Journal of Sustainable Mining 16 (2017) 24–30

Contents lists available at ScienceDirect

Journal of Sustainable Mining

journal homepage: http://www.elsevier.com/locate/jsm

The need for sustainable technology diffusion in mining: Achieving the use of belt conveyor systems in the German hard-rock quarrying industry

Tobias Braun*, Alexander Hennig, Bernd G. Lottermoser

Institute of Mineral Resources Engineering, RWTH Aachen University, Wuellnerstrasse 2, 52062 Aachen, Germany

ARTICLE INFO

Article history:
Received 15 March 2017
Received in revised form
13 June 2017
Accepted 26 June 2017
Available online 27 June 2017

Keywords:
Transportation
Technology diffusion
Sustainable mining
Belt conveyor
Energy efficiency
Cluster analysis

ABSTRACT

The movement of raw materials can be one of the most challenging tasks in open pit mining, with truck transportation representing the largest factor in mining costs and resulting in major greenhouse gas (GHG) emissions. In this study, the transportation methods of bulk materials within German hard-rock open pit mines were investigated. Approximately 450 quarries were studied for their production tonnage, lease areas, mined rock type as well as mining methods and processing equipment. The results demonstrate that 90% of the operations use truck-based transportation methods, with the remainder relying partly or completely on continuous conveyor-based systems. The installation of continuous conveyors compared to trucks represents a real alternative because of reduced dead load, reduced GHG emissions and in many cases even reduced costs. Thus, for in-pit haulage in quarries sustainable technology substitutions exist that are yet to be adopted by the German quarrying industry. As this study shows, in the future the diffusion of sustainable technologies requires site champions and large-scale case studies that demonstrate their successful introduction in the mining value chain.

1. Introduction

The pit and quarry industry is a significant economic enterprise in Germany, as this activity generates a yearly revenue of more than 3600 Million € and supports about 60 000 employees (Basten, 2011, 2015; DESTATIS, 2015a; StMWI, 2014). Every year, 550 Mt of materials are produced, making Germany self-sufficient in the production of crushed stone, sand and gravel (Babies et al., 2011; Schwarzkopp, Drescher, Goring, & Blazejczak, 2013). The largest products include: sands and gravel for construction works (238 Mt annual production), broken natural stones (211 Mt annual production) and carbonate rocks (64 Mt annual production) (Huy et al., 2015). Broken natural stones and most of the carbonate rocks are extracted in more than 1000 quarries in Germany, which are the subject of this study. With an energy consumption of 12.3% of the gross production value, the extraction of natural stones is one of the most energy-intensive industries in Germany (DESTATIS, 2015a). Overall, an annual energy consumption of 1900 Million kWh (DESTATIS, 2015a, 2016; DIHK, 2016; Huy et al., 2014; KTBL, 2012) is incurred, with emissions of about 0.57–1.15 Mt CO2-equivalents (Fritsche & Schmidt, 2007; Icha & Kuhs, 2015), depending on which energy source is used (DESTATIS, 2014, 2016; Frischknecht, Stucki, Flury, Itten, & Tuchschmid, 2012; Icha & Kuhs, 2015). As with other industrial minerals, only the extraction and processing of large masses of broken natural stones and carbonate rocks are economic. Extraction of these mineral resources is almost limited to open pits, and haulage distances up to several hundred meters from the loading point to the dumping area are common. Therefore, internal haulage greatly impacts on extraction costs (about 40%–50%) and energy consumption (about 40%) (Schmieder, 2007; Skrypzak, 2015; Vergne, 2014; Zimmermann & Kruse, 2006, pp. 481–487).

As a contribution to global climate protection, the European Union aims for a reduction of 40% of greenhouse gas-emissions (GHG) of all member countries by the year 2030 compared to the emissions of 1990. The German Government supports these targets with an even more ambitious program, which aims for a reduction of 40% by 2020 and eventually, even an 80%–95% reduction by 2050. Additionally, an increase in energy efficiency by 30% by 2030 should be achieved (Weiβ, Welke, Kahlenborn, & Brünig, 2015). Optimizing existing technologies and operational structures, or

* Corresponding author.
E-mail address: Braun@mre.rwth-aachen.de (T. Braun).

http://dx.doi.org/10.1016/j.jsm.2017.06.003

substituting them with more energy-efficient and low-emission technologies can make a major contribution to this goal and to the sustainable development of the mining industry (Brewer, 2012; Dubiński, 2013).

The introduction of new and alternative technologies is often hindered by risk-barriers and inhibition. In addition to economic risks, reliable information can be missing for new technologies and their possible applications (Corazza, Guida, Musso, & Tozzi, 2016). The primary approach to handling these risk barriers and to reducing these inhibition thresholds, is to generate a broader knowledge base and to make information for branch-specific application potentials available. This can be realized through completed case studies with large sample sizes (Trianni, Cagno, & Worrell, 2013).

The present study is focused on the possible introduction of energy-efficient and low-emission technologies in German hard-rock quarries, while considering their economic impact and viability. Taking into account the economic and energetic importance of internal haulage, transportation of hard-rock commodities is the most significant bottleneck for optimization and, hence, changes in haulage systems are associated with significant uncertainties for the operation. Consequently, conventional transportation using dump trucks has rarely been substituted by other technologies. Yet, continuously working conveyor belts represent a promising alternative for transporting mined materials. Such technology has successfully been implemented in other areas of the raw material extraction business (Moore, 2011, 2012; Stoll, Niemann-Delius, Drebenstedt, & Müllensiefen, 2008). Here, the amount of dead load can be reduced by up to 80%, and local emissions can be prevented and generally down-sized (Norgate & Haque, 2013; Zimmermann & Kruse, 2006). The commonly recognized economic and technical application constraints, which limit the use of conveyor belts to implementation in open pits with great transportation distances, high production tonnages and primarily loose rock, are based on data and experiences from early applications of this technology (Goergen et al., 1987; Korak, 1978) and are therefore partially obsolete. Technological improvements in general and especially the technical advancement of mobile crusher units have loosened the application constraints for conveyor belts at least from a technical point of view (Darling, 2011; Turnbull & Cooper, 2009, pp. 60–77).

The majority of small quarry operations (Basten, 2011) commit to high entrepreneurial risk when testing a new technology in practice. Considering first of all that transportation in quarrying represents the biggest cost factor and secondly that currently neither a benchmark nor a characteristic reference operation for the implementation of alternative transport technologies exists, the implementation is perceived as high risk (Vergne, 2014). This in turn leads to the persistent use of approved conventional transport technologies. As a result, economic and, especially, sustainable optimization potentials through technology-substitutions are generally being ignored (Braun & Hennig, 2016).

The aim of this study is to quantify the sustainable and economic optimization potentials by applying belt conveyors in German hard-rock quarries. The results of this research contribute to continuously growing efforts to have more energy efficient and low-emission technologies applied in the extraction of mineral resources.

2. Methods

A comprehensive analysis of the German quarry industry was completed based on detailed analyses of public databases and published literature, extensive aerial photography examinations of individual mine sites and structured industry surveys. Initially, detailed aerial examinations were conducted on ~450 hard-rock quarries to capture geometric dimensions and optical ascertainable properties of individual mine sites. Subsequently, a structured and tailored research survey comprising a series of questions was submitted to selected pit and quarry companies. The survey questions covered operational and geological data, including production tonnage, lease areas, mined rock type, mining methods and processing equipment. The company survey was distributed to 120 quarry operations in Germany, with an overall response rate of 51% (for a detailed presentation of the survey see Braun & Hennig, 2016).

Additional data was gathered using publically available information. Since publically available data is limited and comprehensive documentation of German quarries is missing, the study had to rely on data gathered for a limited number of mining operations. Yet to ensure that the dataset accurately reflects the entire German hard-rock industry, a large quantity of quarries were chosen (n ~450) whose characteristics represent an unbiased indication of what the industry is like.

Moreover, historical data on energy consumption and equipment application in the German quarry industry (1990–2013) was evaluated. For this, a study on position optimization for primary crushers dating from the year 1990 and evaluating 56 quarries was examined (Stoll, Dohmen, & Platzek, 1990). Furthermore, to come to meaningful conclusions about the development of energy efficiency in the German quarry industry, additional data taken from the cost structure survey, conducted by the Federal Statistical Office of Germany for the years 2003, 2007, 2010 and 2013, was analyzed (DESTATIS, 2005, 2009, 2012, 2015b).

On the basis of cluster analysis, the analyzed database was structured and particular reference operations were determined (cf. section 3). Through the compression of large amounts of data and concentration being placed on the most important properties, clustering reduces the required time and research expenditure while preserving a high quality of analysis (Kijewska & Bluszcz, 2016). The cluster analysis was performed by using the statistical software program "IBM SPSS Statistics" and the spreadsheet program "Microsoft Excel". Subsequently, through a qualitative examination of the cluster solution, the application potentials of belt conveyors in German quarries could be hypothesized (for details on the subject of cluster analysis see Backhaus, Erichson, Plinke, & Weiber, 2011; Hair, Black, Babin, & Anderson, 2010; Kijewska & Bluszcz, 2016).

3. Results

The results from the acquired data demonstrate that the total production of broken natural stones and carbonate rocks has decreased since the early 1990s by 15% from 320 Mt/a to 273 Mt/a in 2013 (BGR, 1997, 2000; Huy et al., 2014; Schwarzkopp et al., 2013). Significant changes in total production have not occurred since 2003 (Fig. 1). While the total production of broken hard-rock material has declined over the last twenty years, the average material produced per quarry remained almost constant over the same period (1990: 280 000 t per quarry; 2013: 270 000 t per quarry).

The average lease area per quarry slightly decreased from 24 ha to 20 ha. Similarly, the average number of levels per quarry decreased from 4 in 1990 to 3 in 2016. The mean bench height still remains at about 20 m (Braun & Hennig, 2016; Stoll et al., 1990).

Evaluation of the in pit process chain shows a nearly constant use of equipment. The material is still almost exclusively extracted by drilling and blasting and the loading is almost always realized by wheel loaders and excavators. Results of the study of Stoll et al. (1990) clearly show that fully mobile crushers were not used in 1990. Moreover, in 14% of all observed quarries, a combination of

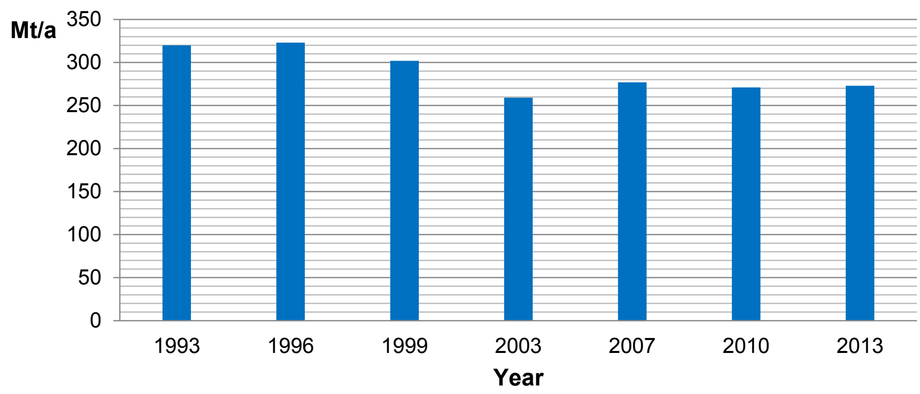

Fig. 1. Total production of broken natural stones and carbonate rocks in Germany from 1993 to 2013 (BGR, 1997, 2000; Huy et al., 2014; Schwarzkopp, 2013).

truck haulage and belt conveying connected by semi-mobile crushers was applied. However, the actual use of semi-mobile crushers may have been lower at that time because the study (Stoll et al., 1990) concentrated on crusher positions in quarries, possibly leading to a bias towards quarries applying these technologies.

Since the 1990s, the application of belt conveyors and fully mobile crushers slightly increased in the German hard-rock mining industry. Analysis of the industry survey data indicates that today 8% of all quarries use a combined transportation method with trucks and belt conveyors and 2% of all quarries use belt conveyors in combination with a fully mobile crusher (Fig. 2) (Braun & Hennig, 2016).

Thus, over the last twenty years there have been no significant changes in the German hard-rock quarry industry with respect to the production rate and the use of energy-efficient transport technologies. This lack of change is also reflected in the energy consumption pattern in the German hard-rock industry over the last ten years (Fig. 3) (DESTATIS, 2005, 2009, 2012, 2015b). From 2003 to 2013, there have been considerable fluctuations in the total energy consumption in the quarry industry. However, fluctuations in total energy consumption depend on the responses to the cost structure survey (2007: 109 companies; 2013: 139 companies) (DESTATIS, 2005, 2009, 2012, 2015b). When considering the total number of quarry companies, a decrease in the specific energy consumption per quarry company from 11.8 to 11.2 Mill kWh can be observed (Fig. 3). However, over the same period there has been a minimal increase of the energy intensity in the quarry industry from 11.9% to 12.3% (Fig. 3). Consequently, while there have been large fluctuations in the total energy consumption in the German quarry industry, the energy intensity per gross production value was largely constant over the last decade.

The European Union targets a 30% reduction of energy intensity for all member countries by the year 2030 compared to 1990. Hence, energy efficiency needs to be increased, or energy intensity should be lowered by 10% per decade. The German Government pursues even more ambitious objectives and decreased the total energy consumption by 12% per citizen from 2003 to 2013 (BMWI, 2016). To achieve similar positive developments in the German quarry industry, appropriate energy-efficient technologies and optimizations need to be implemented. An industry-wide application of belt conveyors in German quarries could support such targets.

In this study an analysis of the application of truck and belt conveyor transportation in German quarries was carried out. This analysis took the form of cluster analysis. Each cluster represents a group of objects with similar characteristics or properties in a representative sample of approximately 450 quarries. This ensures that the research results are valid to the rest of the objects within the group. Whether open pits are suitable for the implementation of different transport techniques depends, predominantly, on the width and length of the pit, which in turn influences the hauling distance. Furthermore, pit depth is also a major controlling factor. For each investigated quarry, the pit depth was determined by multiplying the number of levels and the average bench height in German quarries of 19 m (Braun & Hennig, 2016). Additionally, the required production tonnage as well as the direction (uphill or downhill) and the inclination of the transportation route have a decisive influence on the dimensioning of the equipment. The production tonnage could not be determined for every object in the sample, as the annual production tonnage is often confidential information. Therefore, this characteristic consequently can only be taken into account in the final profiling of a cluster. While the inclination of a ramp

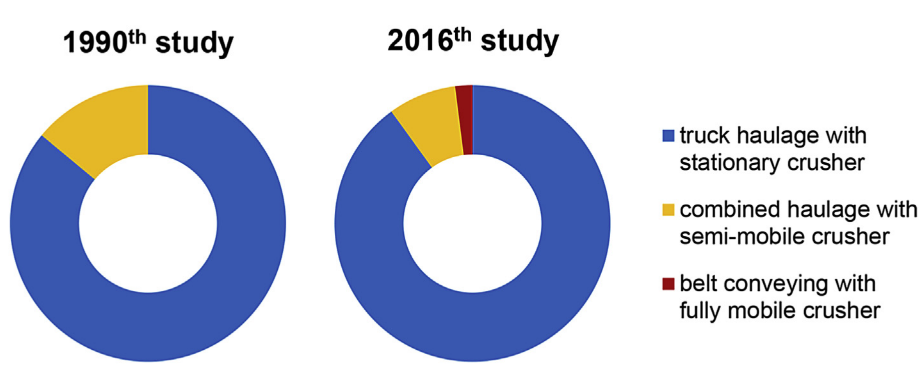

Fig. 2. Distribution of the application of different transportation methods in 1990 and in 2016 (Braun & Hennig, 2016; Stoll et al., 1990).

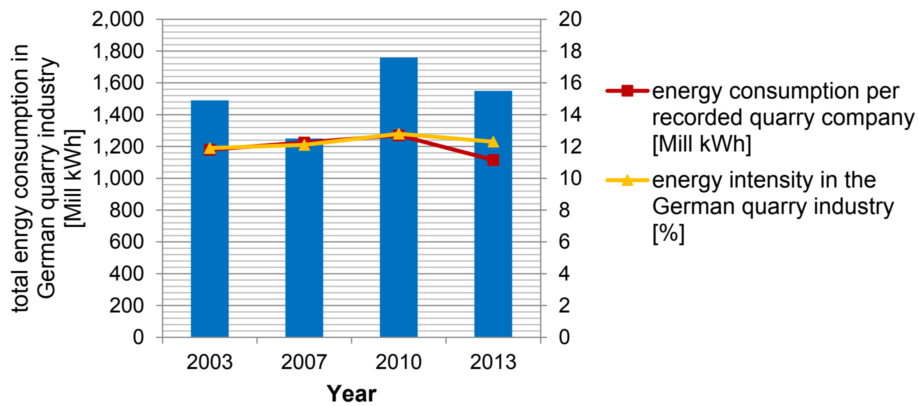

Fig. 3. Development of energy consumption and energy intensity in the German quarry industry from 2003 to 2013 (DESTATIS, 2005, 2009, 2012, 2015b).

depends on ramp length and altitude difference, the direction is determined by the mining method, i.e. slope mining (applied in 49% of all examined quarries), mining to depth (30%) or a combination of both (21%) (Braun & Hennig, 2016). Production tonnage and the different mining methods could not be taken into consideration for the cluster analysis, but they are taken into account in the final profiling and the further subdivision within a cluster. Consequently, the characteristics "pit-depth" and "pit-size" are employed for the profiling (Fig. 4).

Cluster analysis took place once captured quarry data was imported and a z-standardization (Holling & Gediga, 2011; Schels, 2008) of the relevant quarry properties lease pit area and pit depth was carried out (Fig. 4). Outliers in the data base were eliminated through the application of the single linkage procedure (Backhaus et al., 2011; Everit, Landau, Leese, & Stahl, 2011). Afterwards, the determination of an optimum number of clusters, realized through a combination of the Elbow criterion and the Mojena test (Backhaus et al., 2011), led to the successful classification of eleven clusters. For the actual clustering the cluster centroids were determined by first applying the Ward method. In the second stage, the received solution was optimized by using the k-Means method (Bortz, 2005; Eckey, Kosfeld, & Rengers, 2002; Hetzel, 2012). After a validity check using cross validation, the final cluster solution was determined (Table 1).

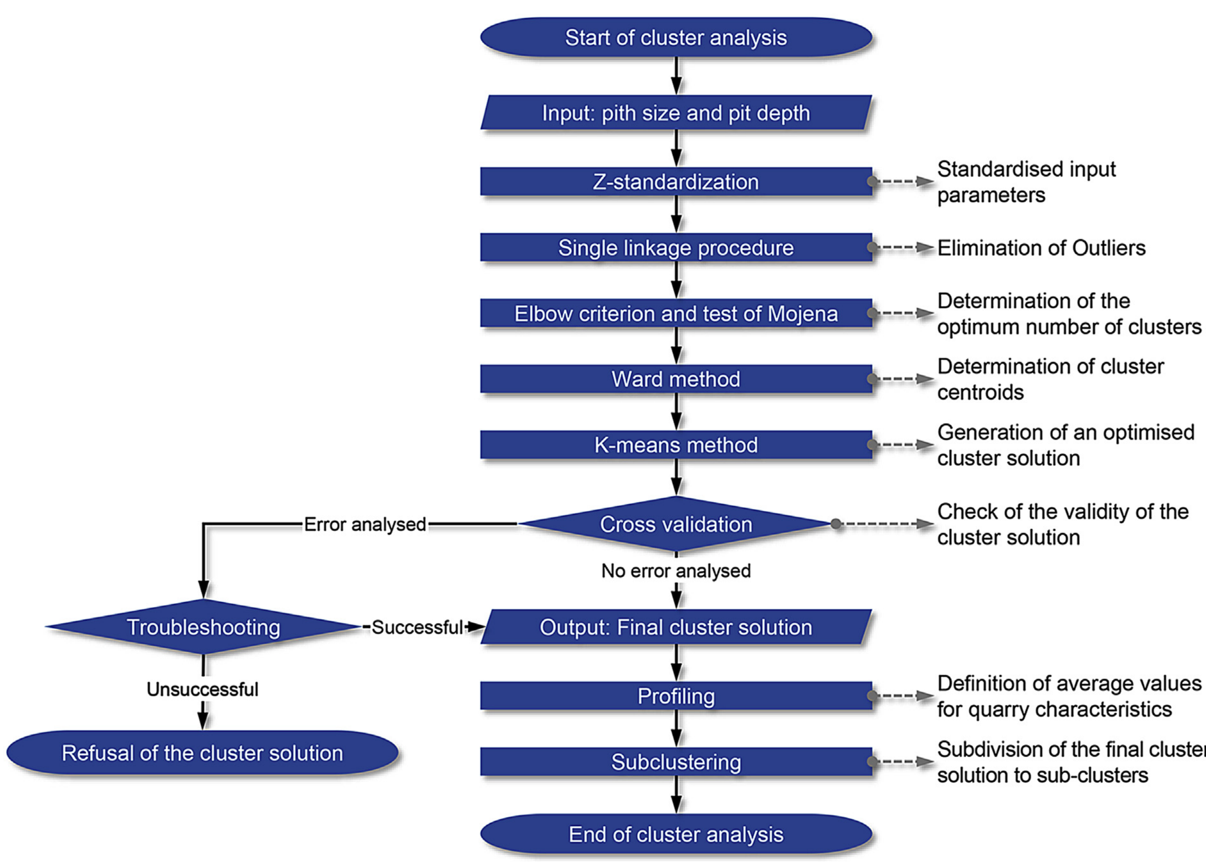

Fig. 4. Procedure of the cluster analysis.

Table 1
Characteristic details of the final cluster solution.

Cluster-no.	1	2	3	4	5	6	7	8	9	10	11
Pit-size [1,000 m^2]	116	220	90	106	224	1030	316	658	257	594	190
Total range of pit-size [1,000 m^2]	25–216	154–357	11–160	17–172	156–370	910–1.140	226–430	540–745	195–398	483–723	72–320
Production tonnage [1,000 t/a]	200	690	275	390	460	2375	680	1610	1400	1640	800
Total range of production tonnage [1,000 t/a]	150–300	380–1200	100–400	300–500	250–675	2000–2750	300–990	960–2800	1300–1500	400–3000	320–1200
Number of levels	3	4–5	1–2	4–5	1–2	4	3	3	8	5	6–7

The further subdivision and specification of the received cluster solution by three mining methods led to 33 sub-clusters. Qualitative examination of the defined clusters shows that 8 out of 11 clusters (cluster no. 1, 3, 4, 5, 6, 7, 8 and 11) include a real quarry in which the in pit haulage has already been realized by a fully mobile belt conveyor system (Fig. 5). Through additional consideration of the mining method, used in the respective quarries, it becomes obvious that in 8 of these quarries mining to depth is executed and in two quarries combined mining takes place. With respect to the proportional distribution of these quarries to the single clusters and to the further subdivision of the mining method, it appears that about 41% of all examined quarries are part of sub-clusters, containing one of these quarries. With regard to the total population of 456 examined quarries, 187 quarries are affected.

The assessment of the characteristics of the respective clusters reveals a broad range for the economic application of belt conveyors (Fig. 5). Current applications of fully mobile belt conveyor systems indicate their possible economically viable application in quarries with: pit depths between 20 m and 140 m, lease pit areas between 90 m^2 and 1030 m^2 and production tonnages from 200 kt/a to 2375 kt/a. Furthermore, no current application of fully mobile belt conveyors is recorded in quarries applying slope mining. Thus it appears that uphill transportation favours the economic application of belt conveyors. The economic application of belt conveyors in 41% of all German quarries would promise a significant reduction in GHG emissions. Considering that 40% of the overall energy consumption in quarries is related to internal haulage a consumption of about 310 Million kWh/a is affected. Hence, depending on the corresponding energy mix, between 0.1 and 0.2 Mt CO2-equivalents can be avoided by the economic application of belt conveyor systems in the proposed application area.

4. Discussion

The findings of the study suggest that the application of belt conveyors could be economically viable in about 41% of the German quarries. A crucial criterion for the economic application of belt conveyors in quarries is their use of the executed mining method. In principle, higher energy intensity is required for uphill transportation than for downhill transportation or transportation on a flat surface. Thus, as the study shows, increased uphill transportation of mined material favours the application of belt conveyors in hard-rock quarries. Compared to current scientific knowledge, the confirmation of this hypothesis will significantly expand the economic application field of fully mobile crushing and belt conveyor systems. The only numerical limitation of the application field dates back to a study from 1987. This study constrains the economic application to open-pit mines, which produce mass movement of more than 1 Mt/a and to a pit depth greater than 250 m (Korak, 1978). In contrast, this paper reveals its potential for annual tonnages between 0.2 Mt/a and 2.4 Mt/a, pit depths between 20 m and 140 m and transport distances of few hundred meters (cf. Table 1). More recent studies limit the economic application to large hard rock mines and mines in which material excavation could be realized without blasting (Darling, 2011) or to mines in which the average truck haulage cycle time exceeds 25 min, which is the case for transport distances of several kilometers (Turnbull & Cooper, 2009).

In order to specify and verify these promising results in a further study, a comparison of belt conveyor transportation and truck transportation must be carried out for every sub-cluster. Moreover, through sensitivity analysis, the fringe of a cluster should be included in the scope of calculation and thus its transferability

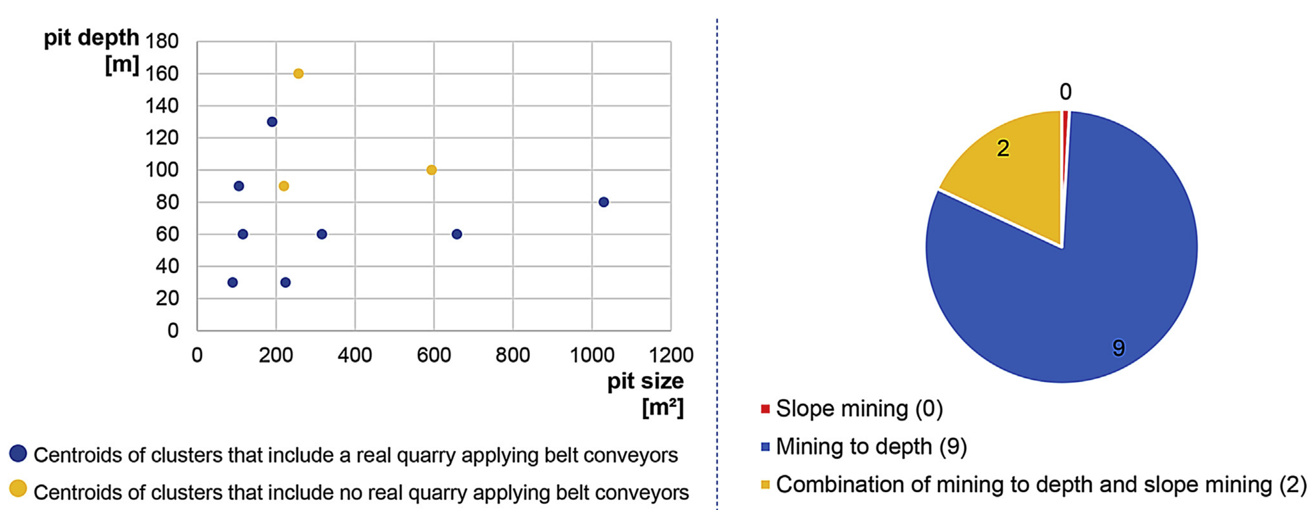

Fig. 5. Illustration of characteristics of clusters that include a real quarry in which the in pit haulage has already been realized by a fully mobile belt conveyor systems.

could be improved. Additionally, the performance and cost parameters of the applied transportation equipment are heavily influenced by the employed extraction method (i.e. single bench mining or multiple bench mining). The capital expenditure for stationary belt conveyor systems, especially, is significantly influenced by whether the material extraction takes place on only one level or on two levels at the same time. Hence, a further subdivision of the current cluster solution by different extraction methods must be carried out. By limiting the cluster analysis to single level mining and multiple bench mining, 66 sub-clusters for the calculation must be examined. Finally, the diffusion of the identified potentials requires site champions that adopt the information of this large-scale case study and introduce energy efficiencies in the German quarry industry.

5. Conclusions

This study demonstrates that the German quarry industry is still characterized by high energy intensity. While the overall energy intensity in Germany decreased by 12% between 2003 and 2013, the energy intensity in the quarry industry remained largely constant. Furthermore, results show that the general quarry structure did not change over the last 20 years. The average production tonnage and the claimed area of single quarries remain nearly constant. Considering the applied equipment in the different process steps as well as operational quarry properties, including bench height and number of levels, only minor changes are visible.

To date, the pursuit of sustainable optimization potentials has often been neglected in the German quarry industry. A major contribution to the optimization of these quarries could be achieved by substituting internal haulage, a procedure with a significant impact on extraction costs, with more energy-efficient and low-emission technologies. A promising alternative is the transport of mined materials by continuously working conveyor belts rather than by conventional truck haulage. The introduction of such technology would reduce dead load, decrease energy consumption and GHG emissions and in many cases even reduce costs. Derived from a first qualitative examination, the study reveals that the use of belt conveyors is economically viable for 41% of German quarries.

Conflict of interest

None declared.

References

Babies, H.-G., Buchholz, P., Homberg-Heumann, D., Huy, D., Messner, J., Neumann, W., et al. (2011). *DERA Rohstoffinformationen – deutschland Rohstoffsituation 2010 [DERA raw material information – Germany raw material situation 2010]*. Retrieved February 16, 2016 from https://www.bgr.bund.de.

Backhaus, K., Erichson, B., Plinke, W., & Weiber, R. (2011). *Multivariate Analysemethoden – eine anwendungsorientierte Einführung [Multivariate analysis methods – a practical introduction]*. Berlin, Heidelberg: Springer.

Basten, M. (2015). *Aufgaben, Themen und Ziele 2015/2016 [Tasks, Topics and Objectives 2015/2016]*. Retrieved February 16, 2016 from http://www.baustoffindustrie.de.

Basten, M. (2011). *Volkswirtschaftliches Porträt der deutschen Baustoffindustrie*. Retrieved February 16, 2016 from http://www.baustoffindustrie.de.

BGR. (1997). *Bundesanstalt für Geowissenschaften und Rohstoffe. Bundesrepublik Deutschland Rohstoffsituation 1996 [Federal Republic of Germany raw material situation 1996]*. Retrieved February 16, 2016 from https://www.schweizerbart.de.

BGR. (2000). *Bundesanstalt für Geowissenschaften und Rohstoffe. Bundesrepublik Deutschland Rohstoffsituation 1999 [Federal Republic of Germany raw material situation 1999]*. Retrieved February 16, 2016 from https://www.schweizerbart.de.

BMWI. (2016). *Bundesministerium für Wirtschaft und Energie. Energiedaten: Gesamtausgabe – stand: Januar 2016 [Energy data: collective edition – state: January 2016]*. Retrieved April 15, 2016 from https://www.bmwi.de.

Bortz, J. (2005). *Statistik für Human- und Sozialwissenschaftler [Statistics for human- and social scientists]*. Heidelberg, BW: Springer.

Braun, T., & Hennig, A. (2016). Untersuchungen zur Betriebsstruktur deutscher Natursteintagebaue [Studies of operation structures in German quarries]. *BHM Berg- und Hüttenmännische Monatshefte, 161*(4), 181–186.

Brewer, T. L. (2012). *International technology diffusion in a sustainable energy trade agreement (SETA)*. Retrieved March 9, 2016 from http://www.ictsd.org.

Corazza, M. V., Guida, U., Musso, A., & Tozzi, M. (2016). A European vision for more environmentally friendly buses. *Transportation Research Part D: Transport and Environment, 45*, 48–63.

Darling, P. (2011). *SME mining engineering handbook*. Englewood, CO: Society for Mining, Metallurgy, and Exploration.

DESTATIS. (2005). *Statistisches Bundesamt. Produzierendes Gewerbe – kostenstruktur der Unternehmen des Verarbeitenden Gewerbes sowie des Bergbaus und der Gewinnung von Steinen und Erden 2003 [Manufacturing industry – cost structures of companies in the manufacturing, mining and quarrying industry 2003]*. Retrieved April 15, 2016 from https://www.destatis.de.

DESTATIS. (2009). *Statistisches Bundesamt. Produzierendes Gewerbe – kostenstruktur der Unternehmen des Verarbeitenden Gewerbes sowie des Bergbaus und der Gewinnung von Steinen und Erden 2007 [Manufacturing industry – cost structures of companies in the manufacturing, mining and quarrying industry 2007]*. Retrieved April 15, 2016 from https://www.destatis.de.

DESTATIS. (2012). *Statistisches Bundesamt. Produzierendes Gewerbe – kostenstruktur der Unternehmen des Verarbeitenden Gewerbes sowie des Bergbaus und der Gewinnung von Steinen und Erden 2010 [Manufacturing industry – cost structures of companies in the manufacturing, mining and quarrying industry 2010]*. Retrieved April 15, 2016 from https://www.destatis.de.

DESTATIS. (2014). *Statistisches Bundesamt. Produzierendes Gewerbe – kostenstruktur der Unternehmen des Verarbeitenden Gewerbes sowie des Bergbaus und der Gewinnung von Steinen und Erden 2012 [Manufacturing industry – cost structures of companies in the manufacturing, mining and quarrying industry 2012]*. Retrieved February 16, 2016 from https://www.destatis.de.

DESTATIS. (2015a). *Statistisches Bundesamt. Produzierendes Gewerbe – kostenstruktur der Unternehmen im Baugewerbe [Manufacturing industry – cost structures of companies in the construction industry]*. Retrieved March 9, 2016 from https://www.destatis.de.

DESTATIS. (2015b). *Statistisches Bundesamt. Produzierendes Gewerbe – kostenstruktur der Unternehmen des Verarbeitenden Gewerbes sowie des Bergbaus und der Gewinnung von Steinen und Erden 2013 [Manufacturing industry – cost structures of companies in the manufacturing, mining and quarrying industry 2013]*. Retrieved April 14, 2016 from https://www.destatis.de.

DESTATIS. (2016). *Statistisches Bundesamt. Preise – daten zur Energiepreisentwicklung - lange Reihen von Januar 2000 bis Dezember 2015 [Costs – energy costs development data – extensive series from January 2000 to December 2015]*. Retrieved February 16, 2016 from https://www.destatis.de.

DIHK. (2016). *Deutscher Industrie- und Handelskammertag. Faktenpapier Strompreise in Deutschland 2016 – bestandteile, Entwicklungen, Strategien [Facts about energy costs in Germany 2016 – components, Development, Strategies]*. Retrieved April 15, 2016 from http://www.dihk.de.

Dubiński, J. (2013). Sustainable development of mining mineral resources. *Journal of Sustainable Mining, 12*(1), 1–6.

Eckey, H.-F., Kosfeld, R., & Rengers, M. (2002). *Multivariate statistik – grundlagen-methoden-beispiele [multivariate statistics – basics-methods-examples]*. Wiesbaden, HE: Gabler.

Everit, B. S., Landau, S., Leese, M., & Stahl, D. (2011). *Cluster analysis*. Chichester, West Sussex: Wiley.

Frischknecht, R., Stucki, M., Flury, K., Itten, R., & Tuchschmid, M. (2012). *Primärenergiefaktoren von Energiesystemen [Primary energy factors of energy systems]*. Retrieved March 9, 2016 from http://www.esu-services.ch.

Fritsche, U. R., & Schmidt, K. (2007). *Endenergiebezogene Gesamtemissionen für Treibhausgase aus fossilen Energieträgern unter Einbeziehung der Bereitstellungsvorketten – kurzbericht im Auftrag des Bundesverbands der deutschen Gas- und Wasserwirtschaft e.V. (BGW) [Final energy related overall emissions of greenhouse gases from fossil fuels including the upstream chain – abstract by order of the Federal Association of the German gas and water industry (registered association) (BGW)]*. Retrieved February 16, 2016 from http://www.iinas.org.

Goergen, H., Heckschen, P., Mählmann, H., Martens, P. N., Maschek, C., Schmitz, T., et al. (1987). *Festgesteinstagebau [hard rock open pit]*. Clausthal-Zellerfeld, NI: Trans Tech Publications.

Hair, J. F., Black, W. C., Babin, B. J., & Anderson, R. E. (2010). *Multivariate data analysis – a global perspective*. Upper Saddle River, NJ: Pearson.

Hetzel, C. (2012). *Arbeitsbedingungen und Gesundheit bei älteren Personen in Familienunternehmen – eine clusteranalytische Betrachtung [Labor conditions and health of elder employees in family-owned businesses – a cluster analytical reflection]*. Retrieved July 7, 2014 from http://www.svlfg.de.

Holling, H., & Gediga, G. (2011). *Statistik – deskriptive verfahren [statistics – descriptive methods]*. Göttingen, Bern, Wien, Paris, Oxford, Prag, Toronto: Hogrefe.

Huy, D., Andruleit, H., Babies, H.-G., Elsner, H., Homberg-Heumann, D., Meßner, J., et al. (2014). *Deutschland – rohstoffsituation 2013 [Germany – raw material situation 2013]*. Hannover, NI: BGR.

Huy, D., Andruleit, H., Babies, H.-G., Elsner, H., Homberg-Heumann, D., Meßner, J., et al. (2015). *Deutschland – rohstoffsituation 2014 [Germany – raw material situation 2014]*. Retrieved February 16, 2016 from https://www.bgr.bund.de.

Icha, P., & Kuhs, G. (2015). *Entwicklung der spezifischen Kohlendioxid– Emissionen des deutschen Strommix in den Jahren 1990 bis 2014 [Development of the specific carbon dioxide-emissions of the German energy mix from year 1990 to 2014]*. Retrieved February 16, 2016 from http://www.umweltbundesamt.de.

Kijewska, A., & Bluszcz, A. (2016). Analysis of greenhouse gas emissions in the European Union member states with the use of an agglomeration algorithm. *Journal of Sustainable Mining, 15*(4), 133–142. http://dx.doi.org/10.1016/j.jsm.2017.02.001.

Korak, J. (1978). *Technisch-Wirtschaftliche Untersuchung der Transportbetriebsmittel unter besonderer Berücksichtigung der Transportmittel-Kombination Fahrbare Brechanlage – gurtbandanlage für den Transport der Haufwerke im engeren Festgestein-Tagebaubereich [Technical-economic studies of transportation equipment considering especially the combination of mobile crusher-conveyor systems for the transportation of blasted rock in narrow open pit areas]*. Aachen, NRW: RWTH Aachen.

KTBL. (2012). *Kuratorium für Technik und Bauwesen in der Landwirtschaft e.V. Pflanzenöl [Plant oil]*. Retrieved February 16, 2016 from https://www.ktbl.de.

Moore, P. (2011). In-pit crushing and conveying – gathering momentum. *International Mining*, 28–38. May 2011.

Moore, P. (2012). The road to IPCC. *International Mining*, 18–28. May 2012.

Norgate, T., & Haque, N. (2013). The greenhouse gas impact of IPCC and ore-sorting technologies. *Minerals Engineering, 42*, 13–21.

Schels, H. (2008). *Vereinfachte Clusteranalyse mit Excel – clusteranalyse mit Excel nach einer der hierrarchischen Methoden (Single-Linkage) – kurzbeschreibung [Simplified cluster analysis with Excel – cluster analysis with Excel using one of the hierarchical methods (Single-Linkage) – abstract]*. Retrieved July 12, 2014 from http://www.staedtestatistik.de.

Schmieder, P. (2007). *Anwendung und Weiterentwicklung der Methodik der Umweltbilanzierung beim Abbau von Festgestein [Application and advancement of environmental balance methods in quarrying]*. Retrieved March 9, 2016 from http://webdoc.sub.gwdg.de.

Schwarzkopp, F., Drescher, J., Goring, M., & Blazejczak, J. (2013). *Die Nachfrage nach Primär- und Sekundär-rohstoffen der Steine-und-Erden-Industrie bis 2030 in Deutschland [The demand of primary and secondary raw materials of the quarrying-industry until 2030 in Germany]*. Retrieved February 16, 2016 from http://www.baustoffindustrie.de.

Skrypzak, T. (2015). *Identifizierung, Quantifizierung und Realisierung von Energieeinsparpotentialen innerhalb der übertägigen Gewinnung von Rohstoffen zur Verringerung der Freisetzung klimaschädlicher Gase und Ressourcenschonung [Identification, quantification and implementation of energy-saving potentials within the surface extraction of raw materials in order to conserve resources and reduce the release of climate-damaging gases]*. Retrieved April 15, 2016 from https://www.dbu.de.

StMWI. (2014). *Bayerisches Staatsministerium für Wirtschaft und Medien, Energie und Technologie. Industriebericht Bayern 2014-mit Branchenreport und Regierungsbezirksprofilen [Industry report Bavaria 2014 – with industries reports and profiles of administrative districts]*. Stamsried, BY: Druck+Verlag Ernst Vögel GmbH.

Stoll, R. D., Dohmen, M., & Platzek, W. (1990). *Optimierung der Standorte von Primärbrecheranlagen – AiF-Forschungsvorhaben Nr. 8701 der Forschungsgemeinschaft Naturstein- Industrie e. V. [Location optimization of primary crushers – AiF research project No. 8701 of the Research Foundation for quarrying (registered association)]*. Bonn, NRW: Forschungsgemeinschaft Naturstein-Industrie e.V.

Stoll, R. D., Niemann-Delius, C., Drebenstedt, C., & Müllensiefen, K. (2008). *Der braunkohlentagebau – bedeutung, planung, betrieb, technik, umwelt [the lignite open-pit – meaning, planning, operation, technology, environment]*. Berlin, Heidelberg: Springer-Verlag.

Trianni, A., Cagno, E., & Worrell, E. (2013). Innovation and adoption of energy efficient technologies – an exploratory analysis of Italian primary metal manufacturing SMEs. *Energy Policy, 61*, 430–440.

Turnbull, D., & Cooper, A. (2009). *In-pit crushing and conveying (IPCC) – a tried and tested alternative to trucks. In the AusIMM New Leaders' Conference 2009*. Carlton, Vic.: Australasian Institute of Mining and Metallurgy.

Vergne, J. de la (2014). *Hard rock Miner's handbook*. Edmonton, AB: Stantec Consulting.

Weiß, M., Welke, M., Kahlenborn, W., & Brünig, L. (2015). *Klimaschutz in Zahlen – Fakten, trends und impulse deutscher klimapolitik [climate protection in numbers – Facts, trends and impulse of German climate policy]*. Retrieved February 16, 2016 from http://www.bmub.bund.de.

Zimmermann, E., & Kruse, W. (2006). Mobile crushing and conveying in quarries - a chance for better and cheaper production. In *RWTH Aachen – Institut für Bergbaukunde III, 8th International Symposium Continuous Surface Mining* (pp. 481–487). Aachen, NRW: Verlag Mainz.