0.006 | €/m²/month | (CostMine, 2012; BBK I, 2013a) |

### Table A-12. Cost parameters of road paving proposed for haulage activity

<table>
<thead>
<tr>
<th>Control Method: Road Surface Treatment – Road Paving</th>
<th>Unit</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduction factor</td>
<td>90</td>
<td>%</td>
</tr>
</tbody>
</table>

**Cost calculation**

1. **Capital cost**
   - Paving material cost | 122 | €/m³ | (Kotzian, 2012) |
   - Material required | 0.3 | m³/m² | (Scheving, 2011; BBK I, 2013a) |
   - Paving application cost | 29.25 | €/m³ | (Scheving, 2011; BBK I, 2013a) |

2. **Operational cost**
   - Maintenance cost | 0.04 | €/m²/month | (Scheving, 2011; BBK I, 2013a) |

### Table A-13. Cost parameters of regulating driving pattern proposed for haulage activity

<table>
<thead>
<tr>
<th>Control Method: Road Surface Treatment – Regulating Driving Pattern</th>
<th>Unit</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduction factor</td>
<td>42</td>
<td>%</td>
</tr>
</tbody>
</table>

**Cost calculation**

1. **Indirect cost**
   - Cost due to reducing working efficiency | 0 | €/month | (BBK I, 2013a) |
# Appendix E. DSS Scenario Assumptions and Data

## E-1. Project Info Parameters

<table>
<thead>
<tr>
<th>Project info</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project duration</td>
<td>20(^{(1)}) to 30(^{(2)}) years</td>
</tr>
<tr>
<td>Currency</td>
<td>€ -</td>
</tr>
</tbody>
</table>

### Mining info

<table>
<thead>
<tr>
<th>Mining info</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yearly coal production</td>
<td>5,150,000 tonnes/year</td>
</tr>
<tr>
<td>Yearly overburden removal</td>
<td>38,878,800 tonnes/year</td>
</tr>
<tr>
<td>Shifts per day</td>
<td>3 shift/d</td>
</tr>
<tr>
<td>Working hours per shift</td>
<td>7 h/shift</td>
</tr>
<tr>
<td>Holidays (no activity days)</td>
<td>1 d/month</td>
</tr>
</tbody>
</table>

### Local info

<table>
<thead>
<tr>
<th>Local info</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yearly interest rate</td>
<td>5.00 %</td>
</tr>
<tr>
<td>Monthly interest rate</td>
<td>0.41 %</td>
</tr>
<tr>
<td>Unit electricity cost</td>
<td>0.090 €/KWh</td>
</tr>
<tr>
<td>Unit water cost</td>
<td>0.045 €/m³</td>
</tr>
<tr>
<td>Unit fuel cost</td>
<td>0.891 €/L</td>
</tr>
</tbody>
</table>

### Meteorological info

<table>
<thead>
<tr>
<th>Meteorological info</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>No of heavy rainy days (&gt;0.254 mm)</td>
<td>135 d/year</td>
</tr>
</tbody>
</table>

\(^{(1)}\) For the reference scenario  
\(^{(2)}\) For the individual scenarios
### E-2. Scenario Assumptions and Data – Reference Scenario

**Table A-15.** Scenario assumptions and data for the reference scenario

<table>
<thead>
<tr>
<th>Mining Activity</th>
<th>Scenario Parameters</th>
<th>Location</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Drilling</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Emission</td>
<td></td>
<td></td>
<td>0.02817</td>
<td>0.32067</td>
<td>1.2798</td>
<td>kg/m</td>
</tr>
<tr>
<td>Drilling depth per shift</td>
<td></td>
<td></td>
<td>53.13</td>
<td>53.13</td>
<td>37.5</td>
<td>m/shift</td>
</tr>
<tr>
<td>Drilling duration per shift</td>
<td></td>
<td></td>
<td>2.34</td>
<td>1.96</td>
<td>1.96</td>
<td>h/shift</td>
</tr>
<tr>
<td><strong>Blasting</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Emission</td>
<td></td>
<td></td>
<td>0.00053</td>
<td>0.00053</td>
<td>0.00053</td>
<td>kg/t</td>
</tr>
<tr>
<td>Amount of blasted material</td>
<td></td>
<td></td>
<td>918</td>
<td>918</td>
<td>918</td>
<td>t/hole</td>
</tr>
<tr>
<td>Number of blast holes</td>
<td></td>
<td></td>
<td>21</td>
<td>21</td>
<td>21</td>
<td>hole/d</td>
</tr>
<tr>
<td><strong>Ripping</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Emission</td>
<td></td>
<td></td>
<td>2.11</td>
<td>2.11</td>
<td></td>
<td>kg/h</td>
</tr>
<tr>
<td>Ripping duration per shift</td>
<td></td>
<td></td>
<td>5</td>
<td>5</td>
<td></td>
<td>h/shift</td>
</tr>
<tr>
<td>Amount of overburden ripped</td>
<td></td>
<td></td>
<td>7397.38</td>
<td>7397.38</td>
<td></td>
<td>t/shift</td>
</tr>
<tr>
<td><strong>Overburden loading</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Emission</td>
<td></td>
<td></td>
<td>0.00393</td>
<td>0.00378</td>
<td>0.00470</td>
<td>kg/t</td>
</tr>
<tr>
<td>Overburden loading rate</td>
<td></td>
<td></td>
<td>11546</td>
<td>19320</td>
<td>9632</td>
<td>t/shift</td>
</tr>
<tr>
<td>Loading duration per shift</td>
<td></td>
<td></td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>h/shift</td>
</tr>
<tr>
<td><strong>Overburden haulage</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Emission</td>
<td></td>
<td></td>
<td>880</td>
<td>1124</td>
<td>880</td>
<td>1124</td>
</tr>
<tr>
<td>Number of truck using the road</td>
<td></td>
<td></td>
<td>23</td>
<td>14</td>
<td>23</td>
<td>14</td>
</tr>
<tr>
<td>Average truck speed</td>
<td></td>
<td></td>
<td>19.5</td>
<td>19.5</td>
<td>19.5</td>
<td>19.5</td>
</tr>
<tr>
<td>Length of road</td>
<td></td>
<td></td>
<td>7.779</td>
<td>4.475</td>
<td>7.779</td>
<td>4.475</td>
</tr>
<tr>
<td>Width of road</td>
<td></td>
<td></td>
<td>12.00</td>
<td>12.00</td>
<td>12.00</td>
<td>12.00</td>
</tr>
<tr>
<td><strong>Overburden dumping</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Emission</td>
<td></td>
<td></td>
<td>0.225</td>
<td>0.225</td>
<td>0.225</td>
<td>0.225</td>
</tr>
<tr>
<td>Dumping rate</td>
<td></td>
<td></td>
<td>18224</td>
<td>5062</td>
<td>8606</td>
<td>8606</td>
</tr>
<tr>
<td><strong>Wind erosion</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Emission</td>
<td></td>
<td></td>
<td>0.200</td>
<td></td>
<td></td>
<td>g/m²*h</td>
</tr>
<tr>
<td>Surface area</td>
<td></td>
<td></td>
<td>4.51</td>
<td></td>
<td></td>
<td>km²</td>
</tr>
<tr>
<td>Perimeter of area</td>
<td></td>
<td></td>
<td>n/a</td>
<td></td>
<td></td>
<td>km</td>
</tr>
</tbody>
</table>
### Appendix E

#### Table A-16. Scenario assumptions and data for the reference scenario – overburden haulage

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Road 1</th>
<th>Road 2</th>
<th>Road 3</th>
<th>Road 4</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length of road</td>
<td>km</td>
<td>7.779</td>
<td>4.475</td>
<td>7.779</td>
<td>4.475</td>
<td>24.508</td>
</tr>
<tr>
<td>Amount of overburden</td>
<td>t/shift</td>
<td>10124.75</td>
<td>10124.75</td>
<td>10124.75</td>
<td>10124.75</td>
<td>40499</td>
</tr>
<tr>
<td>Average truck load</td>
<td>t/truck</td>
<td>55.6</td>
<td>55.6</td>
<td>55.6</td>
<td>55.6</td>
<td>-</td>
</tr>
<tr>
<td>Loading/dumping duration</td>
<td>min/truck</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>-</td>
</tr>
<tr>
<td>Truck speed</td>
<td>km/h</td>
<td>19.5</td>
<td>19.5</td>
<td>19.5</td>
<td>19.5</td>
<td>-</td>
</tr>
<tr>
<td>Duration of one cycle</td>
<td>min/truck</td>
<td>51.87</td>
<td>31.53</td>
<td>51.87</td>
<td>31.53</td>
<td>-</td>
</tr>
<tr>
<td>Truck cycles per shift</td>
<td>cycle/shift</td>
<td>8.10</td>
<td>13.32</td>
<td>8.10</td>
<td>13.32</td>
<td>-</td>
</tr>
<tr>
<td>Number of truck using the road</td>
<td>trucks/shift</td>
<td>23</td>
<td>14</td>
<td>23</td>
<td>14</td>
<td>74</td>
</tr>
</tbody>
</table>

#### Table A-17. Scenario assumptions and data for the overburden haulage scenarios

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Scenario “OH1” to “OH5”</th>
<th>Scenario “OH6”</th>
<th>Scenario “OH7”</th>
<th>Scenario “OH8”</th>
<th>Scenario “OH9”</th>
<th>Scenario “OH10”</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emission</td>
<td>g/km*truck</td>
<td>880</td>
<td>880</td>
<td>880</td>
<td>880</td>
<td>880</td>
<td>880</td>
</tr>
<tr>
<td>Number of truck using the road</td>
<td>truck</td>
<td>58</td>
<td>12</td>
<td>24</td>
<td>36</td>
<td>78</td>
<td>144</td>
</tr>
<tr>
<td>Average truck speed</td>
<td>km/h</td>
<td>19.5</td>
<td>19.5</td>
<td>19.5</td>
<td>19.5</td>
<td>19.5</td>
<td>19.5</td>
</tr>
<tr>
<td>Length of road</td>
<td>km</td>
<td>18</td>
<td>1</td>
<td>5</td>
<td>10</td>
<td>25</td>
<td>50</td>
</tr>
<tr>
<td>Width of road</td>
<td>m</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Yearly interest rate</td>
<td>%</td>
<td>1 to 5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
</table>

#### Table A-18. Scenario assumptions and data for the wind erosion scenarios

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Scenario “WE1” to “WE5”</th>
<th>Scenario “WE6”</th>
<th>Scenario “WE7”</th>
<th>Scenario “WE8”</th>
<th>Scenario “WE9”</th>
<th>Scenario “WE10”</th>
<th>Scenario “WE11”</th>
<th>Scenario “WE12”</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emission</td>
<td>g/m²*h</td>
<td>0.200</td>
<td>0.200</td>
<td>0.200</td>
<td>0.200</td>
<td>0.200</td>
<td>0.200</td>
<td>0.200</td>
<td>0.200</td>
</tr>
<tr>
<td>Surface area</td>
<td>km²</td>
<td>0.9</td>
<td>0.10</td>
<td>0.25</td>
<td>0.50</td>
<td>1.00</td>
<td>2.00</td>
<td>2.50</td>
<td>5.00</td>
</tr>
<tr>
<td>Perimeter of area</td>
<td>km</td>
<td>3.8</td>
<td>2.20</td>
<td>2.50</td>
<td>3.0</td>
<td>4.0</td>
<td>6.0</td>
<td>7.0</td>
<td>12.0</td>
</tr>
<tr>
<td>Yearly interest rate</td>
<td>%</td>
<td>1 to 5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
</table>

#### E-3. Scenario Assumptions and Data – Individual Scenarios
## Appendix F. Comparative Emission Calculations

### F-1. Emission Calculations – Haulage

**Table A-19.** Comparative emission factor (in PM10) estimated for haulage activity based on the USEPA equation (USEPA, 2006a)

<table>
<thead>
<tr>
<th>Measurement Condition</th>
<th>s (%)</th>
<th>W (t)</th>
<th>k (lb/VMT)</th>
<th>a (-)</th>
<th>b (-)</th>
<th>E (lb/VMT)</th>
<th>E (g/km*truck)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Off-highway trucks on dry road</td>
<td>13.2</td>
<td>46.5</td>
<td>1.5</td>
<td>0.90</td>
<td>0.45</td>
<td>5.6104</td>
<td>1,581</td>
</tr>
<tr>
<td>Dump trucks on dry road</td>
<td>13.2</td>
<td>13.9</td>
<td>1.5</td>
<td>0.90</td>
<td>0.45</td>
<td>3.2583</td>
<td>918</td>
</tr>
<tr>
<td><strong>Average - trucks on dry road</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>1,250</strong></td>
<td></td>
</tr>
</tbody>
</table>

(6) s: surface material silt content (%); W: mean vehicle weight (tonnes); k: constant (lb/VMT); a and b: constants (-); E (lb/VMT): size specific emission factor in pounds for unpaved road, per vehicle mile traveled; E: size specific emission factor in grams for unpaved road, per vehicle kilometer traveled (g/km*truck).

(7) Data from real-time measurements were assigned.

**Table A-20.** Comparative emission factor (in SP or PM30) estimated for haulage activity based on the USEPA equation (USEPA, 2006a)

<table>
<thead>
<tr>
<th>Measurement Condition</th>
<th>s (%)</th>
<th>W (t)</th>
<th>k (lb/VMT)</th>
<th>a (-)</th>
<th>b (-)</th>
<th>E (lb/VMT)</th>
<th>E (g/km*truck)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Off-highway trucks on dry road</td>
<td>13.2</td>
<td>46.5</td>
<td>4.9</td>
<td>0.70</td>
<td>0.45</td>
<td>17.9813</td>
<td>5,068</td>
</tr>
<tr>
<td>Dump trucks on dry road</td>
<td>13.2</td>
<td>13.9</td>
<td>4.9</td>
<td>0.70</td>
<td>0.45</td>
<td>10.4429</td>
<td>2,943</td>
</tr>
<tr>
<td><strong>Average - trucks on dry road</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>4,006</strong></td>
<td></td>
</tr>
</tbody>
</table>

(1) s: surface material silt content (%); W: mean vehicle weight (tonnes); k: constant (lb/VMT); a and b: constants (-); E (lb/VMT): size specific emission factor in pounds for unpaved road, per vehicle mile traveled; E: size specific emission factor in grams for unpaved road, per vehicle kilometer traveled (g/km*truck).

(2) Data from real-time measurements were assigned.

**Table A-21.** Comparative emission factor (in SP or PM30) estimated for haulage activity based on the Chakraborty, et al. (2002) equation

<table>
<thead>
<tr>
<th>Measurement Condition</th>
<th>m (%)</th>
<th>s (%)</th>
<th>u (m/s)</th>
<th>v (m/s)</th>
<th>c (t)</th>
<th>f (no./h)</th>
<th>E (g/s*m)</th>
<th>E (g/km*truck)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Off-highway trucks on dry road</td>
<td>5.4</td>
<td>13.2</td>
<td>2.9</td>
<td>5.4</td>
<td>46.5</td>
<td>80.0</td>
<td>0.0342</td>
<td>1,539</td>
</tr>
<tr>
<td>Off-highway trucks on wet road</td>
<td>28.0</td>
<td>13.2</td>
<td>2.9</td>
<td>5.4</td>
<td>46.5</td>
<td>80.0</td>
<td>0.0074</td>
<td>332</td>
</tr>
<tr>
<td>Dump trucks on dry road</td>
<td>5.4</td>
<td>13.2</td>
<td>2.9</td>
<td>5.4</td>
<td>13.9</td>
<td>80.0</td>
<td>0.0313</td>
<td>1,407</td>
</tr>
<tr>
<td>Dump trucks on wet road</td>
<td>28.0</td>
<td>13.2</td>
<td>2.9</td>
<td>5.4</td>
<td>13.9</td>
<td>80.0</td>
<td>0.0067</td>
<td>303</td>
</tr>
<tr>
<td><strong>Average - trucks on dry road</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>1,473</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Average - trucks on wet road</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>317</strong></td>
<td></td>
</tr>
</tbody>
</table>

(1) m: moisture content of haul road dust (%); s: silt content of haul road (%); u: wind speed (m/s); v: average vehicle speed (m/s); c: capacity of dumpers (t); f: frequency of vehicle movement (no./h); E (g/s*m): emission rate in grams per second per meter (g/s*m); E: emission factor in grams per vehicle kilometer traveled (g/km*truck).

(2) Data from real-time measurements were assigned.
## F-2. Emission Calculations – Overburden Dumping

### Table A-22. Comparative emission factor estimated for overburden dumping activity based on the USEPA equation (USEPA, 2006b)

<table>
<thead>
<tr>
<th>Measurement Day</th>
<th>Parameter&lt;sup&gt;(1)(2)&lt;/sup&gt;</th>
<th>Parameter&lt;sup&gt;(1)(2)&lt;/sup&gt;</th>
<th>Parameter&lt;sup&gt;(1)(2)&lt;/sup&gt;</th>
<th>Parameter&lt;sup&gt;(1)(2)&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>k (-) = 0.74 for SP (PM30)</td>
<td>U (m/s)</td>
<td>M (%)</td>
<td>E (g/t)</td>
</tr>
<tr>
<td>2011-11-30</td>
<td>0.74</td>
<td>3.7</td>
<td>5.3</td>
<td>0.595</td>
</tr>
<tr>
<td>2011-12-12</td>
<td>0.74</td>
<td>3.6</td>
<td>4.6</td>
<td>0.700</td>
</tr>
<tr>
<td>2011-12-14</td>
<td>0.74</td>
<td>2.3</td>
<td>5.1</td>
<td>0.338</td>
</tr>
<tr>
<td>2011-12-01</td>
<td>0.74</td>
<td>2.4</td>
<td>7.9</td>
<td>0.194</td>
</tr>
<tr>
<td>2011-12-02</td>
<td>0.74</td>
<td>2.8</td>
<td>5.1</td>
<td>0.437</td>
</tr>
<tr>
<td>2011-12-03</td>
<td>0.74</td>
<td>2.3</td>
<td>4.1</td>
<td>0.459</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td></td>
<td>0.454</td>
</tr>
</tbody>
</table>

<sup>(1)</sup> k: particle size multiplier (-); U: mean wind speed (m/s); M: material moisture content (%); E: emission factor in grams per tonne of material transferred (g/t).

<sup>(2)</sup> Data from real-time measurements were assigned.

### Table A-23. Comparative emission factor (in SP or PM30) estimated for overburden dumping activity based on the Chakraborty, et al. (2002) equation

<table>
<thead>
<tr>
<th>Measurement Day</th>
<th>Parameter&lt;sup&gt;(1)(2)&lt;/sup&gt;</th>
<th>Parameter&lt;sup&gt;(1)(2)&lt;/sup&gt;</th>
<th>Parameter&lt;sup&gt;(1)(2)&lt;/sup&gt;</th>
<th>Parameter&lt;sup&gt;(1)(2)&lt;/sup&gt;</th>
<th>Parameter&lt;sup&gt;(1)(2)&lt;/sup&gt;</th>
<th>Parameter&lt;sup&gt;(1)(2)&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>h (m)</td>
<td>m (%)</td>
<td>s (%)</td>
<td>u (m/s)</td>
<td>c (t)</td>
<td>y (no./h)</td>
</tr>
<tr>
<td>2011-11-30</td>
<td>6.89</td>
<td>5.3</td>
<td>7.2</td>
<td>3.7</td>
<td>57.7</td>
<td>25.5</td>
</tr>
<tr>
<td>2011-12-12</td>
<td>37.18</td>
<td>5.1</td>
<td>6.1</td>
<td>2.8</td>
<td>57.7</td>
<td>54.0</td>
</tr>
<tr>
<td>2011-12-14</td>
<td>7.94</td>
<td>4.1</td>
<td>7.6</td>
<td>2.3</td>
<td>57.7</td>
<td>19.0</td>
</tr>
<tr>
<td>2011-12-01</td>
<td>17.47</td>
<td>4.6</td>
<td>6.5</td>
<td>3.6</td>
<td>26.7</td>
<td>25.5</td>
</tr>
<tr>
<td>2011-12-02</td>
<td>18.38</td>
<td>5.1</td>
<td>6.9</td>
<td>2.3</td>
<td>26.7</td>
<td>27.0</td>
</tr>
<tr>
<td>2011-12-03</td>
<td>40.00</td>
<td>7.9</td>
<td>11.6</td>
<td>2.4</td>
<td>26.7</td>
<td>23.0</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<sup>(1)</sup> h: drop height (m); m: moisture content of unloading material (%); s: silt content of unloading material (%); u: wind speed (m/s); c: capacity of unloader (t); y: frequency of unloading (no./h); E: emission rate in grams per second, (g/s); E: emission rate in grams per tonne.

<sup>(2)</sup> Data from real-time measurements were assigned.
### F-3. Emission Calculations – Wind Erosion

**Table A-24.** Comparative emission factor (in SP or PM30) estimated for wind erosion based on the USEPA equation (USEPA, 1998a)

<table>
<thead>
<tr>
<th>Measurement Day</th>
<th>Parameter</th>
<th>Parameter</th>
<th>Parameter</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$u_{\text{max}}$ (m/s)</td>
<td>$z$ (cm)</td>
<td>$z_0$ (cm)</td>
<td>$u^*$ (m/s)</td>
</tr>
<tr>
<td>2011-11-21</td>
<td>7.58</td>
<td>50</td>
<td>0.3</td>
<td>0.59</td>
</tr>
<tr>
<td>2011-12-15</td>
<td>3.41</td>
<td>50</td>
<td>0.3</td>
<td>0.27</td>
</tr>
<tr>
<td>2011-12-15</td>
<td>5.01</td>
<td>50</td>
<td>0.3</td>
<td>0.39</td>
</tr>
<tr>
<td>2011-12-21</td>
<td>4.81</td>
<td>50</td>
<td>0.3</td>
<td>0.38</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(1) $u$: wind speed (m/s); $z$: height above test surface (cm); $z_0$: roughness height (cm); $u^*$: friction velocity (m/s); $u_t$: threshold friction velocity (m/s); $P$: erosion potential (g/m²); $E$: emission rate in grams per square meter per hour (g/m²*h).

(2) Data from real-time measurements were assigned.

**Table A-25.** Comparative emission factor (in SP or PM30) estimated for wind erosion based on the Chakraborty, et al. (2002) equation

<table>
<thead>
<tr>
<th>Measurement Day</th>
<th>Parameter</th>
<th>Parameter</th>
<th>Parameter</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$m$ (%)</td>
<td>$s$ (%)</td>
<td>$u$ - average (m/s)</td>
<td>$a$ (km²)</td>
</tr>
<tr>
<td>2011-11-21</td>
<td>1.7</td>
<td>10.2</td>
<td>4.0</td>
<td>0.01250</td>
</tr>
<tr>
<td>2011-12-15</td>
<td>1.0</td>
<td>4.2</td>
<td>1.2</td>
<td>0.00630</td>
</tr>
<tr>
<td>2011-12-15</td>
<td>0.9</td>
<td>5.4</td>
<td>2.5</td>
<td>0.00475</td>
</tr>
<tr>
<td>2011-12-21</td>
<td>2.7</td>
<td>10.7</td>
<td>2.8</td>
<td>0.05510</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(1) $m$: moisture content of surface (%); $s$: silt content of surface material (%); $u$: wind speed (m/s); $a$: area (km²); $E$: emission rate in grams per square meter per second (g/m²*s); $E$: emission rate in grams per square meter per hour (g/m²*h).

(2) Data from real-time measurements were assigned.
LIST OF FIGURES

Figure 1. Thesis structure.................................................................................................................. 11
Figure 2. Map of NBCC mining area (BBK I, 2013a) ................................................................. 22
Figure 3. Production development of NBCC from 2003 to 2011................................................... 23
Figure 4. Thesis methodology flowchart........................................................................................ 28
Figure 5. A: Spectrometer on a tripod; B: Spectrometer (GRIMM, 2009); C: USA on a pneumatic mast ......................................................................................................................... 30
Figure 6. Real-time dust emission measurement setup for overburden haulage activity on 2010-11-04 ........................................................................................................................................ 35
Figure 7. Real-time dust emission measurement setup for overburden dumping on 2011-12-03..... 36
Figure 8. Real-time dust emission measurement setup for wind erosion on 2011-12-21............. 38
Figure 9. Haulage truck (left) and water truck (right) operating at the NBCC mining area .......... 44
Figure 10. Real-time dust control performance measurement setup for water spraying on 2012-11-02 ............................................................................................................................................ 46
Figure 11. Dust generation on haulage road after watering during the real-time dust control performance measurements for water spraying on 2012-11-01 .......................................................... 48
Figure 12. DSS development process, adapted from Marakas (1999)......................................... 55
Figure 13. Decision flow diagram of conceptual DSS .................................................................... 58
Figure 14. Flowchart for the reference scenario ............................................................................ 74
Figure 15. Flowchart for the mining operation and the major mine dust sources at the NBCC mining area ................................................................................................................................. 78
Figure 16. Shares (%) of mining activities in total daily dust emission at the NBCC mining area .... 82
Figure 17. Dust reduction factor (%) for water spraying vs. time after water spraying (min) ....... 85
Figure 18. Dust reduction factor (%) for reducing dumping height vs. dumping height (m) ......... 86
Figure 19. Dust-DSS on Vensim: the “Project Info” view .............................................................. 91
Figure 20. Dust-DSS on Vensim: the “Dust Emission and Control Performance” view, an exemplary model structure for overburden haulage ............................................................................ 92
Figure 21. Dust-DSS on Vensim: the “Dust Control Cost” view, an exemplary model structure for overburden haulage .......................................................................................................................... 94
Figure 22. Dust-DSS on Vensim: the “Dust Control Overall Performance” view ......................... 95
Figure 23. Dust-DSS on Vensim: the “Dust Control Overall Cost” view ..................................... 95
Figure 24. BPG on Wiki platform: exemplary web page of the “Introduction” chapter ............... 96
Figure 25. Causes tree diagram of “Truck Haulage: Water Spraying Cost NPV” ......................... 97
Figure 26. Vensim sensitivity analysis of the water spraying cost – NPV (M€) regarding to the unit fuel cost (€/L) over time (month) ........................................................................................................................................... 98
Figure 27. Percentage shares (%) of the dust sources included in the reference scenario .......... 99
Figure 28. Index emission levels (-) for varying road lengths (km) estimated for the reference scenario ............................................................................................................................................... 100
Figure 29. Percentage shares (%) of the mine dust sources included in the reference scenario for varying road lengths (km) ................................................................. 100

Figure 30. Index emission levels (-) for varying wind erosion areas (km^2) estimated for the reference scenario ............................................................................................................................. 101

Figure 31. Percentage shares (%) of the mine dust sources included in the reference scenario for varying wind erosion areas (km^2) ...................................................................................... 101

Figure 32. Total costs (NPV, M€) of the dust control methods proposed for overburden haulage over time (month) ...................................................................................................................... 103

Figure 33. Cost-effectiveness ratio (CER, €/kg) of the dust control methods proposed for overburden haulage over time (month) estimated in the scenario “OH5” (IR-yearly=5%) .......................................................... 103

Figure 34. Cost-reduction ratio (CRR, %) of the dust control methods proposed for overburden haulage over time (month) estimated in the scenario “OH5” (IR-yearly=5%) .......................................................... 104

Figure 35. Total costs (NPV, M€) of the dust control methods proposed for wind erosion over time (month) estimated in the scenario “WE1” (IR-yearly=1%) ................................................................. 105

Figure 36. Total costs (NPV, M€) of the dust control methods proposed for wind erosion over time (month) estimated in the scenario “WE3” (IR-yearly=3%) ................................................................. 106

Figure 37. Total costs (NPV, M€) of the dust control methods proposed for wind erosion over time (month) estimated in the scenario “WE5” (IR-yearly=5%) ................................................................. 106

Figure 38. Cost-effectiveness Ratio (CER, €/kg) of the dust control methods proposed for wind erosion over time (0 to 120 months) estimated in the scenario “WE5” (IR-yearly=5%) ...107

Figure 39. Cost-effectiveness Ratio (CER, €/kg) of the dust control methods proposed for wind erosion over time (120 to 360 months) estimated in the scenario “WE5” (IR-yearly=5%) 107

Figure 40. Cost-reduction ratio (CRR, %) of the dust control methods proposed for wind erosion over time (month) estimated in the scenario “WE5” (IR-yearly=5%) ................................................................. 108

Figure 41. Total costs (NPV, M€) of the dust control methods proposed for wind erosion over time (month) estimated in the scenario “WE6” (area=0.1 km^2) ................................................................. 108

Figure 42. Total costs (NPV, M€) of the dust control methods proposed for wind erosion over time (month) estimated in the scenario “WE10” (area=2 km^2) ................................................................. 109

Figure 43. Total costs (NPV, M€) of the dust control methods proposed for wind erosion over time (month) estimated in the scenario “WE12” (area=5 km^2) ................................................................. 109

Figure 44. Dust reduction factor (%) for reducing dumping height vs. dumping height (m) ............... 120
LIST OF TABLES

Table 1. Short-term average meteorological data of Ha Long between 2010 and 2011 (Bai Chay Meteorological Station, 2012) and number of wet days ............................................................... 24

Table 2. Measurement methods for parameters influencing dust emission (overburden haulage, overburden dumping and wind erosion) .............................................................................. 39

Table 3. Measurement methods for parameters influencing the dust control performance of water spraying for overburden haulage ................................................................. 48

Table 4. Scenario development and simulation approach ................................................................................. 73

Table 5. Parameters influencing dust emission (overburden haulage, overburden dumping and wind erosion) ............................................................................................................................... 79

Table 6. Dust emission factors for haulage, overburden dumping and wind erosion (BBK I, 2013b) ............................................................................................................................................ 80

Table 7. Mine dust control methods (haulage, overburden dumping and wind erosion) ............... 81

Table 8. Cost parameters of water spraying proposed for haulage activity ........................................... 88

Table 9. Developed and comparative dust emission factors ........................................................................ 111

Table 10. Shares (%) of mining activities in total mine dust emission .......................................................... 116

Table 11. Averages of the parameters measured during the real-time measurements for overburden dumping .......................................................................................................................... 121

Table 12. Intersection points (month) of total cost (NPV, in Figure 32) and CER and CRR (in Figure 33 and Figure 34) graphs of dust control methods in scenarios “OH1” to “OH5”................................. 129

Table 13. Intersection points (month) of total cost (NPV) of dust control methods in scenarios “OH6” to “OH10”.................................................................................................................. 131

Table 14. Intersection points (month) of total cost graphs (NPV, in Figure 35, Figure 36 and Figure 37) of dust control methods in scenarios “WE1” to “WE12” ......................................................... 133

Table 15. Intersection points (month) of CER and CRR graphs (in Figure 38, Figure 39 and Figure 40) of dust control methods in scenario “WE5” ........................................................................ 135
# List of Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>AEA</td>
<td>AEA Technology plc</td>
</tr>
<tr>
<td>ANN</td>
<td>Artificial neural networks</td>
</tr>
<tr>
<td>AP 42</td>
<td>Compilation of air pollutant emission factors, USEPA</td>
</tr>
<tr>
<td>AUSTAL2000</td>
<td>AUSTAL2000 dispersion modeling software</td>
</tr>
<tr>
<td>BBK I</td>
<td>Institute of Mining Engineer I, RWTH Aachen University</td>
</tr>
<tr>
<td>BMBF</td>
<td>German Ministry of Education and Research</td>
</tr>
<tr>
<td>BPG</td>
<td>Best Practice Guide</td>
</tr>
<tr>
<td>CBIS</td>
<td>Computer-based information systems</td>
</tr>
<tr>
<td>CDC</td>
<td>United States Department of Health and Human Services, Centers for Disease Control and Prevention</td>
</tr>
<tr>
<td>CER</td>
<td>Cost-effectiveness ratio (€/kg)</td>
</tr>
<tr>
<td>CMRI</td>
<td>Central Mining Research Institute, India</td>
</tr>
<tr>
<td>COPD</td>
<td>Chronic obstructive pulmonary disease</td>
</tr>
<tr>
<td>CRR</td>
<td>Cost-reduction ratio (€/%)</td>
</tr>
<tr>
<td>CWP</td>
<td>Coal workers’ pneumoconiosis</td>
</tr>
<tr>
<td>DBMS</td>
<td>Database management systems</td>
</tr>
<tr>
<td>DDP</td>
<td>DSS development process</td>
</tr>
<tr>
<td>DGMS</td>
<td>Dialog generation and management systems</td>
</tr>
<tr>
<td>DPGM</td>
<td>Department of Geology and Minerals of Vietnam</td>
</tr>
<tr>
<td>DSS</td>
<td>Decision support system</td>
</tr>
<tr>
<td>Dust-DSS</td>
<td>Mine dust control decision support system</td>
</tr>
<tr>
<td>EDSS</td>
<td>Environmental decision support system</td>
</tr>
<tr>
<td>EIS</td>
<td>Executive information system</td>
</tr>
<tr>
<td>ES</td>
<td>Expert system</td>
</tr>
<tr>
<td>EU</td>
<td>European Union</td>
</tr>
<tr>
<td>EUROPIA</td>
<td>European Petroleum Industry Association</td>
</tr>
<tr>
<td>GMR</td>
<td>Greater Metropolitan Region</td>
</tr>
<tr>
<td>GRIMM</td>
<td>GRIMM Aerosol Technik GmbH &amp; CO. KG</td>
</tr>
<tr>
<td>IEA</td>
<td>International Energy Agency</td>
</tr>
<tr>
<td>IR</td>
<td>Interest rate (%)</td>
</tr>
<tr>
<td>IRR</td>
<td>Interest rate of return</td>
</tr>
<tr>
<td>IUCN/WCMC</td>
<td>International Union for Conservation of Nature / World Conservation Monitoring Centre</td>
</tr>
<tr>
<td>LASAT</td>
<td>LASAT (Lagrangian Simulation of Aerosol-Transport) dispersion modeling software</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>-------------</td>
</tr>
<tr>
<td>MBMS</td>
<td>Model-based management systems</td>
</tr>
<tr>
<td>METEK</td>
<td>Meteorologische Messtechnik GmbH</td>
</tr>
<tr>
<td>MIS</td>
<td>Management information system</td>
</tr>
<tr>
<td>MMS</td>
<td>Mail or message management systems</td>
</tr>
<tr>
<td>MySQL</td>
<td>MySQL relational database management system</td>
</tr>
<tr>
<td>NBCC</td>
<td>Nui Beo Coal Joint Stock Company</td>
</tr>
<tr>
<td>NIOSH</td>
<td>United States National Institute for Occupational Safety and Health</td>
</tr>
<tr>
<td>NPV</td>
<td>Net present value</td>
</tr>
<tr>
<td>NRW</td>
<td>Nordrhein-Westfalen</td>
</tr>
<tr>
<td>NSW</td>
<td>New South Wales</td>
</tr>
<tr>
<td>OH</td>
<td>Overburden haulage</td>
</tr>
<tr>
<td>PHP</td>
<td>PHP server-side scripting language</td>
</tr>
<tr>
<td>PM</td>
<td>Particulate matter</td>
</tr>
<tr>
<td>PM1</td>
<td>Particulate matter with an aerodynamic diameter less than 1 μm</td>
</tr>
<tr>
<td>PM2.5</td>
<td>Particulate matter with an aerodynamic diameter less than 2.5 μm</td>
</tr>
<tr>
<td>PM5</td>
<td>Particulate matter with an aerodynamic diameter less than 5 μm</td>
</tr>
<tr>
<td>PM10</td>
<td>Particulate matter with an aerodynamic diameter less than 10 μm</td>
</tr>
<tr>
<td>PM15</td>
<td>Particulate matter with an aerodynamic diameter less than 15 μm</td>
</tr>
<tr>
<td>PM30</td>
<td>Particulate matter with an aerodynamic diameter less than 30 μm</td>
</tr>
<tr>
<td>RAME</td>
<td>Research Association Mining and Environment in Vietnam</td>
</tr>
<tr>
<td>SDLC</td>
<td>System development life cycle</td>
</tr>
<tr>
<td>SP</td>
<td>Suspended particulate with an aerodynamic diameter less than 30 μm</td>
</tr>
<tr>
<td>TCVN</td>
<td>Vietnamese Directorate for Standards and Quality</td>
</tr>
<tr>
<td>TSP</td>
<td>Total suspended particulate with an aerodynamic diameter less than 57 μm</td>
</tr>
<tr>
<td>USA</td>
<td>Ultrasonic anemometer</td>
</tr>
<tr>
<td>USEPA</td>
<td>United States Environmental Protection Agency</td>
</tr>
<tr>
<td>UNESCO</td>
<td>United Nations Educational, Scientific and Cultural Organization</td>
</tr>
<tr>
<td>USGS</td>
<td>United States Geological Survey</td>
</tr>
<tr>
<td>VDI</td>
<td>Verein Deutscher Ingenieure</td>
</tr>
<tr>
<td>Vensim</td>
<td>Vensim system dynamics modeling software</td>
</tr>
<tr>
<td>VINACOMIN</td>
<td>Vietnam Nation Coal Mineral Industries Group</td>
</tr>
<tr>
<td>WB</td>
<td>World Bank</td>
</tr>
<tr>
<td>WE</td>
<td>Wind erosion</td>
</tr>
<tr>
<td>WRAP</td>
<td>Western Regional Air Partnership</td>
</tr>
<tr>
<td>WRD</td>
<td>Waste rock dump</td>
</tr>
</tbody>
</table>