A Systematic Evaluation of Devices for Measuring Abrasive Wear of Mill Liners

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ABSTRACT

Inspection of the liner wear in the mill of an ore dressing plant is one of the critical parameters in the context of mill downtime and production performance. The total downtime cost during measurement can be reduced by a significant fraction by using appropriate measurement devices. Due to the different quality dimensions of a measuring device, e.g. the cost, accuracy, reliability and accessibility, it is necessary to select an appropriate device based on the specific needs of the industry. Customer satisfaction is perhaps the most important performance measure for the service quality of the device, and therefore this paper provides an approach to define the customer satisfaction with reference to the mentioned quality dimensions. The main aim of this paper is to determine a unified measure or quality index for the service quality of the measurement device across all the dimensions. Each quality index will then correspond to the total predicted usability of the particular measurement method based on the industry needs. Furthermore, this study also discusses the advantages and disadvantages of existing measurement methods and proposes an indirect measurement method to reduce the downtime during inspection.

Keywords: Liners, Wear, Mining, Mills, Measurement devices

1. INTRODUCTION

Mills used in the mining industry and ore dressing plants are examples of major bottlenecks in the context of downtime concerning the production of metals. The mills have to be stopped due to planned or unplanned repair, and these stoppages lead to heavy monetary losses due to production losses. Inside the mill, abrasive actions take place due to the comminution of ore, and therefore the inner part of the steel shell is protected by liners, made of rubber and metal or combinations of both. According to [1], and the expert group within the present study, protection of the mill shell from the aggressive impacting and abrasive environment inside the mill is the primary purpose of mill liners. Furthermore, mill performance and liner wear are known to be correlated to the lifter bar geometry [2].

In general, abrasive wear occurs when hard, sharp particles or rough surfaces contact soft surfaces and remove material by shearing it from the softer surface [3]. This abrasive wear, caused by the ore and the milling process, will decrease the liner thickness gradually until the mill has to be stopped for replacement of the liners. Since the repair of the shell will be costly if the protecting liner is too thin, it is important to check the liner thickness periodically. This procedure is time-consuming and will contribute to the total downtime costs of the mill. According to an expert group consisting of personnel from company M and L, out of 6-8 mill stoppages, two stoppages are usually used for pure replacements of liners, and the remaining 4-6 stoppages are used for pure measurements of the dimensions of the liner.

This study focuses on devices for measuring the abrasive wear of mill liners. The study is a survey of the existing and the possible future methods for direct measurements and the possible indirect methods for measurements of liner wear. The study uses a systematic approach to determine the quality index of liner wear and also suggests the most promising existing methods, both for use today and for possible use in the future. The output of this systematic approach can assist both suppliers and users of the measurement equipment concerning the optimum choice of measurement method.

The study has been carried out together with a mining company, M, and a mill liner manufacturing company, L. The study focuses on a particular mill used at an ore dressing plant at the mining company, M, located in Northern Sweden. The present study is a part of a research project whose goal is to find a cost-effective maintenance decision system for mills in ore dressing plants.

The literature study and the opinion of the expert group in the present study indicate clearly that the existing methods today are all based on manual measurement inside the mill, and that the mill has to be stopped in order to make it possible for personnel to enter the mill and perform the measurements. Since the largest contribution to the downtime is due to the stopping and starting-up procedure of the mill, it would be extremely beneficial if it were possible to perform the measurements without stopping the mill.

The measurement of liners is important in terms of mill grinding performance according to [4]. The mill performance first slightly increases and then decreases until the liners are replaced. The liner replacement time should be based on an economic comparison of the mill efficiency and the total lining costs. According to the industrial expert group, the performance of the mill is defined as the throughput of the desired particle size coming out of the mill.

The economic break point occurs when the cost associated with the drop of throughput is higher that the cost of relining. Since the mill throughput does not decrease significantly over the useful liner life, it is practice to replace the liners when they reach a critical thickness susceptible to breakage. Theoretical methods like the Discrete Element Method (DEM) are widely used in order to predict the wear of the liner as a function of time, see for example [5] or [6].

2. LITERATURE SURVEY

This section provides a brief introduction to the mill studied, to facilitate a better understanding of the problem of liner wear. The section briefly presents the different types of existing methods for measuring liner wear. It also describes a proposed method for indirect measurement of liner wear which does not involve the mill having to be stopped.

2.1 A brief introduction to the mill

The mill studied in the present project has a diameter of 5.7 m and a length of 5.5 m. The power of the electric motor is 1800 kW and the capacity is around 100 tons/hour. The mill is controlled by means of angular velocity, which is typically in the region of 8 rpm. Figure 1 shows that there are 18 high lifters and 18 low lifters in the studied mill.

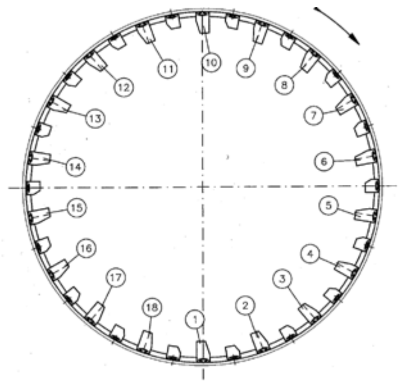

Figure 1, Layout of the liners [Source: Company L]

2.2 Collection of suitable existing and non existent measurement devices

2.2.1 Measurement method No. 1 (existing)

Method no. 1 is an existing measurement method (defined as a measurement method which is practically useable, while non-existent equipment refers to equipment which has not been fully developed yet and is not in use). This method is a direct measurement method based on the technique of the terrestrial 3D laser scanner and data processing algorithms to create a three-dimensional thickness map. It is an active imaging system that measures the range to an object in a series of uniform increments of arc, resulting in a three-dimensional map of the object. All the surfaces with a line-of-sight from the scanner are measured and stored as a three-dimensional coordinate file together with the reflectivity intensity, the latter being used to shade the scan cloud for a natural appearance. The range is typically measured by the time-to-flight of a laser pulse or an amplitude-modulated, continuous wave signal [7].

Terrestrial laser scanners are subject to systematic and random errors, but calibration systems for taking care of significant error sources that are typical of the conditions in a real mill have been developed by [8]. The complete system is today widely used at several plants [9]. See Figure 2.

Approximately five minutes is needed for pure measurement (entering the mill and exiting from the mill are not included) in order to measure all the liners [7].

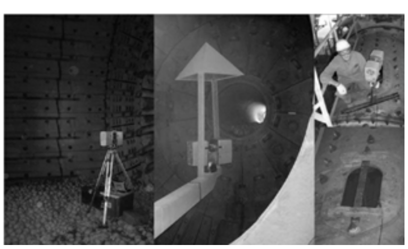

Figure 2 Terrestrial 3D laser scanners

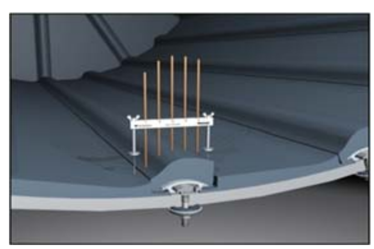

Figure 3 Mechanical wear reading device

2.2.2 Measurement method No. 2

No. 2 is a mechanical wear reading device which consists of a frame and 5 rods and gives an accurate measure of the profile by means of manual inspections. This method is used today at the particular mill within the present study, see Figure 3. The device requires approximately 30 minutes to measure 12 important liners in the mill. However, based on these measurements, it is possible to estimate the dimensions of the other liners. The accuracy of the instrument is +/- 5 mm and the disturbance sensitivity is equal to zero. The thickness capacity covers more than 400 mm. The volume of the transporting box within the device is approximately 12 dm^3 and the mass is less than 2 kg.

2.2.3 Measurement method No. 3

No. 3 consists of ultrasonic gauges. In resonance-type ultrasonic thickness gauges, a frequency-modulated continuous-wave signal is produced [10]. This provides a corresponding swept frequency of sound waves which are introduced into the part being measured. When the thickness of the part equals one half-wavelength, or multiples of half-wavelengths, standing-wave conditions or mechanical resonances occur. The frequency of the fundamental resonance, or the difference in frequency between two harmonic resonances, is determined by the instrument’s electronics. However, the curved liner surfaces will make it difficult to capture thickness measurements that are orthogonal to the liner back, so the readings can easily be biased [6]. It is also claimed by [6] that this method typically only yields a few dozen point measurements at unreferenced locations, and it is virtually impossible to re-measure the same location during any subsequent survey, which causes repeatability problems and therefore survey campaign inaccuracies. In the present study this method has been tested for a rubber liner with a thickness of 400 mm.

2.2.4 Measurement method No. 4 (existing as a prototype)

No. 4 is a direct measurement method, consisting of a thin-film sensor made up of a conductive element embedded in the liner to be measured [11]. The element comprises a first end positioned at a first distance from the wear surface, at least one conductive loop covering a wear portion positioned at a second distance from the wear surface proximate to the first end, and a circuit coupled to at least one element for determining a continuity of the conductive loop. According to [11] this can be practically solved by means of using a conductive trace, for example copper film, on a suitable substrate, resulting in a printed conductive circuit. The substrate can then be fastened to the liner by means of rolling it like a tube and gluing it into a suitable hole in the liner. In principle, this idea has been tested by company L for measurements of rubber thickness in pumps, but the authors could not find any real proof of any testing results in mills or any existing prototypes of this measurement device that would be usable for liners. The conclusion is that this particular concept has to be evaluated further by means of testing it in a real mill. See Figure 4.

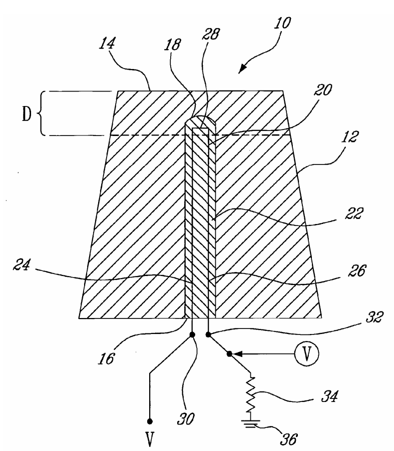

Figure 4 Device inserted in liner [11]

2.2.5 Measurement principle No. 5 (not developed yet)

No. 5 is an indirect method based on the measurement of vibrations on the fastening bolt of lifters, using accelerometers and analyzing the measured data in the frequency domain with Fourier transforms. The system can typically consist of a 20 kHz accelerometer, data memory, an amplifier and a suitable electric battery. Indirect measurements of different parameters, such as unwanted collisions between ore and the liner because of too high an angular velocity of the mill, the density of the pulp inside the mill, the amount of ore in the mill, the viscosity of the pulp etc, have been performed more or less successfully through measurements of vibrations on the mill shell or the fastening bolts for the liner, see for instance [12], [13]. Since the size of the liner most probably will affect the forces acting on the liner, it is here assumed that it should be possible to calibrate measured vibrations on the fastening bolt with real mechanical measurements of the liner and thus achieve a useable method for predicting the wear of the liner without stopping the mill. A prototype has been developed by IT Innovation at Luleå University of Technology, see Figure 5, which shows the prototype mounted on the fastening bolt of a lifter on the shell of a mill.

Figure 5 Device for measurement of vibrations.

According to [14], liner wear is a very complex phenomenon, since it results from several complicated and simultaneous processes. The liner hardness and design, the size and hardness distribution of the charge, the mill speed etc will all affect the wear rate. An attempt to utilise vibration analysis to predict the amount of liner wear was reported in [14]. This study was performed on two 10.6 m-diameter SAG mills in India. The mills are fitted with 48 lifters and operated with a 25% filling with a 6-8% ball load and at a mill speed of 10.4 rpm. An accelerometer was latched to the surface of the gear box. Continuous vibration signals were obtained over a period of 3 days. The vibration data was analyzed in the frequency domain. This data was obtained for both of the mills, one of which was operating with newly installed liners, while the other one was using worn liners (more than half the estimated liner life having been used). Statistical analysis of data from these two mills showed that the intensities of the peaks were higher in the case of the newly lined mill compared to the worn-out mill. The conclusion from the above study is that measurement principle no. 5 is promising and should be developed further.

2.2.6 Other measurement principles

There are other measurement principles which have not been considered for detailed analysis to determine quality indexes, as the required data for different quality dimensions is not available. One such method is an eddy-current-based electromagnetic method. However, due to the magnetic properties of ore, this method is not useful in practice. Another method is based on nuclear radiation thickness gauges (beta radiation, nuclear fluorescence) [10]. Thickness can be determined by measuring the amount of beta radiation or nuclear fluorescence energy absorbed by a material as it passes between an emitter and a receiver.

3. PROPOSED METHOD FOR INDIRECT MEASUREMENT

The present study proposes an indirect measurement method based on power signature diagnosis without stopping the mill. The power consumption in the mill will increase or decrease if there are any changes in the mechanical process. These small changes (typically less than 0.00001%) are measured by means of current and voltage sensors, and the data is collected by measurement computers with A/D converters. The next step is to filter the collected data and analyze it with respect to time and frequencies. Today, the method is in use for the measurement of damages in gears, fans and bearings, etc. The measurement signals can then be compared with the actual dimensions of the liners, resulting in an indirect measurement method for predicting the wear of liners. However, the method has not been tested for predicting the wear of liners.

The measurement signals can be transported to a computer via fibre optical cable for analysis using an ordinary Excel document. Variation in the power supply of the electric motor can be achieved. Within the present project, this technique has been tested on the mill owned by the participating company, M. The power was measured within +/- 0.00001%. The time difference between each measurement was approximately 0.03 seconds and the accuracy of the time measurements was +/-0.0000001 s.

Figure 6 shows a significant connection between the power and the time when the liners approach the charge. There is a possibility that the large and small peaks correspond to the high and the low liners respectively. The height of the lifters will decrease as a function of time due to wear, and this will probably affect the amplitude of the peaks. By means of calibrating the average amplitudes measured with this method with the real measured values of the height of the lifters, this method can be used for estimating the average height of the liners without stopping the mill. This information can be used concerning the remaining lifetime of the liners, and also for optimum process control of the mill. One of the possible explanations of the peaks of power is the phenomenon whereby a stone gets stuck between the liners, causing more power to be needed when the charge strikes that stone.

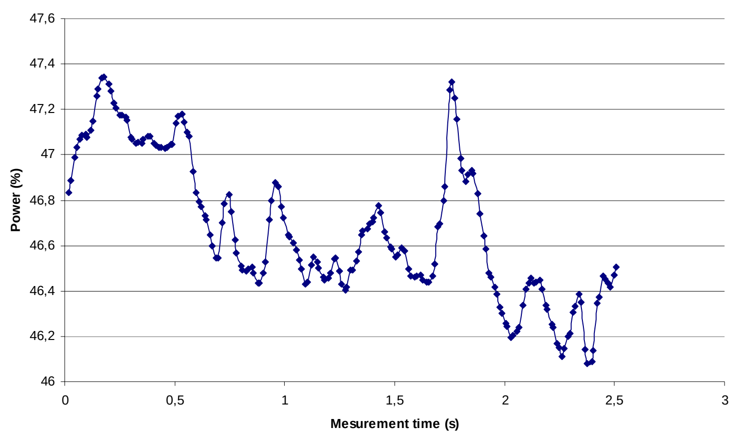

Figure 6 Percent of full power of the electric motor as a function of time

The continuous measurement of liners regarding the average size can be used for process control, in combination with ultrasonic devices equipped with wireless transmitters sending data for measurement of critical spots. These measurements can be used to determine the optimum thickness of the liner in order to maximize the mill performance.

4. METHOD

4.1 Definition of important and relevant terminology used in the paper

- **Demand:** In this study the term "demand" is defined as the minimum requirements for the measurement device which must be fulfilled concerning all the quality dimensions; e.g. the cost of a piece of equipment must not be more than US$247.5 thousand, i.e. equipment will not qualify if it does not satisfy the demand limits.
- **Quality Index (QI)**: QI is defined as a quality measure for a given measurement device.
- **Expert group:** This is the group consisting of experienced personnel from company M and L and from where both data and information are collected for liner measurements.

4.2 Quality dimensions:

For the overall assessment of the measurement devices and determination of the corresponding quality index, the following quality dimensions are briefly described.

4.2.1 Cost

To calculate the total cost, the following cost elements are included in the cost structure, as shown by Figure 7. Since we are considering two types of measuring devices, firstly the one procured through purchase, and secondly the one procured as a service provided by a supplier, we must include the required cost elements to determine the overall cost.

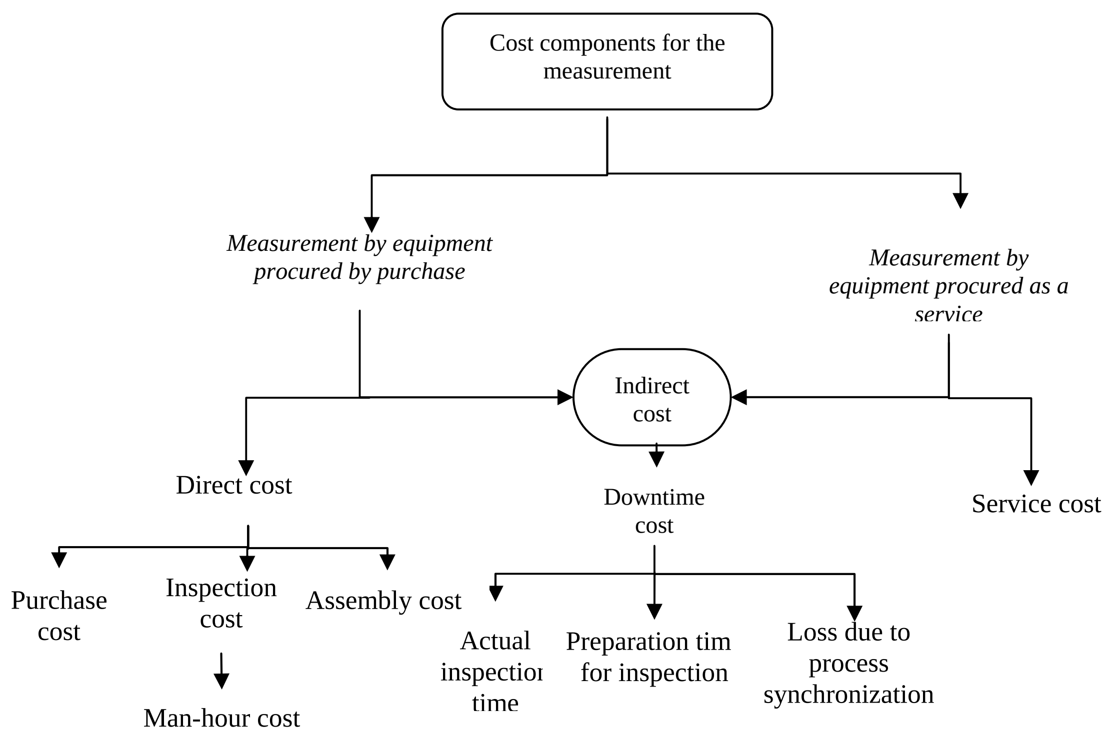

Figure 7: Overall cost structure, including the inspection cost breakdown structure, for the measuring equipment

Since in the present study the downtime cost is very high in comparison with the purchase cost of the measurement equipment and the man-hour cost, we are only considering the downtime cost.
For the particular mill in the present study, the loss of production due to the downtime of the mill costs between US$6,700/h and US$17,000/h, depending on the type of ore, the time used and the amount of ore. Assuming that the mill, and not the other parts of the ore dressing plant, is the real bottleneck, and that the energy costs and mining costs are neglected, and assuming a typical combination of ore used at the participating mining company, then, according to the expert group, this would give a typical downtime cost corresponding to US$11,000/h.

4.2.2 Reliability

In this paper the reliability aspect of the equipment is defined as the percentage of the total measurement time when the measurement device is functional. This reliability dimension also includes the fragility of the equipment.

4.2.3 Accuracy

The term accuracy is defined as the measurement accuracy of the respective measurement methods, in conditions without any harmful disturbances and without sensitivity to disturbances. Based on discussions with experienced industrial personnel from company M, the measurement accuracy concerning critical measuring spots on the liners should be +/- 5 mm.

4.2.4 Accessibility

The accessibility aspect is defined as the ease of handling of the equipment and the ease of taking measurements. For direct measurement of the liner wear, the inspector has to go inside the mill, which is not possible whenever the device exceeds certain dimensions concerning both weight and volume. The key indicator for the assessment of the accessibility dimension can be defined in terms of the weight, volume and height of the device. The weight influences the ease of carrying the equipment and the volume affects how the inspector handles the space constraint while entering into the mill and carrying the equipment. The data for different pieces of equipment was provided by the expert group for the mill.

5. CASE STUDY

A case study has been carried out involving the ore dressing plant and the liner manufacturing company. Data and information have been collected from the expert group consisting of personnel from both the companies. A questionnaire was designed to determine the different quality dimensions and the priority vectors among all the dimensions.

5.1 Qualitative comparison of different measurement devices

The most important advantages and disadvantages of the analyzed measurement principles are summarized in Table 1.

Table 1: Advantages and Disadvantages of measurement devices

Me-thod No.	Advantages	Disadvantages
1	• The only existing method which provides a complete profile based on all the measures of the liners • Only 5 minutes of pure measurement time for a whole mill	• Available only as a service and the service cost is not known to the authors • The mill needs to be stopped. • The accuracy is unknown in humid conditions.
2	• Reliable method, very often used today. • Delivers the complete profile of the liner at the measurement points	• The mill needs to be stopped. • Relatively long measurement time compared with method no. 1
3	• Can be regarded as relatively faster and more	• The mill needs to be stopped.

	accurate for spot measurement	• Does not provide the complete profile
4	• The mill does not need to be stopped, provided that electronics and software have been developed to make it possible to deliver data.	• Not a fully developed product for use in industries • The sensor will be destroyed when the liner is worn out. • Sensitive to mechanical damage • The device must be fastened to the liner before assembly in the mill. • Cannot provide a complete profile of the liner
5	• The mill does not need to be stopped, provided that electronics and software have been developed to make it possible to deliver data.	• No existing fully-developed product on the market • Does not provide a complete profile
6	• The mill does not need to be stopped. • Low purchase and service cost • Continuous data measurement is possible, which can be used to improve production performance.	• The accuracy needs to be tested. • No existing fully-developed product on the market • Cannot provide a complete profile • Provides average measurement of all the liners

Pairwise comparison [15] has been carried out between the different quality dimensions and the results obtained are given in Table 2 below. The information for qualitative comparison has been provided by 5 experts from company M.

Table 2: Pairwise comparison of different quality dimensions

	Cost	Reliability	Accuracy	Accessibility		Results
Cost (W_c)	1	5	1	5	➔	0.414
Reliability (W_R)	1/5	1	1/5	1/3		0.067
Accuracy (W_{Au})	1	5	1	5		0.468
Accessibility (W_{Ac})	1/5	3	1/5	1		0.103

The pairwise comparison has been carried out based on the information obtained from the discussions with the expert group.

5.1.1 Liner interpolation: A liner interpolation method [16], [17] was used for giving grades to various measurement methods for different attributes. The limits for the interpolation were set based on the minimum needs provided by the expert group (demand) in the scale of 1-5. The grade scale was defined as in the table below. The minimum grade '1' is given to a method when it just fulfils the minimum requirement, and the highest grade '5' is given if it is theoretically perfect.

Table 3: Theoretical definition of grades

Grade	Definition
1	Identical with the demand
2	Slightly better than the demand
3	Above the demand
4	Certainly above the demand
5	Theoretically perfect

Table 4: Liner interpolation for quality dimensions

Grade	**Total Cost** ($/year) in thousands)	**Reliability** (%)	**Accuracy** (Error +/- mm)	**Accessibility**
1	247.50	95.00	20	Just possible to carry into the mill
2	185.62	96.25	15	-
3	123.75	97.50	10	Possible to carry into the mill without significant problems
4	61.87	98.75	5	-
5	0	100	0	Possible to carry as hand luggage

Table 5: Interpolated grades for different quality dimensions

Method	Total Cost ($/year in thousands)		Reliability		Accuracy		Accessibility
	Actual value AV	Interpolated Grade IG_c	AV (%)	IG_R	AV +/- mm	IG_{Au}	IG_{Ac}
1	220	1.44	99	4.20	1	4.8	1
2	247.5	1.00	100	5.00	20	1	5
3	225.5	1.35	100	5.00	20	1	5

The interpolated grades were determined based on the liner interpolation from Table ().

5.1.2 Quality index

The quality index was determined by using Table 2 and 5. The formula for the quality index is defined as

$$QI = IG_C \times W_C + IG_R \times W_R + IG_{Au} \times W_{Au} + IG_{Ac} \times W_{Ac}$$

Table 6: Liner interpolation for quality dimensions

Methods		**Quality Index**
1	$1.44 \times 0.414 + 4.20 \times 0.067 + 4.8 \times 0.468 + 1 \times 0.103$	= **3.22**
2	$1.00 \times 0.414 + 5 \times 0.067 + 1 \times 0.468 + 5 \times 0.103$	= **1.73**
3	$1.35 \times 0.414 + 5 \times 0.067 + 1 \times 0.468 + 5 \times 0.103$	= **1.87**

Table 6 shows that method no. 1 is the most preferable measurement method since it has the highest quality index among the three investigated methods.

On the other hand, the service cost, man-hour cost and purchase cost are not included in the quality index. Today the mining company, M, is using method no. 2, and if they prefer to change to method no. 1, as this method has better measurement accuracy (see Table 5), then the maximum acceptable service cost for method no. 1 can be estimated as (247.5 – 220 = US$27.5 thousand/year), provided only the cost aspect is considered.

The limitations of the present study are as follows:

- Liner interpolation was carried out for each quality dimension for defining grades.
- The liner interpolation for the different quality dimensions was defined between two boundaries. The first boundary limit was defined using theoretical perfect values and the other limit was defined using the minimum requirement for each quality dimension provided by the companies involved in the project [16].
- The grade for the accessibility dimension was defined as per an expert opinion based on the weight, volume and height of the equipment.

6. CONCLUSIONS

- A systematic evaluation method is proposed for evaluating the optimum choice of equipment for measuring the wear of liners. The output from the method is highly dependent on the values of the input variables. Therefore, these variables have to be decided with care and it is suggested that further development should be carried out by the user in this connection.
- Significant economic savings can be achieved if suitable measurement devices are developed so that measurements of the liners can be performed without stopping the mill.
- The additional saving of US$27.5 thousand/year for each mill by using laser scanner (method no. 1) instead of the mechanical device (method no. 2) used today can be regarded as equivalent to the maximum acceptable service cost for the laser scanner, provided that the other quality dimensions fulfil the requirements of the company, M.
- Concerning complete measurements of all the dimensions of the liner, the useable method today is laser scanning.
- In this study ultrasonic technique is identified as a promising method capable of measuring rubber liner with a thickness of 400 mm. Due to fast measurement process it is more preferable than a mechanical device if only the height of the liner are of interest.
- Power signature diagnosis is identified as a promising method which should be developed further, since the mill does not need to be stopped and the signals can be used for optimizing the process and for checking the average condition of the liners.
- A possible future setup for measuring the liners is the use of signature power diagnosis for the information concerning the average size of the liners and for process control, in combination with ultrasonic devices equipped with wireless transmitters sending data for the measurement of critical spots.

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