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Review of the Applicability of Discrete Event Simulation for Process Optimization in Mining

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Review of the Applicability of Discrete Event Simulation for Process Optimization in Mining

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Table of contents

List of figures

List of tables

List of equations

List of abbreviations

$\propto$	significance level
DES	discrete event simulation
KPI	key performance indicator
$\mathrm{KS}_{\mathrm{max}}$	calculated Kolmogorow-Smirnow value
$\mathrm{KS}_{\propto,\mathrm{n}}$	tabulated Kolmogorow-Smirnow value
h	hour
km	kilometer
m	meter
max	maximal
min	minute
MTTR	mean-time-to-repair value
n	sample size
P	probability
s	second
μ	mean value
σ	standard deviation

1 Introduction

Simulation has become increasingly popular in mining for project-based optimization and decision-making. Recent publications show that applications can be found for larger projects in open pit mining as well as for underground operations for the analysis of interacting processes. Upadhyay et al. (2015) present the development of a simulation model optimizing truck haulage for a large-scale open pit mine. A conceptual future haulage method for a deep underground mine is developed by Greberg et al. (2016).

Rather than project-based optimization, the Knauf Gips KG company (Knauf) aims to use simulation on a cross-project basis for optimization of mining processes. Knauf is a global producer of building materials and construction systems currently operating in more than 80 countries. The products are based on gypsum which is extracted in various surface and underground operations and processed by the company in locations near to the respective selling markets (Knauf 2016).

Using the software Tecnomatix Plant Simulation from Siemens AG (Plant Simulation), Berner (2015) has developed a simulation tool which is based on discrete event simulation. It includes pre-defined modules of all necessary mining processes suited for fast implementation of a simulation model in mining. Discrete event simulation enables the study of systems which are discrete, dynamic and stochastic (Law 2015). This fits to many applications of simulation in mining, taking into account that the optimization of the fluctuating and discretized load-haul-dump cycle is most critical for achieving higher efficiency and cost reduction (Coronado & Tenorio 2015)

1.1 Objectives of work

According to Knauf's goal to make simulation applicable to a wider range of operations, there will be two case studies performed in two different quarry operations where possible applications of the pre-developed simulation tool are evaluated under the overall goal of transport optimization. Next to individual operative results, this thesis presents a simulation procedure which acts as a guideline how discrete event simulation can be implemented in quarry mining. Finally, all results obtained by simulation are critically reviewed by comparison to solutions obtained by a deterministic spreadsheet approach in order to give a validated answer to best and most effective use of the simulation tool.

1.2 Thesis structure

2 The present role of discrete event simulation in mining

The second chapter introduces the concept of discrete event simulation and explains how the technique is used by the mining industry. Recent literature is reviewed to acknowledge today's variety of applications of discrete event simulation in mining as well as its limitations.

3 Development of simulation models for quarry optimization in Plant Simulation

The third chapter covers the complete implementation process of the simulation tool applied in two different quarry operations. It contains the developed simulation procedure as well as individual case study results including an executive summary at the end of the chapter.

4 Assessment of simulation technique for quarry optimization

A critical review of all simulation results obtained during the case studies is presented in the fourth chapter. The assessment reveals strengths and weaknesses of the applied simulation tool. Finally, recommendations for most effective use are proposed.

2 The present role of discrete event simulation in mining

The concept of discrete event simulation (DES) started to be adopted by the mining industry from the late 1950's when a train transportation system was modeled and investigated by hand calculation for the Kiruna underground iron ore mine (Panagiotou 1999).The appearance of inexpensive and fast computers greatly stimulated the use of simulation as same as the arrangement of the first conference dealing with 'Application of Computers and Operations research in mining (APCOM)' in the year 1961. However, there were only 150 papers published or presented on acknowledged symposia up to the year 1995 for the subject of simulation in mining (Sturgul 1999). In the last decade, fields of application for DES in mining have increased and the technique has evolved as powerful decision-making tool (Upadhyay et al. 2015).

2.1 Principles and use of discrete event simulation

According to VDI (2014), simulation is defined as representation of a system with its dynamic processes in an executable model to reach findings which are transferable to reality. Delimitating to simulation of continuous systems, DES enables the study of systems whose state only changes instantaneously at discrete points of time (events). DES models are dynamic simulation models, because evolving of time plays an important role in the analyzed system. In order to simulate systems whose processes can vary in their completion time, the DES model can contain stochastic components, where process times are realized by random numbers. (Law 2015, p. 5f)

For the correct representation of stochastic processes, statistical distributions represented by fitting density functions need to be evaluated, which will be addressed in detail in the performed case studies. Outcomes of single simulation runs of stochastic models differ from each other because of the random realization of process times. This leads to the fact that stochastic simulation models need to be performed several times followed by an analysis in which extend single outcomes are distributed. (Eley 2012, p. 4).

DES typically embraces the analysis of queuing problems, as they appear in manufacturing plants, inventory systems, distribution systems, communications networks, transport networks and many other environments where performance is measured in delay, number waiting, throughput and resource utilization (Fishman 2001, p. 6). Transferred to mining, fluctuating cycle times as well as queuing behavior make a mine an excellent example of a system where DES can assist in design problems (Sturgul 1999).

2.2 Applications and limitations of discrete event simulation in mining

The mining industry is a capital intensive industry dealing with many uncertainties which results in conservative behavior without bringing in bigger changes to well-proven standards. However, with the use of simulation technique, mine-planning engineers are able to study the behavior of mining systems before they are actually built or introduced in order to evaluate design alternatives, obtain improvements, eliminate problems or justify cost figures (Panagiotou 1999). Furthermore, the user can learn about interdependencies of connected sub-systems and is able to identify bottlenecks along the whole value chain in mining (Basu 1999).

Review of recent literature

By literature review of more recent publications of DES in mining it is noticed that the wide application field of improving the ore transportation system still represents a big share of today’s research. Considerable improvements for ore transport naturally appear in large-scale open pit mines by discontinuous truck and shovel operation, which was formerly addressed by creation of dispatching strategies (Kolonja, Mutmansky 1993). Recently, the problem is increasingly adressed by a combination of simulation and optimization (Upadhyay et al. 2015) (Fioroni et al. 2008).

Next to the optimization of discontinuous transport systems, DES is increasingly applied for simulating performance of continuous transportation systems as they can exemplary be found in large-scale lignite deposits (Shishvan, Benndorf 2014) (Michalakopoulos et al. 2015). General techniques which are needed to process a continuous conveyor system by discretized events is presented in Fioroni et al. (2008).

DES is nowadays also applied in underground operations to optimize ore transport (Greberg et al. 2016). However, there are other applications tested as well. Exemplary, DES helps to identify optional sizes and locations of mine refuge chambers in an underground mine (Tarshizi 2015).

Other applications found in the recent literature deal with increased energy efficiency in mining, which can be achieved by optimized shovel utilization (Awuah-Offei 2012) (Awuah-Offei 2010). Moreover, there are equipment subsystems investigated by the use of availability and reliability data of mining equipment (Gbadam et al. 2015) and even the effect of geological uncertainty on production scheduling is examined by means of DES (Shishvan, Benndorf 2014).

Limitations

Upadhyay et al. (2015) states that the strength of simulation can only be realized if it can replicate the reality to a considerable extent. However, the real system of a mine enclosing the different processes of mining can be complex so that it is of highest importance to build a suitable model which is a valid one and fits to the actual problem (Basu 1999). Moreover, stochastic skills and considerable experience and knowledge in computer modelling are required for the creation of a simulation model. Thus, the time consuming simulation approach has been limited to large mining companies having the financial capacities to afford services of qualified personnel (Basu 1999).

Conclusion

By counting multiple and newly developed fields of application, it can be stated that DES has become a well-accepted tool for decision-making in mining. However, the high-skilled and time consuming modelling work is considered feasible only for large-scale projects which are typically examined in project-based case studies. Leaking of a comprehensive DES tool for daily use in mining on the market, Knauf has adapted a general DES program for mining applications, which will be further outlined.

2.3 Previous adaption work in Plant Simulation

A summary of performed adaption work by Berner (2015) is presented which enables simulation of mining operations on a cross-project basis within the company. A mining-tailored simulation tool was developed by the use of the simulation software Plant Simulation.

The DES software Plant Simulation is a software product made by Siemens which enables simulation of production systems and logistical processes (Siemens 2014). The decision to use simulation software of high flexibility and universality was made in order to ensure universal applicability for open pit and underground mining operations as well as capturing stochastic behavior of mining processes and cycle times by distribution functions. Furthermore, it is pursued to analyze long-term studies by following the complete and dynamic life of mine.

Because the software is not especially developed for capturing mining processes, adaption work has led to facilitated use of the software by the development of a simulation tool that can be used on a cross-project basis. This simulation tool includes a basic model that allows fast modeling by pre-defined modules which capture the logic of all necessary mining processes. They are stored in a modular library in combination with suitable interfaces . Furthermore, all required resources are stored in one central database which includes the entire technical data of the utilized equipment. Both, open pit and underground mining can be realized with the simulation tool.

3 Development of simulation models for quarry optimization in Plant Simulation

Two different quarry operations serve as basis for application of the adapted simulation tool. The mines have been individually observed for optimization tasks under the overall goal of ore transport optimization. Next to individual operative results, the presented case studies examine how simulation models can successfully be implemented for process optimization in open pit mining. The gained knowledge has resulted in the development of a simulation procedure presented in the beginning of the chapter, which guides the complex implementation process of simulation by stepwise approach. An executive summary of relevant operative results is presented at the end of the chapter. Individual case study results including introduction of the quarry's working structure and respective problem outline are presented in the following subchapters:

- Case study one (Castellina M.ma, Lothar di Knauf): Chapter 3.2 pp. 30-44
- Case study two (St.Soupplets, Knauf Platres): Chapter 3.3 pp. 45-55

3.1 Simulation procedure

In literature dealing with discrete event simulation, there can be found several methods how to successfully perform simulation. Although the approaches vary in extent and depth, it is generally agreed that a sufficient and thorough quality control is of great importance. Regular "checks" are considered indispensable, in order to prevent mistakes and save costly adaption work (Eley 2012, p. 15), (Rabe et al. 2008, pp. 29–32)

In Rabe et al. (2008), quality control has systematically been integrated in a simulation procedure model. This model can also be found in the latest version of VDI-Guideline 3633 Page 1 (VDI 2014, p. 18), which is a well-known and influential guideline for simulation, issued by the Association of German Engineers (VDI). It is used in this thesis as a guideline to explain all necessary steps which are needed for simulation. Figure 1 shows the associated model in English translation.

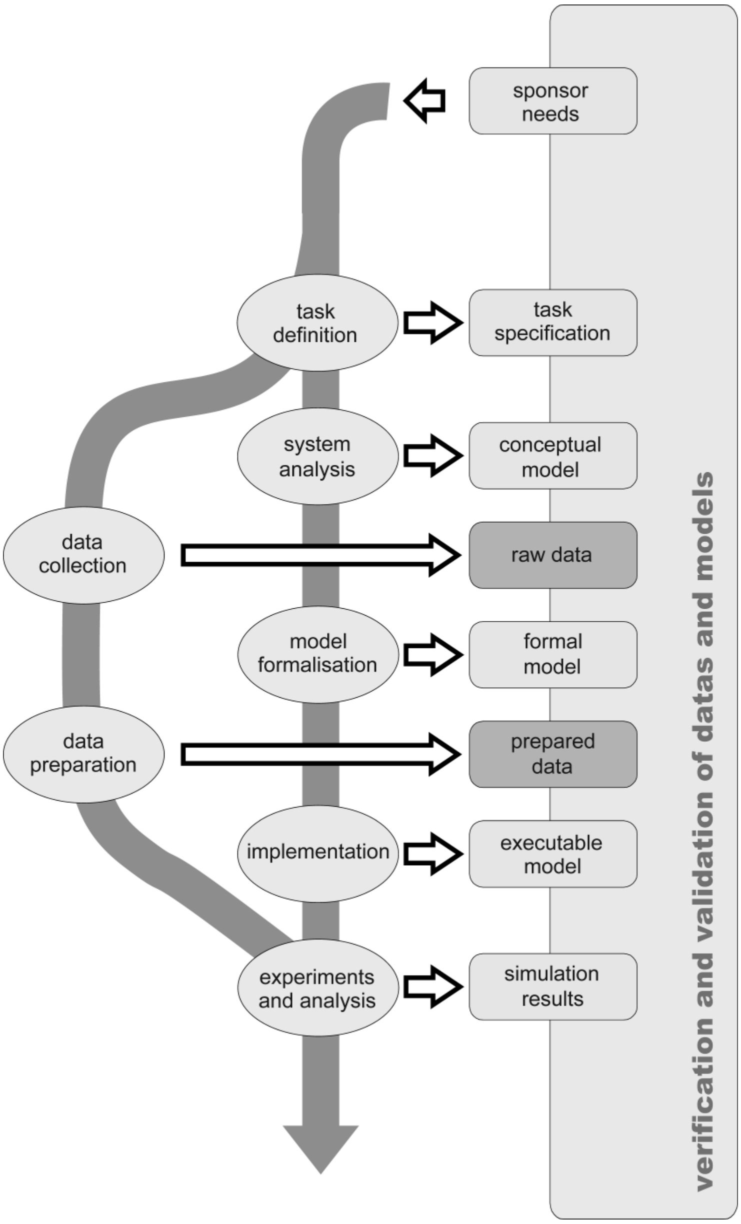

Figure 1: Procedure model for DES, adapted English version according to Rabe et al. (VDI 2014)

In the presented model, the simulation is divided into “phases“(ellipses) which all result into single “phase results” (rectangular boxes). Phases can partly be conducted parallel to each other, which is shown by track division in the model. Successive phases can only be started after having obtained predecessor results which does not mean that an earlier stage must be completed to start the next one. Most importantly, the large rectangular box on the right indicates that every phase result is subject to control measures, expressed by the terms verification and validation. (Rabe et al. 2008, p. 5f), (VDI 2014, p. 18f)

Because these two terms are used frequently in this chapter, a definition is quoted from the literature:

- Verification is defined as test procedure, whether the simulation model works as planned by the staff. (Rabe et al. 2008, p. 14f)
- Validation analyses, whether the simulation model depicts the real system, which is subject to analysis, adequately. (Rabe et al. 2008, p. 15f)

In the following, all important aspects for completion of phase results including methods for verification and validation are discussed for all relevant phases. However, a suitable conceptual model as well as formal model for quarry optimization has already been developed by Berner (2014). Thus, the phases "system analysis" and "model formalization" are not further described in this thesis.

3.1.1 Task definition

Bangsow (2011) stresses on the importance to clearly define the objectives of simulation as a first step in the whole simulation procedure. Furthermore, he recommends working out which units will serve as input parameters and which kind of output parameters are worth to be generated. Generally, the setup of input and output parameters was well as the agreement on the scope of simulation will already determine the extent of the simulation model (Bangsow 2011, p. 1). There is a template attached digitally to this thesis, which allows for fast identification of simulation targets, as well as clarification of input and output parameters for simulation in quarry operations. An extract of this document[1] is shown in Figure 2.

Scope of simulation

The general objective of simulation must be set first, whereas the objective "optimization of ore transport" is set by Knauf for all case studies examined in this thesis. As a next step, it is important to figure out which activities interfere, depending on the quarry, with the general objective. These activities will set the scope of the simulation model. Exemplary, the ore production in the quarry might be regularly interrupted by necessary comminution of boulders which are too big for transport and/or crushing.

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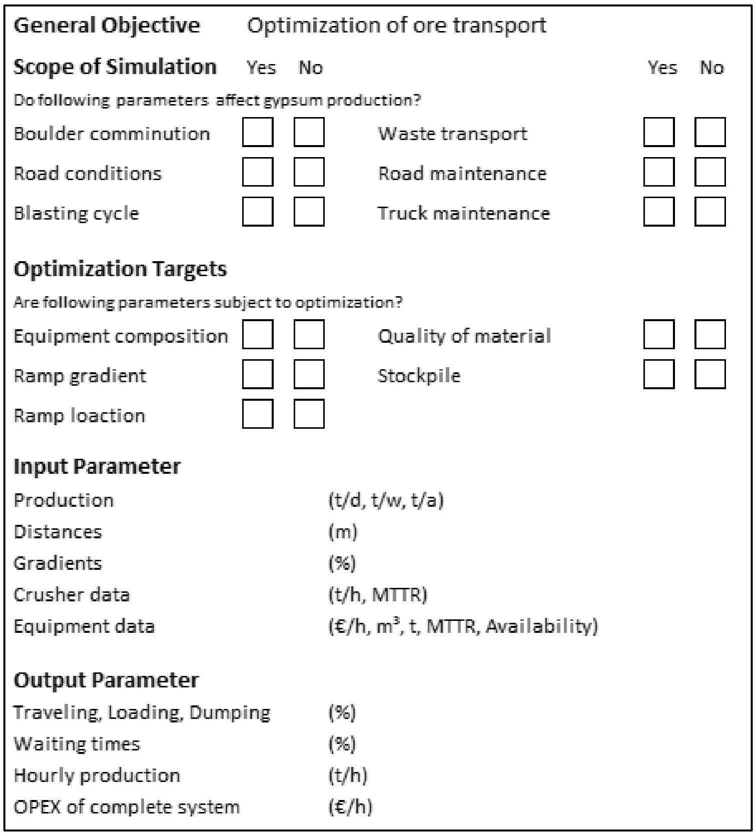
[1] Appendix B – Task definition for quarry mining



General Objective Optimization of ore transport

Scope of Simulation

Do following parameters affect gypsum production?

	Yes	No		Yes	No
Boulder comminution	☐	☐	Waste transport	☐	☐
Road conditions	☐	☐	Road maintenance	☐	☐
Blasting cycle	☐	☐	Truck maintenance	☐	☐

Optimization Targets

Are following parameters subject to optimization?

Equipment composition	☐	☐	Quality of material	☐	☐
Ramp gradient	☐	☐	Stockpile	☐	☐
Ramp loaction	☐	☐			

Input Parameter

Production	(t/d, t/w, t/a)
Distances	(m)
Gradients	(%)
Crusher data	(t/h, MTTR)
Equipment data	(€/h, m^3, t, MTTR, Availability)

Output Parameter

Traveling, Loading, Dumping	(%)
Waiting times	(%)
Hourly production	(t/h)
OPEX of complete system	(€/h)

Figure 2 Task definition for quarry simulation

Another interruption might be the regular transport of waste in order to extract ore. Both parameters might have general influence on the transport of ore, which is listed in Figure 2. The parameters must be considered later in the simulation model if a strong influence is observed. Additionally, the predefined modules of the basic model allow modeling of blasting activity as well as regular maintenance for equipment and driveways.

It is important to mention that many of these activities might take place in the quarry, however, not affecting regular transport work. Depending on the duration of simulation runs, which is set by the executor of simulation, some activities are not reasonable to be modeled. For example, weekly maintenance on road conditions and equipment does not affect a one-shift simulation run of ore transport. In this case, there shall be ticked the box “no” for the maintenance parameters.

Optimization targets

The list of possible optimization targets listed in Figure 2 presents some applications in simulation suited for quarry optimization. Often, the responsible authorities are interested in testing a varied equipment composition, which reaches from changed number of loading/hauling/drilling equipment to a changed size of equipment. Exemplary, a change of the excavator's bucket volume and/or a changed payload capacity of dump trucks can be subject for examination. These kinds of optimization problems are typical for simulation in mining, which has already been outlined in the literature review in the previous chapter. Nevertheless, some other targets for optimization can be considered as well. The change of ramp location and/or its gradient might have positive impact on overall costs for transport and can be implemented in the simulation model. Additionally, the introduction of varying qualities, as well as the influence of a stockpile on the overall transport performance might be considered.

Input parameters

Opposite to the data collected on-site, all listed input parameters in Figure 2 should be provided by the staff of the quarry. The list may act as a guideline for the user which data to ask for. Distances and gradients can possibly be extracted from a recent topographical map. Equipment specifications and availability numbers, as well as hourly cost and production numbers should be based on long-time survey. Naturally, these data can be measured during the data collection phase as well. However, robust average numbers, which are essential to verify and validate simulation results, are difficult to obtain during a time-bound data collection phase.

Output parameters

The listed output parameters in Figure 2 give a short overview on possible end results. It is important that unit definitions are set. For quarry optimization, typical actions of transport equipment (loading, hauling and dumping) are provided in relative percentage, which is useful for comparison of different scenarios. Percentage shares of waiting times are a significant outcome of simulation studies and give insight in the overall effectivity of the examined system. Moreover, parameters of productivity (t/h) and cost estimation (€/h) are essential for economical comparison.

Verification and validation for task definition

Suggestions of possible verification and validation techniques for each phase result presented in the simulation procedure model in the beginning of this chapter are given in Rabe et al. (2008). It is recommended to discuss agreed system specifications with other competent personnel in order to verify task definition (Rabe et al. 2008, p. 109). Exemplary, after setting the scope of simulation and optimization targets with the quarry responsible, the sheet can be discussed with specialists from the technical/mining department on-site and/or in the head-office.

3.1.2 Data collection

For most simulation studies, plenty of data must be collected manually to be able to provide correct input parameters for the simulation model. Exemplary, process times of single processes as well as its downtimes need to be entered accurately with the means of statistical distributions which are based on many different datasets. (Eley 2012, p. 18)

A template for data collection in quarry operations has been developed in MS excel which provided digitally[2]. It is used later in both case studies for data evaluation. Figure 3 shows important features of a typical measurement for the data collection of hauling events. The measurement sheet is standardized for a measurement of all activities in combination with ore transport in a quarry operation. The procedure has shown to be an accurate and time efficient way for data collection.

Important information about the measurement presented in Figure 3 (location, equipment, hauling way, notes etc.) is entered in the fields which are greyed out. Possible events are listed and explained in the legend on the upper right. This list is not limited. Moreover, it is up to the user to enter any event of interest. All events recorded during the measurement are listed chronologically in the data input table in combination with their absolute time of occurrence. Additionally, the number of buckets needed to fill the hauling truck is added to every loading event. Durations of single events are calculated by subtraction of absolute times. Cycles are concluded with the next loading event, resulting in cycle times. Any event of interest can be extracted in one of the following right columns for further evaluation. The

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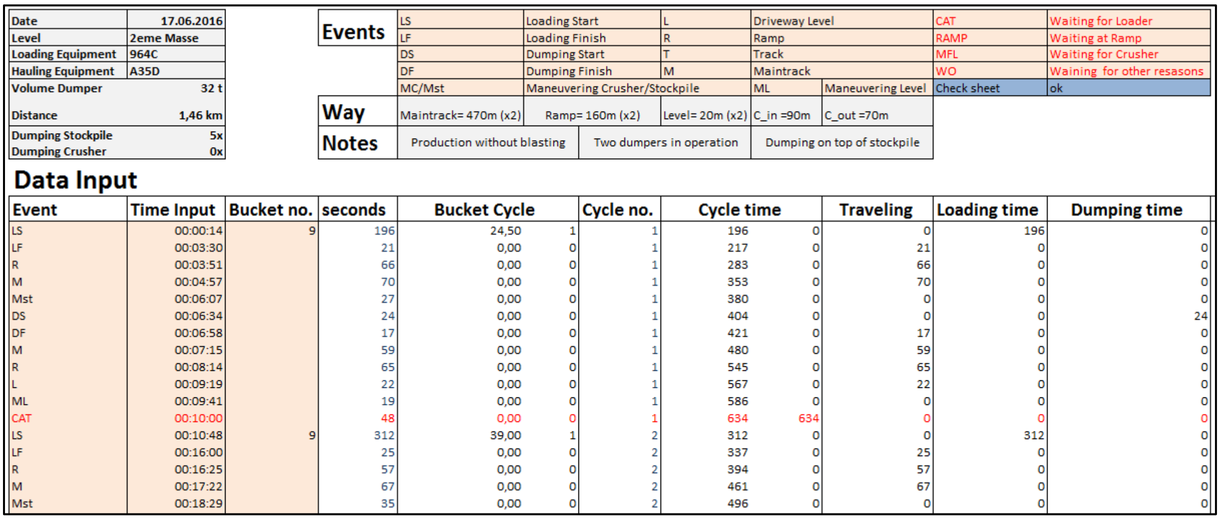
[2] Appendix C- Data collection template

measurement is finished if any important change and/or interruption in the hauling operation takes place. This can possibly be haulage of ore from another level as well as a changed equipment combination. This way of data collection is rated by illustrating its advantages and disadvantages.



Date	17.06.2016
Level	2eme Masse
Loading Equipment	964C
Hauling Equipment	A35D
Volume Dumper	32 t
Distance	1,46 km
Dumping Stockpile	5x
Dumping Crusher	0x

Events	LS	Loading Start	L	Driveway Level	CAT	Waiting for Loader
	LF	Loading Finish	R	Ramp	RAMP	Waiting at Ramp
	DS	Dumping Start	T	Track	MFL	Waiting for Crusher
	DF	Dumping Finish	M	Maintrack	WO	Waining for other resasons
	MC/Mst	Maneuvering Crusher/Stockpile	ML	Maneuvering Level	Check sheet	ok
Way	Maintrack= 470m (x2)	Ramp= 160m (x2)	Level= 20m (x2)	C_in =90m	C_out =70m	
Notes	Production without blasting	Two dumpers in operation	Dumping on top of stockpile			

Data Input

Event	Time Input	Bucket no.	seconds	Bucket Cycle		Cycle no.	Cycle time		Traveling	Loading time	Dumping time
LS	00:00:14	9	196	24,50	1	1	196	0	0	196	0
LF	00:03:30		21	0,00	0	1	217	0	21	0	0
R	00:03:51		66	0,00	0	1	283	0	66	0	0
M	00:04:57		70	0,00	0	1	353	0	70	0	0
Mst	00:06:07		27	0,00	0	1	380	0	0	0	0
DS	00:06:34		24	0,00	0	1	404	0	0	0	24
DF	00:06:58		17	0,00	0	1	421	0	17	0	0
M	00:07:15		59	0,00	0	1	480	0	59	0	0
R	00:08:14		65	0,00	0	1	545	0	65	0	0
L	00:09:19		22	0,00	0	1	567	0	22	0	0
ML	00:09:41		19	0,00	0	1	586	0	0	0	0
CAT	00:10:00		48	0,00	0	1	634	634	0	0	0
LS	00:10:48	9	312	39,00	1	2	312	0	0	312	0
LF	00:16:00		25	0,00	0	2	337	0	25	0	0
R	00:16:25		57	0,00	0	2	394	0	57	0	0
M	00:17:22		67	0,00	0	2	461	0	67	0	0
Mst	00:18:29		35	0,00	0	2	496	0	0	0	0

Figure 3 Exemplary measurement[3] for data collection in quarry operations

Advantages

- The input is not limited to a fixed roster of events. Basically, every event of importance can be recorded which can exemplary be useful for unexpected waiting times or new parts of hauling routes.
- The effort during the measurement is reduced to a minimum (abbreviation + absolute time) and works with the use of any basic watch/ clock. However, a stop watch is helpful if incidences are desired not to be recorded. (Exemplary, breaks for blast preparations can possibly be declared as waiting time but will appear as large share of waiting time in the measurement).
- Structured creation of measurement sheets facilitates comparison of different scenarios.
- Large and independent data sets are available for later validation of simulation model.

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[3] Taken from file: Data Collection_FRA

Disadvantages

- Net process times must be calculated and gathered in separate steps.
- Outliers are not instantly visible and must be found and filtered via control measures.

Although the described method of data collection has clear advantages, the problem of outlier detection must be noticed.

Verification and validation for data collection

Statistical measures are suitable and objective means to verify raw data (Rabe et al. 2008, p. 113, 116). Particularly, statistics can be a useful help for decision-making if all collected data from a data set can be used for further examinations.

Storm (2007) deals with the question whether single measurements which are distinctly smaller or larger than the bulk of measurements inside one data set should be kept or erased as outliers from the data set. Dixon's outlier test, named after W.J. Dixon, is presented in Table 1. It is a one-sided hypothesis test presuming a normal distributed data set. The t-value is calculated by the smallest value (x_1), the sample value (x_n) and the neighbouring value (x_{n-1}), using the following formula:

$$t = \frac{x_n - x_{n-1}}{x_n - x_1} \qquad (1)$$

(Storm 2007, pp. 295–298)

A measured bucket cycle time of 39 s is checked in Table 1. The corresponding data set[4] has been found to be normally distributed, so that the precondition for Dixon's test is met. It can be noticed that the tabulated tau-value (compare table XIX, Storm 2007, p. 407), fitting to the sample size (n) and the chosen confidence interval (alpha), is smaller than the calculated t-value. Thus, the sample (x_n) is considered as outlier and is not used for further analysis. Because the Dixon's outlier test presumes a normal distributed data set, it has only limited applicability in the performed case studies.

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[4] Taken from file: Data collection_FRA, sheet: Evaluation, 28 measurements for bucket cycle time, column R

Table 1 Dixon's outlier test

Dixon's outlier test (based on Storm 2007, p.296)	
Subject	bucket cycle time (s)
Value x_1	17,00
Sample x_n	39,00
Value x_{n-1}	31,00
t	0,364
tau (n: 28, alpha=0,01)	0,341
Result	outlier

Despite using this objective statistical test, it is very important to review collected raw data critically. Significant deviations can mostly be tracked down to certain behavior in the quarry operation. A decision is to be made based on the question whether this behavior should be represented in the simulation model. Thus, it is of advantage if the data collection and further actions for simulation are conducted by the same person.

Table 2 Internal proof of completeness of data set

Action	**Total time**	**66,38**	**min**	**100,00 %**
Transport		28,35	min	42,71 %
Loading	Maneuvering Level	1,50	min	2,26 %
	Loading Time	21,27	min	32,04 %
Dumping	Maneuvering Crusher	0,00	min	0,00 %
	Dumping Time	2,58	min	3,89 %
	Maneuvering Stock	4,23	min	6,38 %
Waiting	Waiting Loader	5,55	min	8,36 %
	Waiting Ramp	0,82	min	1,23 %
	Waiting Other	2,08	min	3,14 %

Table 2 shows an additional test for the verification of data collection. The complete data set is checked if every record is assigned to a defined category, which can either be transport, loading, dumping or waiting. All values in of the third column are separately gathered so that a value of 100 % in the upper right shows that the complete data set is used.

3.1.3 Data preparation

There is a need to prepare the collected data for use in the simulation program. The software "@RISK"[5] is used for further data analysis including the creation of histograms and distribution fitting. All functions of the program are authorized for academic use (Palisade 2016).

Before histograms are plotted from raw data sets, it is important to gather the collected data logically. Exemplary, one single data set is created for all dumping times collected in one operation. The corresponding histogram of this data set is depicted in Figure 4.

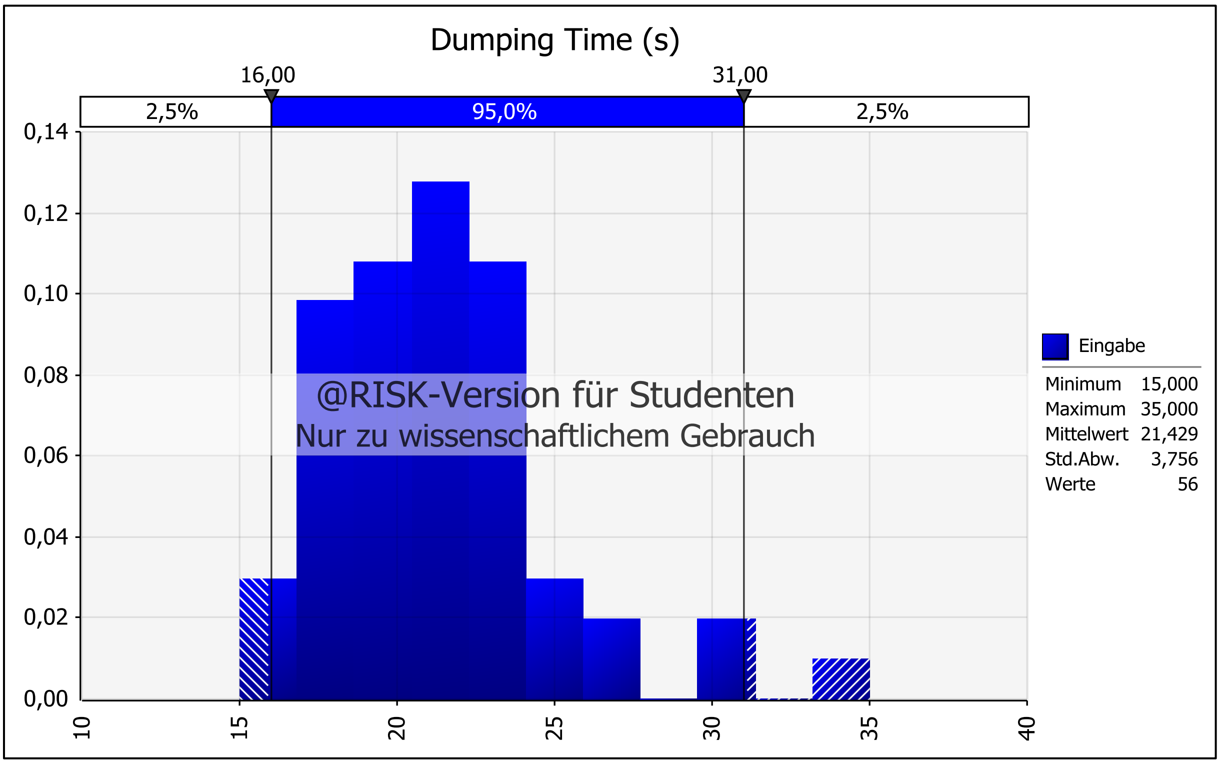

Figure 4 Histogram for data set "dumping time[6]"

Some characteristics[7] of the data set presented in Figure 4 are shown in the legend on the right, namely a minimum recorded value of 15 s, a maximum value of 35 s and a mean value of 21.4 s (rounded). The standard deviation of this data set is 3.8 s. It consists of 56 values. The maximum value has been verified to be part of the data set. Both, the minimum and maximum value are not included in the 95 % confidence interval.

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[5] Link to student version: http://www.palisade.com/risk/de/

[6] Taken from file: Data collection_FRA, sheet: Evaluation, column z

[7] Listed values from top to bottom, commas represent decimal place (translated from German)

Distribution fitting is performed by testing several statistical distributions for conformity to the data set. For complex processes and processing times, certain statistical distributions are favored. The density function of the normal distribution and log-normal distribution play an important role for representation of processes that are influenced by many randomly occurring factors, which fits to typical processes in mining. Exemplary, the loading process of a dump truck depends on many randomly occurring factors like position of loader and truck relatively to each other, size and availability of ore and operator skills. (Storm 2007, p. 72)

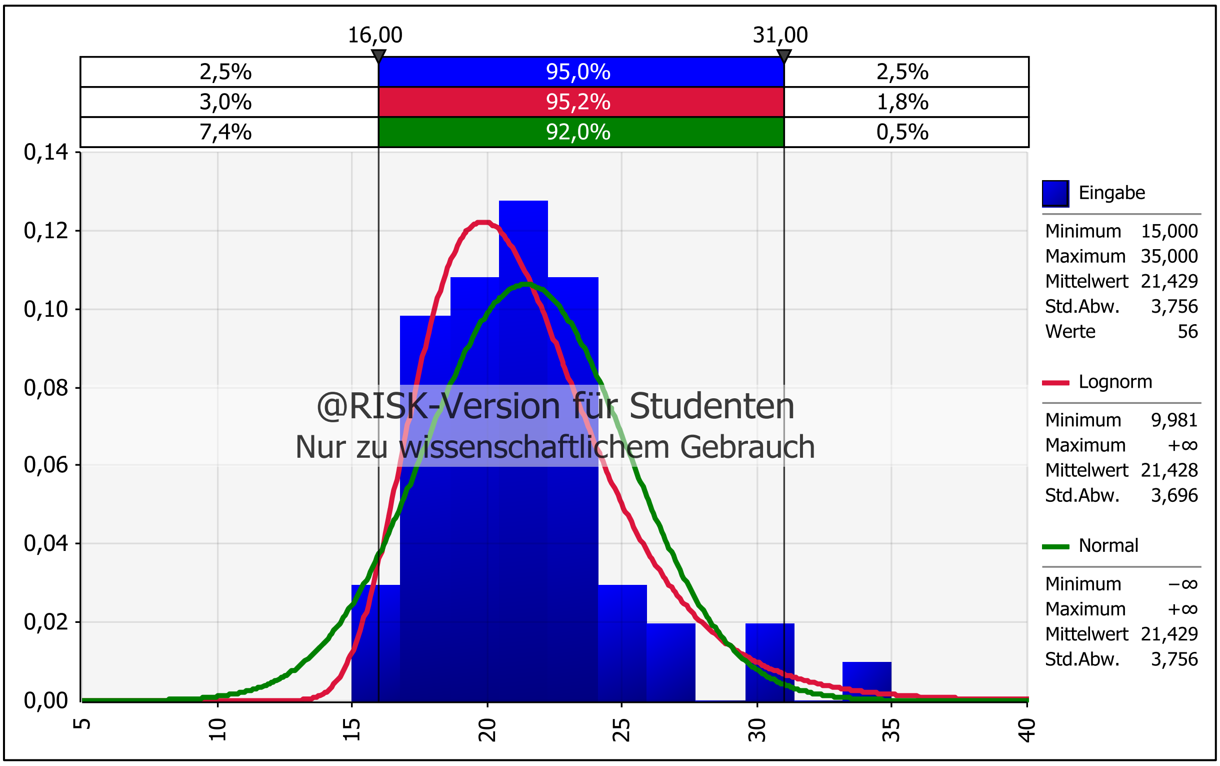

Figure 5 Distribution fitting for data set “dumping time”

The fit of statistical distributions to the data set in can be examined by statistical means, which is shown in Figure 5 exemplary for the data set, discussed in Figure 4. It can be seen that mean value and standard deviation of the corresponding density functions (red/green) are adjusted to the data set represented by the histogram (blue). Significantly, the 95 % interval of raw data accounts for 95.2 % of the density function representing the log-normal distribution (red), while the density function of the normal-distribution accounts for 92 % of the same interval. Transferred to the simulation model, it can be concluded that random variables created in accordance to a log-normal distribution do represent the collected data for dumping process better than a normal distribution.

Furthermore, the density function needs to be restricted by a lower and upper value so that the random variable stays in the corridor of measured data. The lower and upper bound of the 95 % interval are chosen as restriction values because this interval covers sufficient data and at the same time shows best conformity with the density function. The statistical characteristics for the data set presented in Figure 5 are summarized in Table 3. This information is used as input parameters in the simulation program.

Table 3 Input parameters for data set "dumping time"

Activity	**Mean value**	**Standard deviation**	**Lower/upper bound**	**density function**
Dumping time	21.4 s	3.7 s	16 s/ 31 s	lognorm

Breakdown profiles

Breakdown profiles are created by analysis of breakdown data. Significant interruptions of loader activity are recorded in own measurements[8] which are presented in Table 4. Although two loading machines are available in the quarry, the data just originates from one single machine, which is exclusively used for ore transport.

Table 4 Loader breakdown records for first case study

Measurement[9]	Loader's breakdown times	Total time of measurement
L100	35 s 64 s 126 s	125,17 min
L120	158 s	64,35 min
L120b	45 s	145,02 min
Total	428 s	334,53 min
MTTR	1,43 min	
Availability	97,9 %	

Breakdown profiles can be created on the basis of two values. The mean-time-to-repair (MTTR) value of 1.43 min is equal to the average of the recorded breakdown times. The loader's availability (97.9 %) is calculated by dividing the sum of breakdown times through the total time of all measurements. Statistical analysis of the recorded data from loader's breakdown times is shown in Figure 6, whereas values are entered in seconds.

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[8] Listed in file: Data collection_ITA, sheet: Evaluation

[9] Single measurements are named after the loading location (L100 = 100m Level)

Figure 7 shows the statistical analysis of crusher's breakdown times, entered in minutes. The values are extracted from recorded downtimes[10] listed for April 2016. The crusher has a mean-time-to-repair value of 39.7 min and an availability value of 95 %.

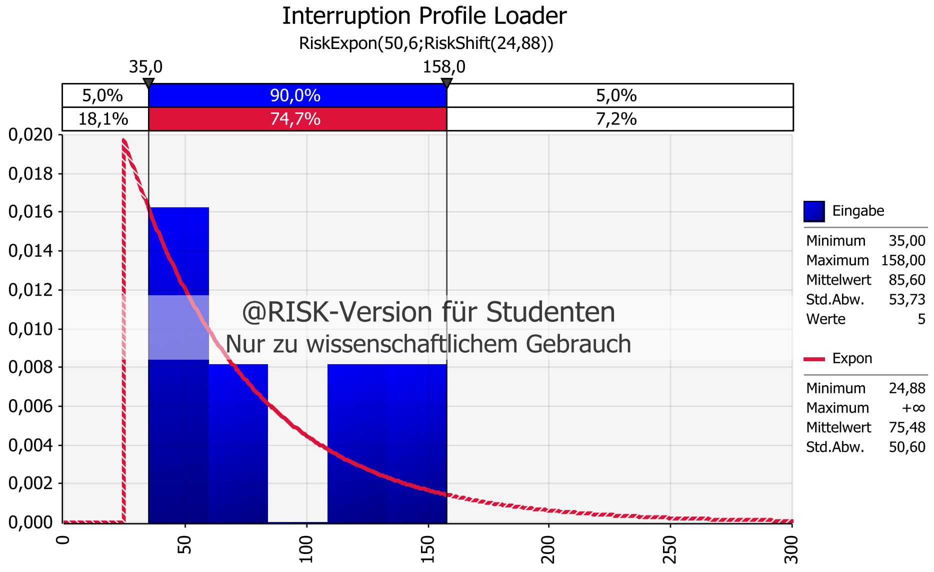

Figure 6 Distribution fitting for breakdown time of loading machine (in seconds)

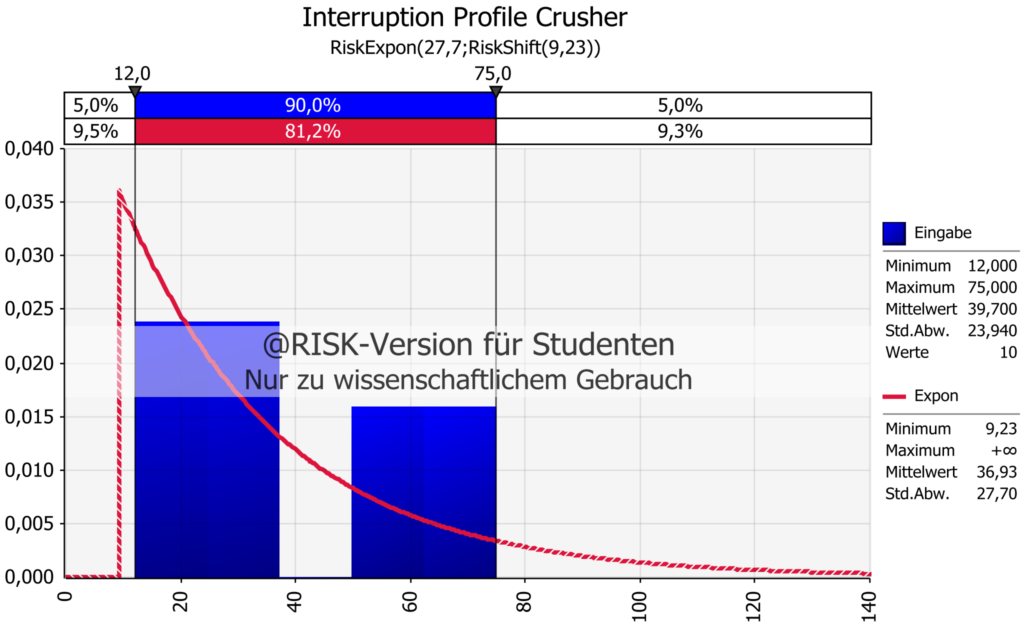

Figure 7 Distribution fitting for breakdown time of pre-crusher (in minutes)

It can be noticed that both histograms have best fitting for exponential distribution. This is typical statistical behavior for Breakdown profiles. (Storm 2007, p. 73)

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[10] Taken from file: Crusher_performance_and_breakdown_data_Castellina

Verification and validation for data preparation

Test procedures can be beneficial to verify performed distribution fitting, especially for data sets consisting of few values. This is often the case for data sets representing maneuvering times on rarely used loading points which cannot be measured extensively.

Rooch (2014) presents the so-called Kolmogorov-Smirnow test in the chapter for statistical tests. It is a so-called non-parametric test, which fits well for simulation because it is valid for every kind of statistical distribution. Moreover, the test can be performed also for small data sets. The tabulated $KS_{\propto,n}$-value, which is dependent on the confidence interval alpha and the sample size n, is compared to the KS_{max}-value, which is calculated from the maximum deviation of data set and corresponding density function. Exemplary, the test is performed for the statistical distributions, presented in Figure 5. The following equation is used as test procedure. The hypothesis for conformity of data set and density function must be rejected if:

$$KS_{max} \geq KS_{\propto,n} \quad (2)$$

(Rooch 2014, pp. 139–143)

Table 5 Performance of Kolmogorow-Smirnow test

Kolmogorow- Smirnow test according to Rooch (2014)	
Confidence interval Sample size	0,01 56
$\mathrm{KS_{max}}$ (normal) $\mathrm{KS_{max}}$(log-normal)	0,1169 0,0918
$\mathrm{KS_{\propto,n}}$	0,2175
Result normal distr. Result log-normal distr.	accepted accepted

Although the KS_{max} value for log-normal distribution is smaller than for normal-distribution in Table 5, the test-result does *not* tell the user to prefer this statistical distribution. It is just stated that both tested statistical distributions must not be *rejected* for distribution fitting.

3.1.4 Model implementation

The realization of the actual simulation model for quarry optimization is built up on preparatory work based on Berner (2015), which is outlined in chapter 2.4. Figure 8 and Figure 9 show the topographical network layer of the simulation model in Plant Simulation which is used for the respective case studies.

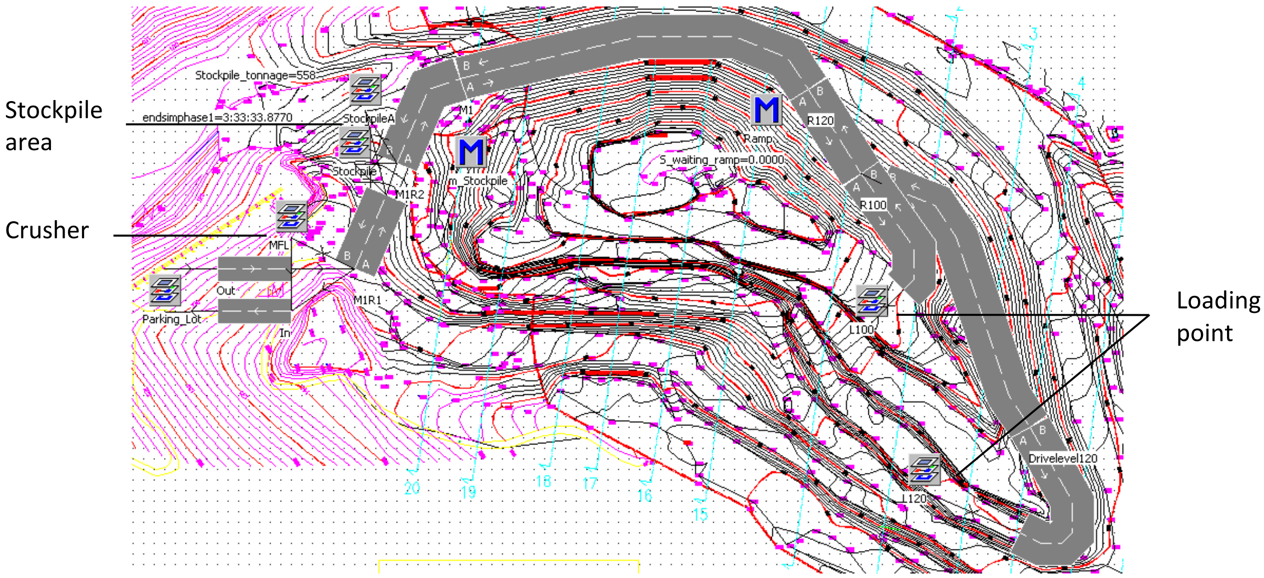

Figure 8 Topographical network layer of simulation model for first case study

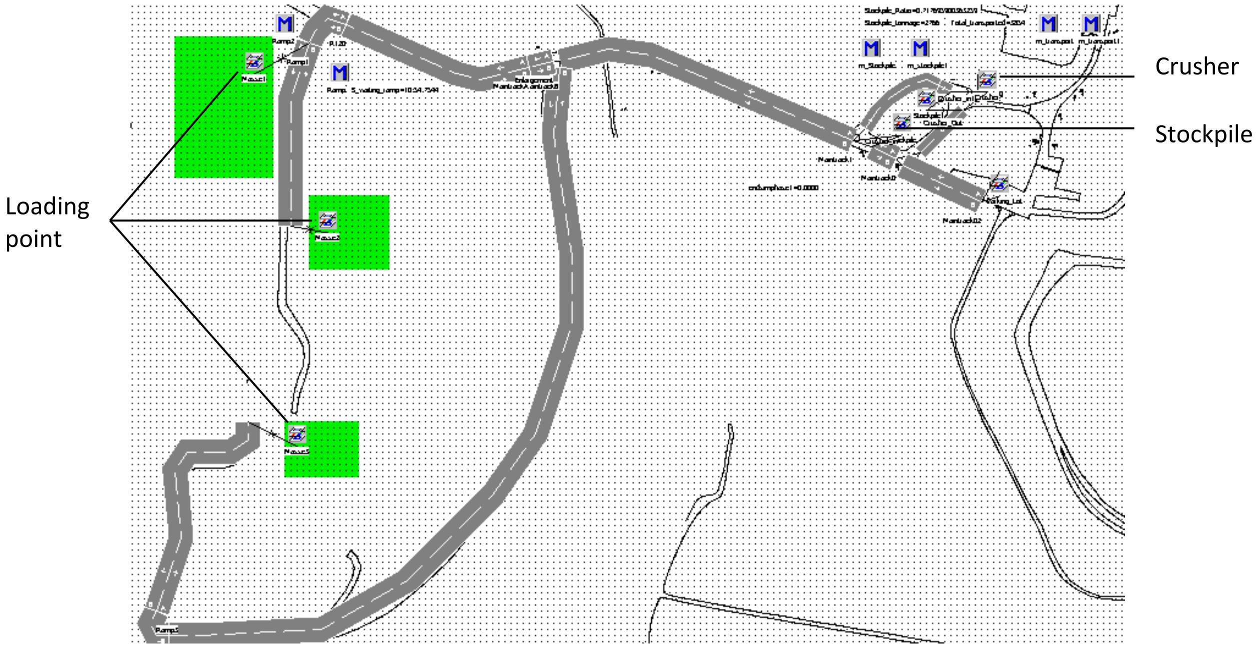

Figure 9 Topographical network layer of simulation model for second case study

Generally, all basic features of the company's quarry operations which are relevant for simulation experiments can be implemented by pre-existing structures. This includes loading points as well as a pre-crushing facility. In Figure 8 and Figure 9 it can be seen that a high visualization degree is achieved by the use of a topographical map used as background. This way of modeling is recommended especially for the typical size of the company's quarry operations because unique structures of the quarry can be easily understood and modeled. Exemplary, it can be noticed from both figures above that a typical main ramp does not exist in any operation so that most driveway connections must be modeled individually.

Furthermore, both examined quarry operations do have a stockpiling facility which is relevant for simulation results. In the first case study it is needed to model a stockpile facility where material can be dumped and loaded again which is realized by two existing networks connected to each other. The dumping feature is created by a crusher network excluding the drain which is situated after the crusher bunker. The stockpiled amount is transferred to a loading point network afterwards.

Verification and validation of executable model

There are a high number of techniques which can be used for verification of an executable model whereas some of the recommended techniques are already implemented in the simulation software. Exemplary, monitoring of processing times and truck behavior is a first measure of correct model implementation. (Compare fig.11 in Rabe et al. 2008, p. 113)

The need of additional objective test procedures can be satisfied by use of the so-called fixed value test. This test procedure uses deterministic input parameters instead of statistical distributions. The simulation outcome is compared to a deterministic spreadsheet calculation based on the same deterministic input parameters. (Rabe et al. 2008, p. 99)

The quarry simulation model is well suited for application of the fixed value test. By setting all statistical distributions to a constant mean value, the network logic as well as all entered equipment parameters and distances can be verified. Figure 10 shows a comparison of a simulation result[11] to a deterministic calculation[12].

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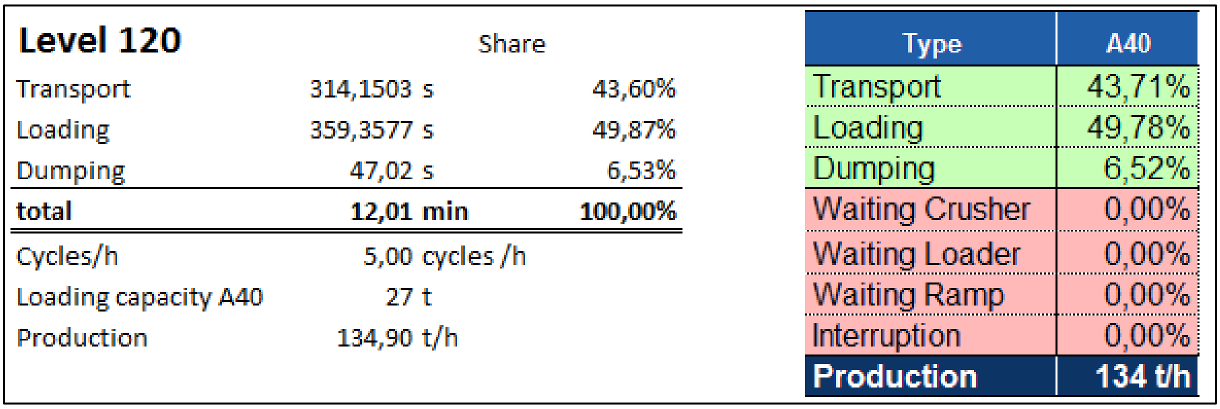
[11] Fixed value test_L120

[12] Taken from file: Data Collection_ITA



Level 120		Share
Transport	314,1503 s	43,60%
Loading	359,3577 s	49,87%
Dumping	47,02 s	6,53%
total	**12,01 min**	**100,00%**
Cycles/h	5,00 cycles /h	
Loading capacity A40	27 t	
Production	134,90 t/h	

Type	A40
Transport	43,71%
Loading	49,78%
Dumping	6,52%
Waiting Crusher	0,00%
Waiting Loader	0,00%
Waiting Ramp	0,00%
Interruption	0,00%
Production	**134 t/h**

Figure 10 Fixed value test applied on loading level in first case study

The deterministic calculation on the left hand side and the simulation outcome on the right hand side in Figure 10 show similar results which can be noticed by comparison of percentage shares and production rate. Small deviations can be accepted in this setup because start and end of simulation might not complete a full hauling cycle. The deterministic comparison should be performed for the easiest possible setup. The case above presents haulage from the 120 m level by usage of one loader and one truck. Typically, there is not included any waiting time in the setup. The following bullet points give hints in order to eliminate system irregularities if larger deviations are noticed by performance of the fixed value test:

- There are exclusively same, mean values used for deterministic calculation and input parameter in the simulation model, including equipment parameters, speeds, process times etc.
- All input parameters are implemented for the specified processes and in the correct way in the simulation model
- All breakdown profiles are deactivated
- Simulation results are recorded in the same way as deterministic calculation

3.1.5 Experiments and analysis

The individual chapters dealing with the first and second case study present how simulation experiments are performed and analyzed in detail. There is a need of a procedure, however, to verify general simulation setup including statistical distributions and breakdown profiles which are developed from data preparation.

Verification and validation of experiments and analysis

A verification method suitable to test behavior of the complete simulation model is called internal validity test. The test procedure is based on multiple replications of the same simulation setup using different starting variables for random number generation, which is a basic feature of a simulation tool. The simulation results give hints about the correct implementation and interaction of statistical parameters. (Rabe et al. 2008, p. 105)

A test procedure is introduced which compares the behavior of the individual simulation model to field measurements in the quarry which have been performed during data collection. Therefore, the setup and duration of the measurement is reconstructed which includes the transported tonnage and the used equipment. Figure 11 shows the comparison between a measured run of the second case study[13] and the setup data for the simulation model. It can be seen that 480 t of material have been transported during the measurement in a total time[14] of 2.04 h by the use of one dump truck filled on the first level by one excavator. This work comprises 15 full cycles of the dump truck whereas seven truckloads are dumped in the crusher but eight truckloads must be stored on the available stockpile. The average cycle time comprises 8.16 min. In the simulation model, the total production of the measurement is reconstructed. The measurement is compared to average values resulting from ten simulation runs in Table 6.

Table 6 Comparison of measurement to simulation runs for internal validity test

	Transport	Loading	Dumping	Waiting	Through put (t/h)	Stock (t)	Dumps on stock	Dumps in crusher	Crusher (t/h)
Simulation average (10 sim runs)	46,99%	38,30%	8,05%	6,65%	237,05	246	7,7	7,3	102,51
Measurement	44,51%	38,13%	8,22%	9,14%	235,20	256	8	7	104,83

It can be noticed that the majority of parameters in Table 6 is reproduced accurately. However, there are some significant deviations. Waiting time is significantly reduced in the simulation runs while the share of transport time is increased. One explanation is the breakdown profile of the loading machine, which is entered with an availability rate of

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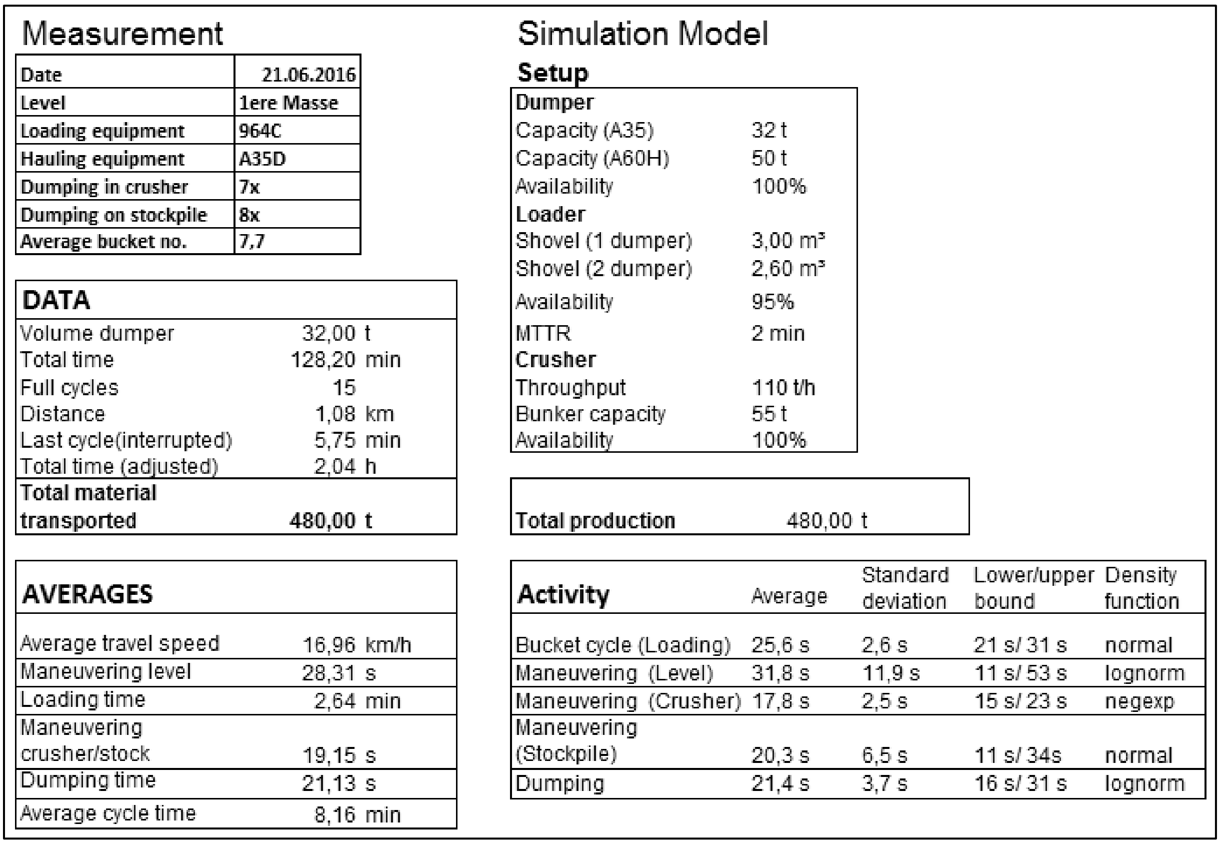
[13] Measurement taken from file: Data collection_FRA, sheet: 1ereMasse(1)

[14] Total time of the measurement is adjusted by the duration of the last cycle which has not been completed

95 %[15] in the simulation model. This leads to an average waiting time of 3.78 %. However, there has been recorded a waiting time of 6.16 % at the loader during the measurement.



Measurement

Date	21.06.2016
Level	1ere Masse
Loading equipment	964C
Hauling equipment	A35D
Dumping in crusher	7x
Dumping on stockpile	8x
Average bucket no.	7,7

DATA		
Volume dumper	32,00	t
Total time	128,20	min
Full cycles	15	
Distance	1,08	km
Last cycle(interrupted)	5,75	min
Total time (adjusted)	2,04	h
Total material transported	**480,00**	**t**

AVERAGES		
Average travel speed	16,96	km/h
Maneuvering level	28,31	s
Loading time	2,64	min
Maneuvering crusher/stock	19,15	s
Dumping time	21,13	s
Average cycle time	8,16	min

Simulation Model

Setup

Dumper	
Capacity (A35)	32 t
Capacity (A60H)	50 t
Availability	100%
Loader	
Shovel (1 dumper)	3,00 m³
Shovel (2 dumper)	2,60 m³
Availability	95%
MTTR	2 min
Crusher	
Throughput	110 t/h
Bunker capacity	55 t
Availability	100%

Total production	480,00 t

Activity	Average	Standard deviation	Lower/upper bound	Density function
Bucket cycle (Loading)	25,6 s	2,6 s	21 s/ 31 s	normal
Maneuvering (Level)	31,8 s	11,9 s	11 s/ 53 s	lognorm
Maneuvering (Crusher)	17,8 s	2,5 s	15 s/ 23 s	negexp
Maneuvering (Stockpile)	20,3 s	6,5 s	11 s/ 34s	normal
Dumping	21,4 s	3,7 s	16 s/ 31 s	lognorm

Figure 11 Comparison of measurement data for internal validity test

The average throughput of the dump truck is slightly increased in the simulation which can be partly explained by reduced overall waiting times. Loading and dumping times are represented very precisely by the simulation model. This is the case if averages of statistical input parameters are similar to the average recorded data. If these values deviate strongly, there can be accepted some differences for the simulation result. It is important, however, to check if under-/overestimation is in a reasonable range.

The dumping behavior at the stockpile mostly matches the recorded data. Seven of ten simulation runs lead to eight dumps on the stockpile while three simulation runs account for seven dumps on the stockpile. This simulation behavior is not problematic and shows that decision-making at the crusher area and crusher throughput are well defined. Important information is also received for crusher performance which is an important parameter in

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[15] Taken from file: Data collection_FRA, sheet: Evaluation

simulation. The presented verification procedure shows that the chosen crusher throughput of 110 t/h leads to an effective throughput of 102.5 t/h.

A graphical interpretation of test results for the internal validity test[16] is presented the diagrams numbered from Figure 12 until Figure 15[17], which is performed to validate the simulation model for the second case study. The graphical solution bears significant advantages compared to the simple tabulation of results shown in Table 6. Whereas the measurement value is represented by a dot on the y-axis[18], the single results from ten simulation runs are successively pictured. An upper and lower bound are included for visualization of minimum and maximum simulation outcome. The advantage of successive presentation of simulation results is the comparability of single runs, which bears valuable information about the behavior of the simulation model.

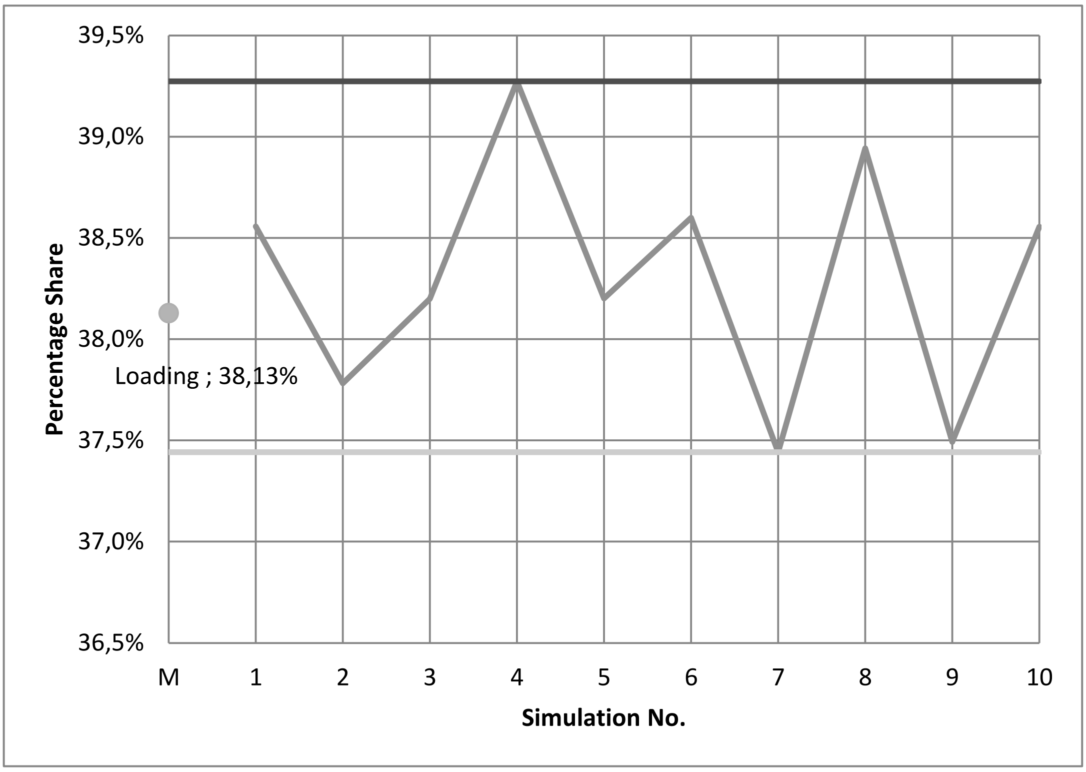

Figure 12 Graphical comparison of loading share by internal validity test

By comparing the measurement values to simulation outcomes, the well-fitting behavior of loading time can be approved in Figure 12. It is noticeable that the spread of loading share is

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[16] Internal validity protocol_1.Masse

[17] In the test procedure files, all graphs are created in one diagram. The graphics is split manually in the thesis for better visualization.

[18] X-axis value shows M for measurement

ranging in a difference of less than two percent, which corresponds to the small spread of bucket cycle time entered as input parameter. Different from the well-fitting behavior of loading time, the measured transport time is not represented by any realization of the model, which is presented in Figure 13. Although the difference to minimum realization value is less than 1.5 percent, it can be questioned if the transport speed is chosen too slow and/or the haulage way is estimated too high.

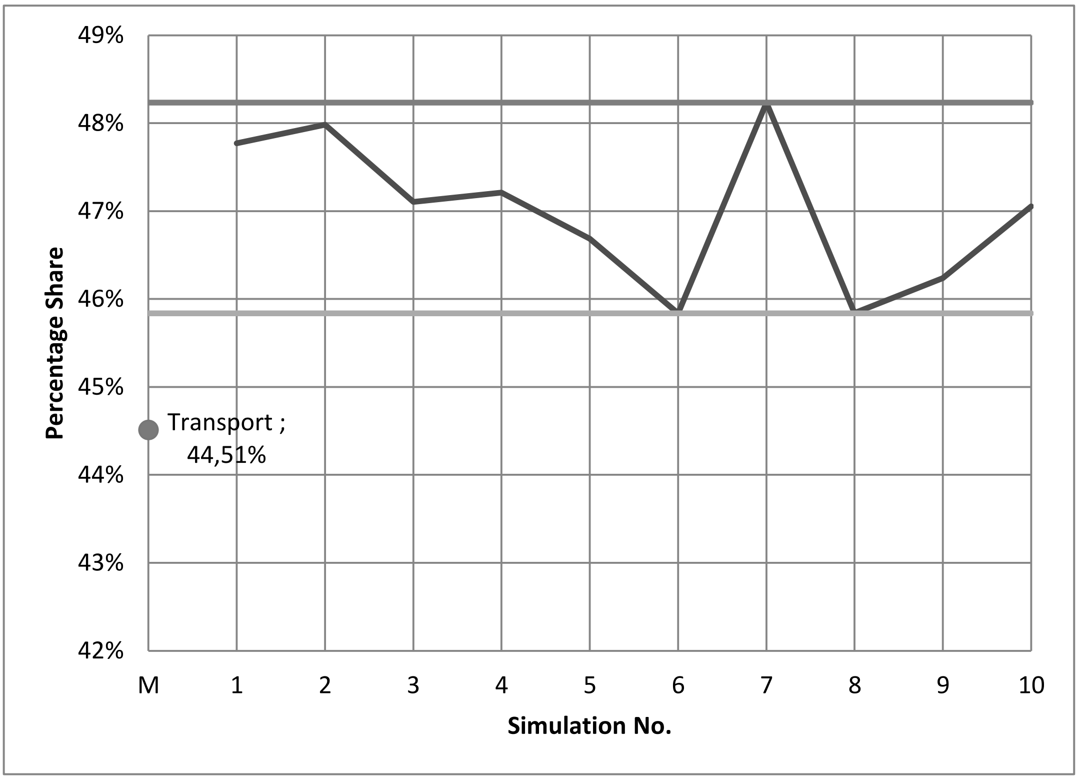


Figure 13 Graphical comparison of transport share by internal validity test

The dumping behavior of the simulation model presented in Figure 14 fits very well to the measurement. It can also be noticed that the spread of dumping time is the largest among all values. This can be explained by two differing dumping scenarios which is realized in the model by assigning different statistical distributions for dumping in the crusher and on the stockpile. The graphics representing waiting time in Figure 15 approves the mismatch of measurement and simulation model concerning the breakdown profile of the loader. There is a continuous underestimation of waiting time noticeable combined with a low spread of simulation results.

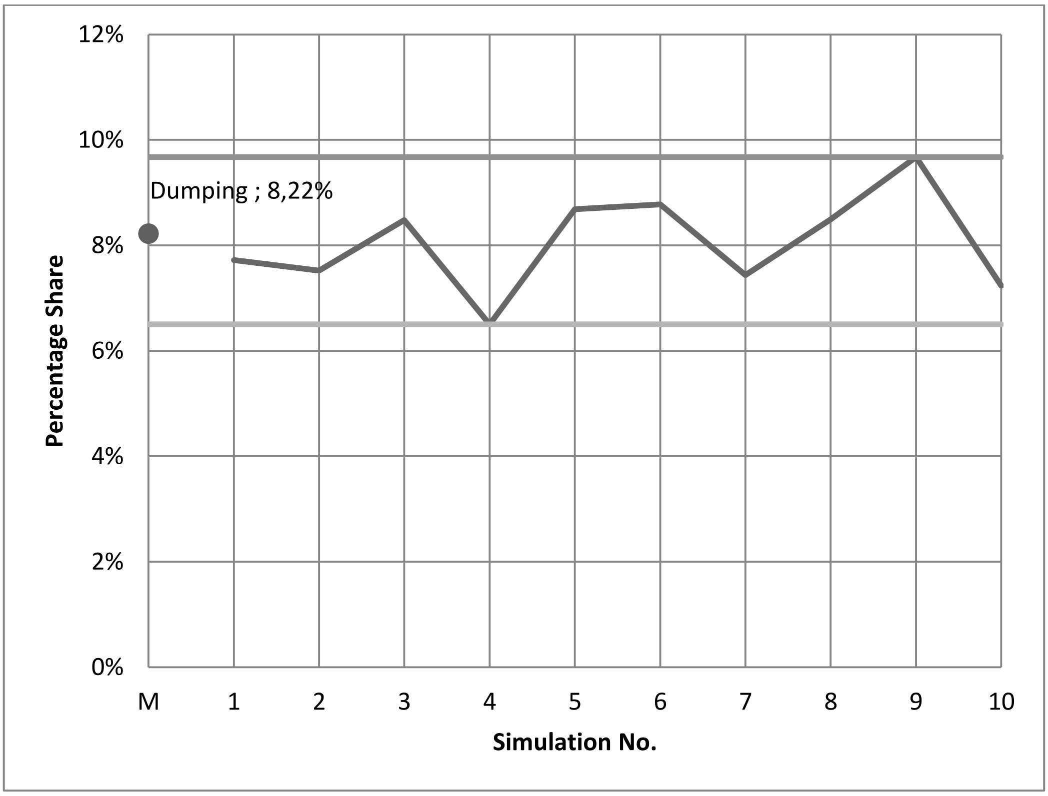


Figure 14 Graphical comparison of dumping share by internal validity test

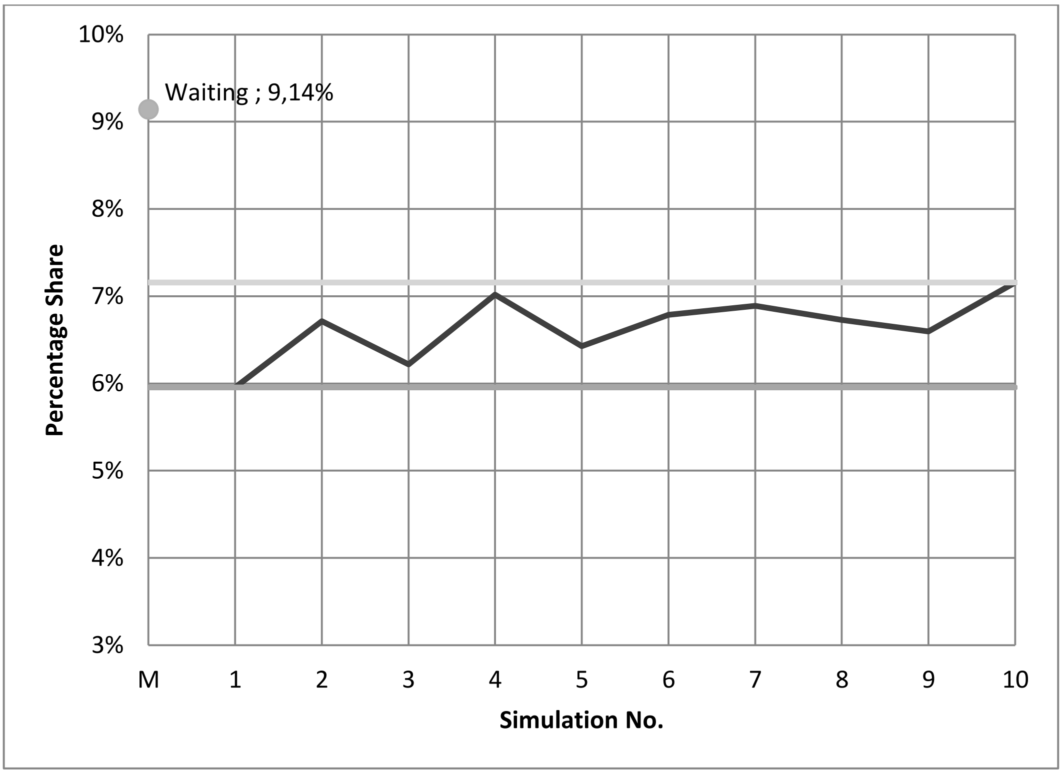
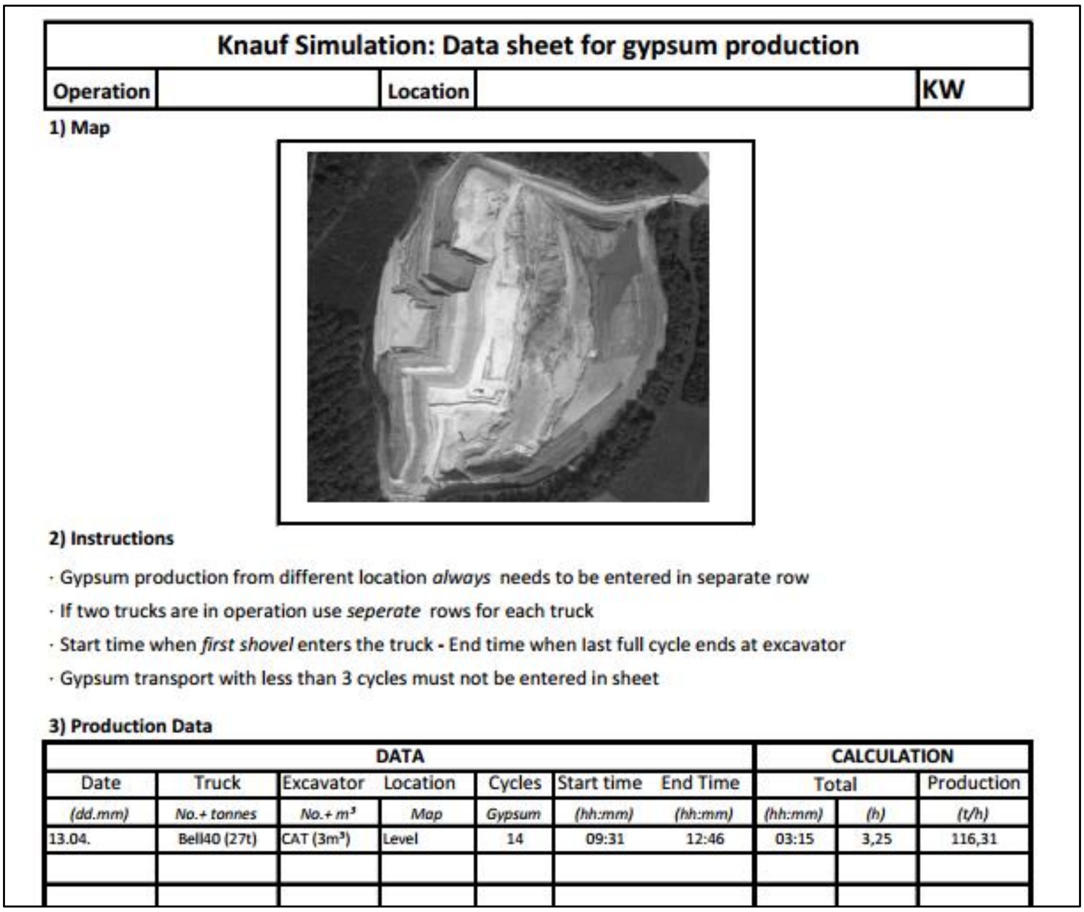


Figure 15 Graphical comparison of waiting share by internal validity test

As additional template for data collection, there is attached a sheet which can be filled manually by the quarry staff[19]. The sheet is standardized for a truck and shovel operation in quarry mines. One possible application is the acknowledgement of the transport performance of a changed loading location if equipment specifications including statistical distributions are already known. Start time and end time must be entered thoroughly for the corresponding number of completed cycles. The loading location is marked on the map which has to be pasted in the top frame. An extract of the template is presented in Figure 16.



Knauf Simulation: Data sheet for gypsum production

Operation		**Location**		**KW**

1) Map

2) Instructions

- · Gypsum production from different location *always* needs to be entered in separate row
- · If two trucks are in operation use *seperate* rows for each truck
- · Start time when *first shovel* enters the truck - End time when last full cycle ends at excavator
- · Gypsum transport with less than 3 cycles must not be entered in sheet

3) Production Data

DATA							CALCULATION		
Date	Truck	Excavator	Location	Cycles	Start time	End Time	Total		Production
(dd.mm)	*No.+ tonnes*	*No.+ m³*	*Map*	*Gypsum*	*(hh:mm)*	*(hh:mm)*	*(hh:mm)*	*(h)*	*(t/h)*
13.04.	Bell40 (27t)	CAT (3m³)	Level	14	09:31	12:46	03:15	3,25	116,31

Figure 16 Extract from data collection template

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[19] Appendix D- Data sheet for gypsum production

3.2 Case study 1

The quarry operation of the production site in Castellina Marittima, located in the south-west of the Italian province of Pisa, serves as a first case study for the implementation of Plant Simulation. It is a typically sized operation within the company where gypsum is exclusively produced for the production plant. Moreover, demand of the plant for raw material is solely responsible for quarry production numbers, which has resulted in a quarry output between 180.000 t/a and 195.000 t/a for the last three years. In order to meet this amount, between 280.000 m^3/a and 305.000 m^3/a of loose waste had to be removed, which results in a waste-to-ore ratio of 3:2 (m^3: t). Because maximum overburden of the lense-shaped deposit has been reached this year, the w/o-ratio is expected to decrease. Remaining reserves of 5 Mt will result in a remaining lifetime of 27 years[20], assumed that the demand of the plant stays constant.

Quarry operation

The mining equipment which is currently used in the quarry operation is presented in Table 7. There are only major equipment specifications presented, which are important for ore transport.

Table 7 Quarry machinery used in operation of first case study

Type	**Manufacturer**	**In operation since**	**Main use**	**Equipment specs**
352 FLME	Caterpillar	01 2016	Loading of ore/waste	3,2 m^3 Shovel
349 ELME	Caterpillar	04 2015	Loading of waste	3,2 m^3 Shovel
325 DLN	Caterpillar	03 2009	Pre-comminution of ore	Krupp-hammer
A40F	Volvo	01 2004	Hauling of ore/waste	27 t ore/24,0 m^3 waste Capacity
A35F	Volvo	01 2011	Hauling of waste	23 t ore/20,5 m^3 waste Capacity
L220F	Volvo	02 2008	Auxilliary work	5,5 m^3 Shovel
ROC D7-11	Atlas Copco	04 2010	Drilling	Drill-bit 89mm Ø

Ore is mined in the quarry by drilling and blasting activity approximately six times a month. There are currently four levels are in operation which are blasted down using a variable

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[20] Information about current production rate and remaining reserves are taken from BDE_Castellina(June 2016)

drilling grid (one-row/ multiple-row). However, mixed zones often lead to manual sorting of ore and waste in the upper two levels. Thus, boulders of raw material are regularly pre-comminuted to a diameter of <1 m by using a hammer-tool attached to excavator 325 DLN in order to fit the maximum crusher feed. All loading and hauling equipment is used for waste transport (except of wheel loader L220), whereas excavator 352 FLME and dump truck A 40 F are mostly used for loading and hauling of ore. It is noticeable that all work in the quarry is currently completed by own staff.

3.2.1 Problem outline

The evaluation of possible objectives for optimization of ore transport has shown that the possibility of stockpiling is worth to be examined by simulation in this quarry operation. Figure 17 shows the pit location where stockpiling is planned. A plain area of approximately 40 m length and 8 m width is provided next to the main haul road. The distance from the stockpile area to the crusher is approximately 100 m, whereas 30 m are leveled and 70 m include a 7 percent gradient from the beginning of the ramp to the closer end of stockpile area.

Figure 17 Location of possible stockpiling (own picture)

The benefit of stockpiling is examined by comparison to conventional ore transport on the basis of daily operational costs. The scenario for which stockpiling is applied includes the additional use of the quarry's wheel loader which needs to empty the stockpile after completed ore transport by dump trucks. On the other hand, conventional ore transport needs to take into account long waiting times because the crusher's performance does not allow permanent dumping. Long-term effects of stockpiling like realization of buffer capacities in case of equipment breakdown and pre-sorting of qualities are explicitly not examined.

3.2.2 Simulation setup

The equipment's input parameters which are received by methods described in the simulation procedure are presented in Table 8. Relevant for simulation are capacity and availability parameters of dump trucks, loading machine, wheel loader and the pre-crushing facility.

Table 8 Equipment input parameters for first case study

Dump truck	
Capacity (A35)	23 t
Capacity (A40)	27 t
Availability	100 %
Loader	
Shovel	2,00 m³
Availability	98 %
MTTR	2 min
Wheel loader	
Capacity	6 t
Availability	100 %
Crusher	
Throughput[21]	129 t/h
Bunker capacity	40 t
Availability	95 %
MTTR	40 min

The capacities of both dump trucks are taken from data received by the quarry staff[22]. The availability rate for the dump trucks is set to 100 % on purpose, because all possible delays of the dump truck are recorded as waiting times in the simulation runs and are important outcomes of the simulation experiments. The shovel capacity is calculated on the basis of recorded bucket numbers per loading event. The corresponding histogram resulting from

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[21] Further outline in sensitivity analysis (P.45f)

[22] Taken from file: Data Collection_ITA, sheet: A40, A35

measured data is shown in Figure 18. There is a clear peak noticeable of ten bucket numbers per loading event. Ore production is exclusively recorded for the bigger A40 dump truck[23], which results in a calculated shovel size of 2.00 m³. The calculation of availability and MTTR data of the loader and the crusher are already presented in the data preparation chapter, where breakdown profiles are shown in Figure 6 and Figure 7. The wheel loader acts as a dump truck in this case study by hauling stockpiled material to the crusher. The machine has a payload of 6 t per hauling cycle by load and carry operation. The crusher throughput is most sensitive in this case study and is subject to large fluctuation. However, there is used an average throughput for the base case experiment whereas the input parameter of 129 t/h is an experimental value for receiving a net crusher output of 118 t/h. The crusher throughput will be addressed again in the sensitivity analysis of case study one, where detailed information can be found. The maximum bunker capacity of 40 t is set by the dumping procedure which allows additional dumping when the filling of the crusher bunker is reduced to about one half of the A40 dump truck's payload.

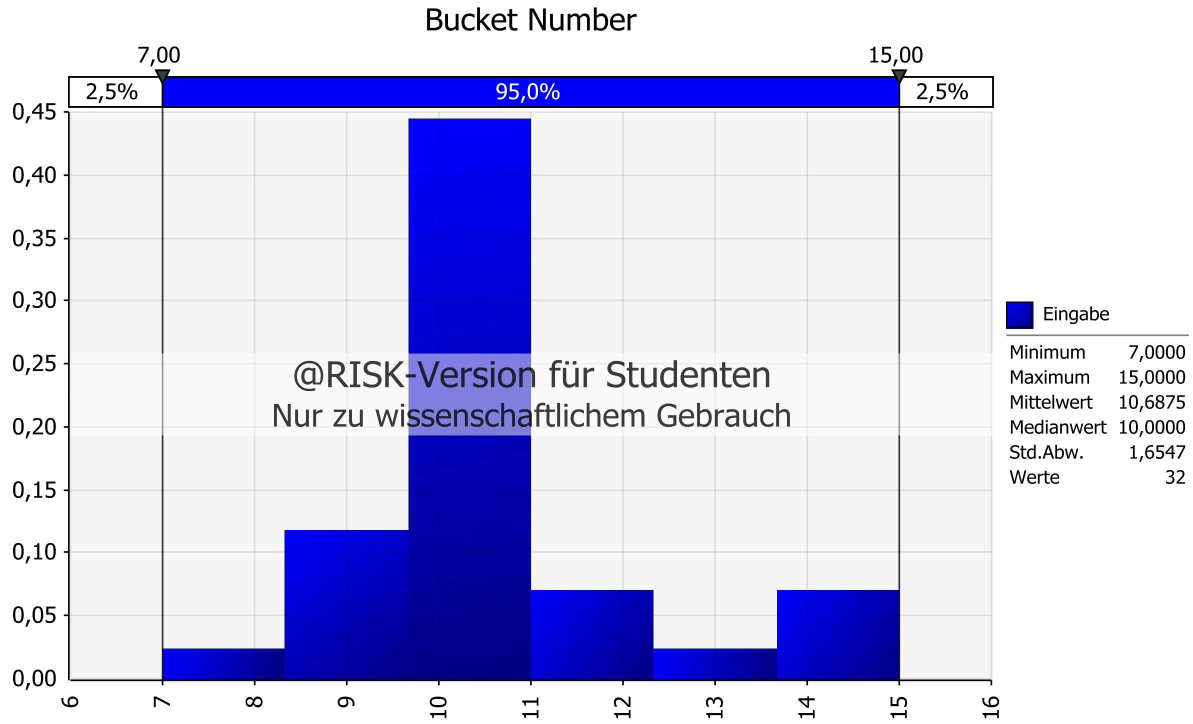

Figure 18 Histogram of recorded bucket numbers per loading event[24]

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[23] Within the time span of measurement, ore transport was completed by A40 dump truck exclusively.

[24] Figure taken from file: Data collection_ITA, sheet: Evaluation

Table 9 presents all relevant statistical distributions for the equipment used in the first case study. The bucket cycle time is represented by one distribution which is relevant for loading time for dump trucks. Maneuvering times applied for the dump truck are separated by location. Exemplary, maneuvering on level 100 is significantly differs from maneuvering on level 120. Level 100 represents the lowest pit level where different maneuvering actions are performed which is shown by a large spread of data. Maneuvering on level 120 generally takes longer but shows less deviation because a standard procedure is performed.

The wheel loader acts as dumping vehicle for emptying the stockpile. Therefore, there need to be assigned maneuvering and dumping times[25]. The process of loading is skipped because of the wheel loader's ability of load and carry operation. Moreover, the maneuvering time at the stockpile represents the complete loading behavior. Time is measured from leaving the main track until the machine starts haulage activity in direction of the crusher. Maneuvering time and dumping time at the crusher are significantly shorter for the wheel loader than those for the dump truck because of its higher agility.

Table 9 Statistical distributions for first case study

Activity/Equipment	**Mean value**	**Standard deviation**	**Lower/upper bound**	**density function**
Excavator				
Bucket cycle (Loading)	27.5 s	4.5 s	20 s/ 41 s	lognorm
Dump truck				
Maneuvering (Crusher)	24.8 s	4.6 s	15s/ 37 s	lognorm
Maneuvering (Level 100)	52.8 s	14.7 s	29 s/ 81 s	normal
Maneuvering (Level 120)	84.1 s	9.4 s	64 s/ 99 s	normal
Dumping	22.2 s	4.1 s	15 s/ 33 s	lognorm
Wheel loader				
Maneuvering (Stockpile)	12.7 s	4.9 s	7 s/23 s	lognorm
Maneuvering (Crusher)	16 s	4.4 s	10 s/26 s	lognorm
Dumping	4 s	-	-	konstant

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[25] Taken from Data Collection_ITA , L220 Stockpile

3.2.3 Simulation results

Within the evaluation of the first case study it is aimed to find the cheapest possible transportation setup by comparing the scenarios of an activated and deactivated stockpile in combination with varying equipment. Optimal comparison is created by recording operation times of every machine given a constant daily production[26].

In order to calculate the key performance indicator (KPI) of total daily costs, it is crucial to determine operational costs (€/h) of every machinery used in the experiment. Capital costs are not included in this calculation on purpose. Incorporating a rate of hourly spent capital costs on equipment would lead to more vague results because total running hours of machinery as well as its net operating time for ore transport are based on estimates. Table 10 shows hourly operational costs for the quarry equipment.

Table 10 Operational costs for quarry equipment in first case study

Equipment	OPEX
A40	54,56 €/h
A35	58,83 €/h
L220	55,04 €/h
CAT352	72,20 €/h
CAT349	77,30 €/h

For the calculation of operational costs (OPEX) in Table 10 there are included the equipment's average fuel consumption[27] , maintenance and repair costs[28] as well as labor costs[29]. Individual results are further discussed in this order:

- 1st scenario: activated stockpile
- 2nd scenario deactivated stockpile
- Sensitivity analysis

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[26] Average daily production ≈ 1000 t, reduced to 999 t because 1 t left for last cycle if 27 t truck in use

[27] Average value, created from monthly consumption of available data, max 2014 -2016

[28] Taken from repair/maintenance costs 2015 for available data, excavators : interpolated 2016 maintenance and repair costs

[29] Standardized value taken from former company's cost calculation

1st scenario: activated stockpile

Table 11 shows a result of one single simulation run, given the following setup:

- one excavator used for loading
- one dump truck used for transport
- stockpile is emptied-out by wheel loader afterwards

Table 11 Simulation result for activated stockpile

Equipment	Operation time	h		€/h	Total	
A40	05:57:06	5,95		54,56	324,72	€
A35	00:00:00	0,00		58,83	0,00	€
L220	02:10:36	2,18		55,04	119,80	€
CAT352	05:54:41	5,91		72,20	426,80	€
CAT349	00:00:00	0,00		77,30	0,00	€
total		**14,04**	**h**		**871,33**	€

By comparing operation times of equipment in Table 11 it can be noticed that running times for the used dump truck and loader only differ slightly. This is logical because the loader's operation time is recorded right after finishing its last loading activity, whereas the dump truck's operation time ends after dumping this material either into the crusher bunker or on the stockpile.

The end of dump truck activity automatically activates the wheel loader, provided that any material has been dumped at the stockpile area. Finally, the wheel loader's operating time is recorded after the stockpile has been completely emptied by the machine. Total daily costs are received by multiplication of hourly operational costs and the recorded operation time. For the given setup, the first result indicates an approximate total work effort of 14 operating hours accounting for 871 € of total operating costs.

Costs resulting from one simulation run, however, do only have limited validity if random variables are used as input parameters. In order to get a clear overview about the spread of results in the simulation setup of scenario one, simulation must be performed several times by the use of different input random variables. Simulation results are then statistically analyzed with the help of confidence intervals (Eley 2012, p. 29)

For further analysis, 30 simulation runs are performed using the same setup which is described above[30]. Analysis of simulation runs is shown in Figure 19, where the corresponding histogram including a 99 % confidence interval is depicted.

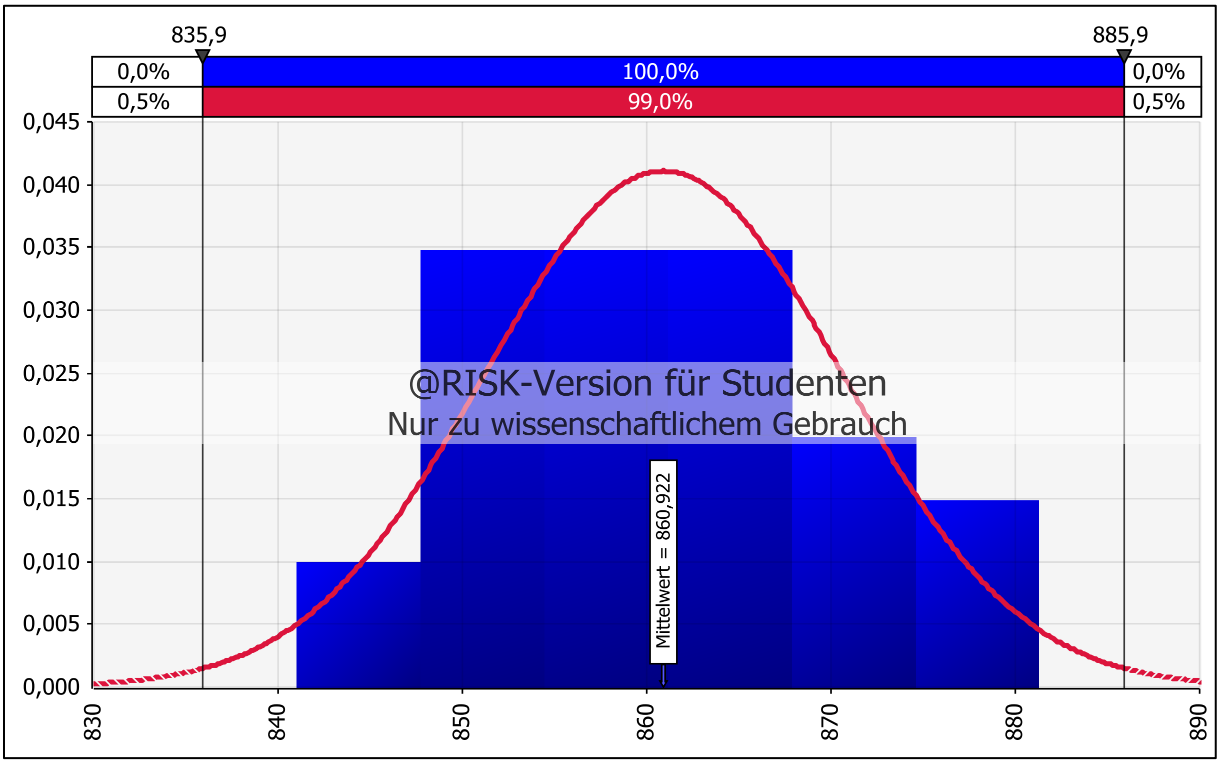

Figure 19 Histogram and 99%-confidence interval of first simulation setup

The analysis reveals expected costs of 861 € including a standard deviation of 9.7. Further, it can be stated that a result of a random simulation run stays in 99 % of the cases in the interval between 835.9 € and 885.9 €.

More importantly, it can be stated that in 99 % of the cases one single simulation result has a deviation smaller than 25 € to the expected average costs. This value can be calculated by multiplying the standard deviation by 2.58, following the formula:

$$P(\mu - 2.58 * \sigma \leq X \leq \mu + 2.58) = 0.99 \quad (3)$$

$\mu = \text{expectation (average) value}$

$\sigma = \text{standard deviation}$

(Erbrecht 2005)

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[30] Taken from file: Simulation_stockpile experiment_complete results, activated stockpile

Addition of a second dump truck

Table 12 shows a single simulation result when adding a second truck to the system. The comparison to ore transport with one truck in use reveals the following results:

- Loading and hauling is completed faster than in the first setup (<3.5 h).
- Stockpile is filled with much larger amount compared to one-truck hauling because stockpile is more frequently used due to limited crusher performance.
- Wheel loader's operating time is increased because of a bigger stockpile tonnage (>4.5h).
- Additional waiting times at the quarry's ramp and at the loading point are recognized.
- Because the calculated costs deviate less than 25 € from expected operational costs of one-truck hauling, there cannot be made any statement yet which setup should be preferred.

Table 12 Simulation result for two dumpers, one loader and activated stockpile

Equipment	Operation time	h	€/h	Total
A40	03:26:49	3,45	54,56	188,07 €
A35	03:12:43	3,21	58,83	188,96 €
L220	04:38:18	4,64	55,04	255,29 €
CAT352	03:24:14	3,40	72,2	245,76 €
CAT349	00:00:00	0,00	77,3	0,00 €
total		**14,70 h**		**878,08 €**

After performance of additional 10 simulation runs[31] average expected costs of two-truck hauling amount to 880.3 € with a total average work effort of 14.7 h. As conclusion, one-truck hauling is the preferred method for stockpile use. However, the difference only amounts 20 € per day on average. One advantage of two-truck hauling is faster completion of ore transport to the crusher/stockpile (3.5 h instead of 6 h). A direct comparison of scenarios is provided in the executive summary in the end of the chapter, where the most important findings within the performed case studies are summarized.

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[31] Taken from file: Simulation_stockpile experiment_complete results, activated stockpile (two trucks)

Truck allocation

The general setup for the scenario of an activated stockpile (1st scenario) is based on the decision-making at which point of time material is dumped on the stockpile. The experiments presented so far are based on the filling level of the crusher bunker. More specifically, the simulation model is programmed to check filling for every loading cycle if material can be dumped into the crusher bunker without additional waiting time. Exceeding this limit automatically causes dumping on stockpile. The decision-making process of the truck allocation method is clarified in a flowchart, presented in Figure 20.

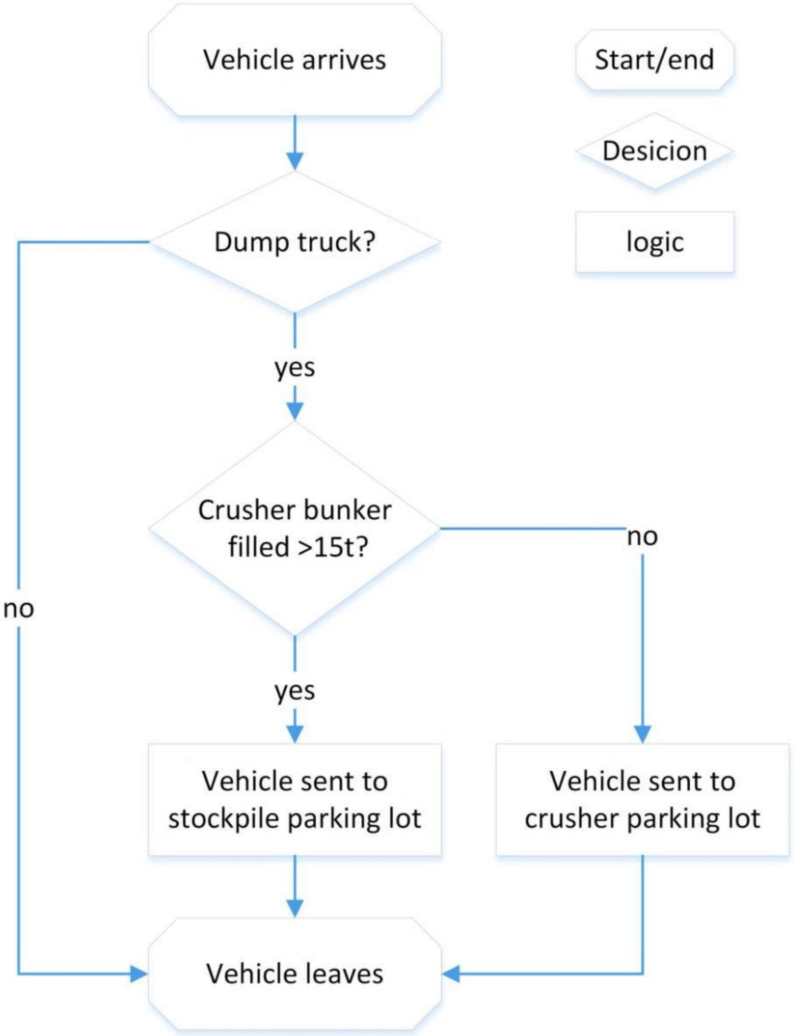

Figure 20 Decision-making process for stockpiling

This decision of truck allocation must necessarily be implemented in the quarry operation. Exemplary, an existing camera system in the quarry can be reactivated, transmitting the crusher bunker on screen into the dump truck. As an alternative, light signals are an effective method for transmitting the filling level of the crusher bunker. By installment of the information system, the distance of 100 m between the crusher and stockpile area must be considered.

Table 13 shows a simulation result by using the same setup presented above, only differentiating by the system of truck allocation. Instead of depending on the bunker filling level, both trucks are assigned to fix destinations, whereas the bigger truck (A40) is assigned to the stockpile, and the smaller truck (A35) is assigned to the crusher.

Table 13 Simulation result for fixed allocation of dump truck

Equipment	Operation time	h		€/h	Total	
A40	03:33:11	3,55		54,56	193,85	€
A35	03:39:53	3,66		58,83	215,60	€
L220	04:28:56	4,48		55,04	246,70	€
CAT352	03:35:42	3,60		72,2	259,56	€
CAT349	00:00:00	0,00		77,3	0,00	€
total		**15,30**	**h**		**915,71**	€

It can be noticed that total operation time and operational costs increase significantly. This is because non-optimal allocation causes additional waiting times. Allocating both trucks the other way around leads to even increased time and cost effort. As a conclusion, optimal use of stockpiling can only be achieved by a reliable truck-allocation system.

2nd scenario: deactivated stockpile

The scenario of deactivated stockpile depicts the situation how ore transport is currently performed. The following equipment is used to receive the simulation result in Table 14

- One dump truck for ore transport
- One excavator for loading of ore

Table 14 Simulation result for deactivated stockpile and one dump truck

Equipment	Operation time	h		€/h	Total	
A40	08:05:07	8,09		54,56	441,13	€
A35	00:00:00	0,00		58,83	0,00	€
L220	00:00:00	0,00		55,04	0,00	€
CAT352	08:00:19	8,01		72,2	577,98	€
CAT349	00:00:00	0,00		77,3	0,00	€
total		**16,09**	**h**		**1019,11**	€

It can be noticed from Table 14 that the total operation time as well as total operating costs are significantly higher compared to the scenario with activated stockpile. For clarification of spread of results, 30 simulation runs of the same setup have been performed by the use of different random variables[32]:

- Expected value: 1010.54 €
- Standard deviation: 10.6
- 99 %-confidence interval : [983 € ≤ X ≤ 1038 €]

In Table 14, it can be seen that loading and dumping vehicle are operated for over 8 hours. This is significantly longer compared to the activated stockpile scenario, where both vehicles are approximately 6 hours in use. The difference can be explained by waiting times which do occur at the crusher. Waiting time for dumping accounts for 25.8 % of the loader's total operating time in the corresponding simulation run[33]. This type of waiting time is completely prevented by stockpiling. Moreover, the loader's waiting time accounts for 65.5 % of total loader's operating time when no stockpile is used. In comparison, active stockpiling reduces waiting times of the loader to 53.3 %[34]. Concluding, stockpiling reduces waiting times significantly so that the additional use of a wheel loader is completely compensated. Direct comparison of scenarios is presented in the executive summary at the end of the third chapter.

Sensitivity analysis

All results which are examined above are obtained by a crusher throughput of 118.8 t/h, which is the median throughput of quarry production in April 2016[35], shown in Figure 21. The presented production rate is calculated by division of transported tonnage and running time of crusher recorded twice a day for the whole month in April 2016. Own measurements underline this fluctuating throughput of the crushing machine[36] which is highly dependent on the comminution grade of ore after blasting is performed.

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[32] Taken from file: Simulation_Stockpile experiment_complete results, stockpile deactivated
[33] Taken from file: Simulation_Stockpile experiment_complete results; sheet: deact(1dump) sim1
[34] Taken from file: Simulation_Stockpile experiment_complete results; sheet: active1.Cr.(1dump) sim1
[35] File: Crusher_performance_and_breakdown_data_evaluation
[36] File: Data Collection_ITA, Production numbers in measurements

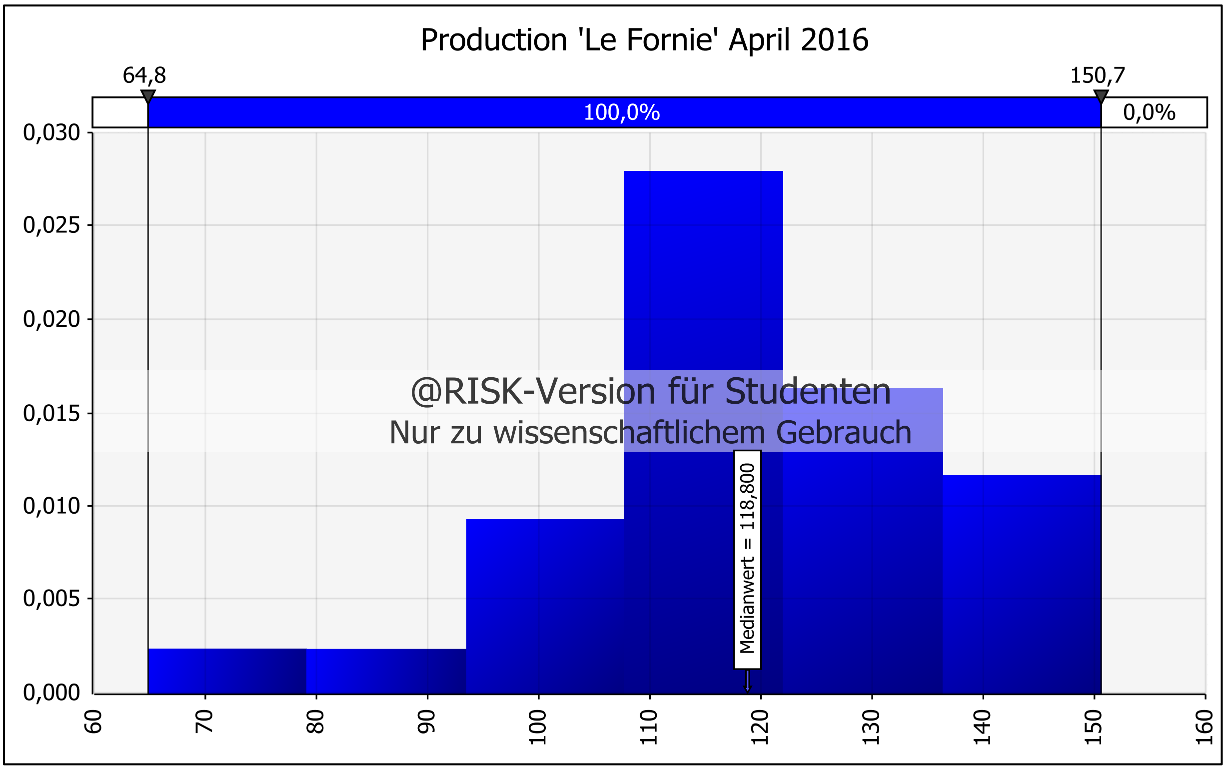

Figure 21 Production rates of quarry operation in tons per hour in April

Crusher throughput

Because of its high fluctuation, it is reasonable to conduct a sensitivity analysis on the basis of crusher throughput. Only the cheapest options are considered for both scenarios, consisting of one loader and one dumper for the deactivated stockpile. For the scenario of an activated stockpile, the wheel loader performance is added. Figure 22 shows the graphs for different crusher throughputs reaching from 90 t/h to 160 t/h. However, these values are input parameters for the crusher and need to be deducted by approximately 10 % to receive net total throughput. Exemplary, the crusher throughput of 140 t/h has resulted in a net throughput of 126.8 t/h.

The graph in Figure 22 Sensitivity analysis for crusher throughput shows that the scenario of an activated stockpile always leads to lower total costs compared to a deactivated stockpile. However, the difference shrinks for higher crusher throughput. Both scenarios benefit from a higher crusher throughput because more material can be dumped into the crusher, resulting in reduced operation time. The advantage of the stockpile becomes less evident the more material can be dumped directly into the crusher because waiting time is less compensated by the stockpile.

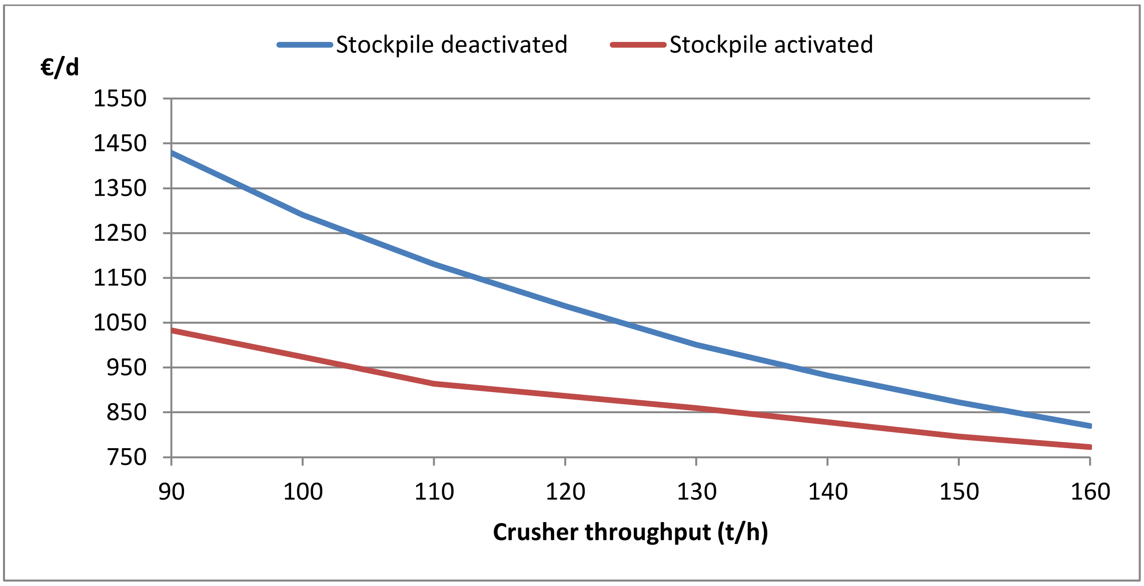

Figure 22 Sensitivity analysis for crusher throughput in first case study

Dumper size

Because it is considered to replace one dumper in the quarry operation in the near future, a sensitivity analysis for different haulage capacity of dump trucks is performed which is presented in Figure 23. For this analysis, crusher throughput is set back to average.

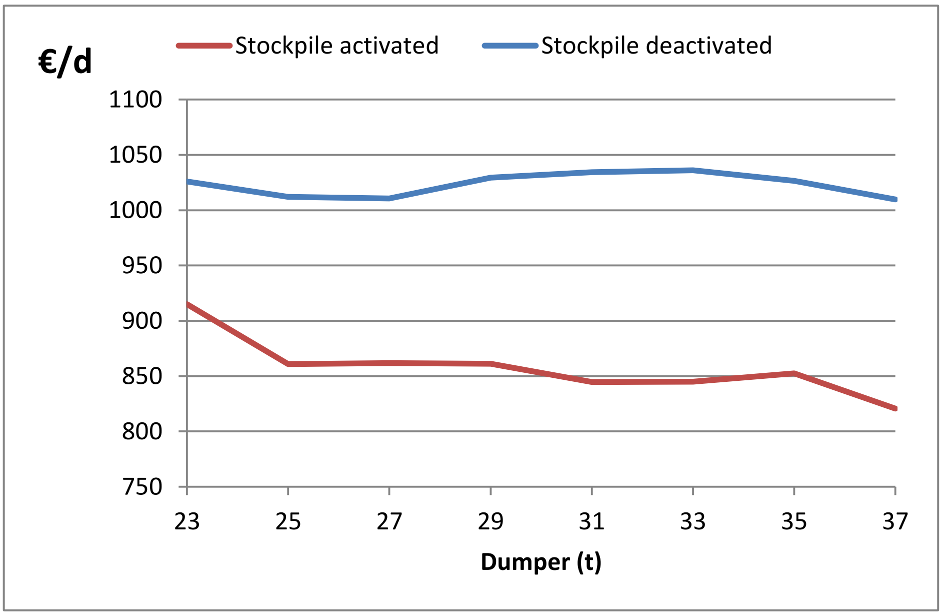

Figure 23 Sensitivity analysis for truck size

It can be noticed that an increased dumper capacity does not create additional value at all for deactivated stockpiling. The possibility of stockpiling makes a higher payload slightly more attractive because additional waiting times at the crusher induced by a larger capacity can be absorbed by the use of stockpiling.

Generally, the simulation setup does not deliver results of adequate accuracy so that no clear answer can be made which dumper capacity is most economical. In this simulation experiment, the key performance indicator (KPI) which was taken over by the base case experiment leads to biased results. The general examination of stockpile use has compared daily transportation costs on the basis of constant daily production. By varying dumper capacity, constant transported tonnage leads to a different number of haulage cycles which does not fall linear to the increased size of the dump truck because of varying remaining material in the last hauling cycle. This behavior can be prevented by a KPI representing transported tonnage per hour. The simulation time should be increased which leads to a minimization of influence of remaining material in the end of simulation. This finding is acknowledged without adjusting the KPI’s of this case study to this one particular experiment.

3.3 Case study 2

The second examined quarry operation belongs to the production plant ‘Knauf Platres’ in St.Soupplets, which is situated in France in the north-west of the greater Paris area. The plant has a yearly planned output of 395,000 t/a gypsum, which is roughly twice as much production as in case study one. In combination with an internal recycling rate of 5 %, the quarry is the only supplier of raw material for the production plant. Raw material is extracted from a flat, layered deposit which is divided in three ore zones containing a total ore thickness of 19.9 m. The ore zones are covered with an overburden layer of approximately 30 m thickness and are separated by interburden layers with an average thickness less than 2 m each. The quarry facilities include a stockpile which is located next to the crusher as well as a two-sided blending yard yielding a capacity of 1500 t each.

Quarry operation

Similar to the operation in the first case study, ore is extracted from multiple levels by truck and shovel operation. However, drilling and blasting activity as well as waste removal is seasonally done by contracting companies. The equipment used for ore transport in the second quarry operation is listed in Table 15 Additional equipment used for auxiliary work is not listed.

Table 15 Quarry machinery used for ore transport in second case study

Type	**Manufacturer**	**In operation since**	**Main use**	**Equipment specs**
L964C	Liebherr	09 2007	Loading of ore	3 m³ shovel
L964B	Liebherr	2001	Loading of ore	
A35D	Volvo	04 2005	Hauling of ore	32 t ore capacity (large augmentation of truck wall leads to higher hauling capacity)
A35E	Volvo	08 2008	Hauling of ore	
A35F	Volvo	04 2014	Hauling of ore	

Standard ore transport is realized by one loader and two dump trucks in this quarry. The newer excavator L964C is preferably used for loading activity, which is replaced by excavator L964B in case of maintenance. Both excavators are equipped with hardened bucket teeth for pre-comminution of ore. This activity needs to be done in some areas of the pit where seasonal blasting has taken place insufficiently. For this reason, the use of a wheel loader for loading activity is unfavorable.

All dump trucks (A35) used in this operation are equipped with equal loading capacity of 32 t. This capacity is realized by an increase of truck walls of approximately 0.5 m. There are mostly two dumpers in use for current operation. A stockpile is partly used for dumping because the hauling capacity of two dump trucks significantly exceeds the crusher's capacity. Raw material from stockpiling is fed to the crusher by a wheel loader machine.

3.3.1 Problem outline

Within the next years, the quarry's exploitation will move further away from the crushing area which will lead to a considerable increase in hauling distance. In the following, the effect of an increased hauling distance on optimal use of hauling equipment is examined by simulation. Furthermore, the experiments include the management's consideration of utilizing a bigger-sized truck. The current exploitation area including concession border is presented in Figure 24.

Figure 24 Overview on current exploitation area of second case study[37]

The crusher and stockpiling area is connected to the entry of the quarry via a graveled main road which is located at the bottom of Figure 24. This main road further divides into two

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[37] Extracted from file: St.Soupplets_Map

separate access roads which are called right access and left access. The right access is significantly shorter and has a current length of 470 m from the crusher area to the right pit entry. The elevation of the right pit entry fits to the top height of the first layer[38]. Because of its massive thickness, the first layer is exploited in up to three separate slices which are connected to each other via temporary ramps created inside the raw material. Access to the second[39] layer is currently provided via a temporary ramp located in the central pit area (marked road, connected to right pit entry). The third layer[40] partly needs to be exploited via the left access road. The graveled part of this access has a current length of about 970 m. However, this hauling route is currently not often in use because of the small thickness of the third layer.

The concession border, which is marked as red line in Figure 24, gives an overview of the largest extension of the quarry where mining will take place. The upper part of the quarry concession is not shown on the original map. However, the maximum distances of both access roads are known and used as final parameters in the simulation experiment.

3.3.2 Simulation setup

Table 16 and Table 17 list all important input parameters in Plant Simulation which are used to parametrize the equipment in the second case study.

Table 16 Equipment input parameters for second case study

Dump truck	
Capacity (A35)	32 t
Capacity (A60H)	50 t
Availability	100%
Loader	
Shovel (one dumper)	3.00 m³
Shovel (more dumper)	2.60 m³
Availability	95%
MTTR	2 min
Crusher	
Throughput	110 t/h
Bunker capacity	55 t
Availability	100%

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[38] 1ereMasse: 10 m thickness, accounts for ≈60 % of production

[39] 2emeMasse: 7.2 m thickness, 1st interburden: 2 m thickness, accounts for ≈30 % of production

[40] 3emeMasse: 2.7 m thickness, 2nd interburden: 0,6 m thickness, accounts for ≈10 % of production

Table 17 Statistical distributions for second case study

Activity/Equipment	Mean value	Standard deviation	Lower/upper bound	density function
Loader				
Bucket cycle (Loading)	25.6 s	2.6 s	21 s/ 31 s	normal
Dump truck				
Maneuvering (Pit)	31.8 s	11.9 s	11 s/ 53 s	lognorm
Maneuvering (Crusher)	17.8 s	2.5 s	15 s/ 23 s	negexp
Maneuvering (Stockpile)	20.3 s	6.5 s	11 s/ 34s	normal
Dumping	21.4 s	3.7 s	16 s/ 31 s	lognorm

The capacity of dump truck A35 presented in Table 16 is valid for all hauling equipment which is currently in use in the quarry. However, a bigger-sized truck is included in this case study in order to gain information about a possible purchase decision. The maximum transport volume of the desired A60H dump truck is 33.6 m³ (SAE 2:1 heaped), which leads to a payload of 50.4 t when a bulk density of 1.5 t/m³ is applied. This also fits its maximum loading capacity of 55 t. (Volvo 2016)

Data preparation has shown that different maneuvering times need to be applied for the dump truck which is shown in Table 17. Exemplary, maneuvering times measured at the crusher are comparable in average with maneuvering times for stockpiling, but highly differ in spread and density function. Maneuvering times in the pit are chosen to be handled as complete data set without differentiating by loading location, resulting in large differences in maneuvering times between 11 s and 53 s. This procedure takes the broad exploitation area of the quarry into account which results in a large variety of different maneuvering actions.

The shovel size for loading activity is divided into two scenarios. It is noticeable from data collection that there are fewer bucket cycles needed for loading if there is only one dump truck in operation. This is because additional waiting time leads to better preparation of bulk material. However, the number of dump trucks has no significant influence on the statistical distribution of bucket cycle times[41]. Values for availability and repair time are created from own collected data by using the same procedure as in the first case study.

The crusher throughput is determined by production data received by own measurements. One-truck hauling has resulted in a crusher throughput of approximately 105 t/h. It reflects the average number of truck loads which can be dumped into the crusher bunker including

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[41] Measurements are compared in file: Data Collection_FRA, sheet: Evaluation

standard wheel loader’s performance at the crusher area. The chosen input value reflects the measured crusher performance which is confirmed by simulation runs performed for validation purpose. The way how validation experiments are executed is explained in the simulation procedure. It should be noticed that the crusher’s performance does not influence the dump truck’s hauling capacity in this simulation study because stockpiling is included in the simulation model. However, the amount of stockpiled material is based on this value.

The way how stockpiling is implemented in the simulation model is comparable to stockpile implementation in the first case study. Information about the amount of total dumped material and the share of stockpiled material is recorded in the model. Furthermore, it is refrained from simulating wheel loader activities emptying the stockpile. All desired results concerning optimization of truck haulage can be received without this feature.

3.3.3 Simulation results

Within the second case study it is aimed to optimize the use of hauling equipment for the quarry operation taking into consideration the utilization of a bigger-sized truck as well as an increased hauling distance until final stage of the pit is reached. A base case is created for general comparison of different equipment composition. A succeeding sensitivity analysis examines the results further by stepwise increase of hauling distance.

At first it is of great importance to determine the required hauling production which is needed to satisfy the demand of the production plant. The basic calculation is presented in Table 18.

Table 18 Estimated production rate for second case study

Budgeted yearly production	395.940	t/a
Recycling 5%	19.797	t
Scheduled working days for quarry	257	d/a
Scheduled ore transport	7	h/d
Daily production (needed)	1464	t/d
Effectivity[42]	85%	
Haulage Capacity	**246,0**	**t/h**

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[42] Medium long-term effectivity (Darling 2011, p. 907)

Budgeted production numbers as well as scheduled working times are taken from the quarry's production plan for the year 2016. The effectivity rate used in the calculation represents general interruptions of hauling activity which lead to a stop of operation. This could exemplary be an interruption due to blasting activity. It is separate from equipment's availability factors which are included in the simulation model. The production rate of 246 t/h represents the minimum haulage capacity for quarry machinery.

Base case

The base case represents ore transport from average distance in the pit. Monthly records of truck haulage from August 2015 until May 2016 result in a medium distance of 847 m from the crusher area to the point of loading[43]. The data shows that ore transport has entirely taken place using the right pit entry. This is reasonable because first and second layer of the deposit, which account for 90% of ore production, are currently exploited exclusively from the right pit entry. Thus, ore transport from the left pit entry is not considered in the base case but will be considered for sensitivity analysis.

The hauling distance for using right pit entry consists of a main road of currently 470 m length and additional paved road way of 175 m. This leads to an average distance of 202 m which needs to be covered in the pit. The evaluation of dump truck's travel speed[44] shows that the average speed in the pit does not differ by loading location. Moreover, it can be stated that hauling speed is comparable in the whole pit area. The measured average speeds are presented in Table 19.

Table 19 Hauling speeds in quarry from second case study

Location	unloaded (km/h)	loaded (km/h)
in-pit terrain:	11,9	10,8
main road	27,9	26,7
Crusher area	10	10

Differences in travel speed are measured for the unloaded and loaded state. The speed limit of 30 km/h for the main road is nearly reached. Because of uneven ground conditions there is no speed greater than 12 km/h possible inside the pit area.

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[43] St.Soupplets_monthly production(May 2016)

[44] Taken from file: Data Collection_FRA, sheet: speeds

Single comparison of dump trucks

The comparison of dump truck A35D and A60H used as single hauling equipment, presented in Table 20 and Table 21 shows that production can be considerably increased with the use of the A60H dump truck[45]. Furthermore, the results show a significant increase in the use of stockpile because the additional capacity cannot be handled by the crusher. The increased cycle time results from the higher loading time due to the bigger volume of the truck. Because these cases deal with one dump truck in operation there are few waiting times of less than 2 percent noticeable which result exclusively from the loader's breakdown profile.

Table 20 Production numbers for A35D dump truck only in use

Production A35D	192.00 t/h	Transport	Loading	Dumping	Waiting
Stockpile use	41.00 %	57.40 %	34.32 %	6.64 %	1.63 %
Cycle time	10.00 min	5.74 min	3.43 min	0.66 min	0.16 min

Table 21 Production numbers for A60H dump truck only in use

Production A60H	254.00 t/h	Transport	Loading	Dumping	Waiting
Stockpile use	64.70 %	48.90 %	43.63 %	5.70 %	1.76 %
Cycle time	11.81 min	5.78 min	5.15 min	0.67 min	0.21 min

Sensitivity analysis

One important outcome from the base case is that the A60H dump truck is able to provide sufficient haulage capacity of 254 t/h to supply the production plant. However, an increase in hauling distance requires additional equipment. Figure 25 shows haulage capacity for four equipment compositions by stepwise increased hauling distance.

The graph of the A60H dump truck in Figure 25 shows that a slight increase in hauling distance leads to decreased capacity below needed capacity of 246 t/h. This situation naturally requires a second hauling vehicle.

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[45] Taken from file: Simulation_Hauling experiment_complete results

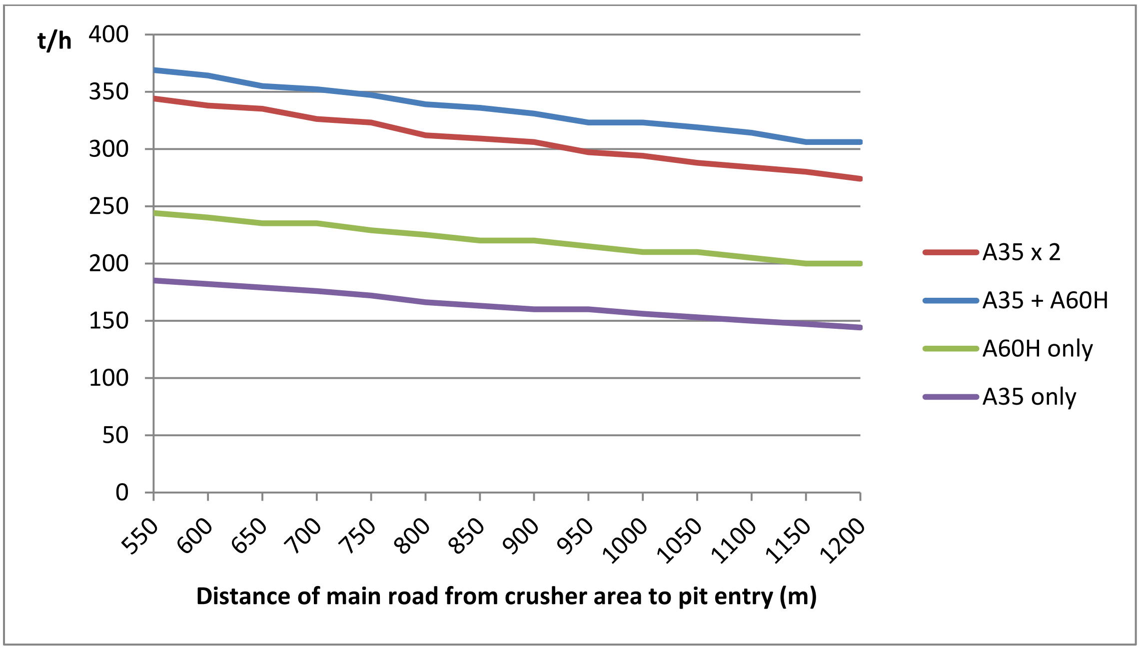

Figure 25 Haulage capacity influenced by hauling distance

Interestingly, the combination of an A60H truck with a standard A35 dump truck does only lead to a slightly increased hauling capacity compared to standard haulage consisting of two A35 dump trucks. This behavior is not caused by a limited capacity of loading equipment which still has a share of 25 % at-rest without loading activity. Moreover, it is now important that cycle times of the two different trucks differ largely so that waiting times for the smaller truck do occur regularly, which can be seen in Table 22.

Table 22 Production numbers for A35D dump truck in combination with A60H dump truck

Production A35 (A35 + A60H in use)	149.40 t/h	Transport	Loading	Dumping	Waiting
Stockpile use (total)	71.2 %	44.42 %	29.03 %	5.01 %	21.55%
Cycle time	12.85 min	5.71 min	3.73 min	0.64 min	2.77 min

Compared to single use, the hauling capacity is largely decreased which is noticeable by an increase of cycle time by 2.85 min. The biggest share of additional time is due to increased waiting time of 2.77 min. Importantly, the use of two standard A35 dump trucks provides sufficient capacity even for maximum hauling distance of 1,200 m which needs to be realized for the right pit entry.

Use of stockpile

Stockpiling is an essential part in the quarry operation. The independence from crusher performance allows larger production in the quarry. One disadvantage of this system is the massive amount of stockpiled material which needs to be handled by a wheel loader machine. Figure 26 shows one additional disadvantage of the A60H dump truck by presenting the percentage share of stockpile use.

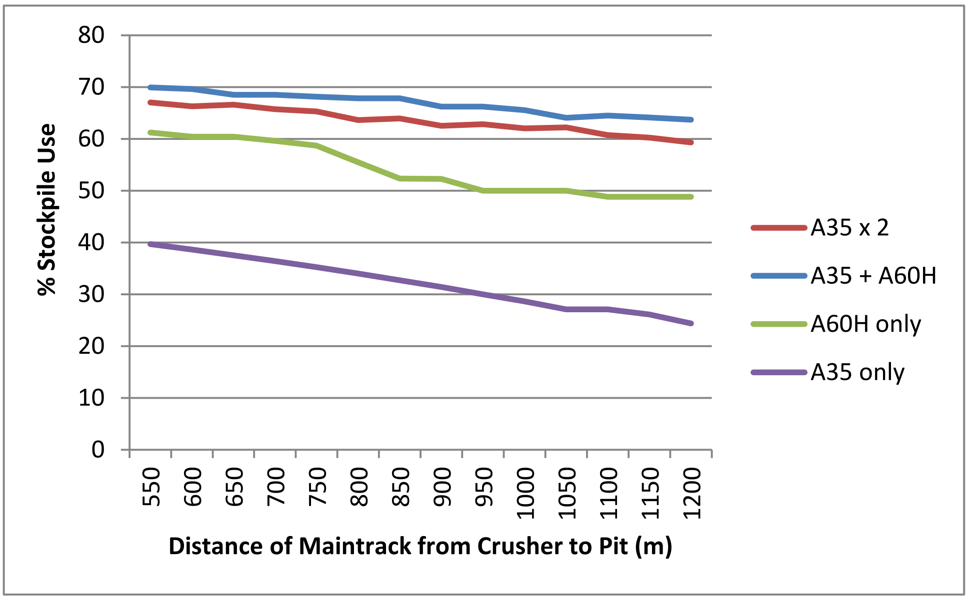

Figure 26 Percentage of stockpile use dependent on hauling distance

The graph of the A60H dump truck, solely in use, shows that single operation of this dump truck leads to a massive stockpile use which does decrease less than the stockpile use of other equipment when hauling distance is increased. The crusher bunker is nearly charged at its limit by every dump which is undertaken by A60H dump truck so that next cycles cannot be dumped in. On the other hand, crusher throughput is reduced to 85 t/h because there are created additional occasions when the crusher bunker runs completely empty before dumping can be accomplished through the next cycle. For the case of two operating dump trucks there is similar behavior noticeable. The stockpile use is slightly decreased by additional hauling distance but is generally on a very high level.

Examination of left access road

The haulage road via the left pit access will have a maximum length of 2500 m from crusher to loading point. In this sensitivity analysis 210 m of this distance are considered to be in the pit where smaller velocity is applied.

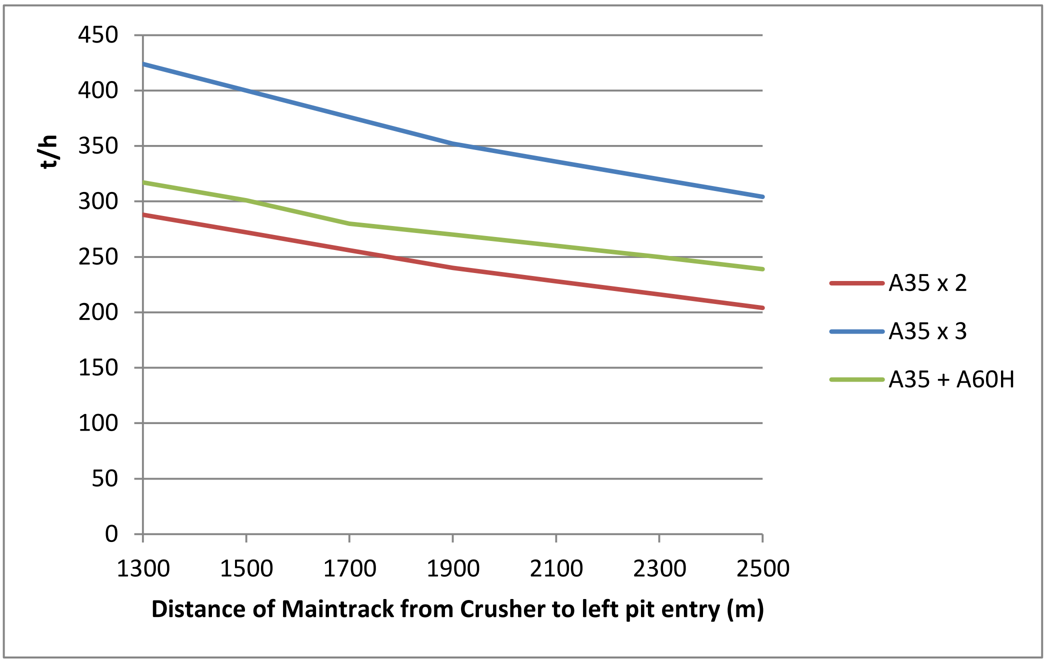

Figure 27 Sensitivity analysis for left access road

It can be seen in Figure 27 that needed haulage capacity of 246 t/h can sufficiently supplied for less than 1800 m haulage way. If one A35 dump truck is replaced by one A60H dump truck, maximum haulage distance can be increased to approximately 2300 m. However, three A35 dump trucks are able to provide needed haulage capacity always.

3.4 Executive summary of simulation results

Case study one – Castellina M.ma, Lothar di Knauf

Primary, the beneficial use of stockpiling for daily production was examined within the quarry operation of the production site in Castellina Marittima. The KPI's of total daily costs and total work effort are chosen. Table 23 shows a summary of performed cases:

Table 23 summary of experiments performed in case study one

Used equipment	Stockpile in use?	Total daily costs (€)	Total work effort (h)
one loader, one dump truck	no	1110.54	16.09
one loader, one dump truck one wheel loader	yes	860.92	14.04
one loader, two dump trucks one wheel loader	yes	880.30	14.70
one loader, two dump trucks one wheel loader	yes, but truck allocation to crusher/stockpile fixed	915.71	15.30

It has been found that, if stockpiling is used, daily operational costs for ore transport can be reduced by 249 € on average, by reducing the total spent work effort by two hours from 16.09 h to 14.04 h. Additionally, there are the following remarks:

- Although an additional wheel loader is used for stockpiling by load and carry operation, significantly reduced waiting times lead to more efficient use of equipment.
- As second option, there can be used two dump trucks for ore transport which reduces initial loading and hauling time to 3.5 h per dump truck (6 h for one dump truck in use) but only increases total costs and total work effort slightly.
- If two dump trucks are in operation, it is of great importance that a well-functioning truck allocation system is in place (light signal, video of bunker filling etc.) because fixed allocation to the stockpile/ crusher increases costs significantly.
- Sensitivity analysis reveals that the use of stockpiling is more beneficial the less throughput is realized by the crusher.
- Furthermore, a bigger sized dump truck could possibly be beneficial for the operation only if stockpiling is introduced.

Case study two – St.Soupplets, Knauf Platres

For the quarry operation related to the production site in St.Soupplets, it was examined which effect the use of a bigger sized dump truck in combination with an increased hauling distance, reaching until the end stage of the pit, has on the optimal equipment composition. Hauling capacity, expressed in produced tons of gypsum per hour (t/h) is used as KPI. Table 24 shows which equipment composition is capable of producing the needed hauling capacity of 246 t/h, which is needed to satisfy the plant's monthly demand.

Table 24 Summary of equipment use dependent on hauling distance

Access road	Main road hauling distance from crusher to pit entry	Dump truck A60H only in use	Two A35 dump trucks in use	Dump truck A60H in combination with A35	Three A35 dump trucks in use
Right (short)	470 m (base case)	ok	ok	ok	overestimated
	550 m	-	ok	ok	overestimated
	1200 m (max)	-	ok	ok	overestimated
Left (long)	1300 m	-	ok	ok	ok
	1800 m	-	-	ok	ok
	2300 m	-	-	-	ok
	2500 m (max)	-	-	-	ok

For the predominantly used right access road there is sufficient hauling capacity available by the use of two A35 dump trucks until the maximum hauling distance is reached. The use of a bigger A60H dump truck is only favorable in current conditions, where hauling capacity is sufficient by single use of this dump truck. For occasional use of the left access road, three A35 dump trucks provide sufficient haulage capacity until maximum distance is reached. Further findings are listed below:

- The additional use of an A60H dump truck in combination with a A35 dump truck does not lead to an effectively increased hauling capacity because waiting times at the loader are inevitable due to significantly increased loading time for the bigger truck resulting in an imbalance of cycle time.
- The stockpile use is considerably increased by single use of the A60H dump truck compared to single use of one A35 dump truck because of the limited crusher bunker capacity.

4 Assessment of simulation technique for quarry optimization

Case study results are subject to a critical review in this chapter in order to determine strengths and weaknesses of the applied simulation tool. Several smaller tasks for process optimization in quarry operations have been addressed by simulation which can also be solved by calculation based on deterministic average numbers. By comparison to solutions obtained by deterministic approach it is possible to determine most beneficial use of the newly developed simulation tool. An important aspect included in the comparison is the amount of work effort spent to obtain individual results.

4.1 Comparison of simulation technique to deterministic spreadsheet calculation

On the basis of the same collected data there are compared solutions for the following optimization tasks:

- Transport capacity by increasing hauling distance
- General stockpile use
- Profitability of stockpile use for ore transport
- Influence of dumper size on ore transport

4.1.1 Transport capacity by increasing hauling distance

Simulation is used in the second case study to gain information about a typical problem of ore transport in mining operations. Because of an increase of distance between the pit and the crusher with advanced mine life, haulage capacity of different hauling equipment is examined considering transport equipment on-site and an additional bigger sized dump truck. Results are obtained by using the performance indicator of transported tonnage per hour (t/h). Exemplary, the deterministic calculation of the base case scenario is presented in Table 25.

Table 25 Deterministic calculation of haulage capacity for base case scenario in second case study

Loading capacity A35	32	t	
Transport	338.60	s	57.26%
Loading	212.22	s	35.89%
Dumping	40.54	s	6.86%
total	**9.856**	**min**	**100.00%**
production	194.81	t/h	

The base case includes ore transport with one A35 dump truck bearing a capacity of 32 t. Transport time is based on average speed measurements which are equally used in the corresponding simulation model. The loading activity is calculated by the use of average bucket cycle time multiplied by the number of loading cycles based on the payload capacity of the dump truck. The availability value measured for the loading equipment is included there. Dumping time is determined by a fixed rate of between dumping in the crusher respectively on stockpile which is a ratio resulting from measurements of this particular setup[46].

By deterministic calculation there is an increase of 1.5 % transport capacity measurable compared to simulation results. The slight difference is based on recording of the chosen performance indicator in the simulation model. During simulation there is only actual loaded material recorded for the dump truck which results in 60 recorded loading cycles completed in a simulation time of 10 h[47]. This equals to six completed cycle times per hour and a corresponding cycle time of 10 min. The performance indicator gives subsequently the value of hourly produced tonnage which accounts for 192 t/h[48]. However, the cycle time is calculated to the exact number of 9.856 min by deterministic approach.

The comparison shows that the used simulation approach slightly underestimates the average possible haulage capacity. However, this information can be beneficial if the simulation time represents daily shift time. The difference between deterministic approach and simulation becomes smaller when simulation time and/or the number of simulation runs are increased. Figure 28 shows the comparison of the complete sensitivity analysis for single truck haulage by both analysis methods.

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[46] Compare file: Data Collection_FRA, Measurement 1ereMasse(1)

[47] Simulation_Hauling experiment_ complete results

[48] 6 completed cycles per hour containing a payload of 32 t each

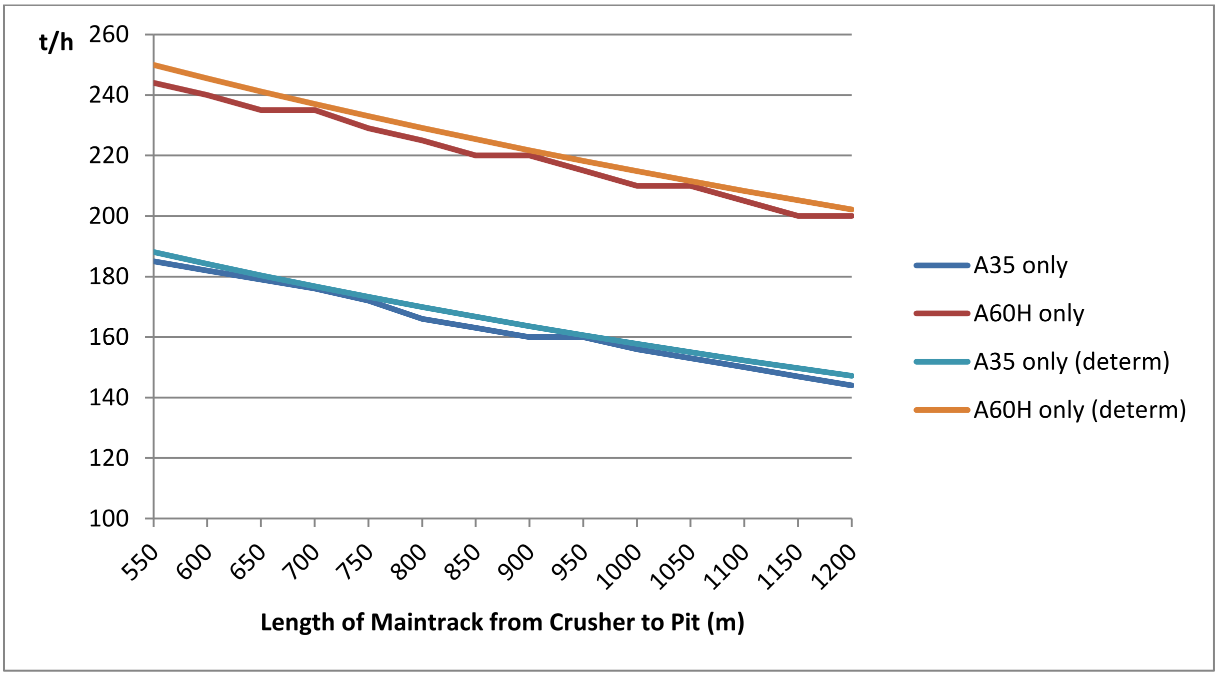

Figure 28 Comparison of analysis methods increased hauling distance by single truck haulage

The results obtained for the base case of truck haulage are approved by comparison of sensitivity results for single truck haulage, presented in Figure 28. The graphs representing both applied dumper capacities show typical, stepwise decreased transport capacity for simulation compared to continuous decrease obtained by deterministic calculation. The stepwise decrease in the simulation model is logical because the same number of hauling cycles can partly be completed even by an increased distance between loading point and crusher. It can also be noticed that deterministic calculation consistently leads to slightly increased transport capacity which is already observed and explained in the base case.

Generally, both ways of analysis are suitable to determine maximal haulage distance for certain production numbers including the difference that simulation results are slightly more conservative. It is important to mention that this statement is only guilty for transport using one single dump truck. The comparison of analysis methods for multiple truck hauling is presented in Figure 29.

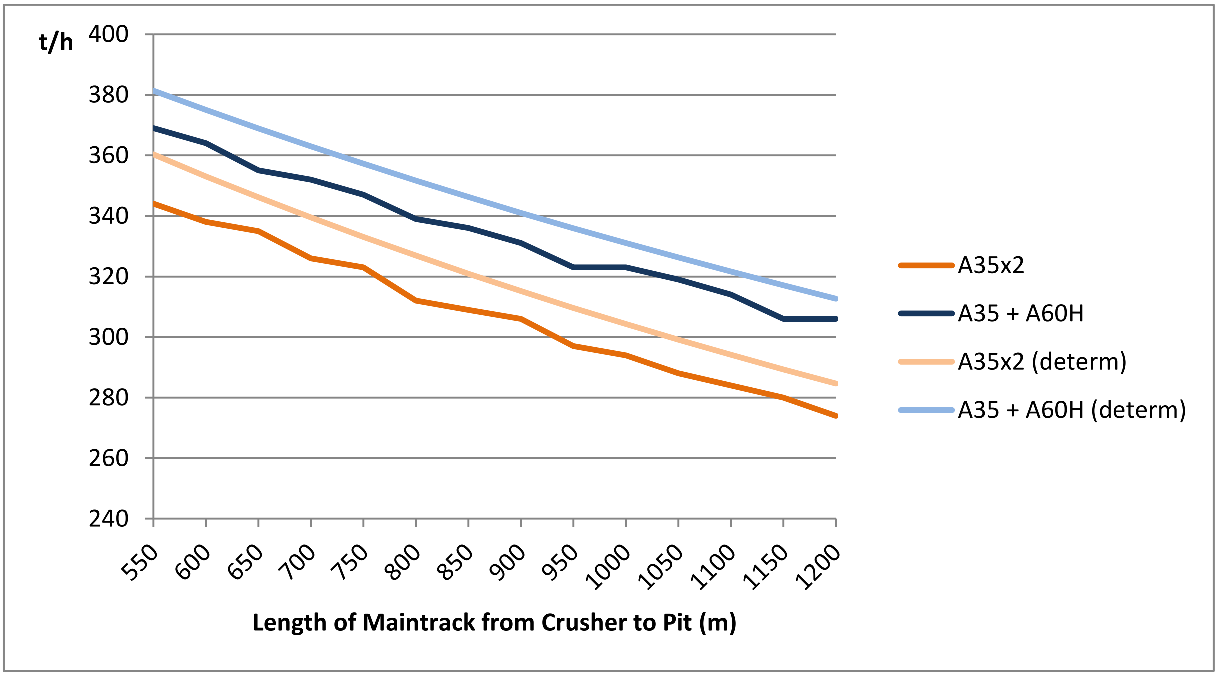

Figure 29 Comparison of analysis methods for increased hauling distance by multiple truck haulage

Compared to previously examined one truck hauling there is greater mismatch between deterministic approach and simulation results noticeable. Differences between the two analysis methods can be determined in waiting time. The base case simulation results of ore transport completed by two A35 dump trucks reveal an average recorded waiting time of 2.80 % of total transport time at the loading point. Although the two dump trucks have equal payload capacity, resulting in similar cycle times, it is reasonable that fluctuating process times lead to waiting times during operation. However, this behavior can only be captured by discrete event simulation through the input of statistical distributions of process times which are realized by a random number generator in the simulation model.

Calculation based on deterministic, average cycle times does not deliver this information. The combination of two different sized dump trucks reveals similar discrepancies between the two evaluation methods. Although the cycle time of the smaller A35 dump truck is adjusted to A60H cycle time for deterministic calculation[49], resulting from the bottleneck at the loading point, simulation results account for lower total transport performance. Because the deterministic approach lacks of analysis of equipment’s interaction due to statistic deviations, simulation results are considered more robust. Concluding, the deterministic

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[49] Compare file: Data Collection_FRA; deterministic calculation

calculation of haulage capacity with more than one dump truck in use results in overestimation of the performance indicator. The results in Figure 29 show an overestimation between 3 % and 5 %.

4.1.2 General stockpile use

The quarry operation representing the second case study includes the use of a stockpile for extracted ore which is located directly next to the crusher. The decision whether material is dumped in the crusher or on the adjacent stockpile is made on the basis of the filling level of the crusher bunker. The truck driver's visual observation of the crusher bunker is critical for this decision. In the corresponding simulation model, the dumping decision is reproduced by an event-based method. The software is therefore asked for the bunker's filling level for a dump truck's arrival at the crusher, which is already presented in the Figure 20 in the previous chapter. This decision is repeated for every haulage cycle. Contrary, the deterministic calculation of stockpile use is based on average oversupply of material sent to the crusher. The obtained oversupply can either be directly related to crusher's performance or be rounded up to multiples of the dump truck's payload capacity. Figure 30 shows the comparison of all mentioned approaches for stockpiling behavior of the A60H dump truck.

By comparing the two graphs resulting from deterministic calculation in Figure 30 the effect of rounding is clearly visible. While oversupply is continuously decreasing with increased transport distance (red graph) there is a sudden drop of stockpile use noticeable if the effect of integer payload capacities is introduced (green graph). Obviously, oversupply is reduced to a lower multiple of dump truck's capacity if the length of the main track exceeds 800 m. Significantly, the graph resulting from simulation results shows stepwise decrease of stockpile use which is mostly located between the two deterministic approaches. This method represents the examined real system more accurately because real dumping behavior is reproduced in the simulation model. This comparison shows that simulation is favorable for the analysis of systems where decisions are situation based. In this analysis, however, the maximal deviation of deterministic stockpile use is less than 5 %.

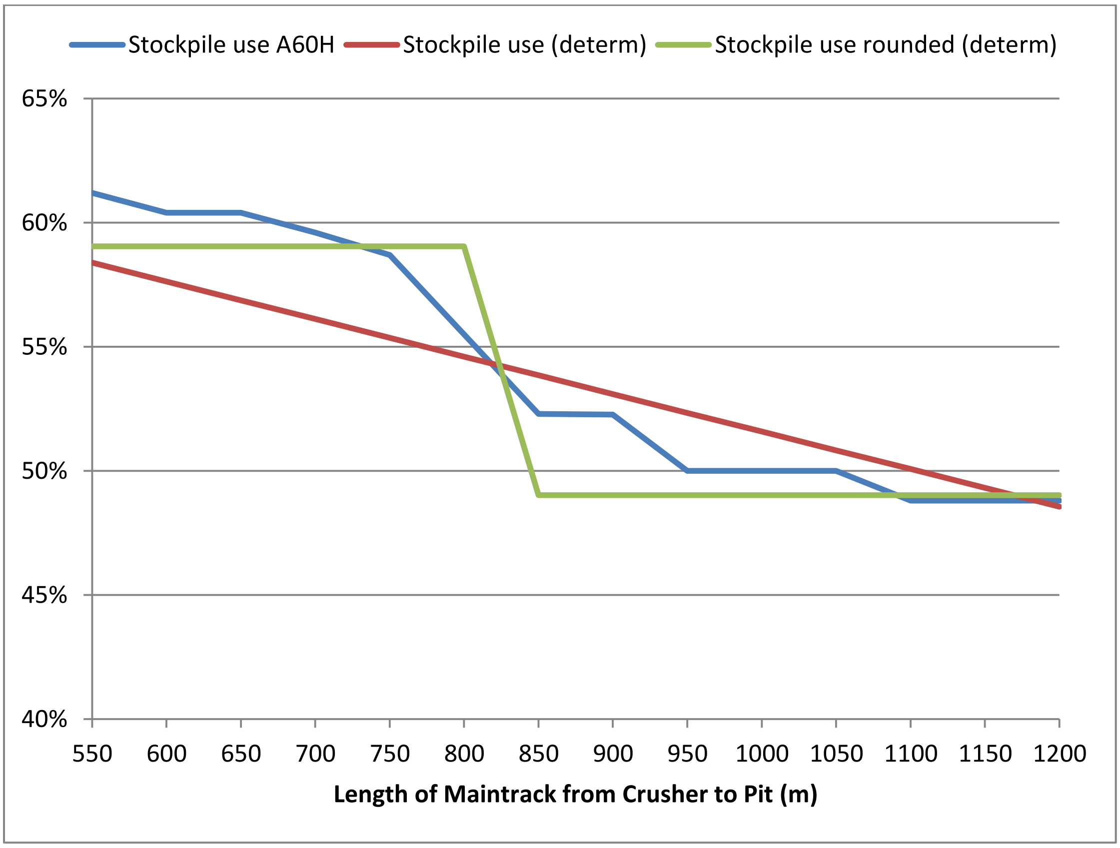

Figure 30 Comparison of analysis methods for percentage stockpile use

4.1.3 Profitability of stockpile use for ore transport

The first case study addresses the question whether a use of a stockpile is profitable for ore transport within the examined quarry operation. Daily operational costs are used as key performance indicator in order to compare the scenario of an activated stockpile to a deactivated stockpile. The deterministic calculation approach used to determine total costs for an activated stockpile scenario is presented in Table 26.

Table 26 Deterministic calculation of daily costs by activated stockpile scenario

Activated stockpile	Payload:	27 t	Equipment	Operation time		€/h		
Overproduction	49,26	t/h	Dumper	5,90	h	54,56	322,10	€
Number of dumps on stockpile	11		Loader	5,83	h	72,20	421,01	€
Stockpile tonnage	297	t	Wheel loader	2,48	h	55,04	136,25	€
			Total				879,36	€

The obtained deterministic result of 879 €/d is slightly higher than the compared simulation result of 860 €/h (compare simulation results of first case study). This is mainly due to a higher stockpile tonnage[50] which leads to increased wheel loader's operation time. The simulation model is equipped with a decision method for dumping between stockpile and crusher, equally to the method described in the previous subchapter, which makes the simulation result more trustworthy. Furthermore, deterministic calculation method is limited in setup variation. The setup of two dump trucks in operation including varied truck dispatch leads to biased results because of a lack of capturing waiting time, which can easily be realized in the simulation model. However, the profitability of stockpile use can also be proven by deterministic approach, which is shown in Figure 31. Both analysis methods show comparable results for a varied crusher performance between 90 t/h and 160 t/h. The deterministic calculation shows slight overestimation of the performance indicator up to 5 % deviation, as already seen in the base case calculation. Nevertheless, the basic behavior of increasing benefit of the stockpile for decreasing crusher performance can be reproduced.

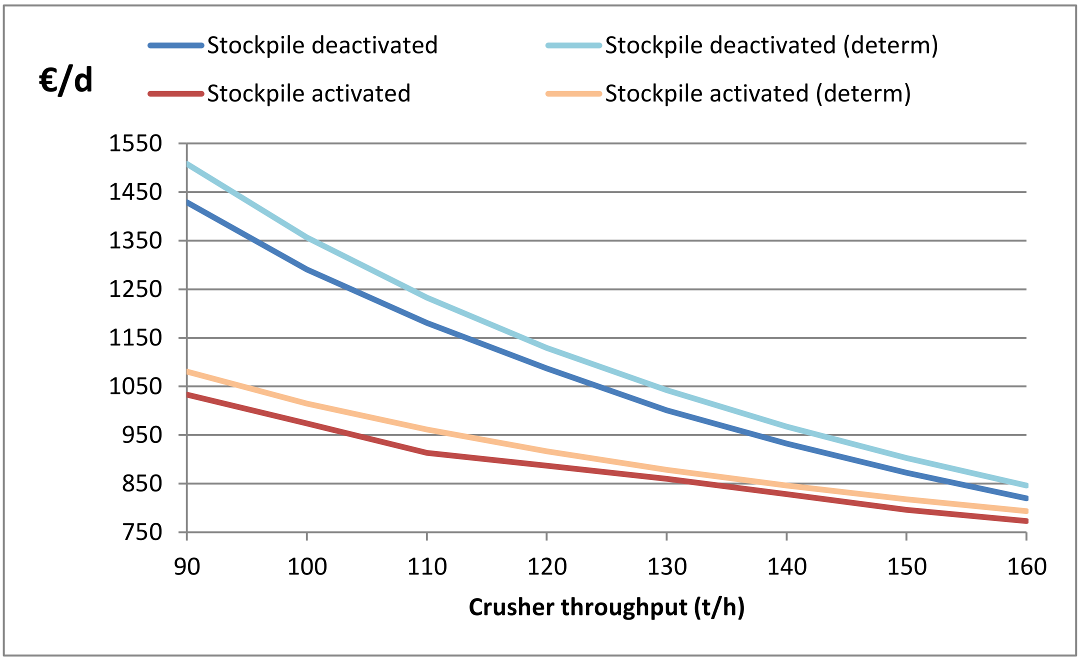

Figure 31 Comparison of stockpile in use

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[50] Number of dumps received by the average overproduction (haulage capacity - average crusher performance) multiplied by the dumper's operation time and divided by the dumper's capacity

4.1.4 Influence of dumper size on ore transport

Investigations regarding profitable stockpile use within the first case study serve as basis for this examination. By using the same performance indicator of daily operational costs, the dump truck’s capacity is increased stepwise as part of the sensitivity analysis of case study one. Daily operational costs are received for activated and deactivated stockpile use. The comparison of simulation results to deterministic calculation for both scenarios is presented in Figure 32. As already discussed in the case study, the simulation setup based on same transported tonnage has a strong influence on results obtained for changed dumper capacity. In contrast, the deterministic approach shows clear results. Constant costs received for the deactivated stockpile scenario (green graph) are logical if crusher performance is constantly lower than haulage capacity. On the other hand, the advantage of a bigger-sized truck for active stockpiling is clearly noticeable by deterministic calculation (purple graph) which cannot be concluded from simulation outcome because of biased results (red graph). This particular case reveals that a double check performed by two different analysis methods can lead to a better understanding of the analyzed objective.

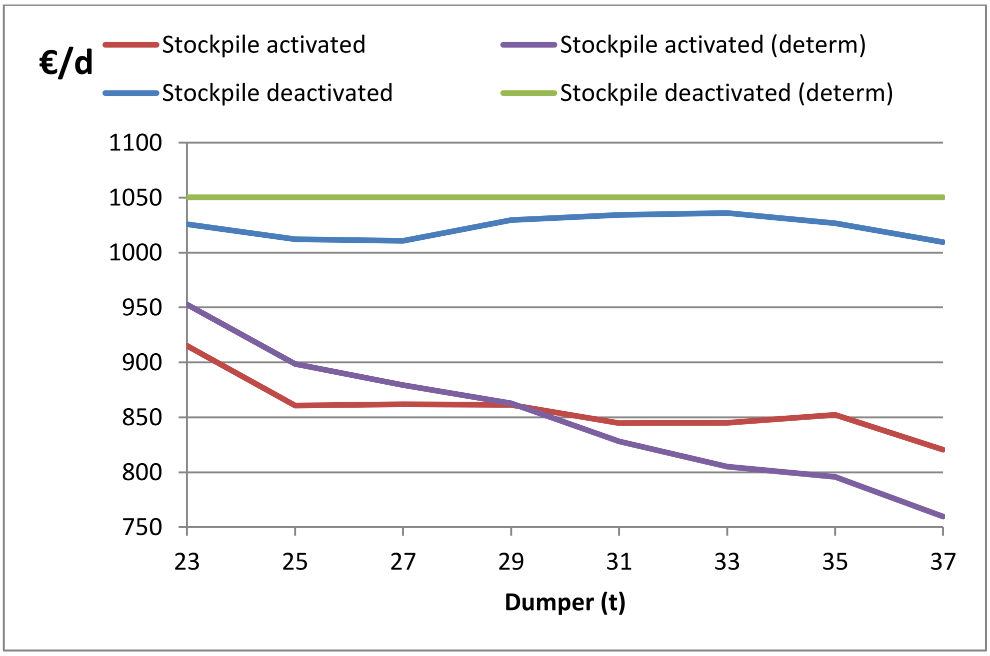

Figure 32 Comparison of analysis methods for investigation of dumper capacity

4.1.5 Comparison of total work effort

The total work effort spent to receive comparable results is recorded for both analysis methods for the second case study which gives a more representative picture than recorded work spent to receive first case study’s results. In Figure 33 there is total work effort compared by measuring working hours for different phases which are presented in the simulation procedure. The graphics does not aim to deliver knowledge of the sequence in which the respective work has been accomplished[51]. Moreover, it is stressed on the comparison of used approaches rather than explaining their way and schedule of execution.

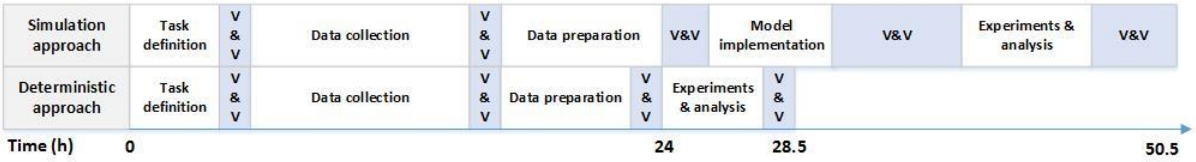

Figure 33 Comparison of total effort by different approaches

There can be noticed an accordance of both approaches for the phases “task definition” and “data collection” including sections of verification and validation of phase results. This is logical because there are examined the same objectives in both approaches which are based on the same data set. Differences in work effort appear for the first time in the data preparation phase, where statistical distributions need to be created and verified for simulation additional to general evaluation of data. Effort of 24 working hours is spent for creation of general acknowledgement which is used by both approaches. Analysis of statistical distributions accounts for an additional effort of three working hours.

The procedure of model implementation and corresponding control measures accounts for the biggest share of additional time spent for simulation. Although the implementation phase is extremely shortened by pre-existing modules, there is adaption work for the specific quarry operation performed. The development of a stockpile module in the first case study has reduced some of the needed adaption work for the second case study. There need to be performed verification measures additional to implementation. The test procedures “fixed value test” and “internal validity test” account for 9.5 working hours in the second case study. The “experiment & analysis” phase is enlarged for simulation because there is

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[51] Refer to detailed listing of single tasks including dates of completion in file: Work effort_FRA

partly the need of multiple simulation runs for one specific acknowledgement in order to create a confidence interval. This leads to a total work effort of 50.5 working hours including 26.5 hours solely spent for simulation after general evaluation of the quarry operation. In comparison, the deterministic approach is characterized by a distinct shorter evaluation phase by usage of 4.5 additional working hours, which is six times faster than simulation.

Possible reduction of effort

The stochastic simulation model in case study one[52] is compared to a reference model where all values for travel speed are set to deterministic values[53]. After the comparison of ten simulation runs, it is found that the transport share is reduced in the deterministic model by concurrent increase of waiting time. As expected, the spread of transport share has reduced. However, the throughput of the dump truck per simulation run has not changed at all. Thus, the simulation model is not biased by entering deterministic speeds instead of creating statistical distributions for travel speeds. This finding, however, depends on the KPI's, used for analysis. As presented, a change of waiting and transport shares might have an effect on the KPI of daily transport costs used in the first case study. In the second case study, however, the throughput of dump trucks is the decisive KPI. A considerable amount of work for data preparation is saved because statistical distributions do not need to be created and validated for travel speeds. This simplification depends on respective experiments and it needs to be decided for every individual case if statistical distributions can be replaced by deterministic values.

4.2 Conclusion and recommendation

The assessment of case study results reveals that the DES approach is advantageous to deterministic spreadsheet calculation if the examined case includes hardly predictable interaction of equipment. One example is the basic examination of stockpile profitability using different equipment combinations in the first case study. While the exact amount of ore placed on the stockpile was difficult to determine by spreadsheet calculation, the DES model could benefit from decision-making based on the filling level of the crusher bunker,

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[52] Model: Castellina_stockpile_active

[53] Model: Castellina_speed_determ

which reproduces the behavior of the real transport system. There are also more precise results obtained for the evaluation of transport capacity when multiple trucks are used simultaneously for ore transport. In contrast, the deterministic approach leads overestimation of hauling capacity by 3-5 %, because waiting times at the loading point cannot be adequately determined. However, no significant deviation can be measured between both approaches if one single truck is used for ore transport. On the other hand, deterministic approach has shown to be favorable for the evaluation of varying dumper capacity as part of the sensitivity analysis for the first case study. Simulation results were biased in that case due to an unfavorable use of the performance indicator for this experiment.

By comparing both analytical approaches there must also be kept in mind the different work effort needed to receive robust results. An increase of 80 % in time was noted for simulation required to complete a case study including the collection and preparation of data on-site. The single work effort of experimental evaluation is about six times higher for simulation than for the evaluation by deterministic spreadsheet calculation. Due to the use of pre-defined modules, the share of modeling effort is kept to an acceptable limit, but a good amount of effort needs to be put on the verification and validation process for both the implemented model as well as for experimental results. While for the latter the use of confidence intervals is inevitable for some experiments, the implemented model needs to be tested on internal validity and correct implementation of all parameters. It can be considered to replace statistical distributions by deterministic values in the model, which can save time in the data preparation phase. However, the validity of this simplification must be checked individually in order to prevent biased simulation results.

Taking into account the considerable increase in work effort by DES, it is recommended to use the DES tool only when a more complex and interactive system is being examined, and it consists of more than one hauling equipment where particular decisions are dependent on other dynamic processes. When DES is applied, it should always be considered to compare simulation results to deterministic spreadsheet calculation, which partly needs to be performed anyway for verification purpose. The application of two independent analytical methods increases the knowledge about the examined problem and thus helps in decision-making.

There are more optimization targets suggested for simulation in quarry operations on the task definition sheet[54] which have not been performed in the presented case studies because there was no potential or no need recognized for optimization. After fulfilling the objectives which were agreed in both operations, it is recommended to use the simulation tool for an even broader variety of applications.

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[54] Appendix B - Task definition for quarry mining

5 Summary

Although DES has become a well-accepted tool for decision-making in the mining industry, the time consuming modelling work and high programming effort is normally only considered feasible for large-scale projects examined in project-based case studies. This is why Knauf has developed an adapted simulation tool for mining for the use on a cross-project basis.

There could be achieved valuable operational goals in each of the two performed case studies by the use of the adapted simulation tool. The quarry operations have been examined for profitability of stockpile use for ore transport, influence of dumper size on ore transport and transport capacity by increasing hauling distance using variable equipment composition.

Gained knowledge during the case studies has been transferred to a simulation procedure suited for simulation studies in quarry mining. Important phases of simulation have been identified and strategies for successful completion including pre-designed spreadsheets have been developed. The procedure highly values the verification and validation of achieved results. Consistently, suitable test methods are proposed for each phase result, which include statistical tests for the data collection and data preparation phase as well as fixed value test and internal validity test for implementation and execution of the simulation model.

The comparison of results achieved by simulation approach and deterministic spreadsheet approach has revealed that simulation is beneficial when interactions of equipment are hardly predictable due to their dependence on dynamic processes. Although the profitable use of stockpiling could be generally determined by both analytical methods, the DES model could benefit from reproduction of the decision-making behavior of the real stockpiling system and thus could determine most effective equipment composition. On the other hand, ineffective use of a bigger sized dump truck by increased hauling distance could be easily analyzed by deterministic calculation by leading only to small deviations compared to the simulation model.

Although modeling effort of the simulation model is low by the helpful use of pre-defined modules, work effort of experimental evaluation, excluding data collection, is still six times higher than spreadsheet analysis due to the need of verification and validation methods and creation of confidence intervals for simulation results. Thus, applicability of DES should be limited to the analysis of more complex interaction of equipment. Reduction of work effort can possibly be achieved by replacing statistical distributions by deterministic values in the simulation model. However, every simplification must be checked individually for the unbiasedness of KPI's.

Bibliography

Awuah-Offei K (2010) Reducing the carbon footprint through improved production practices. With assistance of David Summers. Edited by Illinois Clean Coal Institute (ICCI). Available online at https://www.arenasimulation.com/resources/Reducing_Energy_Consumption.pdf.

Awuah-Offei K (2012) Improving Truck-Shovel Energy Efficiency Through Discrete Event Modeling. In : SME Annual Meeting Preprint, Society of Mining, Metallurgy & Exploration. SME Annual Meeting. Seattle, WA, February 19-22.

Bangsow S (2011) Praxishandbuch Plant Simulation und SimTalk. Anwendung und Programmierung in über 150 Beispiel-Modellen. München, Hanser Verlag. ISBN: 978-3-446-42782-2.

Basu A (1999) Discrete event simulation of mining systems. Current practice in Australia. In *International Journal of Surface Mining, Reclamation and Environment* 13 (2), pp. 79–84. DOI: 10.1080/09208119908944214.

Berner M (2014) Erstellung eines Lastenheftes für eine Bergbausimulations-Software für die Gipsgewinnung und nachfolgendem Abgleich mit marktüblichen Softwarelösungen. Entwicklung und Bewertung eines Prozessmodells. Master's Thesis. With assistance of M.Sc. Markus Dammers. Aachen.

Berner M (2015) Cost optimization of gypsum mining operations using a PLM simulation tool. With assistance of Wolfgang Voigt. In Martens P (Ed.): Aachen Internatinal Mining Symposia (AIMS) (27./28.05.2015). Stolberg (Rhld.), Zillekens, Ralf, pp. 45–57.

Coronado P& Tenorio V (2015) Optimization of Open Pit Haulage Cycle Using a KPI Controlling Alert System and a Discrete-Event Operations Simulator. In Bandopadhyay S (Ed.): Application of computers and operations research in the mineral industry. Englewood, Colo., Society for Mining Metallurgy & Exploration Inc. (SME).

Darling, Peter (Ed.) (2011) SME mining engineering handbook. Society for Mining, Metallurgy, and Exploration (U.S.). 3rd ed. Englewood, Colo., Society for Mining Metallurgy and Exploration. ISBN: 9780873352642.

Eley M (2012) Simulation in der Logistik. Einführung in die Erstellung ereignisdiskreter Modelle unter Verwendung des Werkzeuges "Plant Simulation". Berlin-Heidelberg, Springer. ISBN: 978-3-642-27372-8.

Erbrecht R (2005) Das große Tafelwerk interaktiv. 1. Aufl., 5. Dr. Berlin, Cornelsen. ISBN: 3-464-57148-3.

Fioroni M, Franzese L, Bianchi T et al. Concurrent simulation and optimization models for mining planning. In : 2008 Winter Simulation Conference (WSC). Miami, FL, USA, pp. 759–767.

Fioroni M, Franzese L, Zanin C et al. Simulation of continuous behavior using discrete tools: Ore conveyor transport. In : 2007 Winter Simulation Conference. Washington, DC, USA, pp. 1655–1662.

Fishman G (2001) Discrete-event simulation. Modeling, programming, and analysis. New York, Springer. ISBN: 0387951601.

Gbadam E, Awuah-Offei K& Frimpong S (2015) Investigation into Mine Equipment Subsystem Availability & Reliability Data Modeling Using DES. In Bandopadhyay S (Ed.): Application of computers and operations research in the mineral industry. Englewood, Colo., Society for Mining Metallurgy & Exploration Inc. (SME).

Greberg J, Salama A, Gustafson A& Skawina B (2016) Alternative Process Flow for Underground Mining Operations. Analysis of Conceptual Transport Methods Using Discrete Event Simulation. In *Minerals* 6 (3), p. 65. DOI: 10.3390/min6030065.

Knauf (2016) Knauf Gips KG. Wir über uns. Available online at https://www.knauf.de/profi/wir-bei-knauf/ueber-uns/, updated on 7/4/2016.

Kolonja B& Mutmansky J (1993) Analysis of truck dispatching strategies for surface mining operations using SIMAN. In : Papers for Presentation at the SME Annual Meeting: Reno, Nevada, February 15-18, 1993. Littleton, Colo., Society for Mining, Metallurgy, and Exploration.

Law A (2015) Simulation modeling and analysis. 5. ed. New York, NY, McGraw-Hill Education (McGraw-Hill series in industrial engineering and management science). ISBN: 9780073401324.

Michalakopoulos T, Roumpos C, Galetakis M& Panagiotou G (2015) Discrete-Event Simulation of Continuous Mining Systems in Multi-layer Lignite Deposits. In Niemann-Delius C (Ed.): Proceedings of the 12th International Symposium Continuous Surface Mining - Aachen 2014. Cham, s.l., Springer International Publishing, pp. 225–239.

Palisade (2016). Available online at http://www.palisade.com/cart/products_EN.asp?cat=51&panel=0.

Panagiotou G (1999) Discrete mine system simulation in Europe. In *International Journal of Surface Mining, Reclamation and Environment* 13 (2), pp. 43–46. DOI: 10.1080/09208119908944208.

Rabe M, Spiekermann S & Wenzel S (2008) Verifikation und Validierung für die Simulation in Produktion und Logistik. Vorgehensmodelle und Techniken. Berlin, Heidelberg, Springer. ISBN: 978-3-540-35281-5.

Rooch A (2014) Statistik für Ingenieure. Wahrscheinlichkeitsrechnung und Datenauswertung endlich verständlich. Berlin, Springer Spektrum. ISBN: 978-3-642-54857-4.

Shishvan M& Benndorf J (2014) Performance optimization of complex continuous mining system using stochastic simulation. In Rodrigues H, Herskovits J, Mota Soares C, Miranda Guedes J, Araujo A, Folgado J et al. (Eds.): Engineering Optimization 2014. Hoboken, Taylor and Francis, pp. 273–278.

Siemens (2014) Plant Simulation. Available online at http://www.plm.automation.siemens.com/de_de/products/tecnomatix/manufacturing-simulation/material-flow/plant-simulation.shtml, updated on 9/19/2014.

Storm R (2007) Wahrscheinlichkeitsrechnung, mathematische Statistik und statistische Qualitätskontrolle. Mit 20 Tafeln und 120 Beispielen. 12., [verb.] Aufl. Leipzig. ISBN: 978-3-446-40906-4.

Sturgul J (1999) Discrete mine system simulation in the United States. In *International Journal of Surface Mining, Reclamation and Environment* 13 (2), pp. 37–41. DOI: 10.1080/09208119908944207.

Tarshizi E (2015) Using Discrete Simulation & Animation to Identify the Optional Sizes and Locations of Mine Refuge Chambers. In Bandopadhyay S (Ed.): Application of computers and operations research in the mineral industry. Englewood, Colo., Society for Mining Metallurgy & Exploration Inc. (SME).

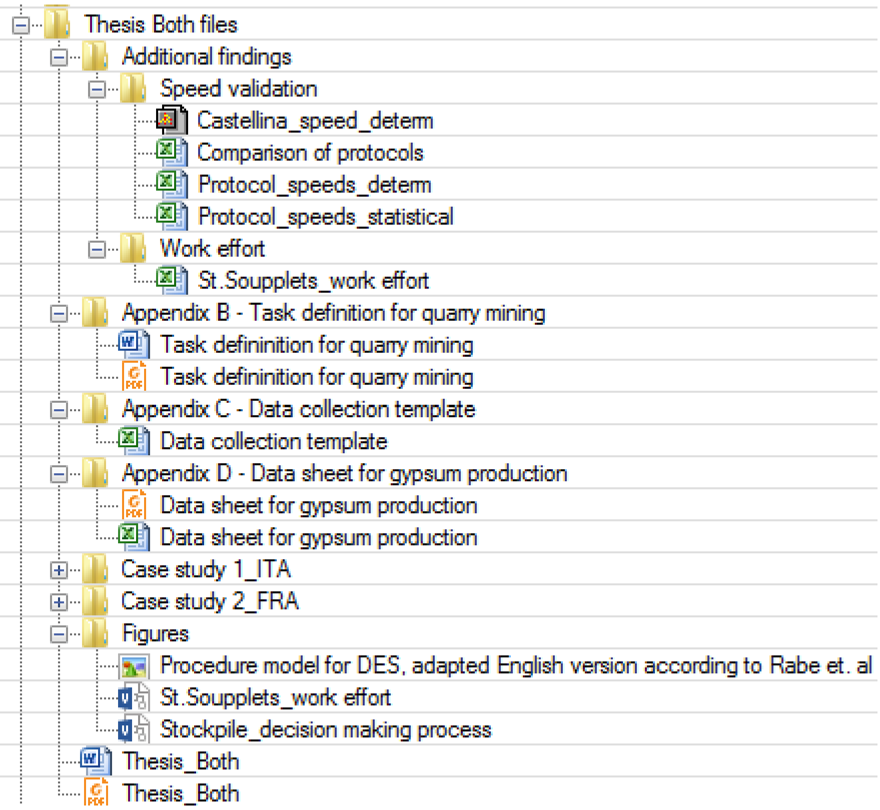
Upadhyay S, Askari-Nasab H, Tabesh M& Badiozamani M (2015) Simulation & Optimization in Open Pit Mining. In Bandopadhyay S (Ed.): Application of computers and operations research in the mineral industry. Englewood, Colo., Society for Mining Metallurgy & Exploration Inc. (SME).

VDI (2014) VDI-Richtlinie 3633 Blatt 1 "Simulation von Logistik-, Materialfluss und Produktionssystemen", engl. : VDI-Directive 3633 Page 1 "Simulation of systems in materials handling, logistics and production". Düsseldorf, VDI (03.100.10).

Volvo (2016) Technische Daten - A60H : Volvo Construction Equipment - Deutschland. Available online at http://www.volvoce.com/constructionequipment/europe/de-de/products/articulatedhaulers/A60H/Pages/specifications.aspx, updated on 7/14/2016.

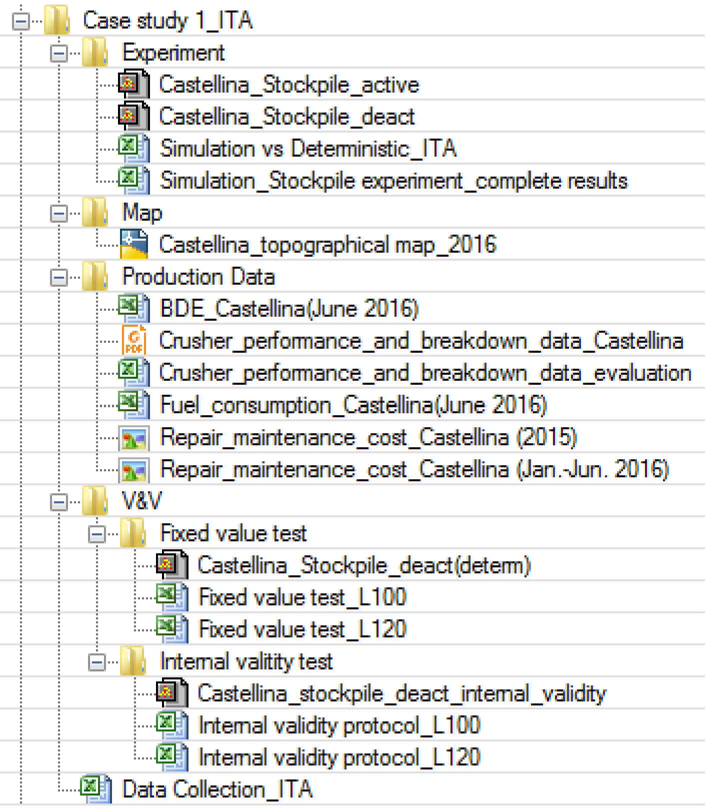
Appendix A – Folder structure of supplemental digital files

Folder structure (case study folders closed)



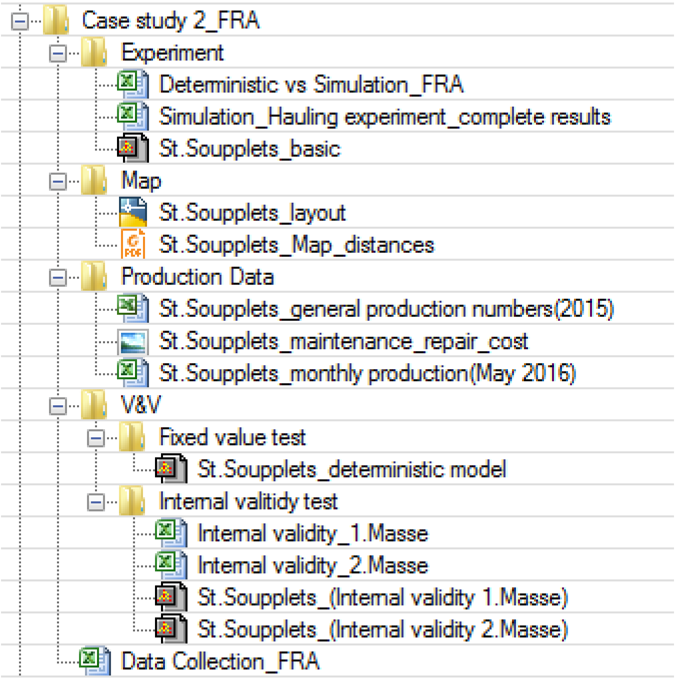
- Thesis Both files
  - Additional findings
    - Speed validation
      - Castellina_speed_determ
      - Comparison of protocols
      - Protocol_speeds_determ
      - Protocol_speeds_statistical
    - Work effort
      - St.Soupplets_work effort
  - Appendix B - Task definition for quarry mining
    - Task defininition for quarry mining
    - Task defininition for quarry mining
  - Appendix C - Data collection template
    - Data collection template
  - Appendix D - Data sheet for gypsum production
    - Data sheet for gypsum production
    - Data sheet for gypsum production
  - Case study 1_ITA
  - Case study 2_FRA
  - Figures
    - Procedure model for DES, adapted English version according to Rabe et. al
    - St.Soupplets_work effort
    - Stockpile_decision making process
  - Thesis_Both
  - Thesis_Both

Folder structure case study 1



- Case study 1_ITA
  - Experiment
    - Castellina_Stockpile_active
    - Castellina_Stockpile_deact
    - Simulation vs Deterministic_ITA
    - Simulation_Stockpile experiment_complete results
  - Map
    - Castellina_topographical map_2016
  - Production Data
    - BDE_Castellina(June 2016)
    - Crusher_performance_and_breakdown_data_Castellina
    - Crusher_performance_and_breakdown_data_evaluation
    - Fuel_consumption_Castellina(June 2016)
    - Repair_maintenance_cost_Castellina (2015)
    - Repair_maintenance_cost_Castellina (Jan.-Jun. 2016)
  - V&V
    - Fixed value test
      - Castellina_Stockpile_deact(determ)
      - Fixed value test_L100
      - Fixed value test_L120
    - Internal valitity test
      - Castellina_stockpile_deact_internal_validity
      - Internal validity protocol_L100
      - Internal validity protocol_L120
  - Data Collection_ITA

Folder structure case study 2



- Case study 2_FRA
  - Experiment
    - Deterministic vs Simulation_FRA
    - Simulation_Hauling experiment_complete results
    - St.Soupplets_basic
  - Map
    - St.Soupplets_layout
    - St.Soupplets_Map_distances
  - Production Data
    - St.Soupplets_general production numbers(2015)
    - St.Soupplets_maintenance_repair_cost
    - St.Soupplets_monthly production(May 2016)
  - V&V
    - Fixed value test
      - St.Soupplets_deterministic model
    - Internal valitidy test
      - Internal validity_1.Masse
      - Internal validity_2.Masse
      - St.Soupplets_(Internal validity 1.Masse)
      - St.Soupplets_(Internal validity 2.Masse)
  - Data Collection_FRA