Decision Support Models for the Maintenance and Design of Mill Liners

Rajiv Dandotiya
DOCTORAL THESIS

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Preface

The research work presented in this thesis has been carried out during the period 2009 to 2011 at the Division of Operation and Maintenance Engineering at Luleå University of Technology (LTU), which is financially supported by Vinnova’s Strategic Mining Research Programme and Boliden Mineral AB.

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Abstract

Mining companies use heavy-duty equipment that work round the clock in highly abrasive environments. Autogenous (AG) mills used in the mining industry and in ore dressing plants are examples of major bottlenecks in the context of downtime and exert an influence on production economics. The rubber liners inside the mill are critical components for mill shell protection and ore grinding. The replacement and inspection of mill liners are major factors regarding mill stoppages and lead to production losses. The wear readings of mill liners are critical when making replacement decisions, and periodic inspections need to be carried out to obtain wear readings. Wear measurement devices are important in terms of measurement accuracy. The appropriate selection of wear measurement devices can lead to a significant reduction in the overall costs, including the device costs and the production loss costs incurred during inspections of the wear of mill liners. An approach has been developed for selection of the optimum wear measurement method, considering the industry specifications. Based on an analysis performed in a case study, a cost-effective wear measurement method has been suggested, taking the industry requirements into consideration.

The wear of mill liners affects the production performance of the mining mill. Hence, the replacement decision for mill liners affects not only the lining cost and the production loss cost, but also the mill revenue due to variation in the metal output. Therefore, the production performance has to be considered when developing decision models for making maintenance replacement policies for mill liners. Variation in the ore properties also affects the liner wear and ore value. Both these parameters have an effect on the cost and revenue parameters. Therefore, consideration of the ore properties in the life cycle profit (LCP) formulation will provide more effective maintenance decisions. A maintenance decision support model has been developed to meet the specific requirements of process, purchase and maintenance departments.

The lifetime of different parts (components) of mill liners also varies due to the wear of the parts, for technical reasons concerning the grinding process and the different wear zones inside the mill. The mill needs to stop on a number of occasions for the replacement of parts of mill liners. These stoppages are also one of the major causes of mill downtime and corresponding production losses, which can be minimized by a cost-effective maintenance schedule for the optimum grouping of mill liners for combined replacement. The maintenance schedule depends on the lifetime of the mill liners. The life cycle cost (LCC) can be reduced further through optimum improvement of the lifetime of different parts of the mill liners. A decision support model has been developed to determine the optimum grouping of parts of mill liners for replacement and the optimum improvement in the lifetime of parts of mill liners. The proposed LCC model is also useful for the design departments of liner manufacturers for optimizing the material and dimensions of mill liners, in order to achieve a proposed improved lifetime. A significant improvement in the annual profit was observed when the maintenance policies suggested in the thesis replaced the existing maintenance policies.

The research presented in this thesis has used a systematic evaluation approach and pair-wise comparison methods for selection of the optimum wear measurement method for mill liners. Time sampling, correlation studies and simulation methods have been used for LCP optimization, in order to determine the optimum replacement interval for major replacements of mill liners. An approach based on an exhaustive enumeration search has been used for LCC
optimization for determining the optimum grouping and the optimum improvement in the lifetime of parts of mill liners.

The usefulness of LCC and LCP analyses for mill liners in mining companies is illustrated in the thesis and decision models for effective maintenance planning are demonstrated. The results of the present research are promising for the possibility of making a significant reduction in production losses and the LCC after optimizing the maintenance activities and the lifetime of the mill liners studied in this specific case study. The results of the present thesis are related to specific industrial requirements, and are expected to enhance the capability of making cost-effective replacement decisions.

**Keywords:** Mining industry; Maintenance decisions; Mill liners; Life Cycle Cost (LCC); Life Cycle Profit (LCP); Mill liner design; Economic model; Production Economics; Optimization; Replacement decision; Wear measurement device; Combined replacement; Life improvement
Sammanfattning

Gruvindustrin är beroende av att deras maskiner fungerar dygnet runt i krävande miljöer. Autogena (AG) kvarnar som används i gruvor och anrikningsverk är exempel på viktiga flaskhalsar när det gäller stillestånd, vilket direkt påverkar produktionen. Insidan av dessa kvarnar är täckta av gumminfördring för att förhindra slitage av kvarnarna och för att optimera deras kapacitet och malningsförmåga. Eftersom infördingen nöts kontinuerligt på grund av malningen, och produktionsstopp är väldigt kostsamma, måste reparation, underhåll och inspektion av infördingen genomföras vid lämpliga tillfällen. Vid inspektionerna mäts slitaget på infördingen och det är därmed väsentligt att måtutrustningen är både tillräckligt noggrann och så snabb som möjligt för att minska stilleståndskostnaderna och så att rätt underhållsbeslut kan fattas. I denna avhandling har bland annat en metod utvecklats för att välja optimala mätmetoder för denna applikation.


Livslängden hos olika komponenter i infördingen, på grund av slitage, varierar beroende på malningsprocessen i kvarnarna och de behöver stoppas vid många tillfällen för byte av infördningskomponenter. Dessa stopp är en av huvudorsakerna till stillestånd i kvarnarna vilket ger produktionsförluster som kan minimeras genom en effektiv planläggning av infördningsbytena och optimal gruppering av de detaljer som skall bytas. Denna planläggning är naturligtvis beroende av livslängden på infördingen. Livscykelkostnaden (LCC) kan reduceras ytterligare genom att på ett optimalt sätt välja infördring med längre livslängd. En modell för beslutsstöd har därför utvecklats som grupperar de olika infördningsdetaljerne på ett optimalt sätt vid byten och som med hänsynstagande till att bättre komponenter har ökade inköpkostnader, föreslår med hur mycket de olika komponenterna borde förbättras för att LCC skall minimeras. Denna modell har visat att betydande besparingar kan göras, om modellen tillämpas fullt ut och ersätter nuvarande underhållsstrategier.

Systematiska utvärderingsmetoder och parvisa jämförelser har använts vid valet av optimala mätmetoder för geometrimätningar av infördningsdetaljer. Provtagnings studier och simuleringer har använts vid LCP-optimeringen för att fastställa optimala bytesintervall för infördingen. En ansats som bygger på en totalomgång av alla tänkbara bytesalternativ har använts för att fastställa optimala grupperningar av infördningsdetaljer vid byte, och för att ta fram förslag på optimala livslängdsförbättringar på komponenterna.
List of appended papers

Paper I

Paper II

Paper III

Paper IV
Distribution of the research work

In this section, the distribution of the research work is presented for all the appended papers. The content of this section has been communicated to and accepted by all the authors who have contributed to the papers.

Paper I: The main idea of a systematic comparison of various wear measurement methods was developed by Prof. Jan Lundberg. Later the idea of incorporating a quality index for the wear measurement methods was extended by Rajiv Dandotiya. Andi Wijaya contributed by proposing a power signature method for indirect wear measurement of the mill liners. The data collection for and the literature survey on the different measurement methods were performed jointly by Rajiv Dandotiya and Prof. Jan Lundberg. The model development and analysis were carried out by Rajiv Dandotiya. The results, discussion and conclusions were discussed with Prof. Jan Lundberg.

Paper II: Rajiv Dandotiya developed the main idea. The literature review, model development, data collection and analysis were performed by Rajiv Dandotiya. The results, discussion and conclusions were discussed with Prof. Jan Lundberg. The first version of the manuscript was prepared by Rajiv Dandotiya and then improved using suggestions and comments from Prof. Jan Lundberg.

Paper III: Rajiv Dandotiya developed the main idea. The literature review, model development, data collection and analysis were carried out by Rajiv Dandotiya. The results, discussion and conclusions were discussed with Prof. Jan Lundberg. The first version of the manuscript was prepared by Rajiv Dandotiya and then improved using suggestions and comments from Prof. Jan Lundberg.

Paper IV: Rajiv Dandotiya developed the main idea. The literature review, model development, data collection and analysis were carried out by Rajiv Dandotiya. The results, discussion and conclusions were discussed with Prof. Jan Lundberg. The first version of the manuscript was prepared by Rajiv Dandotiya and then improved using suggestions and comments from Prof. Jan Lundberg.
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XIII
1 Introduction

1.1 Background

The modern mining industry uses large and heavy-duty equipment that work around the clock in highly abrasive environments. Ore grinding mills are one example of such heavy-duty equipment. The autogenous (AG) mill is one type of grinding mill which is used in mineral processing for particle size reduction, and ore from various mines are processed in such mills. The ore grinding mill (see figure 1.1) is a critical component in the grinding process and is necessary for the achievement of high metal recovery (Product handbook, 2002).

![Grinding mill](Boliden Mineral AB)

Figure 1.1. Grinding mill (Boliden Mineral AB)

In the present research a case study conducted for a standard grinding mill measuring 5.5 m in diameter and 5.7 m in length, and with a power consumption of approximately 1,800 kW has been studied. The present study, the charge inside the studied mill consists of rocks with a particle size distribution ranging from 300 to 20 mm.

From an economic standpoint, it is important to keep any type of ore grinding mill in operation as long as possible, keeping the downtime for maintenance or repair at a minimum.
Decision Support Models for the Maintenance and Design of Mill Liners

Larsen, 1981. A drop in production caused by a long stoppage of the mill, scheduled or unscheduled, leads to heavy monetary losses. Periodic economic evaluation of the productivity of grinding mills and their maintenance policies is therefore necessary to optimize the mill profitability. It is essential to know how the mill and its critical components are performing their functions to achieve a high mill performance. The mill liners inside the mill are one of the most critical mill components in the context of shell protection and ore grinding (according to the reference group). For periodic inspections and replacements of the various components of the liners, the mill needs to stop on various occasions and each mill stoppage leads to heavy production losses. The wear of mill liners also influences the grinding performance in the context of metal recovery (Franke and Lichti, 2005). The significant impact of mill liners on the monetary return for the mill owner has led to the study of maintenance activities performed on mill liners, such as wear measurement and replacement, as well as maintenance scheduling. The main focus of the present research is on the optimization of various activities, such as wear measurement, replacement and maintenance scheduling of mill liners, in order to maximize the profit of mill owners.

Discussions concerning wear measurement, the grinding process, grinding performance, the maintenance activities performed on the grinding mill, and mill liner replacement strategy have been carried out with close cooperation with the reference group of the companies involved in the present thesis. Description of the work profile and years of experience of the industrial reference group is provided in Paper I.

1.2 Mill liners

Mill liners provide the wear-resistant surface within grinding mills and impart motion to the charge (i.e. the grinding process). They are one of the key factors for enhancing the movement of the charge within the mill shell (Kawatra, 2006). The studied mill has various types of mill liner components (see Figure 1.2-1.3). A list of the mill liner components of the studied mill is provided in Table 1.2.

![Figure 1.2. Mill liners inside mill (Boliden Mineral AB)](image1.png)  ![Figure 1.3. Mill liner components (Metso Minerals)](image2.png)
Table 1.2. List of mill liner components of the studied mill

<table>
<thead>
<tr>
<th>Mill liner components</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lifter (shell), Outer, inner lifter bar (discharge), Pebble grate plate (outer), Pebble grate plate (inner), Shell plate and pebble extractor, Filling segment, feed end, Inner and outer head plate, Inner lifter bar, feed end, pebble discharge, inner, Outer lifter bar, filling segment, feed end, Pulp grate plate, inner, discharge end, Pebble discharger, outer, Centre ring, Trunnion plate, feed end, filling end, discharge end, Centre pipe.</td>
</tr>
</tbody>
</table>

Lifter bars are important mill liner components which lift the charge inside the mill. The studied mill consists of thirty-six lifter bars (lifter bars in a high-low configuration, see Figure 1.4, where all the lengths are in mm) spaced circumferentially around the mill shell. The lifter bars are 210 mm wide and 350 mm high; the shell plates between the liners protect the mill shell.

Figure 1.4. High and low lifter bars (source: Metso Minerals)

1.2.1 Function

Figure 1.5 shows that the grinding charge in a mill undergoes circulation and that the axis of charge circulation is not the axis of mill rotation, but is below and to the right-hand side of the mill axis, within the region corresponding to the “kidney” of the charge (Vermeulen and Howat, 1988). The trajectory of charge particles is one of the key parameters which affect the grinding performance in terms of reduction of the particle size. Liner wear is due to abrasive actions and the impact between the charge and the liners, which lead to a reduction in the height of the mill liners, which affects the trajectory and the shape of the charge (Rajamani et al., 2005; Radziszewski and Tarasiewicz, 1993).
1.2.2 Wear measurement

Wear measurement in the present context involves measuring the height and profile of the mill liners over the life cycle period. Due to continuous mill operation, liner wear takes place and continuous monitoring of liner wear is required. In general, abrasive wear occurs when hard and sharp particles, or rough surfaces, contact soft surfaces and remove material by shearing it from the softer surface (Bloch and Geitner, 1990). Liner wear measurement is an important part of this study due to the economic impact of the mill liner replacement interval and inspection. The measurement time during inspections leads to a significant amount of downtime cost. However, the additional cost due to the process synchronization time (start-up time) also needs to be considered, as significant monetary losses occur during the period before the mill starts to operate at 100% capacity. In the present context, the process synchronization time is the time during which the material flow in the process becomes streamlined. Therefore, a time-efficient measurement device is required in order to take the measurement as quickly as possible. However, inspections of the liner wear are also carried out when the mill stops for other maintenance activities.

Another economic aspect related to wear measurements concerns replacement decisions for mill liners. Presently liner replacement decisions mainly depend on the liner wear and the risk of damaging the mill shell. Generally, the efficiency of the milling process depends on the behaviour of the load (charge and mill liners) inside the mill, which governs the nature of the ore presentation at the breakage sites and the subsequent transport. It is, however, well known that mill liners will lose efficiency due to wear (Franke and Lichti, 2005). To determine the throughput capacity of the mill, a number of wear measurements are necessary during the life cycle of the mill liners. The liner wear reading can be used to calculate the available volume inside the mill, as the inner mill volume for ore grinding is a function of the volume of the mill liners. Various kinds of wear measurement methods exist for measuring the mill liner wear. Each method has its advantages and disadvantages.
Therefore, the selection of an appropriate wear measurement method plays an important role concerning mill economics. The first part of the present study presented more detailed literature on liner wear.

1.2.3 Influences of liner wear on mill economics

The periodic economic performance of the grinding mill needs to be assessed to draft appropriate policies governing cost-effective maintenance decisions. An effective maintenance policy can significantly improve the profit of an organization Alsyouf (2009). For this case study, the production loss during liner inspection and replacement in the ore dressing plant is significantly high, costing around SEK 50,000 per hour. Apart from the number of mill liner replacements, the number of inspections is one of the most critical maintenance cost drivers, since each inspection leads to 1.5–2 hours of downtime, which is equivalent to a direct mill production loss. In addition to the production loss cost, there is a cost of approximately SEK 500,000 per production stoppage due to losses occurring during the process synchronization time (start-up time) for this case study. The present study provides an approach to investigating the mill’s economic performance using a proposed mathematical model to make cost-effective decisions regarding mill liner replacement.

(A) Metal recovery

The importance of the link between quality and maintenance has been highlighted by Ben-Daya and Duffuaa (1995). The production quality of the present study deals in terms of higher metal recovery which is one of the success factors concerning higher mill profitability. Mill liners play one the key role in the reduction of particle size (Yahyaei et al., 2009). Milling process efficiency generally depends on the behaviour of the load (charge and mill liners) inside the mill, which governs the ore presentation at the breakage sites and the subsequent transport (Makokha et al. 2007). According to Schena et al. (1996), increasing the feed rate into the grinding sections leads to a decreased particle residence time in the mills and a coarser discharge size. Both higher feed rates and coarser sizes are in turn concurrent causes of lower flotation recovery. The size of the output particles from the investigated grinding mill (more than 200 micron) is not appropriate for extracting metals, while particles of a smaller size of less than 45 micron are flushed out, leading to reduced metal recovery. Bearman and Briggs (1998) have demonstrated that liner wear directly affects both the gap length and the chamber profile. Hence, liner wear is an important variable in the overall crushing operation, as it is intimately related to the product quality (i.e. size consistency and throughput). More detailed studies on the interaction between the charge and the mill liners and mill efficiency have been presented by Latchireddi (2002), Dunn and Martin (1978) and Mishra and Rajamani (1994a; 1994b). The thesis uses the mining company (of the case study) defined parameter “process efficiency” to incorporate the influence of particle size reduction on the metal recovery. The “process efficiency”, defined as the ratio of actual (Net Smelter Return) NSR to theoretical NSR.

\[
\text{process efficiency} = \frac{\text{Actual net smelter return}}{\text{Theoretical net smelter return}}
\]
The theoretical NSR indicates the total monetary value of the metals (Cu, Zn, Pb, Ag and Au) contained in an ore sample before grinding, while the actual NSR represents the monetary value of the obtained metal considering actual particle size after grinding for the same ore sample. This parameter considers the influence of grinding (in the context of reducing particle size) due to mill liners. Therefore, the reasonable assumption has been made that the revenue driver should be a function of the throughput and process efficiency. The values of process efficiency on daily basis have been obtained from database of the mining company.

Since the amount of metal contents affect the NSR value, in order to compare the process efficiency at different stages of the wear of the mill liners, the influence of the metal content in the input feed needs to be normalized. Therefore, to determine the isolated influence of the mill liners on the grinding performance, a comparison of the process efficiency has been carried out at different stages of the life span of the mill liners when the level (amount) of the copper (Cu) content should be the same in the feed. The comparison of process efficiency at same level of Cu is considered due to the dominance of the higher monetary value of Cu on the total monetary value of all the metals in the recovery. However, other metals such as Zn, Pb, Ag and Au also contribute to the process efficiency, but the monetary value of these metals is comparatively smaller than in comparison with monetary value of Cu content.

The process efficiency data has been plotted with between two major replacements of the mill liners. Figure 1.6 illustrates that the process efficiency gradually decreases with the liner wear (reduction in the height of the mill liners) at the same level of metal input (Cu). The average time duration between two major replacements of mill liners in the present case study is about 300-340 days.

(B) Variation in the mill volume (reduction of the liner volume)

In the present study, the feed rate is automatically controlled based on the instantaneous mill load. The mill load comprises the load of the mill shell, the mill liners, and the charge; hence,
the mill liner volume is also one of the key process parameters concerning the throughput. Liner wear leads to a reduced rubber volume inside the mill, which gives space for the ore. The inner volume of the mill increases by 17% between a new liner installation and at the end of liner’s life. Thus, a reduced liner volume not only leads to increased throughput or mill capacity, but also decreases the charge lifting capacity.

(C) Variation in the energy consumption

According to the experimental study carried out by Djordjevic et al. (2004) relatively high lifters consume less power than low lifters under identical conditions (i.e. with identical process parameters such as given angular speed, given mill filling, and given ore type). The increased power is consumed due to increase mill filling leads to an increase the proportion of energy used for the low energy abrasion breakage. Figure 1.7 shows the various shapes of the charge inside the mill for various heights of the lifter bars under the identical conditions. For impact breakage of the particles, charge lifting is required and Figure 1.7 shows the charge lifting is higher in the case of high lifters in comparison of low lifters. Therefore, energy required for the impact breakage of the particles in case of low lifter bars is comparatively higher than high lifter bars (Djordjevic et al. 2004). Similar trends have been reported in literature (Cleary, 2001 and Hlungwani et al., 2003). Based on the obtained process data, the correlation study results also showed that the power consumption increases with the liner wear (see Paper III). The height of the lifter bars of the mill therefore influences the operational cost stemming from energy consumption. Therefore, energy consumption should also be considered when conducting a cost–benefit analysis of mill liner replacement.

![Figure 1.7. Charge shapes inside the mill with lifters of various heights (adopted from Djordjevic et al., 2004)](image)
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(D) Influence of ore density on lifetime of the mill liner

The present study considered a relation between lifetime of mill liner and ore density in order to incorporate the effect of ore properties in the economic model for the mill liner replacement (see equation 1). Let the lifetime of mill liners \( T_{\text{cycle}}(j) \) (time) (when only ore type "\( j \)" is processed) and the ore density is \( \rho(j) \) (gm/dm\(^3\)). The higher wear rate of mill liners implies lower the lifetime of mill liners. Therefore, an inverse relation has been considered between lifetime of mill liners and ore density that means wear rate is directly proportional to density of mill liners.

\[
T_{\text{cycle}}(j) \propto \frac{1}{\rho(j)} \Rightarrow T_{\text{cycle}}(j) = \frac{k_1}{\rho(j)} \tag{1}
\]

Where, \( k_1 \) is the proportionality constant for ore density. However, other unknown factors such as (abrasion angle, loading force etc.) which may also have influence on liner wear, have not considered in the study. The main reason is that there is a lack of the practically available experimental data needed for all the individual ore types.

Radziszewski et al. (2005) developed an advanced wear model for the lifter bar which also suggests a linear relationship between the ore density and the wear rate of the lifter bar, if the other wear model parameters, except the density, are assumed to be constant (see equation 2).

\[
\text{Wear rate} = \rho \cdot \frac{\tan(\beta(F))}{\Pi \cdot H_r} \cdot \mu \cdot F \cdot \varphi \quad (\text{Unit: mg} / \text{kWh}) \tag{2}
\]

where \( \rho \) is the ore density, \( \beta \) is the abrasion angle, \( F \) is the loading force, \( H_r \) is the ore hardness, \( \mu \) is the friction angle and \( \varphi \) is the sliding velocity. Based on past data (lifetime and ore density), the internal properties of the processed ore of the presented case study significantly affect the wear rate of the mill liners up to approximately 25-50%. According to the Pozzo and Iwazaki (1989), Adam et al. (1984) and reference group the amount of pyrite in the ore affect the wear properties. High amount of pyrite leads to high amount of wear on the liners. On the other hand the increased amount of pyrite will also increase the overall density of the ore. This increased density of the processed ore will directly increase the wear forces and thus increase the wear of the liners. Based on a study performed by (Wijaya, 2010) using multivariate analysis of measured process parameters of the present study, ore density was found to be a most significant parameter causing wear of mill liners (see Paper I). The proposed relation between ore density and wear rate was also verified by the wear rate model developed by Radziszewski et al. (2005) i.e. wear rate is directly proportional to the ore density if other model parameters are considered to be constant. Hence, the ore density is assumed to be a significant factor affecting the wear of mill liners. However, an improved lifetime model considering a greater number of parameters for the ore properties may lead to more effective results for the replacement interval of mill liners.
Introduction

(E) Liner maintenance

Friction and impact between the charge and the liner in the mill cause wear, resulting in a changed liner profile and decreased liner thickness. The liners must be replaced when their thickness decreases to the threshold thickness at which damage to the mill shell can occur. Regular inspections are also needed to check the liner thickness and to prevent mill shell damage. For both mill liner inspection and replacement, the mill must be stopped, leading to significant downtime. Unplanned or planned maintenance, including both inspections and replacements, leads to high costs in terms of production loss.

Santarisi and Almomany (2005) discussed a case study of the economic impact of mill liners and developed a mathematical model for the replacement of mill liners in a cement grinding mill. Their replacement decision model is based mainly on the throughput and the replacement cost of mill liners. However, the downtime cost and the liner performance in terms of product quality are not considered by the replacement model. The mill liner thickness and the relining costs are input parameters for the replacement decision model.

The mill liners of the grinding mill consist of different parts (i.e. lifter bars, grate plate, shell plate and discharge ring etc.) perform different functions in the grinding operation inside the mill (see Figure 1.2-1-3). The lifetime of the different parts of the mill liners also varies according to their different functionality. The variation in the lifetime of mill liners leads to different replacement schedules. This thesis deals with 8 different types of group of mill liners based on their lifetime (see the appended Paper IV). The mill needs to stop on several occasions for the replacement of parts of mill liners. As per the present policy of the company in the case study, mill liners are replaced when their thickness decreases to the threshold limit at which the mill shell can be damaged, in order to utilize the usable life of mill liners. However, in a few cases opportunistic replacement is also carried out. The replacement of different parts of mill liners and the frequent mill stoppages required for this lead to heavy monetary losses due to production losses (including mill start-up costs). Therefore, one of the objectives of the present thesis is to determine the optimum scheduling and the optimal lifetime, to minimize the LCC of the mill liners.

1.2.4 Maintenance optimization and life improvement

Extensive research on replacement decisions (e.g. age-based replacement and periodic replacement) for continuously degrading capital assets has been carried out by Barlow (1965), Liao et al. (2006), Scarf et al. (2007), Lam and Yeh (1994) and Jardine (1973) etc., while reviews of maintenance optimization models have been carried out by Scarf (1997) and Dekker (1996). Capital equipment projects are typically driven by the operating cost, technical obsolescence, and the requirements for performance, functionality improvements, and safety. Therefore, decision-making for capital equipment replacement will take into account of engineering, economic, and safety requirements (Liao et al., 2006).

Jardine and Tsang (2005) have discussed an example of a replaceable component (a fuel filter) that deteriorates deterministically. Jardine et al. (1998) have discussed condition-based
maintenance, which considers the age of a component and its condition at the moment of
decision making. Research on the optimum replacement interval for centrifuge machines in a
sugar refinery has been carried out by Jardine and Kirkham (1973). The objective was to
determine the optimum maintenance policy by reducing the mill downtime.

Scarf et al. (2006) have considered the application of capital replacement models at the Mass
Transit Railway Corporation Limited (MTRCL) in Hong Kong. They also considered issues
relating to the estimation of delay costs and failure consequences and their influence on the
replacement decision. Track points and escalators were used as particular examples and
technical obsolescence criteria were considered in decision making. Extensive research on
maintenance optimization for systems with multi-components has been carried out by
researchers such as Dekker et al. (1992; 1997), Wojciechowski (2010) and Zhou et al.
(2009).

Similarly, the proposed LCP model in the thesis deals with replaceable components (mill
liners) that deteriorate deterministically for a specific product (an ore type with specific
physical properties such as a specific density, a specific energy cost and a specific throughput
of a desired particle size). The present study also considers the economic influence of the
wear of the mill liners. The maintenance optimization in the present study considers
deterministic modelling with optimization of the maintenance scheduling of the mill liners at
the group and component level, while considering mill process parameters such as the
grinding performance of the mill liners, the ore properties, the ore value and the ore
processing time. The replacement policy and budget constraints for mill liners play a major
role in selecting the alternative maintenance strategies. Major replacements of mill liners
significantly affect mill economics due to variation in the process, downtime and
maintenance costs, while an optimum scheduling for replacement of the mill liners can
significantly reduce the life cycle cost (LCC).

Life cycle profit (LCP) analysis, an engineering economics technique, can be used to focus
on determining the optimum replacement interval for the mill liners to maximize the mill
profitability, while considering the process and maintenance parameters together (for detailed
information on the parameters used in the proposed LCP approach, see the appended Papers
II and III).

The LCC of mill liners can be minimized by optimum improvement of the lifetime by
determining the optimum grouping for the replacement of parts of the mill liners. The study
presented in the thesis also focuses on life improvement parameters, and the proposed
methodology can be used to reduce the LCC of the mill liners further while considering all
the possible cost components, such as the lining cost, downtime cost (including the start-up
cost), labour cost, improvement cost and premature cost (for more details of the cost
parameters considered in the proposed methodology, see the appended Paper IV.
1.3 Motivation of the study

A pilot study was conducted of the maintenance activities performed on the ore grinding mill of the present case study, in order to identify the bottlenecks in the mill which cause a reduction in productivity. The mill stoppage data connected to all types of maintenance activities performed on the grinding mill was obtained from the mining company. This data had been continuously collected manually over the period of 2003 to 2009. After analyzing the mill stoppage data, it was found that approximately 75% of the total number of mill stoppages was due to maintenance activities performed on mill liners, while 25% of the stoppages were due to other maintenance activities. For the investigated mill, for the cases when enough ore is available at mines for running the mill at 100% of its capacity, a mill stoppage leads to heavy monetary losses, which need to be minimized. Hence, the main focus and the scope of the research study presented in the present thesis covers the maintenance activities performed on mill liners.

Figure 1.8. Grinding circuit diagram (source: Boliden Mineral AB)

Figure 1.8 shows the mill circuit examined in the case study, extending from the grinding of an ore fed into the mill to the feed to flotation. As discussed earlier the reduction of the particle size plays an important role in metal recovery and significant amount of particle size reduction takes place in primary mill of the investigated ore dressing plant (reference group). Therefore, the study of the thesis is mainly focused on the mill liners of primary mill only.

A literature survey focused on the mill liners was conducted in order to identify the gap in the past research. Studies on grinding efficiency related to mill liners are discussed by researchers such as Kalala et al. (2008), Cleary (2001), Yahyaei et al. (2009), Sinnott et al.
(2006), Cleary et al. (2006), and Bearman and Briggs (1998) etc. while Santarisi and Almomany (2005) discussed maintenance planning for mill liners. However, researchers have not considered combined economic influence of grinding process and maintenance planning in the decision making for the mill liner replacement. Moreover, optimizing the replacement intervals and life improvement of mill liners have not been discussed at the component level, and this is one of the important aspects concerning mill profitability. The present research integrates maintenance activities with the grinding performance of mill liners and optimized maintenance activities on both a component and a group level, which leads to significant monetary savings.
2 Thesis approach

2.1 Problem description

With the increasing demand for production, reducing mill downtime and increasing productivity are major concerns for the mining industry. Maintenance managers are facing demands for reduction of the downtime of mills, while process departments need to improve production quality in terms of high metal recovery, and purchase departments always face the pressure of cost cutting. Figure 2.1 shows the links between the different departments’ individual goals and the entire organization’s overall goal. The maintenance activities performed on grinding mills in the mining industry have a maintenance goal, i.e. reduction of the mill downtime, which needs to be linked with the activities of both the process and the purchase departments, and which helps in achieving the overall goal of the mining industry concerning mill profitability. To achieve this maintenance goal, a critical assessment of maintenance activities and policies for mill liners needs to be carried out. The research presented in the thesis considers the wear of mill liners and its corresponding economic impacts on overall mill production economics and replacement decision making.

Figure 2.1. Attainment of the organizational goal linked with the departments’ goals
The overall maintenance strategy for mill liners consists of various key success factors that are necessary in order to achieve the overall goals of maintenance. These key success factors include time-efficient and accurate wear measurement, optimum replacement intervals and the optimum combination of components for the replacement of mill liners. Therefore, there is a need to develop effective maintenance decision support tools, i.e. models and demonstrators which can achieve the overall goal of the mining industry in the most cost-effective way.

Liner wear measurement is one of the critical activities concerning production losses, as the investigated mill needs to be stopped for the accurate wear measurement and inspection of mill liners. Different types of wear measurement methods exist in the market. Therefore, the selection of an appropriate wear measurement method is an important task which should consider economic and technical aspects based on the industry specifications, e.g. for the equipment cost, the time needed for the measurement, and the equipment’s reliability, measurement accuracy and accessibility, when taking wear measurements inside the mill.

In addition, ores from different mines are processed in the grinding mill. The variation in the ore properties, such as the density, hardness, ore retention and the processing time inside the mill etc., leads to variation in the operation and maintenance costs and the revenue parameters. The variations in these parameters increase the problem complexity regarding the appropriate time for cost-effective replacement of grinding mill liners of ore dressing plants.

The problems concerning maintenance of the mill liners of grinding mills used in the mining industry include determining (i) how cost-effective and time-efficient wear measurement of mill liners can be carried out, (ii) how the replacement of mill liners can be optimized for maximizing mill profitability, (iii) which components of mill liners should be selected for combined replacement, and (iv) what should be the optimum improvement in the lifetime of different parts of mill liners, in order to minimize the overall cost together with the mill downtime for better mill profitability. One of the important problem areas of the thesis is linking the maintenance decision with other departments’ goals, such as improvement of production quality in cost-effective ways.

2.2 Overall research goal

The overall research goal is to develop decision support methodologies and tools for the maintenance planning of the mill liners, in order to facilitate and enhance the capability of cost-effective decision making for maintenance and design decisions for mill liners and thereby increase the profit of the mill owners.

2.3 Research questions

A literature review, in addition to personal discussions with the reference group, whose members represented the field of maintenance and ore processing within the mining industry and the liner manufacturing industry, gave rise to interesting research areas in the field of developing tools for making cost-effective maintenance policies for mill liners. On the basis
of the literature review and the economic impact of the maintenance activities of the mill
liners the following research questions were formulated.

1. What are the potential areas for improvement within the investigated ore dressing
   plant?
2. How does one select the most appropriate wear measurement device, taking technical
   and economic considerations into account?
3. What should be the optimum replacement interval for mill liners in order to maximize
   the mill profitability?
4. What should be the optimum grouping for combined replacement and necessary life
   improvement of different parts of mill liners?

Table 2.1. Relationship between the appended papers and research questions (RQ 1-4)

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The links between the different activities carried out during the various phases (reported in
Papers I, II, III and IV) of the research study, as described in the thesis, are shown in Figure
2.2. The boxes with a dashed outline in the figure show the input parameters for the
Corresponding papers, while the boxes with a bold outline show the research output of the
papers. The centre box shows the overall research goal, which is linked to the research
outputs of the individual papers of the research study.
2.4 Limitations of the study

As discussed in Section 1.3, maintenance activities performed on mill liners are one of the major contributors to mill downtime. Therefore, the scope of the present thesis is limited to the maintenance activities of mill liners only.

The selection of a wear measurement method for mill liners is mainly dependent on the input parameters concerning quality and the demand limits. These input parameters have been determined through discussions with the reference group of the participatory companies. The results concerning the optimum wear measurement method are limited to the specifications and demands of the company concerned. Therefore, in this connection, research results can vary from one company to another.

Mill performance and liner wear are known to be correlated to the lifter bar’s geometry and size (Napier-Munn et al., 1999). Nevertheless, the liner design (geometry and profile) is excluded from this study due to a lack of data on the liner profile over the lifetime of the mill liners. This lack of data is a consequence of the fact that an exact profile of the liners is not measured completely during the inspections. As discussed in section 1.2.3 (C and D) the height of lifter bars mainly affects the particle size reduction therefore in the proposed replacement policy the reduction in height of lifter bars were considered as wear of mill liners.

A correlation analysis between the liner wear and the process data, it was concluded that no significant variations in the process data have been observed before and after the installation.
of small parts of mill liners. Therefore, the effect of minor replacements (replacements of one or two lifter bars) on the production performance has not been considered in the models presented in the thesis.

In the thesis, due to a lack of data, the decreasing trend of process efficiency has been considered to be the same for all three investigated ore types. However, as discussed earlier, the mill liners’ loss of efficiency due to wear varies depending on the ore type.

The methodology proposed in the thesis for combined replacement and life improvement is applicable only for preventive replacement of non-repairable components with a pre-determined age or guaranteed life. The worst-case scenario of the earliest failure is considered as guaranteed life, so that the risk of early failure can be avoided, and therefore no corrective replacement is considered.

The basis of the combined replacement and life improvement model is a minimization of the LCC by reducing the number of mill stoppages, and therefore the model assumes that the mill operates at full capacity (100%) around the clock. Hence, mill stoppages due to ore unavailability at the mines are not considered.

The lifetime of mill liners also depends on the percentage fill of ore inside the mill. The feed level varies when the mill needs to be stopped for different reasons, as the feed level is reduced before stopping the mill. The present study assumes that there are no variations in the lifetime due to changes in the throughput levels. The two main reasons for this assumption are as follows: (i) the total time with a lower level of feed inside the mill is very small in comparison with the overall lifetime of the mill liners, and (ii) it is extremely difficult to measure the liner wear due to the very few liner wear measurement occasions.

The result for the percentage reduction in the LCC of the mill liners presented in the thesis is based on the present industry policy of replacing mill liners when they reach the threshold level at which the mill shell can be damaged. However, premature replacement (opportunistic maintenance) is also carried out occasionally, and that has not been considered when comparing the present and the optimum LCC of the mill liners.

The proposed decision support model for the design of mill liners is limited to suggestions for improvement of the lifetime only.
3 Research methods

A research approach can be quantitative or qualitative or a combination of both. In simple terms, quantitative research uses numbers, counts and measures of things, whereas qualitative research adopts questioning and verbal analysis (Sullivan, 2001). Both qualitative and quantitative research methodologies have been applied in the research presented in this thesis. The focus is on applied research whose purpose is to apply LCC and LCP optimization methodologies to develop models for maintenance decisions for mill liners used in the operations of mining companies. The knowledge gathered from the literature study and the discussions with the industrial reference group was applied to describe the usefulness of LCC and LCP analysis in mining companies for maintenance planning, so as to make the planning more cost-effective for both users and suppliers of mill liners. The following methods, presented here in brief, are elaborated in the appended papers.

3.1 Data collection and analysis

Data can be defined as facts obtained by researchers from a studied environment (Cooper and Schindler, 2006). For qualitative information, a literature survey was carried out based on peer-reviewed journal papers, conference proceedings articles, research and technical reports, Licentiate and PhD theses and discussions were held with the reference group. Quantitative information was obtained from the databases of the companies participating in the present case study. Specific keywords were used to search for information in well-known online databases, including Google Scholar, Elsevier, Science Direct and Emerald etc.

3.1.1 Data collection

Process data for three years was obtained from the mining company. The process data includes the throughput, power consumption, torque, mill load, mill speed, metal recovery and water flow for different types of ore. The mill in this case study processed ore types which came from different mines and possessed different physical characteristics, such as different grade values, densities, hardness indexes etc. The variation in the characteristics of the different ore types affects the wear rate of the mill liners due to their corresponding abrasive index, which leads to variation in the grinding performance (Product handbook, 2002). Cost and revenue data obtained from the companies were used in the model, but the results were scaled to keep their confidentiality.
Raw process data (on the feed flow, power consumption, angular speed, torque, metal recovery and process efficiency) and data on the maintenance activities performed on the grinding mill, collected from the company’s databases, were treated to extract the information that is used in the models. Information concerning the correlation between the process data and the liner wear data was also collected through discussions and consultations with the reference group of the mining company. This information concerned the practical complexities related to the grinding process inside the mill, such as a physical explanation of the energy consumption during different wear phases of the mill liners, and the various kinds of monetary losses, such as production losses and start-up costs incurred during mill stoppages etc.

(b) Metso Minerals

An important source of raw data concerning the liner replacement schedule and the practical complexities arising during replacement was Metso Minerals. In addition to this, information about the maintenance contract with Boliden Mineral AB and the history of replacement schedules and inspections were also obtained from Metso Minerals.

Discussions on liner-related issues such as maintenance, replacement, inspection and grinding performance were held with experts from both companies. Our understanding of the technical complexity involved in grinding operations and its interrelation with maintenance activities was also enhanced in consultation with the industrial reference group.

3.1.2 Data Analysis

Correlations among the model parameters are one of the most important parts of the data analysis in the present study. Correlation studies were carried out for the process, maintenance and liner wear data. The main objective of this analysis was to examine the correlation between the wear of the liners and the process parameters over the life span of the liners. The redundant parameters were taken away from the investigation in order to minimize the model complexity. Figure 3.1 shows the flow chart for the data collection and analysis process for the LCP model in Paper II and III. The boxes with a dashed border in the figure briefly explain the activity performed during the process.

The analysis of the process and maintenance data in the present study is useful concerning replacement decisions for the mill liners. This is an alternative and practical approach by which replacement decisions for mill liners can be made without using periodic wear measurement of the mill liners; hence, the mill does not need to be stopped for periodic wear measurement.

The data trends and the outcome of the correlation studies were used as inputs in the model. In this connection, the outliers of the process data were removed in order to achieve an appropriate correlation and appropriate trends. The causes of the outliers in the data were identified. The main reasons for the outliers in the data were unexpected mill stoppages and variation in the process data, i.e. ore hardness and rock size variation etc.
The replacement model for mill liners combines the process and maintenance parameters in order to take cost-effective decisions. The mill data used in the methodology come from a mill that uses various types of ore which are different from each in terms of physical properties, such as density, grade value (% of metal content), ore hardness, rock size etc.

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**Figure 3.1. Flowchart for data collection and analysis process used for LCP model**
Therefore, another important part of the data analysis was to segregate the process data for each individual ore type, so that an appropriate correlation between the lifetime of the mill liners and the process data could be established.

A detailed explanation of process data segregation for individual ore types is provided in the appended Paper III. For the distribution analysis, trend tests (Kumar and Klefsjö, 1992) were used, and thereafter interpolation and extrapolation (Brezinski, 1982) were carried out for the generation of process data for individual ore types. Different types of statistical distributions were examined and their parameters were estimated by using the EasyFit software (Mathwave, 2011).

3.2 Methods used in Paper I

A systematic evaluation approach (Pahl and Beitz, 1996; Lundberg, 2000) was used as a basis for determining the quality index for investigated wear measurement methods. In the present study, the term “quality index” is defined as an overall measure of goodness for particular wear measurement method. The quality index is unified measure of a method which considers together industry specified attributes i.e. (in the present study the industry specified attributes are cost, reliability, accuracy and accessibility). It is also important to notice that an individual value of quality index doesn’t provide any exact information about a specific measurement device. It provides an overall relative importance of measurement devices in the particular investigation. The key objective of using this approach was to incorporate the quantitative and qualitative inputs together, taking into account internal weightings of the quality attributes based on their importance. Qualitative inputs from the reference group were used for assigning weights to the attributes, e.g. cost, reliability, accuracy and accessibility. A method involving a pair-wise comparison method (Saaty and Thomas, 2001) was used to assign weights to the quality attributes. The demand limits for each quality attribute were acquired from the reference group. The quantitative inputs, i.e. data on costs, reliability and accuracy, were also obtained from the participating companies.

Four wear measurement methods were selected for the investigation from twelve measurement methods using the proposed approach for selection of an appropriate method (see Figure 3.2). The detailed information concerning the determination of the quality index of the investigated wear measurement methods using liner interpolation, the demand limits, the technical feasibility, advantages & disadvantages of the all twelve considered wear measurement methods is provided in the appended Paper I. A literature survey was carried out on the existing measurement methods and their advantages and disadvantages. A discussion of experimental wear measurement methods that can be applied without stopping the mill is also presented in the Paper I.
3.3 Methods used in Paper II

Approaches involving simulation, time sampling and correlation studies were used to maximize the life cycle profit of mill liners to determine the optimum replacement interval. An LCP model for single ore type was formulated (see Paper II for mathematical formulations) to incorporate the effect of variation in the production performance, i.e. variation in the mill revenue, and the maintenance policies. The data analysis includes correlation studies between the process and the maintenance parameters, determination of the distribution types, trend tests and a serial correlation test, in order to use the desired process data in the LCP model. The LCP model also includes maintenance parameters such as the production loss cost, relining cost, labour cost and inspection cost. Time sampling was used to incorporate the variation in the cost and revenue parameters due to changes of the ore types and their order of processing. Simulation was carried out in order to incorporate the randomness of the throughput parameters.

The LCP is a useful method and indicator and is used in organizations for the coordination of maintenance, technical and economic criteria in decision making (Hunkeler, 2000; Borg, 2001; Markeset and Kumar, 2004; Patra, 2009). In the present research, the LCP model has been used for maintenance decision making which combines the economic influences of process variations and maintenance activities in the system.

Time sampling is a commonly used approach to quantifying and measuring the behavioural phenomena of a system (Powell et al., 1975). This method has been used to assess the behaviour of the economic efficiency of the mill, over the lifetime of the mill liners.

Correlation studies (Rodgers and Nicewander, 1988) were used in Paper II and III and are an important part of the research methods used in these papers. The main objective of the correlation studies was to determine the correlation between the lifetime and the parameters affecting mill economics, so that these parameters could be incorporated in the LCP model.

A literature survey on correlation among process parameters is briefly discussed in Paper II. The paper also briefly discusses the physical explanation of variations in the process parameters with the liner wear. A computer program in the form of a demonstrator was
developed for simulation and the large amount of computation. EasyFit (Mathwave, 2010) was used to carry out the distribution analysis in the paper.

### 3.4 Methods used in Paper III

Correlation studies, experimental results and the experience of industry experts were used for developing relations between the ore properties and the lifetime of the mill liners, while simulation and time sampling methods were used for maximizing the mill profitability, to develop an economic decision model. Variations in process parameters such as different ore properties due to the use of multiple ore types influence the lifetime of mill liners, while a random order of processing, the processing time and the monetary value of different ore types lead to variation in the mill profitability. The weighting approach and simulation were utilized to emphasize the contribution of parameters such as the ore value and the processing time of a specific ore type to the final result. The methodology used in Paper III is an extension of the LCP model proposed in Paper II in order to develop a combined model for optimum replacement of the mill liners interval for multiple ore types. As discussed earlier, the proposed relation between lifetime of the mill liners and the ore density have been incorporated in the LCP model (see Paper III, for detailed derivation of the combined model).

The data analysis part of the research method includes distribution analysis, trend tests, a serial correlation test, interpolation and extrapolation, simulation etc. Data analysis was also an important part of this paper, as it was used to segregate the individual economic effects of different ore types over the lifetime of the mill liners and to incorporate the uncertainty in the throughput (feed flow) in the LCP model.

An approach of determining the optimum replacement interval, for the case of multiple ore types are processed in the grinding mill is shown in Figure 3.3. An example is considered for the ore types from three different mines i.e. mine A, B and C. The dotted boxes containing the process data and the operational and maintenance cost data which were used in the advanced LCP model (see Paper III) for single ore type to determine the optimum replacement interval for given ore types. Later, the three parameters of each ore types (1) the optimum replacement interval for individual ore types \(T_i\); (2) the ore processing time \(t_i\); and (3) the monetary value for each ore type were combined in order to determine the optimum replacement interval \(T_{\text{eff}}\) for multiple ore types (for details of mathematical formulations, see Paper III).
Research methods

3.5 Methods used in Paper IV

Life cycle cost (LCC) modelling (for details of the formulation of the LCC model, see Paper IV) and an approach based on an exhaustive enumeration search (Nievergelt, 2000) were used to determine the optimum grouping for combined replacement and the optimal life improvement of different parts of the mill liners. In this paper LCC modelling considers the relining cost and the production losses occurring during replacement for all the possible scenarios for the grouping of different parts of mill liners. The approach based on an exhaustive enumeration search was used to determine the optimal life improvement of the parts of the mill liner based on the minimum LCC. An algorithm (see the following section 3.5.1) was proposed in the paper for selecting the best scenario for combined replacement from all the possible scenarios.

A computer program in the form of a demonstrator was written using Microsoft Excel and Visual Basic for combining the LCC with an exhaustive search. The life-cycle costing method is used for quantifying the cost-related parameters in a production system or a product during its life cycle (Dhillon and Reiche, 1985; Blanchard, 1986). Asiedu and Gu (1998) stated that LCC analysis should be regarded not only as an approach for determining the cost of a system, but also as an aid for decision making in design, maintenance, etc. The main reason for using...
LCC analysis was to include all the possible cost components that are related to liner replacement.

3.5.1 Algorithm for optimum maintenance scheduling and improvement in lifetime

Taking replacement decisions for different parts of the system concerns the task of the appropriate design of a maintenance schedule, and, in this connection, it is important to take into account interactions among all the cost components and technical considerations. The present approach further optimizes the solution and provides the optimal combination jointly with the optimum improvement in lifetime of the mill liner components. A flow chart of the algorithm used in the present methodology is shown in Figure 3.4. To start with, the algorithmic model takes various inputs, such as the component types with their different lifetime and improvement costs, the planning horizon period, the preparation time before actual installation, the mean time to replace (MTTR) and the technical feasible allowable improvement in lifetime \((\Delta T_i)\) of the mill liners (for details of the considered parameters, see Paper IV). In order to minimize the mathematical computation components should be grouped in the beginning based on their lifetime i.e. component with the same life should be in placed in one group. The algorithm defines all the possible maintenance replacement scenarios (for “m” components, the all possible replacement scenarios will be \(2^m-1\)). Then it takes the maximum achievable lifetime of each component as an input which is used to determine and eliminate all the unfeasible scenarios/all the impossible combinations \(N_j\) (see the following section 3.5.2). It takes all the types of cost inputs and determines the new lifetime of each component, if it is economically feasible. The economic feasibility of a component is determined by comparing the cost required for improvement in lifetime and the savings to be made through reduction of the downtime cost and the number of mill stoppages. The new lifetime cost of each component, the new LCC, is calculated by adding the downtime cost, including the labour cost, the total lining cost and the cost needed for life improvement. The scenario with the minimum LCC and the corresponding lifetime are recorded in a separate table. In the next iteration, the improvement in lifetime variable is increased by 1 time unit and the condition is checked as to whether the improvement is technically feasible. For each iteration of the improvement of the lifetime, the scenario with the lowest LCC and the corresponding lifetime are stored. The scenario with the lowest LCC among all the stored LCCs for each step of the improvement in lifetime will be selected as the optimum scenario and the corresponding lifetime provides the necessary life improvement for each component. Finally, the optimum replacement frequency is determined using the optimum lifetime of the components.
Figure 3.4. Flow chart of algorithm used in the proposed model
3.5.2 Elimination of unfeasible scenarios (N)

The unfeasible scenarios are determined and eliminated. The main reason for the elimination of the unfeasible scenarios is to reduce unnecessary mathematical computation when there are a higher number of components in the system. In case of different components the total number of possible scenarios will be $2^m-1$ (see Paper IV, for the details of all possible maintenance scenarios).

The algorithm of the present study considers the life improvement parameter as input in the model, which means that, at each level of improvement in lifetime, each possible maintenance scenario needs to be considered. Therefore, for the elimination of unfeasible scenarios, the proposed algorithm checks the technical feasibility of the improvement in lifetime. To elucidate this phenomenon, the example consisting of three components is considered. Let us consider a scenario where component 1 of lifetime $t_1$ has to be rescheduled with component 2 or 3 of lifetime $t_2$ and $t_3$ respectively as shown in Figure 3.5.

In Figure 3.5, the vertical dashed lines represent the scheduled stoppages and $\Delta T_{ij}$ represents the technically feasible improvement in lifetime of component 1. The relative comparison of the wear lives is $(t_1 > t_2 > t_3)$. For the case $t_1 + \Delta T_{ij} < t_2$, that means that component 1 cannot be rescheduled with component 2, since, even after the improvement in lifetime, the replacement interval of component 1 is smaller than the replacement interval of component 2, and such scenarios are considered as unfeasible maintenance scenarios, which are eliminated before all mathematical calculations to reduce the complexity and make the algorithm fast.
4 Demonstrators

In the present study, two demonstrators have been developed. The first demonstrator (1) is based on the methodology developed in Papers II and III and determines the optimum replacement interval for major replacements of the mill liners, considering the process and maintenance data. The second demonstrator (2) determines the optimum grouping of the mill liners and the optimal improvement in the lifetime of the mill liners by minimizing the LCC of the mill liners based on the methodology presented in Paper IV.

The thesis presents the demonstrator (2) on the methodology developed in Paper IV for optimizing the maintenance schedules and wear lives of the mill liners. The demonstrator (2) has been developed using Macros in Excel. This demonstrator can be used as a decision support tool for assisting the maintenance manager in determining the optimum grouping and the optimal improvement in the lifetime for the replacement of different parts of mill liners in a cost effective manner. The demonstrator can be used for systems consisting of mill liners with different lifetimes. The optimum maintenance schedule and life of different parts of the mill liners have been determined through minimizing the LCC of the system using the demonstrator. The technical feasibility related to maximum improvement of the lifetime and variations in the improvement costs for different parts etc. have been considered. The LCC for all the possible maintenance scenarios has been calculated. A user manual has been provided in the demonstrator for better usability.

4.1 Inputs

The inputs need to be given in the demonstrator in order to determine the optimum grouping for combined replacement and the cost effective optimum improvement of the life of different lifetime categories of mill liners. A description of the inputs and parameters in the various tabs (in the Excel sheet) in the demonstrator are given in this section.

The components or parts of the mill liners are categorized based on their pre-determined lifetime and the cost needed for the improvement of the lifetime. This means that two or more parts of the mill liners are considered as belonging to one category if the lifetime, the cost needed for the improvement of the lifetime, and the maximum achievable improvement in the lifetime of these components are the same.
In the present context, the planning horizon period covers the replacement planning cycle for all the mill liners. The present study deals with different types of mill liner components based on eight different lifetime categories. The planning horizon period is based on company policy. In the present case study, the planning horizon period for the LCC calculation is the same planning horizon period as that of the company. For detailed information about the input and output parameters of the demonstrator, see the appended Paper IV.

**Number of lifetime categories/components (No.):** The components or parts of the mill liners are categorized based on their pre-determined lifetime and cost improvement function. This means that two or more parts of the mill liners are considered as belonging to one category if the lifetime, cost improvement function and maximum achievable lifetime of these components are the same.

**Planning horizon period/ (weeks):** In the present context, the planning horizon period covers the replacement planning cycle for all the mill liners. The present study deals with different types of mill liner components based on 8 different lifetime categories. The investigated components had different wear lives, and the lifetime of the longest lifetime category is considered as the planning horizon period for LCC calculation in the present case study due to company planning horizon policy.

**Downtime cost (SEK/hour):** Total value of lost production during the installation of mill liners

**Start-up time/Preparation time (hours):** Preparation time is the total time (excluding the actual liner installation time) from the time when the mill is put out of operation for the mill liner installation to the time when it starts to function at full production level

**Labour (SEK/hour):** Average cost per hour for entire crew during the installation of the mill liners.

**Cost required for life improvement (SEK/week):** Defines cost needed for improvement in wear life based on components.

**Maximum achievable improvement in lifetime (weeks):** This is the maximum achievable improvement in lifetime of component which is technically feasible. Its value varies from one component to another.

**Component life time (MTTF) (weeks):** The mean time to failures (MTTF) of a component represents the average time duration from its installation to its removal when it has completed its lifetime.

**Replacement time MTTR (hours):** Time needed to installing a particular category of mill liners.

**Replacement cost (SEK/component):** Total purchase price of each component/category.

### 4.2 Outputs

The outputs of the demonstrator provide the optimum scenario with the optimum improvement in the lifetime among all the possible maintenance scenarios. A description of the outputs and parameters in the various tabs (in the Excel spread sheet) in the demonstrator are given below.

**Frequency:** This column indicates the new calculated replacement frequency of a certain lifetime category for the entire specified time horizon.
**Improvement in lifetime (weeks)**: Suggested improvement in lifetime or reduction for each category to find optimum scenario. The positive "+" sign means life improvement, whereas "-" represents reduction of life.

**Lifetime categories with fixed replacement schedule**: Indicates categories which are selected to have a fixed replacement schedule based on the original lifetime input.

**Lifetime categories to be rescheduled**: Indicates categories which are selected to be rescheduled.

**Reduction in downtime cost due to combined replacement (SEK/planning horizon period)**: Indicates reduction of downtime cost when two or more categories are merged to be replaced at the same time.

**Downtime cost for a given scenario (SEK/planning horizon period)**: Indicates total downtime cost (lost revenue).

**Lining cost for a given scenario (SEK/planning horizon period)**: Indicates total lining cost for a given scenario, including cost for improvement of lifetime.

**Additional cost for improved lifetime (SEK/planning horizon period)**: Indicates total cost for improvement of lifetime only.

**Value of prematurely replaced parts (SEK/planning horizon period)**: Indicates lost value (based on remaining lifetime) of all wear parts moved to (aligned according to) an earlier replacement date. Note that this assumes that the liner life is not adjusted over the time horizon, which is normally not the case and must be considered when reviewing this cost or when inputting the weekly cost of improvement.

**Labour cost (SEK/planning horizon period)**: Total labour cost for the given scenario.

**Total cost for the scenario (SEK/planning horizon period)**: Total cost for a given scenario (LCC) = (Total downtime cost + total lining cost + total labour cost) - reduction of downtime and labour cost during combined replacement due to rescheduling as well as by default replacement occasions.

**Optimum scenario**: Indicates best scenario based on minimum LCC. The scenario number identifies the optimum alternative. The total cost is also indicated in the same row.

**Maintenance schedule options**: The demonstrator provides various maintenance schedule options, along with the improvement in lifetime at different levels of LCC. The main objective of considering various maintenance schedule options is to synchronize the periodic maintenance overhaul and other maintenance activities e.g. periodic mill maintenance and maintenance overhaul etc. with liner replacement activities.

**NPC**: No possible combination

The discussions on the results obtained from the demonstrator are briefly described in Chapter 6 of the thesis, entitled “Results and discussions”.

### 4.3 Demonstrator generality

The demonstrator for determining the optimum grouping and the optimum improvement in the lifetime can be obtained by contacting author of the thesis. The demonstrator can be used in general for other systems with non-repairable components with a pre-determined age (guaranteed life) through mapping and reformulating the model input parameters. The lifetime categories can be used as the pre-determined age and the cost of improvement needs to be modified as per the components’ specification. The maximum achievable improvement in the lifetime is an important model input variable in terms of keeping the technical feasibility of the
life improvement and can be used for components of other systems. A detailed discussion of
the algorithm and mathematical model used in the demonstrator for determining the optimum
scenario is presented in Paper IV. The demonstrator can be used for optimizing the
maintenance scheduling of a system consisting of a maximum of eight components with
different lifetimes.
5 Extended abstracts of appended papers

5.1 Paper I

**Purpose:** Measurement 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. The objective is to determine the best wear measurement method among the methods which qualify by reaching the threshold level of quality attributes specified by the companies involved in the case study.

**Study approach:** A systematic evaluation method was used for determining the most cost-effective method of the methods which fulfilled the company-specific requirements. A pairwise comparison method was used to determine the relative weights among the quality attributes specified for the wear measurement method.

**Methods:** A discussion on the bottlenecks causing the downtime of a grinding mill in an ore dressing plant is presented. The paper investigates mill liners, which are critical components and play an important role in terms of mill profitability. The study in this paper shows that liner wear measurement leads to heavy monetary losses due to the measurement time and mill stoppages required. However, in some cases, inspection involving wear measurement of mill liners is also carried out during mill stoppages for other maintenance activities which are not related to mill liners. Various types of existing and non-existing liner wear measurement methods are proposed and a short description of the technical and economic feasibility, and the advantages and disadvantages of each method is provided. After the completion of a literature survey and discussions with the industrial reference group and, four quality attributes (cost, availability, reliability and accessibility) of wear measurement methods were included for assessment of the methods. This paper highlights the importance of an indirect measurement method to reduce the downtime during inspection and of making cost-effective replacement decisions for mill liners. Significant savings through using an appropriate wear measurement method have been observed and they are presented in the paper.
5.2 Paper II

**Purpose:** This paper develops a decision support model to help maintenance managers determine the optimal cost-effective interval for replacing grinding mill liners used in ore dressing plants. The decision support model is based on a detailed analysis of the mill performance, liner wear, and maintenance statistics.

**Methods:** Mathematical models for the life cycle profit and the economic efficiency of the mill were developed based on the results obtained from the correlation studies between the studied parameters. A time sampling approach was used in order to observe the effect of process efficiency on mill economics at each stage of the lifetime of the mill liners. Correlation studies between the process parameters and the liner wear were carried out to determine the necessary mode parameters.

**Findings:** A model for the replacement interval for the grinding mill liners was developed, considering the process parameters of a single ore type. The new model for the replacement interval for ore grinding mill liners considers the economic influence of the replacement decision on the process parameters (production quality, energy consumption and random variation in the feed flow) in the decision making. A brief description of the parameters’ characteristics and the interrelation between the maintenance and process parameters is presented. A physical explanation of each parameter is provided to give an in-depth picture of the influence of maintenance decisions on mill production economics. The model presented is only useful for the mill which processes single ore types, as the model does not consider the effect of different ore types on the model results. The time sampling approach shows the combined influence of the maintenance and process parameters on the overall mill profitability. Significant savings (a 0.5% to 1% improvement in the annual profit) were observed when the current replacement policy was replaced by the proposed replacement policy for the specific ore type studied in the presented case study. The novelty is that the model uses practically available process and maintenance data to make optimum replacement decisions without considering periodic wear measurement data between two consecutive replacements.

5.3 Paper III

**Purpose:** The lifetime of mill liners is an important parameter concerning maintenance decisions for mill liners. Variations in the process parameters, such as different ore properties due to the use of multiple ore types, influence the lifetime of mill liners, while a random order of processing and the different processing times and monetary values of different ore types lead to variation in the mill profitability. The objective of this paper is to develop an economic decision model considering the variations in the process parameters and maintenance parameters, to make more cost-effective replacement decisions for mill liners.

**Methods:** This paper uses and extends the LCP model developed in Paper II by incorporating ore density parameters and a wear model in order to improve the model usability for multiple ore types. The data collection and analysis process related to mill liner replacement is briefly
described in this paper, and this is important in the context of model usability. Hence, the steps required for using the model in various industry scenarios are briefly described.

**Findings:** A model for estimating the lifetime of mill liners was developed based on ore properties. The lifetime model was combined with a replacement interval model to determine the optimum replacement interval for the mill liners, considering the process parameters of multiple ore types. The proposed combined model also shows that an optimum maintenance policy can not only reduce the downtime costs, but also affect the process performance, which leads to a significant improvement in the savings of the ore grinding mill. The model results show that an earlier replacement than that specified in the current replacement policy (i.e. replacement when the mill liners reach the threshold limit at which the mill shell can be damaged) can lead to a 0.3-0.5% improvement in the annual mill profit for the case study. The novelty is that the new combined model is applicable and useful in replacement decision making for grinding mill liners in a complex environment, e.g. processing multiple ore types and with different monetary values for the ore types and a random order of ore processing. A brief description of the usability of the proposed model is also discussed for different scenarios, showing that the model can be used for different types of grinding mills.

### 5.4 Paper IV

**Purpose:** Replacement decisions concerning the liners in grinding mills of ore dressing plants play an important role in mill economics. The grinding mill uses various types of mill liner components with different lifetimes. Minor stoppages during replacement lead to production losses and to losses that occur during the start-up time. The objective of this paper is to determine the optimum grouping for combined replacement and the necessary life improvement of different parts of mill liners.

**Methods:** An approach based on an exhaustive enumeration search was used to determine the optimal scenario of all the feasible scenarios, for each step of improvement of the lifetime of the mill liner parts. Optimized maintenance decisions are based on a trade off analysis between the savings to be gained from a reduction of the downtime cost and the investment needed for improving the life of the part of the mill liners in question. The scenario with the minimum LCC for every stage of the life improvement provides the optimum grouping and optimum life of the parts of the mill liners.

**Findings:** A model for the optimum grouping and lifetime improvement of grinding mill liners was developed. The developed model provides an optimized maintenance scheduling through optimum improvement of the lifetime of the mill liners, with the focus on minimizing the LCC by reducing the number of unnecessary mill stoppages for replacement of the mill liners. The model results show a reduction of 32% in the LCC of the mill within the investigated case study. Moreover, the model results also show a 12% reduction in the LCC of the same mill when the optimal maintenance strategy does not consider any investment for optimizing the lifetime of the mill liners. That means that the LCC can be minimized further if the lifetime of the mill liners is also optimized, together with the replacement schedule of the
mill liners. The results of the developed model are useful for the design departments of liner manufacturers for optimizing the material and dimensions of mill liners, in order to achieve a proposed improved lifetime.
6 Results and discussions

The findings of the conducted research are in this chapter discussed and presented according to the stated research questions.

6.1 Results and discussions related to the first research question (RQ1)

The first research question (RQ1) of the study is answered by Section 1.3, “Motivation of the study”, and the research presented in Papers I, II, III and IV. In the ore dressing plant, the main potential areas for improvement that need to be focused on have been identified and are described below.

The downtime cost (including the start-up cost) incurred during inspections of the wear of mill liners should be minimized. Therefore, the study should focus on the optimum wear measurement method for mill liners, so that the measurement time and mill stoppages can be minimized in order to reduce the downtime cost. A concise but detailed discussion on the selection of optimum wear measurement devices is provided in Section 6.2.

The monetary losses due to extending the mill liner replacement interval beyond the useful economic life of the mill liners should be minimized. Therefore, the study should focus on the reduction of grinding efficiency of the mill due to the wear of mill liners when taking a replacement decision. A concise but detailed discussion on the selection of an optimum replacement interval for mill liners is given in Section 6.3.

The production losses (including the start-up cost) due to multiple stoppages of the grinding mill for major and minor replacements of mill liners should be minimized. Therefore, the study should focus on the optimum replacement scheduling for the parts of mill liners. A concise but detailed discussion on the selection of an optimum replacement schedule for the parts of mill liners is provided in Section 6.4.

6.2 Results and discussions related to the second research question (RQ2)

The second research question (RQ2) of the study is answered by the research presented in Paper I. A detailed overview of the maintenance activities performed on a grinding mill showed that one of the main contributors to downtime and production economics is the maintenance activities (inspection and replacement) performed on mill liners. The aim of Paper I was to understand the maintenance of mill liners in a broad perspective that would widen the scope of the present research activity.
The importance and the appropriate selection of wear measurement methods, from the perspective of cost-effectiveness, are highlighted in the present research work. Yowell (1992) and Radzisewski et al. (2007) discussed the technical aspects of various liner wear measurement methods. In Paper I, the identified quality attributes (i.e. the cost, measurement time, equipment reliability, measurement accuracy and accessibility for taking measurements) of a measurement device were combined into a single unit defined as the quality index, which is the basis of the selection of an appropriate measurement method based on the users’ requirements. The quality index of the investigated measurement devices gives an overall idea of the equipment’s effectiveness with respect to all the quality attributes described in Paper I.

An overall evaluation process for wear measurement devices is described in the paper. The output of the evaluation is highly dependent on the values of the input variables. Therefore, a careful assessment is needed when performing objective analysis. The quality index of the investigated measurement devices gives an overall idea of the equipment’s effectiveness with respect to all the quality attributes described in the paper. Four wear measurement methods were qualified for the investigation from twelve measurement methods. The remaining eight disqualified methods did not fulfil the company-specific requirements. The quality index for each investigated method was determined. The value of the quality index is relative and represents the relative importance of the investigated wear measurement methods, and the method having the highest value for its quality index is the most appropriate method.

The proposed approach for assessing the investigated wear measurement devices is based on both objective and subjective parameters. The value of the “accessibility” parameter for each measurement device was obtained through discussions with the project reference group and experts. The grade value of each quality attribute for calculation of the quality index was determined using linear interpolation. Hence, the results of the proposed approach depend on qualitative judgments. Therefore, the quality index values of the parameters should not be considered as a standard value. The quality index value for the same method may differ from one group to another.

Concerning complete profile measurements of all the dimensions of the liner, the most useable method today is laser scanning, which can provide more accurate wear data and can be used effectively to make more robust replacement decisions. Paper I also suggests the development of a wear measurement method for mill liners that could take continuous wear measurements without stopping the mill. Such a wear measurement method could be used to reduce the number of mill stoppages needed for inspection, and the continuous wear measurement data would be useful for optimizing the production performance of and replacement decisions for the mill liners.

6.3 Results and discussions related to the third research question (RQ3)

The third research question (RQ3) of the study is answered by the research presented in Papers II and III. Mill liner replacement at the group level, from the perspective of process efficiency,
is briefly discussed in Paper III, which shows the influence of maintenance decisions for the mill liners on the mill profitability. A cost-effective replacement decision model for the life cycle profit (LCP) is proposed in the present case study, with joint consideration of the technical, economic and maintenance parameters together. The technical aspects include the product quality in terms of metal recovery, ore density, processing time, power consumption and mill liner lifetime, while the maintenance and economic aspects comprise the downtime cost, labour cost, relining cost, energy cost and ore value (revenue) etc. (for more information on the technical considerations, see Cleary (2001), Kalala et al. (2005a) and Kalala et al. (2005b)).

Process efficiency is an important parameter of the proposed model for considering the quality of the metal output. Hence, sufficient data on the process efficiency is needed for making more effective replacement decisions. In the present thesis, due to a lack of data, the decreasing behaviour of the process efficiency is considered to be the same for all three investigated ore types. According to Paper I, the proposed continuous wear measurement of mill liners can provide accurate data on the behaviour of the process efficiency for each ore type, leading to more effective decision making.

Historical process data, maintenance data, production planning data (i.e. data on the processing time), the tonnage to be processed, and the grade values of specific ore types are needed for predicting the optimum replacement interval. Hence, these data should be collected in order to achieve more effective decisions. The model usability in different scenarios is also briefly described in Paper III.

Paper II and III suggest a methodology that combines the different optimum decisions for individual products (ore types) into a single optimum decision, while taking the economic and technical characteristics of each ore type into consideration. This methodology also suggests an alternative method of decision making that does not use periodic wear measurements, which are very difficult to obtain in practice. The model usability in different kinds of scenarios, which can be helpful for users with different specifications and data availability, is explained in Paper III.

The results of the LCP model (developed in Paper II) show that the optimum replacement interval for major replacements of mill liners turned out to be 290 days for a specific throughput value of 1,874 tonnes/day. Figure 6.1 shows a graph for the profit fractions (for normalized profit, see relation 3) for a single ore type versus the optimum replacement interval.
The reason for the lower gross profit on the left side of the optimal point, in comparison with the gross profit at the optimal point, is the dominance of the losses due to the downtime cost (due to the short intervals between the mill stoppages for liner replacement) over the benefits due to better process efficiency, in comparison with the scenario for the optimum replacement interval. On the other hand, the reason for the lower gross profit on the right side of the optimal point is the dominance of the losses due to a decrease in the process efficiency (see Figure 1.6) over the savings due to fewer stoppages resulting from a longer replacement interval, in comparison with the scenario at the optimal point.

The extended LCP model (developed in Paper III) was simulated for all three investigated ore types and the results for the optimal replacement intervals converged between 258 and 286 days with a 95% confidence interval (see Figure 6.2). Significant monetary savings were indicated with replacement of the current replacement policy of replacing liners on day 330 with a suggested policy of replacing liners between day 258 and 286. The results obtained for the optimum replacement interval show an increase of 0.3% to 0.5%, with a 95% confidence interval, in the gross profit per year, by changing the current replacement policy to a proposed policy based on the given case study.
The developed replacement model in Paper II should be used for mills which process a single ore type, as this model does not deal with parameters such as ore properties, processing time and the order of processing of different ore types. The extended replacement model developed in Paper III should be used for mills which process multiple ore types, as it is a more complex model compared to the model proposed in Paper II. The extended model also needs information related to the ore processing schedule in advance, and therefore the model results also depend on variations in the production planning schedule over the lifetime of the mill liners. The results of the sensitivity analysis show no technical risk, because, for the worst-case scenario, the model considers the average life cycle of the mill liners as a constraint, and the model results for the optimum replacement interval will always be less than the threshold limit or the average life cycle of the mill liners (the maximum delay in the replacement of mill liners). However, the information on the production planning of the company involved in the present study is commonly available for one year in advance.

Process efficiency is a critical parameter in the replacement model and is used to incorporate the economic influence of the performance of the mill liners. The results of the model are also highly dependent on the process efficiency (see Figure 1.6). Due to a lack of process efficiency data, it was assumed that the decreasing pattern of the process efficiency for all three investigated ore types was the same, and only one set of process efficiency data between two major replacements of mill liners was considered. However, for better model results, the trend of the process efficiency data for a specific ore type should be verified for more replacement cycles.

The discussion section in Paper III describes the model usability in different practical scenarios. The developed LCP model uses the process and maintenance data as model inputs, and therefore it is important to use the data in an efficient way. It is quite common that the data format and data availability vary from one mining company to another, and therefore a stepwise procedure is described for using such data in the model. A discussion on both the technical and the economic risk associated with the model under worst-case scenarios, due to unexpected variations in the ore properties, is presented in Papers I and II. The present model
can also be used for replacement decisions for other similar systems (manufacturing units) consisting of non-repairable equipment, by considering the periodic operational cost data, the performance index (e.g. process efficiency) and the revenue, together with the downtime and inspection costs.

6.4 Results and discussions related to the fourth research question (RQ4)

The fourth research question (RQ4) of the study is answered by the research presented in Paper IV. After a detailed analysis of historical replacement data for mill liners at the parts level, a heavy downtime cost due to multiple mill stoppages was observed. Paper IV discusses the usefulness of combined replacement and necessary life improvement of the parts of the mill liners. An approach for optimum grouping for combined replacement with necessary improvement of the life period of different parts of mill liners is presented. The basis of optimizing replacement scheduling is cost-benefit analysis relating the reduction in the downtime cost (including the start-up cost and labour cost) to the costs incurred due to improvement of the lifetime and premature replacement.

The research presented in Paper IV revealed that an effective improvement of the lifetime of mill liner components can also lead to additional savings for the mill. The findings show that a combination of optimum grouping and necessary improvement of the lifetime component leads to a potential reduction in the downtime cost of up to 32% (see Figure 6.3). The results show that an increment of 6% in the lining cost due to premature replacement or the cost needed for improvement of the lifetime, or a combination of both, may lead to a significant reduction in the LCC. In the present case study, the downtime cost is very large in comparison with the lining cost, and hence the results show that there is a significant amount of savings to be obtained through a reduction in the downtime cost.

The four ore grinding mills of the mining company of the present case study, located in four different regions, follow the same replacement policy for mill liners. Therefore, the level of savings for the company will be very high if the existing replacement policy is modified according to the proposed replacement policy.

The cost data was normalized to preserve confidentiality for the company concerned, but the original cost ratios were kept the same in order to maintain a correct percentage variation in the LCC and other cost components. In order to normalize the costs, the LCC of the present scenario was considered as 100 and the other costs were based on the LCC of the present scenario.
Due to a budget constraint for new investments for design changes that would improve the lifetime of mill liners, the present methodology was used without considering improvement of the lifetime. The results show that there is a reduction of 12% in the LCC to be gained by applying an optimum grouping of the different parts of the mill liners, which means that the proposed methodology can still be useful for reducing the LCC significantly, considering the budget constraint of the company. This reduction in the LCC in this case is due to a reduction in the number of mill stoppages and corresponding downtime costs.

The sensitivity of the model results is also based on the planning horizon period. The present study considers a planning horizon period of 120 weeks, which is the planning horizon period according to the company’s maintenance policy. The results of the present study show three optimum scenarios for different planning horizon periods, and for those three scenarios, the model results converge at a specific optimal scenario for a long planning horizon of more than 700 weeks. However, the sensitivity of the model results varies from 1-2% for the different optimal scenarios.

The proposed methodology also provides various maintenance schedule options with corresponding improvements in the lifetime at different levels of LCC of the mill liners. The main objective of the different maintenance schedule options is to consider the periodic maintenance overhaul or other maintenance activities and to synchronize them with liner replacement activities. Figure 6.4 shows four different maintenance schedule options at different levels of LCC. The analysis shows that a slight increment in the LCC can provide a
better maintenance option which is technically more feasible concerning synchronization with other maintenance activities performed on the grinding mill. An example for a system consisting of 8 components with different maintenance schedules is briefly discussed in the appended Paper IV.

A sensitivity analysis was also performed on the improvement in the lifetime, in order to validate the logical expectations for the proposed algorithm for hypothetical cost inputs. Figure 6.5 shows different cost curves and the vertical dotted line shows the zone of optimum improvement in the lifetime. In Figure 6.5, the lining cost (including the improvement cost) increases when the improvement in the lifetime increases due to an increment in the lining cost with an improved lifetime, whereas the downtime cost (including the labour cost) decreases due to a reduction in the number of mill stoppages. Therefore, the minima of all the LCC are observed at an optimum improvement in the lifetime. Figure 6.6 is the same LCC curve as that presented in Figure 6.5, although with a different scale for better visibility of the minima.
The deterministic approach for maintenance optimization was used in the present demonstrator, and the results of the demonstrator may vary due to uncertainties, i.e. variation in the lifetime of the components, different planning horizon periods, and technological changes. Therefore, the demonstrator results for the optimum maintenance policy should be considered as an indicator for choosing an appropriate maintenance policy. However, the demonstrator also presents different maintenance schedule options based on the LCC, which can help users to select the appropriate maintenance policy based on the company requirements.
7 Conclusions

The following conclusions have been made in the thesis:

- The maintenance activities (inspection and replacement) performed on mill liners and the different lifetimes of liner components are two of the main contributors to production losses concerning maintenance of the grinding mill. Therefore, maintenance policies for mill liners are identified as potential areas for improvement and hence it should be carefully assessed.

- The wear measurement of mill liners plays an important role in the context of mill downtime during inspections and in the making of replacement decisions. Hence, it is important to evaluate the existing methods systematically, so that an optimum wear measurement method that satisfies the specified requirements can be selected.

- The maintenance activities performed on mill liners affect not only the maintenance costs, but also the grinding performance of the mill. Therefore, a cost-effective maintenance policy for mill liners should integrate the process parameters, ore property parameters, operation and maintenance cost parameters together.

- A decision support model for major replacements of mill liners has been developed which correlates the maintenance policies for mill liners and the process performance of the mill and combines them. The results obtained from the model show that an optimum maintenance policy not only reduces the maintenance cost, but also affects the process performance.

- The proposed LCP approach is an alternative method of decision making for liner replacement that does not use periodic wear measurements, which is especially useful due to the unavailability of sufficient mill liner wear data for analyses.

- The mill has to stop on several occasions due to major and minor replacements of different parts of mill liners owing to their different lifetimes, which leads to heavy monetary losses. These mill stoppages can be reduced by optimizing the grouping for combined replacement of different parts of mill liners.

- The replacement schedule and design for different parts of mill liners can be optimized further through optimum improvement of the lifetime of different parts of mill liners.
8 Future research

Based on the research conducted in the thesis, the following areas are considered especially suitable for further research:

- Power signature diagnosis is identified as a promising indirect wear measurement method which should be developed further, since, when using this method, 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 liner wear. The continuous liner wear data obtained with this method can be used for making more effective decisions through the proposed model for major replacements of mill liners.

- The research presented in the thesis has mainly focused on the studied mill (a primary mill). The maintenance activities performed on the mill liners of a secondary mill (a mill used for reducing the particle size in the same ore dressing plant) can be synchronized with replacement decisions for the mill liners of the primary mill, which can further lead to additional savings.

- The proposed LCP model can be used to determine the optimum replacement interval for the degrading spare parts of other systems, by modifying the model parameters based on the industry specifications.

- The LCC model for combined replacement considers all kinds of replacements (major and minor). The model can be improved further by considering the grinding performance in relation to the replacement activities by applying the following two steps. The first step is to implement the maintenance schedule obtained from the LCC model. The second step is to collect process data after the implementation of the new maintenance policy for replacements. The obtained process data can be used in the LCP model for further optimization of the replacement policies.

- The LCC model and the demonstrator for combined replacement can be used for optimizing the maintenance activities and life improvement of other systems by considering the probabilistic life of the components and simulating the model. For example, the model and demonstrator can be used for replacement decisions for the scaling machines of mining companies, considering the different life cycle periods of the different components of the scaling machine. A modified version of the present LCC model can be used to synchronize the maintenance activities of railway systems for maximizing the track availability at a minimum level of LCC.

- The LCC model can also be modified by considering the current lifetimes of different components as inputs. This modification in the methodology will enhance the model usability, so that the model results can be used at any stage of the system to determine the optimum maintenance policy.
References


References


Appended papers
Paper I

Evaluation of Abrasive Wear Measurement Devices of Mill Liners

Evaluation of Abrasive Wear Measurement Devices of Mill Liners

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Abstract
Measurement 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 attributes 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. The main aim of this study is to determine a unified measure or quality index for the service quality of the measurement device across selected attributes. Each quality index will then correspond to the total predicted usability of the particular measurement method based on the industry needs. Furthermore, this study includes test of selected measurement methods and discusses the advantages and disadvantages for the same. It also proposes a new concept of an indirect measurement method to reduce the downtime during inspection.

Keywords
Mill Liners, Wear measurement, Mining, Mills, Measurement devices, Evaluation, Quality index

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 (expert). 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 (expert), 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 and size [2].

A case study has been carried out together with a mining company, M, and a mill liner manufacturing company, L. The study focuses on a particular a grinding mill. A detailed description of the grinding mill is given in section 2.2. 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.

For the case study, according to a preliminary analysis of maintenance data, 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 (expert). However, this information has to be verified in a future study.

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 mill 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.

This study focuses on devices for measuring the abrasive wear of mill liners. The study is a survey of the existing and possible future methods for direct measurements and 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 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 measurements 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 (expert).

The liner replacement time should be based on an economic comparison of the mill efficiency and the total lining costs. The performance of the mill is defined as the throughput of the desired particle size coming out of the mill (expert). The economic break point occurs when the cost associated with the drop of monetary output due to wear of liners is equal to the cost of relining. The replacement policy used today is due to customary to replace the liners when they reach the critical thickness in order to avoid the damage of mill shell. However, 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 [4,5].

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 discusses methods 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 case study 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 (experts). 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. Figure 1 shows that there are 18 high lifters and 18 low lifters in the studied mill.

However according to [6], suggested that the advantages of a High/Low arrangement are lining cost savings and performance benefits as a profiled configuration is always maintained. On the other hand the main advantage of an equal height design is reduced downtime as a result of fewer stops for maintenance and for monitoring of wear rates.

2.2 Importance of measurement devices

The motivation of this study is due to the economic consideration of the mill liner replacement interval and inspection. The measurement time during inspections leads to a significant amount of downtime cost. But the additional cost due to process synchronization time also needs to be considered as significant amount of money is lost due to loss of metal at output end (experts). In the present context the process synchronization time is the time duration during when the material flow in the process becomes streamlined. Therefore a time efficient measurement device is required which can take measurement as quick as possible.

Another economical aspect related to the measurements is due to the replacement decision of mill liners. The current policy of the case study, the liner replacement decisions mainly depends on liner wear and risk of damaging the mill shell. Generally, the efficiency of the milling process depends on the behaviour of the load inside the mill, which governs the nature of ore presentation of breakage sites and subsequent transport. It is however well known
Choosen liner will lose efficiency due to wear [7]. For determining time based performance i.e. throughput capacity of the mill, a number of wear measurements are necessary during the life cycle of mill liners. The liner wear reading can be used to calculate available volume inside the mill as the inside mill volume for ore grinding is a function of volume of mill liners. The measurement of liners can also be used to estimate the grinding performance and the monetary output of the mill.

2.3 Terminology

This section briefly describes the important terms and which has been frequently used in the paper.

2.3.1 Expert group (personal communication, Feb 2008): In the present case study, the authors have obtained inputs and information regarding process and maintenance related to grinding mill after visiting and discussing with concerned expert groups of the mining and liner manufacturing industry. Detailed information such as work profile and experience in years is provided in table 1.

Tabel 1: Brief description of expertise of the expert group for the study

<table>
<thead>
<tr>
<th>Current position at Company (M) &amp; Company (L)</th>
<th>Expert field &amp; experience (year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maintenance engineer (M)</td>
<td>Maintenance of stationary equipments in mining industry (15)</td>
</tr>
<tr>
<td>Maintenance engineer (M)</td>
<td>Maintenance of process systems &amp; mobile systems (14)</td>
</tr>
<tr>
<td>Manager maintenance (M)</td>
<td>Maintenance in plant (15)</td>
</tr>
<tr>
<td>Senior metallurgist (M)</td>
<td>Autogenously comminution &amp; ore dressing processing (20)</td>
</tr>
<tr>
<td>Technical expert (M)</td>
<td>Process control &amp; measurement of mill parameters (38)</td>
</tr>
<tr>
<td>Manager R&amp; TD (L)</td>
<td>Product development of mill liner (11)</td>
</tr>
<tr>
<td>General manager, R&amp;T&amp;D (L)</td>
<td>Engineering, wear properties &amp; application of mill liners (35)</td>
</tr>
<tr>
<td>Technical support engineer (L)</td>
<td>Applications &amp; performance of mill liner (42)</td>
</tr>
<tr>
<td>Vice president mill lining (L)</td>
<td>Marketing &amp; need finding for mill liner (39)</td>
</tr>
<tr>
<td>Service &amp; Maintenance (L)</td>
<td>Measurements &amp; maintenance of mill liner (10)</td>
</tr>
</tbody>
</table>

2.3.2 Demand limits: In this study the term “demand” is defined as the minimum requirements on the measurement device which must be fulfilled. Therefore, a measurement device will be selected for assessment only when it will fulfill the minimum requirement of each quality attributes. The investigation of measurement devices therefore considers the demand limits in order to achieve the threshold limits of all the quality attributes.

2.3.3 Quality Index (QI): In the study, the authors have introduced “quality index” which is defined as a quality measure for a particular measurement device. The quality index is unified quality measure of a device which considers together other quality attributes i.e. cost, reliability, accuracy and accessibility. It is also important to notice that an individual value of quality index doesn’t provide any exact information about a specific measurement device. It provides an overall relative importance of measurement devices in the particular investigation.

2.3.4 Quality attributes:

Based on the detailed discussion with the experts of the companies of the case study, four suitable quality attributes are identified which are Cost, Reliability, Accuracy & Accessibility. For
overall assessment of various measurement devices and determination of the corresponding quality index, the following quality attributes are briefly described.

The demand limits is decided on the recommendation of the expert group of the case study.

2.3.4.1 Cost

To calculate the total cost, the following cost elements are included in the cost structure, as shown by Figure 2. 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.

![Cost components for the equipment](Figure 2: Overall cost structure, including the inspection cost breakdown structure, for the measuring equipment)

In the present case study the total cost of equipment includes the downtime cost, purchase cost and service cost. The other cost components such as assembly cost and labour cost are included in downtime cost.

For the mill from the case study, the loss of production due to the downtime of the mill costs approximately US$10,000/h depending on the type of ore, the time used and the amount of ore based on the information from experts of the case study.

**Demand limits:** The demand limits for cost component is set to US$ 14860 (including downtime cost) based on current practices of the case study. The reason for setting this demand limit is that the authors do not want to exclude measurement equipment from the study, which has promising properties concerning other important quality attributes. The cost of the equipment used in case study includes both purchasing cost & downtime cost during measurement. See table [5, 6]

2.3.4.2 Reliability

The equipment has to be reliable when it is required to perform measurement. In the study 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 includes the fragility of the equipment.

**Demand limits:** The demand limit for reliability attribute is 95%. This implies that the equipment will be considered for investigation if it is 95% reliable when it is required for use. However, the measurement devices which are being used

2.3.4.3 Accuracy

The measurement accuracy is very critical in terms of taking replacement decision of mill liners. The objective of taking overall measurement of mill liners is not only important in terms of risk of damaging mill shell but also to determine the capacity which eventually leads to estimate the instantaneous mill revenue. 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.

The measurement accuracy of rubber liners are defined in two categories spot measurement and overall measurement.

**Spot measurement:** Spot measurement is concerned of taking measurement at certain point on liners and which is important in order to estimate the risk of damaging mill shell. Spot measurement not only deals with the thickness at the spot but also the profile measurement of liners. A spot measurement tells us how much rubber material is left leading to estimation of remaining time until when the rubber liner needs
to be replaced in order to avoid the risk of the damaging mill shell.

**Overall measurement:** Overall wear measurement of rubber liners corresponds to determine the inside capacity of the mill during measurement period which is used to determining mill production capacity. However some measurement equipments take only the spot measurement and based on these measurements wear of other liners and overall mill volume are estimated.

**Demand limits:** The risk of damaging mill shell the measurement accuracy concerning critical measuring spots on the liners should be +/- 5 mm. Also, for determining the exact inside mill volume the accuracy for overall measurement of mill liners should be +/-20 mm.

2.3.4.4 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 due to anthropometric consideration 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.

**Demand limits:** The measurement equipment will be qualified for investigation at least if it can be taken inside the mill for measurement. During the case study 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.

2.4 Collection of measurement methods

This section briefly describes the characteristics of most of all existing measurement devices. It also describes the qualification criteria for each measurement method for investigation and the determination of quality index based on demand limits. For more clear understanding all measurement methods are divided in to three categories.

A. Methods selected for determining quality index based on demand limits
B. Methods developed but not used in real mills.

2.4.1 Measurement method (M1)

Method 1 is a direct measurement method based on the technique of a 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 [8].

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 3.

Approximately five minutes is needed for pure measurement (entering the mill and exiting from
2.4.2 Measurement method (M2)

Method 2 is a mechanical wear reading device which consists of a frame and 5 rods and gives measure of the profile at the measurement point by means of manual inspections. This method is used today at the mill considered in the present study, see Figure 4. The device requires approximately 30 minutes for measuring 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. Based on these measurements the accuracy of overall measurement is +/- 13 mm (expert). The thickness capacity covers more than 400 mm. The volume of the transporting box within the device is approximately 12 dm³ and the weight is less than 2 kg.

The other added advantage of this method is due to moisture and temperature resistant. As the mill is shut down the inside surface (above the charge) is typically flushed with water to make inspection easier and from safety point of view to minimize the risk for falling objects.

2.4.3 Measurement method (M3)

Method 3 consists of ultrasonic apparatus and probes. In resonance-type ultrasonic thickness equipment, 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 [8]. It is also claimed by [8] 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. However, in the present case study this method has been successfully tested for a rubber liner with a thickness of 400 mm with an accuracy of +/- 2 mm.

Figure 5 shows an example the output from the measurement device. The y axis is indicating a dimensionless voltage which is proportional to the detection level of the sound wave. The x-axis is indicating a dimensionless time because of the propagation time of the signal, which will be transformed to corresponding thickness of the
measured object. In this particular case, the object was a piece of rubber of the same material as the liner and with a thickness of 200 mm. The horizontal mark on the high response peak is due to a manual choice of the signal to be detected. Since amplitude of this peak is large compared with the scatter it can be concluded that a thickness of 200 mm is no problem. Also rubber with a thickness of 400 mm has been successfully been measured.

2.4.4 Measurement method (M4)

Method 4 consists of laser equipment with dimension of (15 cm x 10 cm x 10 cm). It takes 2 dimensional measurements diametrical with in a range of 270 degree. The principle of the method is to obtain an obstacle free distance between measurement equipment and object. The measurement instrument has been successfully tested inside the mill when new liners are installed inside the mill. As shown figure 7 the wear measurement of all the liners in the range of 270 degree is taken all together. The measurement accuracy of the instrument was found to be +/- 5-10 mm.

Disadvantage:
1. The thickness measurement is based on two relative measurements. Therefore it is not possible to obtain the liner thickness at the one time measurement
2. A small change in orientation of the instrument leads to error in wear measurement.
3. The measurement needs to be performed at exactly same location where previous measurement was taken.

The overall measurement time for the whole mill was found to be about 85 minutes which includes entering into the mill and instrument set up time (25 min), measurement time (10 min) at a given location. Two measurements at same location at two occasions are needed, since the measurement principal is based on relative measurements.

Advantages:
1. The instrument is capable to obtain the liner thickness of three quarter of mill at the same location.
2. The method provides the profile of each liner and plate as well.

The authors have collected information and specifications of this measurement instrument from the supplier of the measurement equipment.

Figure 7: Liner measurement on inside the secondary mill. The non lined by green dots also lined by the red dots (Source: Damill AB)

Advantages:
1. The instrument is capable to obtain the liner thickness of three quarter of mill at the same location.
2. The method provides the profile of each liner and plate as well.

2.5 Category B: Methods not used in real mill

Under this category a description has been given for measurement methods which have been tested in the laboratory but not used in real mill.

2.5.1 Measurement method (M5) (existing as a prototype)

Method 5 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 8.

Since this method is not used in the real mill and specific mill liners needs to be made to fit the device it provides the wear measurement of specific liner in which this circuit is embedded, hence overall measurement of all the liners will be predicted based on wear of the specific liner. Therefore this method is not considered for the investigation.

2.5.2 Measurement method (M6) (not developed yet)

No. 6 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 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, 14]. 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 wear and thus achieve a useable method for predicting the wear of the liner without stopping the mill. A prototype has been developed by Process IT Innovation at Luleå University of Technology, see Figure 9, which shows the prototype mounted on the fastening bolt of a lifter on the shell of a mill.

According to [15], 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 [15]. 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. But on other hand it is doubtful that the accuracy concerning wear of liners is sufficient.

However the most important usability of this method is measurement without stopping the mill which leads to a huge savings due to downtime. Since it is not fully developed yet therefore it is excluded from the group of quality index determination.

2.5.3 Measurement method (M7) (not developed yet) [16], [17] is an electro magnetic method with open transformers placed on the rubber liner. If an AC electromagnetic coil is moved closer or further away from a conductive target, a current, commonly referred to as an eddy current, is induced in the target. The electromagnetic field induced within the target opposes and reduces the magnetic field in the sensing coil. This loss of field strength due to the eddy current is detected by an inductance bridge circuit and the resulting current output is converted to linear voltage which is proportional to the distance between the coil and the conductive target.

However, the ore is often more or less magnetic which probably will dramatically reduce the accuracy below the demand limits, thus this measurement principle is not further examined in the present study.

2.5.4. Measurement principle (M8) [11], [17] is based on the principle of X-Ray thickness gauges. Thickness can be determined by measuring the amount of X-ray energy absorbed by a material as it passes between an emitter and a receiver. An X-ray sensor uses the same principle as a nuclear sensor, i.e. a radiation source and a radiation detector arranged in either a transmission or backscatter configuration. In the case of an X-ray source, however, no dangerous radioisotope is used. Instead, the measuring radiation is generated electrically from an X-ray tube.

However, the present method can provide x-ray devices which are capable of measuring thin film rubber sheet with a thickness far less than 1 mm which is far less than the demand 400 mm. therefore it is excluded from the group of quality index determination.

2.5.5 Measurement principle (M9) [17] is based on infrared sensors. Normally the method is associated with temperature measurements, but can also be used for measuring thin layers. When measuring thin layers, this principle is based on absorption of infrared radiation into the material whose thickness is to be measured. The absorption is non-linear dependent on the thickness. The principle can be configured with the infrared source and detector on the same side of the product to be measured.

Infrared sensors are extremely sensitive to compositional variations in the product to be measured [17]. This in combination with that the present authors not have found any supplier that can provide infrared devices which are capable of measuring rubber of significant thickness. The other properties are not examined in the present study since the thickness demands not are fulfilled.

Other possible methods, close to No 10, can eventually be based on using cameras with traditional optics. By using a number of cameras it will be theoretical possible to take pictures of the liners at several angles and occasions and then achieve the wear by means of subtracting the photos form each other. This technique can eventually also being solved by means of using infra red cameras by subtracting temperature pictures from each other, but then the accuracy will be drastically reduced since infrared temperature cameras not are optimized for geometric accuracy.

2.6 Category C: Experiments on the methods for indirect measurements
Under this category a brief description is given for some of the proposed methods which can be used for indirect measurements. The main objective of indirect measurements is to reduce the downtime cost during the inspection as the mill not needs to be stopped during the measurements.

Also the charge dynamics in tumbling mills can be predicted by means of vibration signature technique [18, 19] therefore the present authors also address this method to be of eventual use in order to predict the abrasive wear of the rubber lifters.

2.6.1 Measurement method (M10) (not developed yet): An experiment was carried out to develop an indirect method based on power signature diagnosis. The power consumption and angular velocity of the mill will increase or decrease, if there are any changes in the mechanical process. This small change (typically less than 0.00001%) is measured by means of current and voltage sensors, and collected by measurement computers with A/D converters. Next step was to filter the collected data and analyzing it with respect to time and frequencies. Today, the method is in use for measurement of damages in gears, fans and bearings, etc. These signals can then be compared with the actual dimensions of the liners, resulting in an indirect measurement method for predicting the wear of liners.

The obtained signals from the frequency converter, aimed for controlling the speed of the electric motor of the mill. These signals can be transported to a computer via fibre optical cable for analyzing within excel sheet. Both the variation in speed and power supply of the electric motor can be obtained. The present case study this technique has been tested. The power was measured within +/- 0.00001% and the angular speed of the electric motor was measured within +/- 0.0001 rpm. The time difference between each measurement is approximately 0.03seconds and the accuracy of the time measurements is +/-0.0000001 s.

For a typical case of average angular velocity of the electric motor, 600.8 rpm, this corresponds to 8.380 rpm of the mill (gear ratio of the gearbox is equal to 5.647 and 23 gear teeth on the pinion gear of the mill and 292 teeth on the ring gear of the mill). This corresponds to 7.16 seconds/revolution on the mill. With 18 large lifters and 18 small lifters this corresponds to 0.398 seconds between each contact between the large lifter and the charge and 0.199 seconds between the small and the large lifters. Random fall of the ore in the mill will cause scatter in the measurement curves but in spite of this, the test results clearly indicate peaks when both the small and the large lifters are approaching the charge, see figure 10 and 11.

![Figure 10 Angular velocity of electric motor as a function of measured time](image)

Figure 10 shows a small variation of the angular velocity which coincides with the time between each contact between the large lifters and the charge. A reasonable explanation is that when the lifters hit the charge, the speed of the mill will be somewhat decreased because of the extra torque needed to move the charge which is hitting the lifter. The main increase of the angular velocity is because of the speed controlling of the mill due to the processing. However, as showed in Figure 10, the influence of the lifters on the speed of the mill is not very significant since it is not possible to recognize the small influence of the small lifters.

By means of studying the influence of the lifters on the power supply to the mill, more significant results was achieved, see Figure 11.
Figure 11 Percent of full power of the electric motor as a function of time

Figure 11 shows a significant dependence between the power and the time when the lifters approach the charge. There is a clear possibility that the large peaks correspond to the large lifters and the small peaks correspond to the small lifters. 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 real measured values of the height of the lifters, this can be a useable method for estimating the average size of the liners without stopping the mill. This information can be of use concerning remaining life time of the liners and also for optimum process control of the mill.

The effect of the lifter wear cycle on the charge behaviour and power draw wear on a ball mill was also studied by means of using discrete element methods, DEM, [20]. He found that at sub-critical speeds, the wear induces increases in lifter face angle and reductions in lifter height lead to steadily decreasing amounts of cataracting material thrown shorter distances and higher toe positions. At low speeds, the steepest lifters produce the highest power draw. With increasing mill speed, the highest power draw is expected in the first half of the lifter life and then declines slowly. At higher speeds, the power draw initially increases as the lifters wear and then decreases. The face angle producing the highest power draw decreases steadily with increasing mill speed.

Measurement method No. (not developed yet)

No. 12 (Wijaya, 2009) is an indirect method based on multivariate data analysis of measured process parameter. This approach is based on the statistical principle of multivariate statistics that deal with the observation and analysis of more than one statistical variable at a time [21]. In this study, the technique is used to reveal the internal structure of the data in a way which best explains the variance in the data and their effect on the response of interest.

As mill operation is governed by Programmable Logic Controller (PLC) that adjusts all process parameters to keep a constant torque, torque can be expressed as a function of process parameters and volume inside the mill as follow,

\[ \tau = f(P, \omega, w, mf, wf, \delta) \cdot f(V) \]

where \( \tau \) is torque, \( P \) is power consumption, \( \omega \) is angular velocity, \( w \) is total weight of mill, \( mf \) is mass flow, \( \delta \) is density of ore, and \( V \) is volume inside the mill. Since torque is maintained constant, expression is altered as

\[ f(P, \omega, w, mf, wf, \delta) \approx k / f(V) \]

and can be rewritten as

\[ f(P, \omega, w, mf, wf, \delta) \approx g(V) \]

This relation indicates that volume inside the mill could possibly be predicted by taking into account of the variation of other process parameter. Due to the fact that process parameters correlated each other, approach is developed by utilizing multivariate data analysis [22]. Preliminary study shows that different mine has different ore properties (e.g. density) and from Partial Least Squares (PLS) and Principle Component Analysis (PCA), it indicates that different type of ore has a great contribution to the model, see figure 12.

![Figure 12 Scores plot t1 vs t2 for PLS model of Torque](image-url)
Thus Principle Component Regression (PCR) model is developed for each type of ore. In case of type of ore with low density (type I), model can accurately predict the change of volume inside the mill, see figure 12. It gives MAPE (Mean Absolute Percentage Error) value of less than 5%. However model can not perform a good prediction for type of ore with high density (type II). Possible explanation for this behaviour is due to the fact that variation of density within the type II ore is quite big.

3. EVALUATION APPROACH

A systematic approach [23] is used as a basis in order to determine the quality index. The key objective of using the approach is to incorporate the quantitative and qualitative inputs together taking internal weightings of the quality attributes based on its importance into account. The qualitative inputs from the expert group are used for giving weights to qualitative attributes such as cost, reliability, accuracy and accessibility. The demand limits for each quality attributes are also determined from the expert group. The quantitative inputs i.e. cost, reliability and accuracy were achieved by means of a combination of the opinion from expert group and experiments by the authors used to make the evaluation more robust.

3.1 Selection of measurement equipments for determining quality index using demand limits

Since each measurement equipment needs to fulfil the minimum requirements of each quality attributes, therefore a screening is done based on these quality attributes. The screening process of demand limits is shown in figure 14. As described earlier some of the methods are not selected due to feasibility criteria as they are not used in the real mills. A selection process mentioned in the figure deals with the measurement equipments which are existing and usable in real mills.

![Figure 13 Comparison of measured volume and predicted volume](image)

To overcome the limitation of the model, other parameters that can explain variation within type of ore and can represent variation of density in different way, such as retention time, fraction of ore as a function of volume, shape of ore, etc. should be considered.

3.2 Qualitative comparison of different measurement devices

A survey is designed in order to collect data for determining the importance of quality attributes of a measurement device for both supplier (liner manufacturer) and user (mining industry) perspective. The survey was conducted and among the experts in the field of mill process and characteristics of rubber liners and researchers at operation and maintenance division, Luleå University of Technology.

A pairwise comparison matrix [24] has been developed among the quality attributes and the results have been obtained which are given in Table 2. An example of pairwise comparison between O_i and O_j is shown in table 1. For comparison between two attributes a preference ratio are used (ratio w_i/w_j indicates how much attribute i is preferred to relative to attribute j);

- \( w_{ij} = 1 \) if the two objectives (O_i, O_j) are equal in importance
- \( w_{ij} = 3 \) if O_i is more important than O_j
– $w_{ij} = 5$ if $O_i$ is very much important than $O_j$

Table 2: A sample of pairwise comparison between quality dimensions

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$O_i$</td>
<td>3</td>
<td>1</td>
<td>5</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>$O_j$</td>
<td>1</td>
<td>5</td>
<td>3</td>
<td>1</td>
<td>3</td>
</tr>
</tbody>
</table>

The information for qualitative comparison has been provided by 5 experts from company M. Relative importance of quality attributes was calculated based on pairwise comparison. See Table 3

Table 3: Pairwise comparison for four quality attributes

<table>
<thead>
<tr>
<th>Attribute</th>
<th>$W_c$</th>
<th>$W_R$</th>
<th>$W_{ac}$</th>
<th>$W_{dc}$</th>
<th>Relative weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost ($W_c$)</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>5</td>
<td>0.375</td>
</tr>
<tr>
<td>Reliability ($W_R$)</td>
<td>1/3</td>
<td>1</td>
<td>1/5</td>
<td>1/3</td>
<td>0.082</td>
</tr>
<tr>
<td>Accuracy ($W_{ac}$)</td>
<td>1</td>
<td>5</td>
<td>1</td>
<td>5</td>
<td>0.417</td>
</tr>
<tr>
<td>Accessibility ($W_{dc}$)</td>
<td>1/5</td>
<td>3</td>
<td>1/5</td>
<td>1</td>
<td>0.125</td>
</tr>
</tbody>
</table>

3.3 Linear interpolation: A linear interpolation method [25] was used for giving grades to various measurement methods for different attributes. The limits for the linear interpolation were set based on the minimum needs or demand limits provided by the expert group.

The main reason of selecting linear scale was due to unavailability of required data to obtain the precise correlation function.

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. See Table 4

Table 4: Theoretical definition of grades

<table>
<thead>
<tr>
<th>Grade</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Identical with the demand</td>
</tr>
<tr>
<td>2</td>
<td>Slightly better than the demand</td>
</tr>
<tr>
<td>3</td>
<td>Above the demand</td>
</tr>
</tbody>
</table>

Table 5: Linear interpolation for quality dimensions

<table>
<thead>
<tr>
<th>Grade</th>
<th>Total Cost ($) per measurement</th>
<th>Reliability (%)</th>
<th>Accuracy (+/-mm)</th>
<th>Accessibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>14860</td>
<td>95.00</td>
<td>20</td>
<td>Just possible to carry into the mill</td>
</tr>
<tr>
<td>2</td>
<td>11145</td>
<td>96.25</td>
<td>15</td>
<td>Possible to carry into the mill without significant problems</td>
</tr>
<tr>
<td>3</td>
<td>7430</td>
<td>97.50</td>
<td>10</td>
<td>Possible to carry as hand luggage</td>
</tr>
<tr>
<td>4</td>
<td>3715</td>
<td>98.75</td>
<td>5</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>100</td>
<td>0</td>
<td>Possible to carry as hand luggage</td>
</tr>
</tbody>
</table>

3.4 Total cost calculation: The cost calculation for each method is calculated according to the cost structure mentioned in figure 2. As described earlier the major cost component of the equipment is due to downtime cost. Thus a breakdown of downtime and cost calculation is shown in Table 6.

Table 6: Down time cost calculation per measurement

<table>
<thead>
<tr>
<th>Methods</th>
<th>Down time (Minutes)</th>
<th>Total downtime cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prepa-ration</td>
<td>Measurement</td>
<td>Total time (hr) × downtime cost ($/hr)</td>
</tr>
<tr>
<td>1</td>
<td>30</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>30</td>
<td>50</td>
</tr>
<tr>
<td>3</td>
<td>30</td>
<td>25</td>
</tr>
<tr>
<td>4</td>
<td>30</td>
<td>60</td>
</tr>
</tbody>
</table>

Preparation time represents the time taken to stop the mill, entering into the mill and come out from the mill. Measurement time represents the actual time during the measurement.

Since the service cost for method $M_1$ is not known therefore a variable (X) is taken as a service cost.
Table 7: Total cost calculation for each measurement instruments

<table>
<thead>
<tr>
<th>Methods</th>
<th>Downtime cost ($)</th>
<th>Equipment cost ($)</th>
<th>Service cost ($)</th>
<th>Total cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5833</td>
<td>X</td>
<td>5833+X</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>13333</td>
<td>20</td>
<td>13353</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>9166</td>
<td>236</td>
<td>9402</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>15000</td>
<td>694</td>
<td>15694</td>
<td></td>
</tr>
</tbody>
</table>

In this investigation the equipment cost is distributed over a period of ten years. Since the company policy is assuming that the life time of all measurement equipment is to be a period of 10 years. Therefore, in order to incorporate the equipment cost, these costs are normalized over 10 year period. On an average in a year 5 inspections are needed, hence in 10 years the total number of inspection will be 50. The equipment cost per measurement is calculated in table 7.

Cost per measurement = (Equipment cost/50)

The value of other quality attributes is determined from expert opinion and supplier. The value of reliability and accuracy attributes are obtained from the equipment suppliers. Since, accessibility is a subjective attribute therefore after using expert opinion and discussion among researchers in the operation and maintenance division it is categorized into three categories as shown in table 5. An average values of mentioned quality attributes each method are mentioned in table 8. Thereafter by using table 5 and liner interpolation the values of interpolated grades of each quality attributes for corresponding methods are determined.

3.5 Quality index determination

The quality index was determined by using Table 7 and 8. The formula for the quality index is defined as

\[ QI = IG_c \times W_c + IG_R \times W_R + IG_a \times W_a + IG_{ac} \times W_{ac} \]

Table 8: Interpolated grades for different quality dimensions

<table>
<thead>
<tr>
<th>Method</th>
<th>Cost ($)</th>
<th>Reliability (%)</th>
<th>Accuracy (+/- mm)</th>
<th>Accessibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>M</td>
<td>AV*</td>
<td>IG_c**</td>
<td>AV**</td>
<td>IG_R**</td>
</tr>
<tr>
<td>1</td>
<td>5833+X</td>
<td>-</td>
<td>99</td>
<td>4.2</td>
</tr>
<tr>
<td>2</td>
<td>13353</td>
<td>1.59</td>
<td>100</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>9402</td>
<td>2.61</td>
<td>100</td>
<td>5</td>
</tr>
<tr>
<td>4</td>
<td>15694</td>
<td>1</td>
<td>99</td>
<td>4.2</td>
</tr>
</tbody>
</table>

* AV: Average value
**IG: Interpolated grade value

C: Cost, R: Reliability, A: Accuracy, Ac: Accessibility

Table 9: Liner interpolation for quality dimensions

<table>
<thead>
<tr>
<th>Method</th>
<th>Quality Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>M</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>f(X)+4.2×0.082+4.8×0.417×1×0.125</td>
</tr>
<tr>
<td>2</td>
<td>1.59×0.375+5×0.082+2.4×0.417+5×0.125</td>
</tr>
<tr>
<td>3</td>
<td>2.61×0.375+5×0.082+1×0.417+5×0.125</td>
</tr>
<tr>
<td>4</td>
<td>1×0.375+5×0.082+4×0.417+3×0.125</td>
</tr>
</tbody>
</table>

An affordable service cost for the industry for 3D laser equipment is estimated by putting quality index of method 1 to the quality index of method 4.

From table (6) the total cost of method 1 is the function of service cost (X). The value of f(X) is determined by using liner interpolation for the cost parameter.

The cost component is linearly interpolated between (1, 14860) and (5, 0) i.e. (grade, cost). The grade for cost element for the 3D laser equipment is then estimated from the liner interpolation.

\[ f(X) = ((13575 -X)/3715) \times 0.414 \]
If we equate the quality index of 3D laser equipment equal to the highest value of quality index as given in table 6 then the value of X will be

\[
\begin{align*}
\phi(X) + 2.47 & = 2.82 \\
((13575 -X)/3715) \times 0.414 + 2.47 & = 2.82 \\
\Rightarrow X & = \text{USD 10434}
\end{align*}
\]

When only down time cost is considered then the affordable service cost for each measurement will be

\[
5000+X = 14860 \\
\Rightarrow X = \text{USD 9860}
\]

Table 9 shows that method no. 4 is the most preferable measurement method since it has the highest quality index among the three methods investigated for quality index determination.

On the other hand, the service cost, 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 8), then the maximum acceptable service cost for method no. 1 can be estimated as US $ 9860 per measurement provided only the cost aspect is considered. On other hand if all quality dimensions are considered together the maximum acceptable service cost will be US $ 10434 per measurement. However these are the maximum additional cost that company can bear for getting the similar monetary benefits what they are currently getting. Therefore, for taking a decision of using service based method a negotiation should to be carried out between company using the service and service provider.

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 [23].
- The grade for the accessibility dimension was defined as per an expert opinion based on the weight, volume and height of the equipment.
- It is assumed that grades and weighting can be multiplied.
- The delay due to unavailability of equipment is not considered.

The most important advantages and disadvantages of the analyzed measurement principles are summarized in Table 10.
Table 10: Advantages and Disadvantages of measurement devices

<table>
<thead>
<tr>
<th>Category</th>
<th>Method No.</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Method selected for determining QI</td>
<td>1</td>
<td>• 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, useful for overall mill volume calculation</td>
<td>• 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</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>• Reliable method, very often used today. • Delivers the complete profile of the liner at the measurement points • No problem under moisture and temperature inside the mill</td>
<td>• The mill needs to be stopped. • Relatively long measurement time compared with method no. 1 • Does not provide good accuracy in complete liner volume calculation</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>• Relatively faster and more accurate for spot measurement than method 2</td>
<td>• The mill needs to be stopped. • Does not provide the complete profile</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>• Provide complete profile of all liners and rubber plate at measurement location</td>
<td>• Relative measurement i.e. two measurements are required to know the liner thickness • Imperfect orientation of the instrument leads to inaccuracy</td>
</tr>
<tr>
<td>Method developed as prototype but not used in real mill</td>
<td>5</td>
<td>• The mill does not need to be stopped, provided that electronics and software have been developed to make it possible to deliver data.</td>
<td>• 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. • Does not provide complete profile of the liner</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>• The mill does not need to be stopped, provided that electronics and software have been developed to make it possible to deliver data.</td>
<td>• No existing fully-developed product on the market • Does not provide a complete profile</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>• The mill is not needed to be stopped provided that electronics and software are developed in order to make it possible to deliver data.</td>
<td>• Not possible to use since magnetic properties of the ore will reduce the accuracy significantly</td>
</tr>
<tr>
<td>Method developed in the present study</td>
<td>8</td>
<td>• Not investigated in the present study</td>
<td>• Can not measure thickness more than 1 mm hence not fulfilling the demand limits for thickness of 400 mm</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>--do--</td>
<td>--do--</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>--do--</td>
<td>--do--</td>
</tr>
<tr>
<td>Indirect Measurement Methods</td>
<td>11</td>
<td>• Continuous measurement without stopping the mill which can be used to determine economic performance of mill and cost effective decision making for liner replacement • The measurement data can eventually be used for continuously optimizing the process</td>
<td>• Not fully-developed • Provides only approximate value of overall wear of liners • Does not provide full profile of liner wear</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>--do--</td>
<td>--do--</td>
</tr>
</tbody>
</table>
4. CONCLUSIONS

An overall evaluation process for abrasive measurement devices is described in the paper. Various types of data were collected from the industries of the case study and corresponding results have been obtained from the evaluation method. Based on overall study, following conclusions have been made.

- 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, a careful assessment is needed while doing objective analysis.

- Quality index of investigated measurement devices gives an overall idea of equipment effectiveness with respect to all quality attributes described in the paper.

- 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.

- 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.

Acknowledgements

We would like to thank VINNOVA mining research program and the supporting companies for the financial support and the expert group for their inputs and helps in this project. We would also like to thank Mr. Dan Sandström for providing useful information in this study.

REFERENCES


Paper II

Replacement decision model for mill liners

Replacement decision model for mill liners

Abstract

Purpose – The purpose of this case study is to develop a decision support tool to assist maintenance managers to determine the optimally cost-effective interval for replacing grinding mill liners used in ore dressing plants.

Methodology/approach – Simulation based approach are used to maximize the life cycle profit (LCP) of mill liners of ore dressing mill for determining optimal replacement interval for grinding mill liners. The development of LCP model is based on detailed analysis of mill performance, liner wear, and maintenance statistics. Time sampling approach is used to determine the economic efficiency of the mill.

Findings – A model for replacement interval for the grinding mill liners has been developed considering process parameters of single ore type. The results of the optimum replacement interval shows an improvement of 0.5% to 1%, with a 95% confidence interval in the annual gross profit of the mill by changing the current replacement policy to the proposed replacement policy of the present study.

Originality and Value – The new model for the replacement interval for ore grinding mill liners considers the economic influence of the replacement decision on process parameters (production quality, energy consumptions and random variation in feed flow) in the decision making. The novelty is that the model uses practically available process and maintenance data to make optimum replacement decisions without considering the periodic wear measurement data between two consecutive replacements.

Practical implications – The approach used in the paper to study, analyse and developed tool can be useful for maintenance managers and asset owners of dressing mill to make cost effective maintenance decisions. The results from the economic efficiency model also assist the organization to keep track of performance process and maintenance activities together.

Paper type – Case study

Keywords – Mill liners; Life cycle profit (LCP); Production economy; Optimization; Replacement decision; Decision support tool

1. Introduction

Mining industries use heavy-duty equipment that must work around the clock in highly abrasive environments. Autogenous (AG) mills are used in mineral processing for particle size reduction, and various types of ore are generally processed in such mills. The autogenous mill is a critical component in the grinding process necessary to obtain high metal recovery. A major industry
concern is grinding mill downtime for periodic maintenance (i.e., inspection and replacement), which causes significant monetary losses. Ongoing economic evaluation of the productivity of grinding mill maintenance policies is therefore necessary in the interests of profitability. It is essential to know how the mill and its critical components perform their functions in order to achieve high mill performance. Rubber liners inside the mill are among the most critical mill components in the context of shell protection and ore grinding (Reference group). For the details of expertise and experience of the reference group of the present case study (see reference Dandotiya et al., 2011). The present paper introduces and examines the maintenance cost and grinding performance (in terms of metal recovery) of mill liners, as well as their influence on mill profitability. The overall objective of this paper is to determine the optimally cost-effective replacement interval for mill liners. The studies identify the combined influence of maintenance policy and mill process parameters on mill profits using a decision-support model for mill liner replacement. This paper also uses process data from an ore dressing plant in assessing the cost and revenue drivers of the mining company, with the ultimate aim of increasing industry profits. A brief description of mill liners and its characteristics are defined in the section 2 of the present paper.

Researchers such as (Santarisi and Almomany, 2005; Kalala et al., 2008; Cleary, 2001; Yahyaei et al., 2009; Bearman and Briggs, 1998) have examined the effect of mill liners on mill performance. Santarisi and Almomany (2005) proposed liner replacement strategies based on mathematically modelling the wear rate of mill liners in cement grinding mills. Their findings mainly concern the facts that optimal replacement interval increased mill productivity (tones/hour), reduced specific power consumption, and reduced spare part cost in the cement industry. However, in examining cement mill productivity, the paper does not consider quality, i.e., grinding performance in terms of reducing particle size.

The objective of the present paper is to develop the replacement model based in broad perspective as it includes the economic influence of maintenance decisions on quality and quantity of mill production. This paper also suggests a methodology which uses the practically available process and maintenance data to make optimum replacement decisions without considering the wear measurement data between two consecutive replacements.

Yun and Choi (2000) studied optimum replacement intervals in a repairable system using a random time horizon. They modelled a system that is minimally repaired at failure and replaced with a new one at a predetermined age, determining the optimal replacement interval by minimizing the total expected cost. However, in the mill liner case considered as replaceable components as no repair actions are carried out between two consecutive replacements. The effect of mill liner degradation is considered to incorporate production efficiency, energy consumption, and metal recovery into the model.

Cleary (2001) examined the sensitivity of mill behaviour and charge characteristics, explaining variations in power drawn using several process parameters, such as mill rotation at different levels of mill fill and effect of lifter
shape on charge trajectory. As liners wear, mill performance first slightly improves, then worsens until they are replaced, preferably when the cost associated with the poorer performance is higher than the cost of relining.

Production system under failures and its maintenance is one of the significant areas (Ben-Daya et al., 2000) of study due to its fallouts on the production systems’ objectives and key parameters. Generally, preventive maintenance determines a lower rate of failure, reducing, as a consequence, costs of consequential damage and downtime (Ben-Daya et al., 2009).

Jardine and Tsang (2005) have discussed an example of replaceable component (fuel filter) that deteriorates deterministically. Jardine et al. (1998) have also discussed the condition-based maintenance, which considers age of the component and its condition at the moment of decision making. Similarly, the proposed model in the present paper deals with replaceable component (mill liners) that deteriorates deterministically for a specific product (ore type with specific physical properties such as density, energy cost and throughput of desired particle size).


2. Case study

This paper presents a part of collaborative research conducted by Luleå University of Technology for a mining company (Boliden Mineral AB) and a liner manufacturer (Metso Minerals), all located in Sweden. Within the defined research framework, the comminution process and current replacement decision policies for the liners were analyzed as whole. The research focuses on assessing liner replacement policy considering the correlation between throughput, grinding performance, power consumption, and maintenance cost.

The present study jointly considers cost and revenue drivers related to the production process and maintenance for more effective decision making concerning liner replacement. It incorporates the economic influence of process parameters related to recovery and energy consumption as well as maintenance parameters related to replacement, inspection, and the cost of downtime during replacement and inspection (see Fig. 1). Additional information regarding process and maintenance related to grinding mills and mill liners was obtained from the experience of the reference group.

Functions of mill liners and its economic influences: In an AG mill, the mill liner shares 37% of the total cost for grinding (Product handbook, 2002). The one of the main functions of mill liners is to protect the steel mill shell from damage due to the movement of the rock charge in the mill during the grinding process. The other objective of the mill liners transmit energy to the mill load and lift up the grinding media (Yahyaei et al., 2009). According to Powell (1991), the impact
point at which the grinding element strikes the mill shell is considered of primary importance in the analysis. However, Latchireddi and Morell (2006) described how the charge motion and particle breakage inside the mill depends on the shell lifter design, while the discharge of ground particles is controlled by the grate and pulp lifters.

What is the optimum replacement interval & how it can be determined

Model formulation

Model run, verification, simulation, etc.

Optimum replacement interval

Maximized profit

Objective of the study

Goal of the study

Economic influences of wear of mill liners on mill economics: The periodic economic performance of the dressing mill needs to be assessed to draft appropriate policies governing cost-effective maintenance decisions. Production loss during liner inspection and replacement in the ore dressing plant is significantly high, in the range of $10,000 per hour (Reference group). Apart from production loss, approximately $65,000 per production stoppage is lost due to metal loss start up process the mill.

Metal recovery: Mill liners play a key role in mill performance (Yahyaei et al., 2009). According to Makokha et al. (2007) and the reference group, milling process efficiency generally depends on the behaviour of the load inside the mill, which governs ore presentation at breakage sites and the subsequent transport. It is, however, well known that a chosen liner loses efficiency due to wear. For more details on process efficiency and liner wear see (Makokha et al., 2007; Schena et al., 1996 and Bearman and Briggs, 1998). Moreover, both liner replacement cost and the cost associated with variations in crusher performance should be attributed to liner wear. In order to incorporate the metal recovery from the grinding process, the case study uses a “process efficiency” term, defined as mill performance in the context of metal recovery. Based on industrial reference group, process efficiency is based mainly on the product size distribution and the content of input metal and its recovery after flotation. The revenue driver should therefore be a function of the throughput and the process efficiency. The project reference group calculated the process efficiency for each day using the following relation
The theoretical NSR indicates the monetary value when no losses of metal recovery occur due to grinding and flotation, while the actual NSR represents the actual monetary value of the recovery. The process efficiency data was collected and shown in Fig. 2 which depicts that process efficiency gradually decreases with liner wear.

Variation in mill volume (reduction of liner volume): In the present case study feed rate is automatically controlled based on instantaneous mill load. Liner wear leads reduced rubber volume inside the mill. In the present case study, the inside volume of the mill increased by 17% between new liner installation and the end of the liner's useful life. Thus, reduced liner volume leads to increased throughput or mill capacity, but to decreased charge lifting capacity.

Maintenance of mill liner: Friction and impact between charge and liner in the mill causes wear, resulting in changed liner profile and decreased liner thickness. Liners must be replaced when their thickness decreases to the threshold thickness at which damage to the mill shell can occur. Regular inspections are also needed to check liner thickness and to prevent mill shell damage.

Variation in energy consumption: According to Djordjevic et al. (2004), relatively high lifters consume less power than do low lifters under identical conditions (process parameters such as angular speed, mill load, and ore type). The lifter bars of the mill also influence the operational cost stemming from energy consumption. Besides the theoretical explanation, based on the obtained process data, correlation study results observed that the power consumption increases with the liner wear. Therefore, energy consumption should also be considered when conducting a cost–benefit analysis of mill liner replacement.
3. Model for replacement decision

The mathematical modelling for life cycle profit formulated here is based on obtained process and maintenance data from the involved companies. This approach maximizes profit by optimizing the mill liner replacement interval. The life cycle profit modelling includes the cost and revenue drivers associated with mill liners. Our approach to mathematical modelling for optimum mill liner replacement is similar to that described by Scarf (1997); the present study uses the following steps:
1. Problem recognition through industry visits and discussion with experts
2. Data collection and analysis exercise
3. Correlation study
4. Mathematical formulation of the proposed maintenance policy, considering encountered practical problems
5. Comparison with existing replacement policy

3.1. Encountered practical problems:

The model is formulated after considering the following practical problems.

3.1.1. Lack of wear measurement data for mill liners: For the present case study, periodic liner wear measurement was necessary to correlate process performance with the wear life of mill liners and to ensure that the mill shell would not enter the damage risk zone. Due to economic considerations regarding process performance, liner wear measurement is important when it comes to making replacement decisions. However, in the case study, various liner wear data are available for only one replacement cycle. The other problem is due to fewer wear observations (five measurements) within the life span of mill liners of period of approximately one year.

3.1.2. Variability in feed flow: As described earlier, the variation in feed flow should be a function of available volume inside the mill. In practice, however, feed flow is controlled manually based on ore availability in the mines. To handle this problem, time sampling and a simulation-based approach are used to investigate the mill efficiency and to make the optimum replacement decision.

3.2. Model assumptions

The following assumptions have been made:

- *Only the primary mill is considered in the investigation:* Due to the reference group, metal recovery during flotation is mainly dependent on product size distribution, and according to reference group a majority of particle size reduction takes place in primary mill only. It is therefore reasonable to exclude the secondary mill from consideration in the present investigation.

- *Trend of process efficiency:* The trend of process efficiency is based on collected process efficiency data between the major replacement intervals
Liner wear process is independent of ore type: Due to fewer measurement of liner wear and use of multiple ore types it is difficult to find a correlation between liner wear and different ore types. Therefore, this study assumes that liner wear process is independent of ore type and hence average value of maximum wear life of mill liner is considered for all ore types and the present model is limited to single ore type.

Liner profile is not considered in the model: Liner wear directly affects the gap between the liners and chamber profile, which in turn affects the grinding process. In addition, the replacement decision is based on the wear of all liners together, ignoring the change in profile of all section mill liners in the mill, so only liner thickness of lifter bars is considered.

Minor replacement of mill liners does not influence the mill performance: Replacements of mill liners are needs to carry out due to the reason of mill shell safety and different lives of liners. Based on reference group, it was concluded that minor replacements have negligible influences on production performance.

3.3. Abbreviations

- \(i\): Number of sampling intervals in one liner life cycle
- \(k\): Number of days in one time sample
- \(t_{in}\): Duration of the sampling intervals [days]
- \(T_{Cycle}\): Replacement cycle length of mill liners [days]
- \(T_{rep}\): Time taken during the mill liners installation including preparation time [days]
- \(T_{max}\): Threshold life (including line installation time) of mill liners when risk of mill shell damage arises [days]
- \(\varepsilon_i\): Mill economic efficiency during the \(i^{th}\) time interval
- \(M_i\): Mass flow from the mill during the \(i^{th}\) time interval [tones/hour]
- \(E_i\): Energy consumed by the mill during the \(i^{th}\) time interval [kWh]
- \(\eta_{p}\): Process efficiency for the ore
- \(\Omega\): Revenue generated by processing ore [$/tone]
- \(C_{dur}\): Downtime cost per replacement cycle [$/hour]
- \(C_{rep}\): Total cost incurred during liner replacement (i.e., liner cost, labour cost, startup cost) [$/replacement]
- \(C_{energy}\): Energy cost [$/kWh]
- \(C_{ins}\): Total inspection cost per day (including downtime cost) [$/inspection/day]
3.4. Definitions and model parameters

This section briefly describes and explains the terms and parameters used in the paper and the mathematical model.

**Time sampling:** The model presented here is based mainly on the time sampling approach. In this approach, the technical life of a mill liner is divided into a grid of equal time intervals (see fig 3). The technical life of a mill liner extends to the time at which the liner must be replaced due to the risk of mill shell damage.

![Fig. 3. Time sampling over mill liner life cycle](image)

**Economic performance:** In the present context, the economic performance of a mill is defined as the influence of mill liner maintenance actions on the monetary benefits of the mill over the mill liner life cycle. A time sampling approach was used to determine economic performance at different stages of the mill liner life cycle.

**Economic efficiency, \( \varepsilon_i \):** To determine the economic performance, an economic efficiency term, \( \varepsilon_i \), is introduced. The economic efficiency includes revenue and cost drivers concerning the maintenance and performance of mill liners. Efficiency is formulated so as to produce a dimensionless number with which to compare the economic performance of the mill at different stages of the mill liner life cycle. An expression has been formulated to describe mill efficiency over the mill liner life cycle. The efficiency for the \( i^{th} \) time sample will be as follows:

\[
\varepsilon_i = \frac{\text{total revenue} - \text{total cost}}{\text{total revenue}} \quad (\text{For a given Sampling Interval})
\]

The economic efficiency of the mill is also known as the gross profit margin. This ratio captures a business’s ability consistently to control its production costs or to manage the margins it makes on the products it buys and sells. A small increase (or decrease) in profit margin, however, can produce a substantial change in overall profits. The gross profit margin is a measure of a company's manufacturing efficiency throughout the production process.

**Mill revenue:** As described earlier, the revenue driver of the mill is defined as a combination of feed flow (tones/hour) and process efficiency. The total monetary gain is formulated as follows:
The revenue for the $i^{th}$ time sample = $\left( \sum_{i=1}^{k} M_i \cdot \eta_i \right) \cdot \Omega$ [\$] (2)

Equation 3 considers the joint effects of throughput $M$ and process efficiency/grinding performance, $\eta_i$. The revenue parameter $\Omega$ ($/\text{tone}$) includes the overall monetary value of the ore. The total cost, contains the following cost components:

Total cost = $\left[ \text{Operational cost (energy cost) + Replacement cost} \right.
\left. + \text{Inspection cost} + \text{Downtime cost during replacement & inspection} \right]$

Energy cost: Energy cost is considered an operational cost of the mill. The energy consumption cost for the $i^{th}$ sampling interval is as follows:

$$E_i \cdot C_{\text{energy}} = \left( \sum_{i=1}^{k} E_i \right) \cdot C_{\text{energy}}$$ [\$] (3)

Replacement cost: The replacement cost is taken to be the relining cost, since this cost is constant over the liner life cycle. The replacement cost for each $i^{th}$ sampling interval

$$C_{\text{rep}} \frac{T_{\text{Cycle}}}{T_{\text{Rep}} + T_{\text{Rep}}} \cdot t_w$$ [\$] (4)

The replacement cost for relining includes both lining cost and the cost of downtime during liner replacement.

Downtime cost: The downtime cost or production loss cost is the most critical parameter in the decision model; it is the duration of mill stoppage for inspection and liner replacement. However, the downtime cost per hour will differ depending on the replacement interval, since the energy cost and production performance also vary with replacement time. However, in the present case study, the downtime cost per hour is assumed to be constant for each replacement cycle time. The downtime cost for each $i^{th}$ sampling interval as follows:

$$C_{\text{DTRY}} \frac{T_{\text{Cycle}}}{T_{\text{Cycle}} + T_{\text{Rep}}} \cdot t_w$$ [\$] (5)

Inspection cost: The decision making approach uses the time sampling approach, which needs the value of cost and revenue drivers for each time sample. In addition, due to the policy of variable inspection frequency, company policy leads to variable inspection costs over the liner life cycle. The inspection cost model (see eq. 6) provides the inspection cost per day for each time sample. The piecewise periodic inspection cost function is used represented as follows:

$$C(t) = \begin{cases} 
C_1(t) : 0 \leq t \leq t_1 \\
C_2(t) : t_1 \leq t \leq t_2 \\
C_3(t) : t_{n-1} \leq t \leq t_n 
\end{cases}$$ (6)
**Economic efficiency:** To determine the production and maintenance efficiency of the mill, a mathematical expression has been formulated to describe economic efficiency of $i^{th}$ sampling interval is present as by using relation 1

$$
\varepsilon_i = \left( \sum_{k=1}^{\Omega} M_i \cdot \eta_p \right) \cdot \Omega - \left( \sum_{k=1}^{\Omega} E_i \cdot C_{\text{energy}} \cdot \frac{C_{\text{rep}}}{(T_{\text{Cycle}} + T_{\text{rep}})} \cdot t_{\text{in}} + C_{\text{n}}(\tau_{\text{n}}) + \frac{C_{\text{DF}}}{(T_{\text{Cycle}} + T_{\text{rep}})} \cdot t_{\text{n}} \right) \cdot \Omega
$$

......................................................... (7)

**Optimization approach an example:** The optimization approach used in this model is based on comparing the gross profits at different replacement intervals. The calculation of gross profit is explained in greater detail in this section.

Fig. 4. Gross profit determination for scenarios L and S.

For a better understanding of the optimization technique used here, let us consider scenarios L and S with sampling interval of one day. The replacement intervals of scenarios S and L are $T_l$ and $T_s$ days, respectively, where the replacement interval for scenario L is larger than the replacement interval of scenario S, i.e., $T_l > T_s$.

Over a time horizon of $T_{\text{max}}$, a comparison is performed to determine the best replacement interval. Where, $T_{\text{max}}$ is the threshold life (including liner installation time, $T_{\text{rep}}$) of mill liner when risk of shell damage arises. In this study, the life span is expressed in terms of threshold life of mill liners.

Fig. 4 shows two scenarios of type L and S with corresponding profit curves. The total area of the profit curves in scenario S is larger than the total area of the profit curves in scenario L due to the better process efficiency and lower power consumption in the initial phases of the mill liner life cycle. At the same time, scenario S has more replacement occasions than does scenario L, which leads to more downtime cost. Therefore, the mill liner life cycle is optimized based on maximizing the total profit curve area over a given time horizon.
If $T_{rep}$ days are considered as the downtime during mill liner replacement, then the number of replacement cycles $N_L$ and $N_S$ for scenarios L and S, respectively, can be determined as follows:

$$N_L = \left( \frac{T_{max}}{T_i} \right) ; \quad N_S = \left( \frac{T_{max}}{T_s} + T_{rep} \right)$$

(8)

To compare the two scenarios L and S, the gross profit is calculated over the period of $T_{max}$ days. For the period of $T_{max}$ days, the total gross profit can be calculated as

$$= \text{Total revenue} - \text{Total cost}$$

The operating conditions (e.g., throughput and energy cost) and liner performance are considered identical for all replacement cycles.

For a given scenario L, the gross profit over $T_{max} = (\text{Total revenue generated during }(T_i) - \text{Total energy cost during }(T_i) - \text{Total inspection cost (including downtime cost during inspection) over }(T_i) - \text{Replacement cost - downtime cost during one replacement during }(T_i))$ for one cycle $\times$ (no. of cycles over $T_{max}$).

$$P_{gross}^i = \left( \sum_{i=1}^{T_i} M_i \cdot \Omega \cdot \eta_p - \sum_{i=1}^{T_i} E_i \cdot C_{energy} - \sum_{i=1}^{T_i} C_{disp} - C_{Dil} - C_{rep} \right) \times (N_i)$$

(9)

Using equations (11, 12)

$$P_{gross}^i = \left( \sum_{i=1}^{T_i} M_i \cdot \Omega \cdot \eta_p - \sum_{i=1}^{T_i} E_i \cdot C_{energy} - \sum_{i=1}^{T_i} C_{disp} - C_{Dil} - C_{rep} \right) \times \left( \frac{T_{max}}{(T_i + T_{rep})} \right)$$

(10)

The choice between two replacement scenarios, L and S, can be made by comparing the gross profit determined from equation 10:

If $P_{gross}^L > P_{gross}^S$, then replace the liners at time $T_i$; otherwise replace them at $T_s$.

A similar process will be carried out, and gross profit is simulated and calculated for $(k = 1, 2, 3 \ldots T_{risk})$, where $T_{risk}$ represents the maximum number of days mill liners can run before mill liner thickness is reduced to the danger zone, i.e., implying a risk of mill shell damage. Also, discounting rate is not considered due to short technical life cycle of the mill liners in comparison with the life of ore dressing mill.

The throughput and process efficiency varies day to day due to change of the grade value of ore and feed input. Therefore, the data input for feed flow and process efficiency are simulated based on the distribution obtained from the existing mining mill data. In this case study, a computer program was devised in Visual Basic to simulate the results; the program is integrated with the process and maintenance data for one replacement cycle as simulation inputs.
4. Results and conclusions

The real data set for a given ore type (consisting of the process, maintenance and operational (energy) data) was collected from the ore dressing plant and the liner manufacturing company.

Model input data: The cost and revenue data are classified information and were used in the model to obtain the result. Therefore, in order to hide the real value a term “profit fraction” is introduced, which is calculated by dividing the actual profit by the maximum profit at the optimum replacement interval. In other words, the profit fraction is defined as the ratio of the actual profit to the maximum profit for the optimum replacement interval.

\[
\text{Profit fraction} = \frac{\text{Gross profit for replacement interval } t}{\text{Gross profit at optimum replacement interval}}
\]

Inspection data: The inspection scheduling data was obtained from the liner manufacturing company and used in the model.

<table>
<thead>
<tr>
<th>Inspection Number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inspection Interval (Days)</td>
<td>120</td>
<td>120</td>
<td>83</td>
<td>23</td>
<td>15</td>
</tr>
</tbody>
</table>

As described earlier, in order to deal randomness in throughput, the EasyFit software was used to detect the distribution within real throughput data and its corresponding parameters, which is shown in Fig. 5. The software detects the best fitted distribution based on the P-value of the Kolmogorov Smirnov test. It detects a Wakeby distribution in the throughput (feed flow) data obtained from the company and a Log-logistics (3P) distribution in the optimum replacement intervals obtained from the replacement model shown in Fig. 6.

The optimum replacement interval was determined using the proposed LCP model. Due to the large variation in the throughput data (1,500 – 2,500 tonnes/day) (see Fig. 5), a wide range of optimum replacement intervals (250 to 310 days) was obtained (see Fig. 6). Figure 6 shows the outputs for the
replacement interval for each simulation run for a random throughput. The x-axis of the curve shows the optimum replacement interval, while the y-axis shows the frequency of outcome of a specific optimum replacement level.

Fig. 7 shows a graph for the profit fractions with the life cycle of the mill liners at the average value of the throughput (1,874 tonnes/day). The optimization curve shows that the optimum replacement interval turned out to be 290 days. The reason for the lower gross profit on the left side of the optimal point, in comparison with the gross profit at the optimal point, is the dominance of the losses due to the downtime cost (due to the short intervals between the mill stops for liner replacement) over the benefits due to better process efficiency, in comparison with the scenario for the optimum replacement interval. On the other hand, the reason for the lower gross profit on the right side of the optimal point is the dominance of the losses due to a decrease in the process efficiency (see Fig. 2) over the savings due to fewer stops resulting from a longer replacement interval, in comparison with the scenario at the optimal point.

![Fig. 7: Profit fraction vs the optimum replacement interval](image)

The economic efficiency of the mill is calculated using equation 7 for a sampling interval of 15 days and shown in Fig. 8 for specific throughput data set. The main objective of investigating the economic efficiency of the mill is to look into the cost and benefit implications of liner replacement for mill production economics. It can be observed that economic efficiency displays a decreasing trend after 260 days for specific throughput value, which signals that the organization should consider maintenance process and policy. This is another approach to checking the production performance while jointly considering both process and maintenance aspects.
The studied process parameters that affect the overall mill economy are power consumption, throughput, and process efficiency.

The studied maintenance parameters that affect overall mill economics are downtime cost, liner component cost, inspection cost, labour cost, and start-up / process synchronization cost.

A mathematical model has been developed that determines the optimum replacement interval for mill liners, taking account of relevant process and maintenance parameters.

This paper suggests a methodology which uses the practically available process and maintenance data to make optimum replacement decisions without considering the periodic wear measurement data between two consecutive replacements.

The results obtained for the optimum replacement interval show an increase of 0.5% to 1%, with a 95% confidence interval, in the gross profit of the mill/year by changing the current replacement policy to a proposed policy based on the given case study for a given ore type.
The results from the economic efficiency model also assist the organization to keep track of performance process and maintenance activities together.

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REFERENCES


Paper III

Economic model for maintenance decision: a case study for mill liners

Economic model for maintenance decision: A case study for mill liners

Abstract

**Purpose** – Wear life of mill liners is an important parameter concerning maintenance decision for mill liners. Variations in process parameters such as different ore properties due to the use of multiple ore types influences the wear life of mill liners whereas random order of processing, processing time and monetary value of different ore types leads to variation in mill profitability. The purpose of the present paper is to develop an economic decision model considering the variations in process parameters and maintenance parameters for making more cost effective maintenance decisions.

**Methodology/approach** – Correlation studies, experimental results and experience of industry experts are used for wear life modelling whereas simulation is used for maximizing mill profit to develop economic decision model. The weighting approach and simulation have been considered to emphasize the contribution of parameters such as ore value and processing time of a specific ore type to a final result.

**Findings** – A model for estimating lifetime of mill liners has been developed based on ore properties. The lifetime model is combined with a replacement interval model to determine the optimum replacement interval for the mill liners considers process parameters of multiple ore types. The finding of the combined model results leads to a significant improvement in mill profit. The proposed combined model also shows that an optimum maintenance policy can only not reduce the downtime costs, but also affect the process performance, which leads to significant improvement in the savings of the ore dressing mill.

**Originality and Value** – The novelty is that the new combined model is applicable and useful in replacement decision making for grinding mill liners, in complex environment e.g. processing multiple ore types, different monetary value of the ore type and random order of ore processing.

**Practical implications** – The proposed economic decision model is practically feasible and can be implemented within the ore dressing mill industries. Using the model, the cost effective maintenance decision can increase the profit of the organization significantly.

**Paper type** – Case study

**Keywords:** Economic model; Replacement decision; Mill liners; Ore properties; Optimization; Process parameters
1. Introduction

Autogenous mills are used in mineral processing for particle size reduction. Mill liners are important spare parts of grinding mill in terms of reducing particle size and mill shell protection. Replacement decisions of mill liners are critical concerning mill profit due to influence of maintenance activities on process efficiency and production losses. Therefore, it is important to combine maintenance parameters with process parameters for the decision making of replacement of mill liners.

Based on correlation studies, liner wear causes an increase in energy consumption and reduction in process efficiency which leads to significant monetary losses. Mill liners also need to be replaced at regular intervals once they worn out which causes heavy monetary losses due to production loses during the mill stoppage for liner installation. The study of the present paper is the part of the same case study which has been discussed by Dandotiya and Lundberg (2011a). A detailed explanation on economic influence of maintenance activities on mill liners, uses of mill liners, variation in energy consumption, metal recovery, process efficiency and correlation studies can be found in the same reference.

Many researchers have performed research in the field of liners performance and replacement strategy. In the study Santarisi, N.S. and Almomany R.M. (2005), have proposed the liner replacement strategies based on mathematical modeling of wear rate. The influence of load behaviour on liner wear using DEM simulation was discussed by Kalala et al. (2008).

Dandotiya and Lundberg (2011a) have briefly described different characteristics of mill liners. They presented a replacement model based on life cycle profit which combines process parameters with maintenance parameters. However, their model has not considered the influence of ore properties on liner wear and their model is limited to the mill, processes single ore type.

The purpose of present paper is to develop a economic decision support model for mill liner replacement which considers influence of variation in process parameters and its affect on maintenance decisions. The present paper also suggests approaches for combining various process parameters with the maintenance parameters. The proposed model in the present study extends the life cycle profit model presented by Dandotiya and Lundberg (2011a) by considering the characteristics of various types of ore from different mines, together with the cost associated with maintenance activities performed on the mill liners.

2. Case study

This paper presents a part of collaborative research conducted by Luleå University of Technology for a mining company (Boliden Mineral AB) and a liner manufacturer (Metso Minerals), all located in Sweden. Within the research framework, the comminution process and current replacement decision policies for the liners were analyzed as whole. The research focuses on assessing liner
replacement policy using the correlation between throughput, grinding performance, power consumption, ore properties and maintenance cost. The “standard” grinding mill used here is 5.5 m in diameter and 5.7 m long with a power consumption of approximately 1800 kW (for more details see Dandotiya and Lundberg, 2011a).

3. Data collection and analysis

The data for the process parameters and the replacement of mill liners, such as the replacement schedule, the inspection data and data for other maintenance activities, were obtained and analysed. The process parameters, e.g. power consumption, process efficiency, torque, throughput, mill speed, mill load etc., were correlated over various life cycle periods of the mill liners. By performing a correlation study, redundant parameters were removed from the investigation. A process flow chart was made, as shown in Figure 1, which briefly explains the data collection and analysis process and its uses during the various stages of the investigation.

As shown in Figure 1, an hourly based process and maintenance data collected from the industry. For this study, periodic discussions with the reference group were carried out at different phases of the research work. For the details of mill liners and expertise and experience of the reference group of the present case study (see reference Dandotiya and Lundberg, 2011b).

**Data collection**

The mill in the case study processed ore types which came from different mines and possessed different physical characteristics, such as different grade values, ore densities etc. Besides the process data, the maintenance department of the mining company also provided the data for all the maintenance activities concerning the mill studied in the present case study, such as data on mill stops due to mill liner inspection and replacement, motor repair, overhauling etc. This data is important for making decisions on replacements, making it possible to synchronize the replacement activity with other scheduled mill stops, so that the overall downtime of the mill can be minimized.

**Data analysis**

Correlation studies were carried determine the correlation between the liner wear and the process parameters over the life span of the liners. The other objective was to determine and remove the redundant parameters to minimize the model complexity. The trends of the data and the correlation of the data sets to each other were used as model inputs and this has a significant influence on the model outcomes. Hence, the outliers from the process data needed to be removed in order to achieve an appropriate correlation and appropriate trends.
Fig. 1: Data collection and analysis process

Data analysis for the single ore type: In the context of the present study, the term “single ore type” is used to denote a given ore type which comes from a specific mine and possesses a specified range of physical properties, such as density, grade value (% of metal content), ore hardness, rock size etc. In the
The present case study the mill grinds various ore types which come from different mines and exhibit variations in their material properties and characteristics, such as density, grade value, rock size etc.

The order of processing for the different ore types in the mill over the life span of the mill liners also varies, as the ore milling schedule also depends on the availability of ore in the mines. Therefore, in order to develop a generalized approach to investigating the economic efficiency of the mill and the optimum replacement interval, the process data for each ore type is segregated (see Figure 2 and 3).

Using the methodology (see Dandotiya and Lundberg, 2011a) requires continuous process data for a single ore type over the life span of the mill liners. Therefore, the process data for a single ore type was segregated from the mixed ore data over one replacement cycle of the mill liners. In the present case study, multiple types of ores were processed between two consecutive replacements of liners shown in Figure 2.

Figure 2 shows various types of ore processed over the period of one life cycle of the mill liners, with $t_i^j$ representing the milling time of ore type “j” for time sample “i” of a life cycle period of the mill liners. The data for a single ore type was segregated from the life cycle of the mill liners and is shown in Figure 3.

The process data set for a single ore type “1” was collected for the time intervals, i.e. for $t_{i1}^1$, $t_{i2}^1$, $t_{i3}^1$ (see Figure 3). A given ore type is processed in discrete intervals of time over a life cycle period of the mill liners; i.e. no continuous process data is available for the ore type over one life span of the mill liners.

Based on the segregated data, the process data was generated for one whole life span of the mill liners. For example, as described in Figure 2 and 3, data segregation was performed for the process parameter “power consumption” (see Figure 4a and 4b). Figure 4a shows the segregated data for a given ore type and the blank space between the data points shows that ore was not processed in the mill during that time interval. Furthermore, using a trend test, simulation, interpolation and extrapolation, data was generated for the whole life cycle period of the mill liners (see Figure 4b).
Fig. 4a: Segregated power data

Fig. 4b: Generated power data

Fig. 5: Data generation for the whole life span of the mill liner from a mixed ore type to a single ore type
Figure 5 shows the various activities performed in the case study for data generation for each process parameter for a specific ore type over the life span of the mill liners. Apart from trend analysis, distribution analysis and simulation were also performed in order to generate a continuous data set over the life span of the mill liners. The Easy-Fit, Visual Basic and Matlab software tools were used to perform the analysis of the process data. The time series method is helpful in finding a best fit line in a type of data when it has both trend and randomness (Box and Jenkins (1976); Kendall (1984) and Shumway (1988).

If a trend in the data was found, then linear interpolation and extrapolation were used to generate the data for the periods when the specific ore was not actually being processed in the mill (see Figure 4a and 4b). Independent and identical distribution (IID) has been verified before fitting the the data in any distribution (Ascher and Feingold, 1984; Kumar and Klefsjö, 1992).

4. Model formulation

The approach of the present paper improves the replacement model for single ore type proposed by Dandotiya and Lundberg (2011a). The present model also included the ore density parameter in the replacement model which incorporates the influence of ore properties on wear life of mill liners which makes the optimization approach applicable for multiple ore types.

Literture on maintenance optimization models can also be referred in the references e.g. Dekkar (1996); Roll and Naor (1968); Ben-Daya et. al (2000); Dogramaci and Fraiman (2004); Al-Najjar (1999); Christer and Scarf (1994); Sethi and Chand (1979); Jardine et. al. (1998); Wang (2002); Yun and Choi (2000); Duffuaa and Al Sultan (1999); Hsu (1988).

Model assumptions: The following assumptions have been made

- *Liner profile is not considered in the model*
- *Minor replacement of mill liners does not influences the mill performance*
- *For the detailed explanation of first two assumptions see Dandotiya and Lundberg (2011a).*
- Due to lack of process data, it is assumed that the decreasing pattern of process efficiency for the mine A ore type was the same for the ore types from mine B and C (see Figure 7).
- Throughput influences the wear life of mill liner i.e. an increase in throughput leads to decrease in wear life. However, the present study random throughput but the variation in wear life due to randomness in throughput assumed to be constant.
- The mill profit is linearly dependent on the milling time; i.e. the total profit is proportional to the milling time of a given ore type, \( P_i \propto t_i \). The
A weighted arithmetic mean is considered for calculating the overall or
effective replacement interval of the mill liners for the multiple ore types.
Relative importance is given to a specific ore type based on its value and
quantity processed over a life span of the mill liners.

Simulation is used to merge different distributions of replacement intervals
for corresponding ore types.

The lifetime model considers the ore density parameter in order to
incorporate the influence of processing multiple ore types on lifetime of
mill liners. The other unknown factors (see equation 1) which may also
have influence on liner wear, are assumed to be constant in the study. The
main reason is due to lack of experimental data which is needed for all
individual ore types for establishing the relationship between lifetime and
ore properties. Hence, as per the experience of reference group, the ore
density is assumed to be a significant factor. Radziszewski et al. (2005)
have developed an advance wear model for lifter bar which also suggests a
linear relationship between density and wear rate of lifter bar, if other
parameters are assumed to be constant (see equation 1).

\[
\text{Wear rate} = \rho \cdot \frac{\tan(\beta(F))}{\Pi \cdot H_r} \cdot \mu \cdot F \cdot \phi \tag{1}
\]

where \( \rho \) is the ore density, \( \beta \) is the abrasion angle, \( F \) is the loading force,
\( H_r \) is the ore hardness, \( \mu \) is the friction angle and \( \phi \) is the sliding velocity.

Abbreviations

i : Number of sampling intervals in one liner life cycle
j : Ore type
k : Number of days in one time sample
\( t_{int} \) : Duration of the sampling intervals [days]
\( T_{Cycle}(j) \) : Threshold life of mill liners for ore type “j” when risk of mill shell
damage arises [days]
\( T_{rep} \) : Time taken during the mill liners installation including preparation time
[days]
\( M_i \) : Mass flow from the mill during the \( i^{th} \) time interval [tones/hour]
\( N \) : Number of replacement cycles during the period \( T_{Cycle}(j) \)
\( E_i \) : Energy consumed by the mill during the ith time interval [kWh]
\( \eta_p \) : Process efficiency
\( \Omega \) : Revenue generated by processing ore [$/tone]
$C_{dtc}$: Downtime cost per replacement cycle [$/hour$]

$C_{rep}$: Total cost incurred during liner replacement (i.e., liner cost, labour cost, startup and synchronization cost) [$/replacement$]

$C_{energ}$: Energy cost [$$/kWh$$]

$C_{ins}$: Total inspection cost per day (including downtime cost) [$$/inspection/day$$]

$P_{gross}$: Gross profit over a $T_{max}$ [$S$]

$\rho_{avg}$: Average density of group of different ore types

$\rho_j$: Density of ore type “$j$”

A detailed discussion on model inputs parameters can be found in reference (Dandotiya and Lundberg, 2011a).

Relation between ore properties and wear life: According to the reference group, the processed ore type, depends on its internal properties, will significantly affect the wear rate of the liners up to approximately 25-50%, in the present particular case study. The amount of pyrite in the ore by some reasons affects the wear properties. The high amount of pyrite has been seen leading to high amount of wear on the liners. On the other hand, increased amount of pyrite increases the overall density of the ore, this increased density of the processed ore will directly increase the wear forces and thus increase the wear of the liners. The densities of the ores in the present case study are also varying between approximately 3.0-3.8 kg/dm$^3$ because of the amount of pyrite.

In order to incorporate the effect of physical properties of ore from different mines on the life cycle of mill liners, a relation between density ore density and life cycle of mill liners has been considered. Let the life cycle of mill liners $T_{cycle}(j)$ (when only ore type “$j$” is processed) and the ore density is $\rho(j)$ therefore, based on information provided by reference group an inverse relation has been considered between life cycle of mill liners and ore density

$$T_{cycle}(j) \propto \frac{1}{\rho_j} \quad \Rightarrow \quad T_{cycle}(j) = \frac{k_j}{\rho_j}$$

(2)

Where, $k_j$ is the proportionality constant for ore density. Therefore, from the above explanation, a relation between the life cycle of mill liners $T_{cycle}(j)$ (when only ore type “$j$” is processed) and the average life cycle for mill liners for multiple ore types $T_{avg}$ has been established and represented by equation 3.

$$T_{Cycle}(j) = \frac{\rho_{avg}}{\rho_j} T_{avg}$$

(3)

The relation for gross profit over a replacement cycle and optimization approach is adopted from Dandotiya and Lundberg (2011a) which is represented by equation 4. In the proposed approach of the present paper the maximum life cycle period for each ore type will be different as wear life of mill liners depends on ore properties, therefore in the present model the maximum wear lives will
vary from one ore type to other, hence in the present case $T_{\text{max}}$ will be $T_{\text{max}}(j)$. Where, $T_{\text{max}}(j) = T_{\text{Cycle}}(j) + T_{\text{rep}}$ and the no. of replacement cycle is $N = \left( \frac{T_{\text{Cycle}}(j) + T_{\text{rep}}}{T_{\text{Cycle}} + T_{\text{rep}}} \right)$

The gross profit is calculated at different life cycle period. Where, $T_{\text{Cycle}}$ varies from 1 to $T_{\text{max}}(j)$ with the sampling interval of $\Delta T = 1$ day.

$$P_{\text{gross}} = \left( \sum_{i=1}^{T_{\text{Cycle}}} M_i \cdot n_i \cdot \Omega - \sum_{j=1}^{T_{\text{Cycle}}} E_j \cdot C_{\text{energy}} - \sum_{j=1}^{T_{\text{Cycle}}} C_{\text{imp}} - C_{\text{DT}} - C_{\text{rep}} \right) \times (N)$$

(4)

The replacement model for the single ore type considers the corresponding process parameters, various cost parameters and ore density. Since each ore type possesses a different grade value and density and different process parameters, the cost and revenue parameters also vary from one ore type to another. Hence, the processing time and monetary value of a specific ore in the mill become important key parameters concerning optimum replacement decisions for grinding mill liners.

An approach is proposed in the present study by considering an example (see Figure 6). In this example three ore types from three different mines are considered, because, in the present case study, these three ore types were processed over the investigated life span of mill liners.

After using the process and maintenance data in the model developed, the optimum replacement intervals for individual ore types are determined. The total milling or processing time and profit per unit of a specific ore type in the mill are used as an inputs for the mathematical formulation for determining the overall or effective replacement interval, which is represented as $T_{\text{eff}}$. The term “overall or effective replacement interval for multiple ore types” is used to denote the optimum replacement interval for mixed ore types that combines the influence of all the ore types which have been processed over the investigated life span of the mill liners.

Figure 6 shows the investigated ore types from mine A, B and C, the process data, operational and maintenance cost data which were used in the proposed combined model for single ore type to determine the optimum replacement interval for given ore types. The three inputs of the model for replacement intervals for the multiple ore type are: (1) the optimum replacement interval; (2) the ore processing time; and (3) the monetary value for each ore type.

The evaluation criteria are named “weighting factors” and must be taken into consideration during the subsequent evaluation to determine the optimum solution (Pahl, 1996). A weighting factor is a real, positive number. It indicates the relative importance of a particular evaluation criterion. The present model assumed the average profit per day ($/day) for a specific ore type to be a relative importance of
the given ore type. Hence, for a given ore type, the average profit per day is
determined and is later used to determine the overall profit during the
corresponding process time of the given ore type. An example is considered (see
Figure 2) where $t'_i$ denotes the processing time for the $j^{th}$ ore type for the "$i^{th}$" time interval. Therefore, the total processing time of ore type "$j$" in one
replacement cycle of the mill liners will be

$$t_j = \sum_{x=1}^{j} t'_x$$  \hspace{1cm} (5)$$

Let the average profit per day for ore type "$j$" be $p_{avg}(j)$ ($$/day) and let the
corresponding process (milling) time be $t_j$ (days) during the life cycle period of the
mill liners. Then the total profit over one life cycle period of the mill liner for a
given ore type, "$j$", is

$$P_{(j)} = p_{avg(j)} \times t_j$$  \hspace{1cm} ($) \hspace{1cm} (6)$$

Therefore, the gross profit of the mill for all three ore types is

$$P_{\text{total}} = \sum_{j=1}^{3} P_{(j)}$$ \hspace{1cm} (7)$$

Fig. 6: Approach used for determining the overall replacement interval
A term “profit share” ($w_j$) is introduced to consider the worth of the ore together with the processing time inside the mill over the life span of the mill liners. The profit share can be defined in another way, i.e., as the ratio of the individual profit of a given ore type, $j$, to the gross profit from all the ore types over the life span of the mill liners, which can be determined by equation 8. If $w_j$ is the profit share of the given ore type $j$, then,

$$w_j = \frac{P_j(t)}{P_{\text{total}}}$$  

Later, the value of $w_j$ is used as a weight for a given ore type to estimate the overall replacement interval, determined using equation 9

$$T_{\text{eff}} = \sum w_j \cdot T_j$$  

where $T_1$, $T_2$… $T_j$ are the optimum replacement intervals for ore 1, 2…$j$, combining equation 8 and 9

$$T_{\text{eff}} = \sum p_j \cdot T_j$$

$$\sum p_j$$

Due to the randomness in throughput, the replacement model generates a specific distribution for the optimum replacement interval rather than a discrete value. Therefore, in order to determine the overall replacement interval, these distributions need to be combined. Hence, the overall replacement interval formulation is simulated for merging these distributions together. After simulation a convergence in the result for the overall replacement interval was obtained (see Figure 10).

5. Results and conclusions

The real data set for each ore type (consisting of the process, maintenance and operational (energy) data) was collected from the ore dressing plant and the liner manufacturing company. The cost and revenue data are classified information and were used in the model to obtain the result.

A decreasing trend in the process efficiency was found when the liner was worn out, which means that, at the end phase of the liners’ life, the grinding performance decreases (see Figure 7). Based on the process efficiency data (at the same level of input metal (Cu) content), a trend curve was set up for ore from mine A with a 95% confidence interval. The same comparison of the process efficiency should also be carried out for mine B and C. However, due to a lack of desired process efficiency data at similar levels of metal content for mine B and C and discussions with the reference group, the process efficiency for the ore types from mine B and C follow the trend for process efficiency of ore from mine A; i.e. that the decreasing trend was the same for all three ore types, as shown in Figure 12.
7. However, the values of the average level of process efficiency for the different ore types were considered, i.e. Mine A ore: 0.83, Mine B ore: 0.71 and Mine C ore: 0.84.

Density and ore processing time data: The density and process time data for each ore type was collected from the company and is given in Table 6.

Table 6: Ore type specific inputs for mine A, B and C

<table>
<thead>
<tr>
<th></th>
<th>Mine A (Ore type (j=1))</th>
<th>Mine B (Ore type (j=2))</th>
<th>Mine C (Ore type (j=3))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Processing time over the mill liners’ life span (days) (t_j)</td>
<td>115</td>
<td>132</td>
<td>72</td>
</tr>
<tr>
<td>Density (kg/dm³) (\rho)</td>
<td>2.99-3.77</td>
<td>3.55-3.66</td>
<td>3.25-3.34</td>
</tr>
<tr>
<td>Profit share(**) (w_j)</td>
<td>0.28</td>
<td>0.25</td>
<td>0.46</td>
</tr>
</tbody>
</table>

**The profit share or weights were calculated based on the methodology given in Section 3.

Results for the optimum replacement interval for ore from mine A: The process data were segregated for the whole life cycle period (see Figure 5). The life cycle of mill liners depends on the density of the specific ore and, therefore, the life cycle of the mill liners for ore from mine A is determined using equation 2. In the present case the average life of the mill liners is 319 days. As the wear is assumed to be directly dependent on the ore density, it is also important to consider the total processing time of the given ore in the mill. Therefore, the weighted mean of all the densities is assumed to be the average density of the mixed ore types, and the processing times of the different ore types are assumed to be weights.
Using the data from Table 6, the value of the average density of the mixed ore type is calculated as $\rho_{\text{avg}} = 3.48$ kg/dm$^3$, where the average values of the densities of individual ores are considered. Using equation 3, the average life cycle of the mill liners when ore from mine A is processed will be $T_{\text{cycle}}(A) = 330$ days. However, if the variation in the density (see Table 6) within the same ore is considered, the variation in the life cycle of the mill liners for the case of ore from mine A will be $294 \leq T_{\text{cycle}}(A) \leq 371$ days. The objective of determining the average life cycle for individual ore types is to determine the feasibility of the model results; i.e., in the case of ore from mine A, in the worst case scenario, if ore with a high level of density, $\rho_{\text{avg}} = 3.77$ kg/dm$^3$, is processed, then the threshold limit for the replacement of mill liners will be 294 days. In order to generate the throughput data for simulation, the EasyFit software was used to detect the distribution within real throughput data and its corresponding parameters (see Figure 8).

The optimum replacement interval was determined using the proposed replacement model of the present study. Due to the large variation in the throughput data (1,500 – 2,500 tonnes/day) (see Figure 8), a wide range of optimum replacement intervals (250 to 310 days) was obtained (see Figure 9).

**Ore from mine B:** Similarly, the value of the average life cycle of the mill liners in the case of ore from mine C was found to be $T_{\text{cycle}}(B) = 308$ days and the average life of the mill liners varies between 303 and 312 days and the optimum replacement interval was found to be within the range of 245 to 290 days.

**Ore from mine C:** Similarly, the value of the average life cycle of the mill liners in the case of ore from mine C was found to be $T_{\text{cycle}}(C) = 334$ days and the average life of the mill liners varies between 324 and 338 days and the optimum replacement interval was found to be within the range of 240 to 275 days.
Estimation of the overall optimum replacement interval for the case of mixed or combined ore types: Clemen and Winkler (1999) and Winkler and Makridakis (1983) have discussed methods of combining subjective probability distributions in decision making, and these researchers have provided an excellent summary of the current state of information regarding the uncertainty of interest. They stated that decision and risk analysis applications involving the combination of probability distributions or other quantities have often used simple combination rules (e.g. a simple average) and tend to perform quite well because of this usage. More complex rules sometimes outperform in some instances.

The present study uses a weighted mean approach in order to combine three distributions for the optimum replacement interval for the ore from mine A, B and C. The weights are defined based on a monetary value (profit/day). The processing time of the ore type in the mill is also an important parameter in terms of determining the overall profit over the life span of the mill liners. Equation 5 was used and simulated to determine the optimum replacement interval for multiple ore types.

Since the replacement intervals for individual ore types are used as input and since the replacement intervals also follow different distribution types, in order to combine the three distribution inputs, the results for the overall replacement intervals were simulated until the results started to converge. After running the simulation, the optimal replacement interval converged between 258 and 286 days with a 95% confidence interval (see Figure 10). In addition, the process time for each individual ore was obtained from the case study and used as input in the model in order to determine the annual profit. Hence, in order to obtain the optimum replacement interval, the processing time needs to be known in advance.

Economic influence of the suggested maintenance policy: An economic analysis of the suggested maintenance policy was performed. In order to determine the financial benefits for the mill over the life cycle period of the mill liners, the average profit per day is calculated. The average profit per day $M_{avg}(i)$ for a given ore, “i”, is calculated from the following relation

$$M_{avg}(i) = \frac{P_{gross}(i)}{T_{cycle}(i)} \text{ (\$/day)}$$

(12)
Fig. 10: Effective replacement interval for the combination of different ore types

$P_{\text{gross}}(j)$ is the gross profit for ore type “$j$” for a time period of $T_{\text{cycle}}(j)$.

Let $M_{\text{avg}}(1)$, $M_{\text{avg}}(2)$ and $M_{\text{avg}}(3)$ be the average profit per day for the ore types from mine A, B and C, respectively, when the maintenance management follows the present replacement policy of 310 days. Similarly, let $M_{\text{avg}}(N1)$, $M_{\text{avg}}(N2)$ and $M_{\text{avg}}(N3)$ be the new average profit per day generated when the replacement interval is changed to a suggested 265 days (determined through the mathematical model), and let $t_1$, $t_2$ and $t_3$ be the processing time in the mill for the ore from mine A, B and C, respectively. The percentage change in the profit is calculated as follows.

$$P_{\text{present}} = M_{\text{avg}}(1) \cdot t_1 + M_{\text{avg}}(2) \cdot t_2 + M_{\text{avg}}(3) \cdot t_3$$

$$P_{\text{suggested}} = M_{\text{avg}}(N1) \cdot t_1 + M_{\text{avg}}(N2) \cdot t_2 + M_{\text{avg}}(N3) \cdot t_3$$

$$\% \text{ change in total profit} = \frac{100}{P_{\text{present}}}{(P_{\text{suggested}} - P_{\text{present}})}$$

(13)

Based on the case study, if the present maintenance policy of applying a replacement interval of 310 days is changed and a suggested replacement interval of 265 days is applied, the % change in the total profit of the mill during one life cycle of the mill liners is 0.5%. This is a significant amount of savings when the profit amount is of a high order. For the studied case in this paper, if the suggested maintenance policy is considered with a 95% confidence interval, i.e. if the replacement interval varies from 258 days to 286 days, then the corresponding savings vary from 0.3% to 0.5% of the annual profit of the mill, respectively. This means that, if the maintenance management schedule the replacement action with other maintenance activities within a range of one month, the management can
still have an approximate significant saving of 0.3% of the annual profit of the mill.

However, the savings also vary with the types of ore and the duration of the processing time. Therefore, the savings mentioned (0.3% to 0.5%) are only valid for the given case provided in the paper. Based on the influence of individual ore types on the financial benefits, it was also found that the financial benefits could go up to 1%. Therefore, the processing time and the ore types play a critical role in terms of financial savings.

Model usability

Data is available for the ore types which are going to be processed in the future:
For prediction of the replacement interval of mill liners, in the case where data such as the power consumption of the mill, throughput (tonnes/day), process efficiency, downtime cost (per hour), liner cost, energy cost and inspection cost are available for the ore types which are going to be used in the future, the present model can be used simply according to the methodology described in both parts of the present paper.

Data is not available for the ore types which are going to be processed in the future:
Let us consider the case where a mining company with a completely different setup concerning the mill dimensions, liner properties, ore properties etc. wants to use the proposed model to predict the optimum replacement interval and its corresponding savings. In this type of case, the prediction can be accomplished by comparing the physical properties of the ore types which are going to be processed with those of the ore type for which data is available.

As far as the present model is concerned, the variation of the throughput, process efficiency and energy consumption needs to be considered. In order to determine the approximate range of the values of model parameters, the mill should be run for each new ore type for 10-15 days, so that the average level of throughput, process efficiency and energy consumption can be obtained for the new types of ore that are to be processed. The next step is to incorporate the trends of process efficiency and energy consumption over the life span of the mill liners for the ores which have been processed in the past. Based on this information, the presented model can provide a rough estimate of the replacement interval of the mill liners for the given case.

Model risk: After performing a sensitivity analysis, it was found that the model sensitivity depends on the following parameters: throughput, process efficiency and downtime cost. The process efficiency and the throughput level may change in the future due to significant changes in the ore properties and the availability of ore in the mines, which might lead to a variation in the results in reality compared to the results predicted by the developed model. Hence, there can be a technical risk (the hazard of damaging the mill shell) and an economic risk (financial loss) associated with the model, which is explained as follows:

Technical risk: No technical risk is associated, because, for the worst case scenario, the model considers the average life cycle of the mill liners as a
constraint and the model results for the optimum replacement interval will always be less than the threshold limit or the average life cycle of the mill liners (the maximum delay in the replacement of mill liners).

Economic risk: The present model considers a slight decrease in the process efficiency parameter, which means that the grinding efficiency decreases when the liner is worn out. Therefore financial losses can occur only in the case where the grinding efficiency of the liners is considered to be constant at each phase of the mill liners’ life, which is only theoretically possible. Based on the case studied in the paper, the maximum loss that could occur is 0.15%.

The present model can also be used for replacement decisions for other similar systems consisting of non-repairable equipment by considering the periodic operational cost data and performance index (e.g. process efficiency) and the revenue together with the downtime and inspection costs.

Conclusions

- An economic decision model for mill liner replacement has been developed considering maintenance policies and the process performance for the mill liners. The results obtained from the model show that an optimum maintenance policy can not only reduce the maintenance cost, but also affect the process performance, which leads to significant savings.
- The results obtained for the optimum replacement interval show an increase of 0.3% to 0.5%, with a 95% confidence interval, in the gross profit of the mill per year, by changing the current replacement policy to a proposed policy based on the given case study.
- A methodology is suggested that combines the different optimum decisions for individual ore types into a single optimum decision while taking the economic and technical characteristics of each ore type into consideration.
- The study presents an alternative method of decision making that does not use periodic wear measurements, due to the unavailability of sufficient mill liner wear data for analyses. The present approach also deals with the problems related to variation in the process data due to technical problems in the plant.

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REFERENCES
Paper IV

Combined replacement and life improvement model for mill liners

Combined Replacement and Life Improvement Model for Mill Liners: A Case Study
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Replacement decisions of the grinding mill liners in grinding mill of ore dressing plants plays an important role of the mill economy. The grinding mill uses various types of mill liner components with different lifetime due to its wear. Therefore, mill needs to be stopped for replacement of different parts at several occasions which leads to significant monetary losses. The aim of this study is to develop a decision support system to find the combined optimum group of components for the replacement of the different components of mill liners and necessary life improvement of individual components by minimizing life cycle cost (LCC). An exhaustive search approach with LCC modeling is used to determine the optimum grouping and necessary improvement in lifetime of the mill liner components.

Significance: The proposed optimization approach can be useful for the mill liner user in optimizing the LCC of mill liners, and it can be useful to the manufacturer of mill liner components in the design of new components to achieve an optimal maintenance strategy.

Keywords – Decision support systems, combined replacement, optimization, maintenance policy, LCC, Life improvement

1. INTRODUCTION

When a mill has to be stopped for the replacement and inspection of degrading spare parts, this leads to heavy production losses, which is a major concern for mining companies. The goal of the company’s maintenance department is to assure the running of the mill all around the clock. A stoppage of the grinding mill not only incurs production losses during the actual stoppage, but also entails losses due to production process synchronization or start-up costs.

Mill liners are important spare parts of the grinding mill concerning the overall production quantity and quality. When the grinding mill is in operation, over a period of time a process of degradation of mill liners starts due to the abrasive forces between the ore and the mill liners inside the grinding mill. Mill liners located in different sections inside the mill have different wear rates due to variation in the design and the stresses caused by the load. Moreover, the life cycles of mill liners in different sections also differ from each other.

Mill liners are also the most critical components concerning the economic performance of a grinding mill. In the case of the AG mill, the mill liner cost represents 37% of the total cost for grinding, see Product handbook (2002). The various components of a mill liner, such as the pulp grate plate, pebble grate plate, lifter bar, and head plate etc.

This paper presents a collaborative research conducted by Luleå University of Technology for Bolden Mineral and Metso, all located in Sweden. The standard grinding mill used with thirty-six lifter bars (high–low system) are spaced circumferentially around the mill shell. The mill shell lifter bars are 210 mm wide and 350 mm high; the shell plates between the liners protect the mill shell. For the more details of the present case study of mill liners, expertise and experience of the reference group of the present case study see Dandotiya et al. (2011).

The mill needs to stop several times in a year for installing new liners when the liners of a specific section are worn out, which entails heavy costs due to production losses. Apart from the
downtime cost, the cost of the mill liner components also needs to be considered. The activities involved in replacing grinding mill liners (which are non-repairable parts) consume time and resources.

The issue of cost-effective maintenance planning in the present case has arisen due to the heavy downtime cost and due to the different replacement activities for the different parts of the mill liners, which often require the same preparatory work (Reference group). The motivation for the present research work is to minimize the LCC of the grinding mill by optimizing the maintenance schedule of the mill liner components in co-ordination with planned shutdowns for overhauling. The present study also aims to assist the liner manufacturers in optimizing maintenance schedule and the life cycles of individual components of mill liners.

A detailed explanation on economic influence of maintenance activities on mill liners and uses of mill liners etc. can be found in the reference Dandotiya and Lundberg, (2011). They discussed maintenance and economic aspects related to mill liners of grinding mill. They have highlighted the influence of maintenance decisions for the mill liners on mill production economy and process performance together.

The present paper proposes a methodology which jointly optimizes the grouping of different mill liner components and their life cycle periods by minimizing the overall cost (the production loss cost, replacement cost and cost incurred for necessary life improvement) over a planning horizon period. The paper investigates the issues related to the optimum grouping of components for replacement and the issues related to determination of the optimum life of each individual part of the mill liners. The present study highlights the optimized variations in the life cycle of different components in order to attain additional savings. The study presented in the paper deals with non-repairable mill liner components of a pre-determined age. The findings show that premature replacement, delayed replacement because of life improvement, or a combination of both for different parts of the mill liners can reduce the overall life cycle cost further, which can lead to significant financial savings.

Abrasive forces between the charge and the liner in the mill cause wear, resulting in a changed liner profile and decreased liner thickness (Bloch and Geitner (1990)). Regular inspections are needed to check the liner thickness and to prevent mill shell damage and inspections are normally done when mill is stopped for other maintenance activities. For the replacement of mill liners, the mill must be stopped, leading to significant downtime. Unplanned or planned maintenance, including both inspections and replacement, leads to heavy financial losses due to production losses. Within the framework of the present case study, the mill needed to stop on several occasions for major and minor replacements of different parts of the mill liners due to their different lifetime. A minor replacement not only incurs losses during the mean time to replace (MTTR) of the component, but also incurs financial losses connected with production synchronization/start-up costs. Therefore, these replacements need to be optimized cost-effectively through optimum grouping and optimum improvement in lifetime of the parts of the mill liners.

2. DATA COLLECTION AND ANALYSIS

All the data on the replacement of different parts of the mill liners were continuously collected the liner manufacturing company over a period lasting from 2003 to 2009. An analysis revealed that the mill had to stop on several occasions for both major and minor replacements of mill liners when the liners had become worn out (Reference group). The pessimistic value of average lifetime (guaranteed life) of each component was determined using the replacement data obtained from the mining company (see section 4, table 4).

3. MODEL FORMULATION

Extensive research on joint replacement of components and opportunistic maintenance has been carried out by several researchers. Dekker (1995) describes the use of penalty functions. These penalty functions also serve as basic elements in a method to determine the optimal combinations of activities and in maintenance planning. Dekker et al. (1997) presented a
methodology involving a system consisting of “n” independently operating components, where each component was subject to stochastic failure and had a known time-to-failure distribution. They considered the use of a penalty cost function if a component failed before the estimated time of failure and preventive maintenance had to be carried out. Failure-based maintenance with group replacement is also referred to as opportunity-based maintenance by Pintelon and Gelders (1992).

Paz and Leigh (1993) focused on area of research related to maintenance scheduling and its importance in terms of maintenance and opportunity costs. Jardine et al. (1998) claimed that condition-based maintenance takes into account both the age of the component and its condition at the moment of the decision-making. Jardine and Tsang, 2005, have discussed an example of replaceable component (fuel filter) that deteriorates deterministically.

Jiang and Ji (2002) proposed an age replacement policy considering multi-attributes. An opportunity-based age replacement policy with minimal repair was also developed by Jhang and Sheu, 1999. A warranty-based replacement model considering downtime and cost was proposed by Jung et al. (2008). Cho and Parlor (1991); Scarf (1997), have made an extensive review of maintenance models for joint replacements, e.g. block replacement and group replacement models, and opportunistic models etc. A more detailed presentation and discussion of models related to component replacement and scheduling have been provided by Cox (1967); Easton et al. (1992); McKendall et al. (2008); Tango (1978); Park et al. (2011); Hontelez et al. (1996) etc.

Present paper proposed a mathematical model for determining the optimum grouping for combined replacement and the necessary life improvement of mill liners. Consider a mill with “m” different mill liner components are categorized and grouped based on their pre-determined lifetime. Each replacement includes various types of cost components, i.e. the production loss cost during the stoppage, the process synchronization (start-up) cost and the cost of the mill liner components on each replacement occasion. Another cost type, the “cost improvement function”, is incorporated in the model for improving the lifetime of the mill liner components, and it is presented in Section 3.4.10. The present methodology adopts an exhaustive enumeration search based approach (Nievergelt, 2000), i.e. it searches for the optimal solution, considering all the possible replacement scenarios.

3. 1 Encountered practical problems

The present study deals with a non-linear cost function for improvement of the lifetime of the mill liner components. Due to difference in design, profile, weight and height of the mill liners influence the grinding process (Cleary (2001)) therefore, the investments for life improvement of different components of mill liners may not be same and may vary from one lifetime category to another lifetime category.

3. 2 Assumptions

1. Proposed methodology is applicable only for preventive replacement of non-repairable components with pre-determined age or guaranteed life.
2. Based on a discussion with the reference group of the liner manufacturer, the base price of the mill liner is fixed and cannot be reduced, and therefore no reduction in a component’s cost in the LCC calculation is considered when a reduction of the life cycle cost of a component is proposed.
3. The liner wear has been correlated with the process data and it has been observed that only major replacements of mill liners have a significant influence on the grinding performance. The present study deals with the rescheduling of replacements of mill liners which can be considered as minor replacements and the effects of such replacements on grinding performance are assumed to be negligible in the LCC model.
4. The worst case scenario is considered and the values for the earliest ending of the lifetime/guaranteed life are taken as input in the LCC model, so that risk of early failure can be avoided. Therefore, no corrective replacement is considered in the model.
The basis of the present model is minimization of the LCC by reducing the number of unnecessary mill stoppages, and therefore it is assumed that the mill is running at full capacity (100%) all around the clock. Hence the case of opportunistic replacement has not been considered for mill stoppages due to ore unavailability at the mines.

### 3.3 Model parameters

The following input parameters have been considered in the proposed methodology. The model parameters are briefly described in the next section of the paper.

- $m$: Total number of mill liner components (as per lifetime category)
- $T_{pht}$: Planning horizon period (time unit)
- $t_i$: Mean time to failures (MTTF) of component “$i$” (time unit)
- $t_{max}$: Mean time to failures (MTTF) of component “$i$” (time unit) with a maximum lifetime for all the components of the system
- $t_{min}$: Mean time to failures (MTTF) of component “$i$” (time unit) with a minimum lifetime for all the components of the system
- $T_{tr}^i$: Mean time to replace (MTTR) of component “$i$” (excluding preparation time) (time unit)
- $T_{prep}^i$: Preparation time (stop and start-up time) for any replacement occasion (time unit)
- $\Delta T_{il}$: Maximum allowable improvement in lifetime for component “$i$” (time unit)
- $\Delta T_{im}$: Improvement time (time unit)
- $\Delta T_{inc}$: Optimum improvement of the lifetime of component “$i$” (time unit)
- $S$: Replacement scenario
- $C_{dor}^i$: Downtime cost or production loss cost during the mill stoppage for the replacement (SEK/time unit)
- $C_{l}$: Labour cost during the mill stoppage for the replacement (SEK/time unit)
- $C_{rep}$: Cost of component “$i$” for each replacement occasion (SEK/component)
- $C_{imp}$: Cost improvement function (SEK/time unit)
- $f_{ori}$: Current replacement frequency over the planning horizon period of component “$i$”
- $f_{nri}$: New replacement frequency over the planning horizon period of component “$i$”
- $f_{add}$: Total number of occasions when two or more components are replaced together for scenario “$S$” over the planning horizon period
- $f_{ore}$: Number of occasions when two or more components are replaced together by default for scenario “$S$”
- $f_{res}$: Number of occasions when two or more components are replaced together when the replacement of a component is rescheduled
- $L_{prem}$: Losses which occur due to premature replacement in order to reduce multiple stoppages.

### 3.4. Description of the model parameters

This section presents a brief description and definitions of the model parameters and variables used.

**Planning horizon period** ($T_{pht}$): In the present context, the planning horizon period covers the replacement planning cycle for all the mill liners. The present study deals with different types of
mill liner components based on 8 different lifetime categories. The investigated components had different wear lives, and the lifetime of the longest lifetime category is considered as the planning horizon period for LCC calculation in the present case study due to company planning horizon policy.

Component types ($m$): The components or parts of the mill liners are categorized based on their pre-determined lifetime and cost improvement function. This means that two or more parts of the mill liners are considered as belonging to one category if the lifetime, cost improvement function and maximum achievable lifetime of these components are the same.

Mean time to failures (MTTF) of component "i" (T$_i$): The mean time to failures (MTTF) of a component represents the average time duration from its installation to its removal when it has completed its lifetime.

Preparation time $T_{prep}$: Preparation time is the total time (excluding the actual liner installation time) from the time when the mill is put out of operation for the mill liner installation to the time when it starts to function at full production level, as shown in the schematic diagram in Figure 2. The preparation time is one of the key parameters of the maintenance decision model for the replacement of mill liners. As shown in Figure 2, the preparation time is equal to the sum of all the time segments during the mill stoppage, excluding the actual component installation time. $T_{prep} = T_1 + T_2 + T_3 + T_4$, where $T_1$ and $T_2$ are the mill-stopping time (during which the production is reduced and the mill has to prepare for a stoppage) and the mill start-up time, respectively. $T_3$ and $T_4$, on the other hand, are the time periods when other maintenance activities (such as the removal of the chute and the outer part of the mill shell, fixing the external mill components etc.) have to be carried out before the component is installed. The actual installation time is $T_R$ and is shown in Figure 2 (time allocation are not scaled).

![Figure 2: Time allocation during a mill stoppage for replacement](image)

Mean time to replace (MTTR) of component "i" ($T^R_{i}$): The actual installation time for a specific mill liner component is considered as the MTTR.

Maximum achievable improvement in lifetime for component "i" ($\Delta T_{i,\text{max}}$): This is the maximum achievable improvement in lifetime of component "i" which is technically feasible. Its value varies from one component to another.

Improvement time ($\Delta T$): This is the model variable and represents the hypothetical improvement of the original lifetime of a component.

Maximum improvement in lifetime ($\Delta T_{i,\text{max}}$): This parameter is used for determining the optimal improvement in lifetime. The proposed algorithm calculates the LCC at each incremental step of the improvement time until the value of $\Delta T_{i,\text{max}}$ is achieved. The theoretical maximum possible allowed improvement in the model can be determined by $\Delta T_{i,\text{max}} = T_{\text{max}} - T_{\text{min}}$, which is the difference between the maximum and the minimum lifetime categories. That would be achieved if all the components were to be replaced together, giving the component the maximum lifetime.

Optimum improvement time for component "i" ($\Delta T^*_{i}$): The optimum value of the improvement time for each component is defined as the optimum improvement time for component "i".
Cost improvement function \( (C_{imp}(t)) \): The cost improvement function in the present context is defined as the relation between the costs required for improving the lifetime of the mill liner component and the improvement time. In the present case, the costs required for life improvement are not linearly related and they vary from one lifetime category to another lifetime category. The main reason for the variation in the life improvement costs is that different materials are needed for the improvement in lifetime of the mill liners. Therefore, a stepwise cost function is used to incorporate this practical complexity. A generalized improvement cost function has been used in the replacement model (see relation 1), where cost \( C_{1i}, C_{2i}, ..., C_{mi} \) are the costs required (in SEK/week) for different levels of improvement of the lifetime of category “i”.

\[
C_{imp}(t) = \begin{cases} 
C_i^1 & \text{if} \quad 0 < T_{i}^\text{imp} \leq t_i \\
C_i^2 & \text{if} \quad t_i < T_{i}^\text{imp} \leq t_i \\
\vdots & \\
C_i^m & \text{if} \quad t_{i-1} < T_{i}^\text{imp} \leq t_i 
\end{cases} \quad (1)
\]

Replacement scenarios (S): All the possible combinations of replacement schedules are defined as the replacement scenarios of different parts of the system (see Table 1). The total number of possible replacement scenarios for “m” components is \( 2^m - 1 \).

3.5 Component grouping to reduce the effective number of components in the system

A system with a large number of components will have a very large number of possible replacement scenarios, and therefore it is important to reduce the number of components by categorizing the components into different groups, so that the effective number of components can be reduced for reducing the computation. The components in the system will be considered as belonging to the same category if the following criteria can be satisfied together:

i) The components should have the same lifetime, so that they can be replaced on the same occasion.

ii) The costs required for improvement in lifetime of the components should be largely equal, so that the components can be considered as having equal life improvement costs.

iii) The technically feasible improvement of the lifetime of the components should be the same, so that the same optimal improvement of the lifetime can apply to the components.

3.6 Groups (X and Y)

Groups X and Y make up one of the most important parts of the proposed algorithm in the paper. For generating all the possible replacement scenarios, the present methodology defines two types of component groups. The components that belong to group X possess a fixed replacement schedule, whereas the components that belong to group Y are those which are rescheduled with the components of group X. An example consisting of three components with different wear lives is considered and presented in Table 2. The arrows (→) shown in Table 2 represent the rescheduling of the components of group Y to group X. The three components in the example \( (C_1, C_2, C_3) \), their lifetime periods \( (t_1, t_2, t_3) \), respectively, and 7 different possible replacement scenarios (S) are listed in Table 2.
Table 2: Possible replacement scenarios

<table>
<thead>
<tr>
<th>Replacement Scenario</th>
<th>Group (X) Components with fixed replacement schedule</th>
<th>Group (Y) Components which are rescheduled for replacement with the components in group X</th>
<th>Total cost $T_C$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$C_1$ $C_2$ $C_3$</td>
<td>$C_1$ $C_2$ $C_3$</td>
<td></td>
</tr>
<tr>
<td>$S_1$</td>
<td>$t_1$ $t_2$ $-$</td>
<td>$-$ $-$ $t_3$</td>
<td>$C_{S_1}$</td>
</tr>
<tr>
<td>$S_2$</td>
<td>$t_1$ $-$ $t_3$</td>
<td>$-$ $t_2$ $-$</td>
<td>$C_{S_2}$</td>
</tr>
<tr>
<td>$S_3$</td>
<td>$-$ $t_2$ $t_1$</td>
<td>$t_3$ $-$ $-$</td>
<td>$C_{S_3}$</td>
</tr>
<tr>
<td>$S_4$</td>
<td>$t_1$ $-$ $-$</td>
<td>$-$ $t_3$ $t_2$</td>
<td>$C_{S_4}$</td>
</tr>
<tr>
<td>$S_5$</td>
<td>$-$ $t_2$ $-$</td>
<td>$t_3$ $t_1$</td>
<td>$C_{S_5}$</td>
</tr>
<tr>
<td>$S_6$</td>
<td>$-$ $t_3$ $t_1$</td>
<td>$t_2$ $-$ $-$</td>
<td>$C_{S_6}$</td>
</tr>
<tr>
<td>$S_7$</td>
<td>$t_1$ $t_2$ $t_3$</td>
<td>$-$ $-$ $-$</td>
<td>$C_{S_7}$</td>
</tr>
</tbody>
</table>

**Frequency:** It is defined as the number of replacement occasions for any mill liner component over the planning horizon period $f = \frac{T_{ph}}{T}$.

**Frequency of parallel replacement occasions ($f_{add}$):** This is the number of occasions when two or more replacement occasions take place together over the planning horizon period. These parallel replacement occasions occur in two ways:

(i) *By default* ($f_{add}$): This happens when two or more components are replaced together, when the lifetime of one component is an integral multiple of the other component/components. For example, if a system has three components with a lifetime of 30, 45 and 60 time units, then over a planning horizon period of $T_{plh}$ = 150 time units, there will be three occasions (shown as rectangles in Figure 3) when two or more components are replaced together.

![Figure 3: Default occasions for joint replacement over a planning horizon period](image)

The Venn diagram approach has been adopted for determining the number of occasions when two or more components are replaced together for each maintenance scenario. Let us define the different sets $Z_i$, $Z_j$, $Z_k$ for the group of 3 components. The elements belonging to the set “$Z_i$” correspond to integral multiples of the lifetime of the $i^{th}$ component over the planning horizon period: $Z_i = \{t_1, 2t_1, ..., ft_i, t_i\}$, $Z_j = \{t_j, 2t_j, ..., ft_j, t_j\}$, $Z_k = \{t_k, 2t_k, ..., ft_k, t_k\}$ (see figure 4).

![Figure 4: Venn diagram representation of combined maintenance activities](image)
The calculation of $f'_{\text{def}}$ for a given scenario can be performed using a Venn diagram representation. In Figure 4, the shaded area represents the occasions when two or more replacements take place together and the number of such occasions is calculated using equation 2:

$$f'_{\text{def}} = \text{No. of elements of } \{Z_i \cap Z_{i+1}\} + \text{No. of elements of } \{Z_i \cap Z_j\}$$

where $Z_i$ represents the set of elements of the $i^{\text{th}}$ component, and $Z_{i+1}$ represents the set of elements of the $(i+1)^{\text{th}}$ component.

(ii) By rescheduling ($f'_{\text{res}}$): This happens when the components of group Y are replaced together with any component of group X after rescheduling. The calculation of the new frequency for the components belonging to group Y is achieved by using the proposed algorithm. The number of parallel replacement occasions $f'_{\text{res}}$ for the $(i+1)^{\text{th}}$ component which belongs to group Y but is rescheduled with a component that belongs to group X can be calculated with equation 3:

$$f'_{\text{res}} = \text{Original frequency} - \text{New frequency after rescheduling} = f_{\text{res}} - f_{\text{res}}\text{old}$$

where $f_{\text{res}}$ is the current replacement frequency over the planning horizon period without rescheduling, and where $f_{\text{res}}\text{old}$ represents the new replacement frequency when a component belonging to group Y is rescheduled with another component belonging to group X. The optimum replacement frequency is determined through the proposed algorithm explained in Section 3.8.

An absolute value is considered, as the rescheduling can be due to either premature replacement or replacement after the improvement in lifetime. The total number of such repeated occasions will be the sum of the number of occasions when the components of group Y are rescheduled with components of group X, and this sum is calculated using:

$$f_{\text{res}} = \sum_{i=1}^{n} f'_{\text{res}}$$

Therefore, the total number of parallel replacement occasions for a given scenario (S) is determined using relation 4:

$$f_{\text{old}} = f'_{\text{def}} + f'_{\text{res}}$$

3.7 LCC formulation for scenario Si ($C^S_i$)

A mathematical formulation of the life cycle cost (LCC) for a given scenario over a planning horizon period has been developed and is presented in this section. As described earlier (see Section 3.6), various cost elements have been calculated separately for group X and Y. The total cost (LCC) $C^S_i$ for the scenario Si will be calculated by $C^S_i = C^X_i + C^Y_i - C^\text{red}_i$, where $C^X_i$ and $C^Y_i$ are the total cost over the planning horizon period for the components that belong to group X and Y, respectively. Here $C^\text{red}_i$ represents the reduction in the production loss cost, including the labour cost, when two or more parallel replacement occasions take place after rescheduling of the components.

$$C^\text{red}_i = \sum_{k=1}^{n} f'_{\text{res}} \cdot C^\text{red}_k$$

$$C^X_i = \sum_{k=1}^{n} f'_{\text{def}} \cdot C^\text{def}_k + \sum_{k=1}^{n} f'_{\text{res}} \cdot (C^\text{def}_k + C^\text{lab}_k) \cdot (T^k + T^\text{prep})$$

$$C^Y_i = \sum_{k=1}^{n} f'_{\text{def}} \cdot C^\text{def}_k + \sum_{k=1}^{n} f'_{\text{res}} \cdot (C^\text{def}_k + C^\text{lab}_k) \cdot (T^k + T^\text{prep}) + \sum_{k=1}^{n} f'_{\text{res}} \cdot \Delta T^k \cdot C^\text{red}_k(t)$$

In equation 7, $\Delta T^k = (\text{New lifetime} - \text{Old lifetime})$ and $f'_{\text{res}}$ is the new frequency for the component “k” after the rescheduling of its replacement. The algorithm for the determination of the new frequency is given in the following section.

8
3.8 Algorithm for optimum maintenance scheduling and improvement in lifetime

Taking replacement decisions for different parts of the system concerns the task of the appropriate design of a maintenance schedule, and, in this connection, it is important to take into account interactions among all the cost components and technical considerations. The present approach further optimizes the solution and provides the optimal combination jointly with the optimum improvement in lifetime of the mill-liner components. A flow chart of the algorithm used in the present methodology is shown in Figure 6. To start with, the algorithmic model takes various inputs such as the component types with their different lifetime categories and improvement costs, the planning horizon period, the preparation time, the MTTF and the average lifetime period. The algorithm defines all the possible maintenance replacement scenarios. Then it takes the maximum achievable lifetime of each component as an input which is used to determine and eliminate all the unfeasible scenarios/all the impossible combinations. It takes all the types of cost inputs and determines the new lifetime of each component, if it is economically feasible. The economic feasibility of a component is determined by comparing the cost required for improvement in lifetime and the savings to be made through reduction of the downtime cost and the number of mill stoppages. The new lifetime cost of each component, the new LCC, is calculated by adding the downtime cost, including the labour cost, the total lining cost and the cost needed for life improvement. The scenario with the minimum LCC and the corresponding lifetime are recorded in a separate table. In the next iteration, the improvement in lifetime variable is increased by 1 time unit and the condition is checked as to whether the improvement is technically feasible. For each iteration of the improvement of the lifetime, the scenario with the lowest LCC and the corresponding lifetime are stored. The scenario with the lowest LCC among all the stored LCCs for each step of the improvement in lifetime will be selected as the optimum scenario and the corresponding lifetime provides the necessary life improvement for each component. Finally, the optimum replacement frequency is determined using the optimum lifetime of the components.

3.8.1 Elimination of unfeasible scenarios (N_f)

The unfeasible scenarios are determined and eliminated. The main reason for the elimination of the unfeasible scenarios is to reduce unnecessary mathematical computation when there are a higher number of components in the system; i.e. the number of scenarios will be 2^n-1. The algorithm of the present study considers the life improvement parameter as input in the model, which means that, at each level of improvement in lifetime, each possible maintenance scenario needs to be considered. Therefore, for the elimination of unfeasible scenarios, the proposed algorithm checks the technical feasibility of the improvement in lifetime. To elucidate this phenomenon, the example consisting of three components is considered which is discussed in Section 3.4. Let us consider a scenario where x_1 ∈ [2, 3], y_1 ∈ [1], which means that component 1 has to be rescheduled with component 2 or 3, as shown in Figure 5.

In Figure 5, the vertical dashed lines represent the scheduled stoppages and ΔI represents the technically feasible improvement in lifetime of component 1. The relative comparison of the wear lives is t_1 > t_2 > t_3. For the case t_1 + Δt_1 < t_2, that means that component 1 cannot be rescheduled with component 2, since, even after the improvement in lifetime, the replacement interval of component 1 is smaller than the replacement interval of component 2, and such
scenarios are considered as unfeasible maintenance scenarios, which are eliminated before all mathematical calculations to reduce the complexity and make the algorithm fast.

![Flow chart of algorithm used in the proposed model](image-url)

Figure 6: Flow chart of algorithm used in the proposed model
3.9 Maintenance overhaul consideration

Heavy-duty equipment also needs periodic maintenance overhauls. In the present case study, the grinding mill needs to stop for major maintenance overhauls for other maintenance activities in addition to mill liner replacement. Therefore, it is important to consider the overall maintenance, so that the replacement of different parts of the mill liners can also be synchronized with that. Hence, the maintenance overhaul can be considered as a component with a specific schedule which can be synchronized with the mill liner replacement schedule.

4. REAL LIFE EXAMPLE

A computer program has been developed based on the proposed algorithm and mathematical model, using an example consisting of 8 different lifetime categories from the mill considered in the present case study. The model input data have been obtained from the mining company and are presented in Table 3 and 4. The data for cost of mill liners at component level and investment needed for life improvement are classified and not shown in the paper. However, the data for the downtime cost and labor cost have been modified in order to maintain confidentiality as per the company’s regulations. The cost ratios among the various cost components have been kept the same as they were in the real data, in order to obtain the real trends in the outputs.

Table 3: Model inputs 1

<table>
<thead>
<tr>
<th>No.</th>
<th>Component description (m)</th>
<th>MTTF (Weeks)</th>
<th>MTTR (hours)</th>
<th>Crep (SEK)</th>
<th>ΔTmax (weeks)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>Lifter (Shell, -1), Outer, Inner lifter bar (Discharge, 1,1), Pebble grate plate (outer)</td>
<td>30</td>
<td>12</td>
<td>Classified</td>
<td>15</td>
</tr>
<tr>
<td>C2</td>
<td>Lifter (Shell, -5)</td>
<td>33</td>
<td>24</td>
<td>Classified</td>
<td>15</td>
</tr>
<tr>
<td>C3</td>
<td>Pebble grate plate (inner), Lifter bar (Shell, -5)</td>
<td>40</td>
<td>20</td>
<td>Classified</td>
<td>15</td>
</tr>
<tr>
<td>C4</td>
<td>Filling segment, feed end</td>
<td>45</td>
<td>20</td>
<td>Classified</td>
<td>15</td>
</tr>
<tr>
<td>C5</td>
<td>Shell plate and pebble extractor</td>
<td>60</td>
<td>16</td>
<td>Classified</td>
<td>15</td>
</tr>
<tr>
<td>C6</td>
<td>Inner and outer head plate, Inner lifter bar, feed end, Pebble discharger (inner)</td>
<td>72</td>
<td>16</td>
<td>Classified</td>
<td>5</td>
</tr>
<tr>
<td>C7</td>
<td>Outer lifter bar, filling segment, feed end, Pulp grate plate (inner), discharge end, Pebble discharger (outer)</td>
<td>90</td>
<td>24</td>
<td>Classified</td>
<td>5</td>
</tr>
<tr>
<td>C8</td>
<td>Centre ring, Trunnion plate, feed end, filling end discharge end</td>
<td>120</td>
<td>30</td>
<td>Classified</td>
<td>15</td>
</tr>
</tbody>
</table>

Table 4: Model inputs 2

4.1 Results and discussion

The model output/results obtained after performing exhaustive enumeration search and a demonstrator run are presented in Figure 7, 8 and 9. A decreasing trend for the production losses has been observed with improvement of the lifetime. Figure 7 shows the trends for all four cost components with improvement in lifetime. The lining and labour costs are very small in comparison with the production loss cost. The production losses decrease due to the reduction in the number of mill stoppages which occurs when the replacements of the different components are
combined through necessary improvement of the lifetime of the components. Moreover, the LCC also follows a decreasing trend due to the dominance of the production loss cost.

Figure 7: Costs vs improvement in lifetime

Figure 8 shows an irregular trend for the lining cost, which includes the component costs and the cost incurred due to improvement in lifetime. The irregular variation in the lining cost is caused by: (i) premature replacement, which leads to an increased replacement frequency over the planning horizon period, and (ii) improvement of the lifetime, which leads to increased component costs. In the present case, the production loss cost dominates the other cost components (see Figure 7) and the algorithm searches for the optimum solution based on the minimum LCC; therefore, a combination with a higher lining cost may also provide the optimal solution. Figure 9 shows the decreasing trend in the labour cost with improvement in lifetime. The labour cost is dependent on the use of man hours during the mill stoppage time. Therefore, the explanation for the trend of the labour cost curve is the same as that provided for the trend of the curve of the production loss cost.

When the model results were analyzed for a higher value of improvement in lifetime ($\Delta T_\text{c} > \Delta T_\text{p}$) for the same cost improvement function, the LCC values were analyzed. Figure 10 shows a decreasing trend in the LCC curve for a higher value of improvement in lifetime. This means that there is still scope for a further reduction in the LCC, if new mill liner technology is introduced.

Figure 8: Lining cost vs improvement in lifetime

Figure 9: Labour cost vs improvement in lifetime
Based on the model inputs presented in Tables 3, 4 & 5, the demonstrator has determined the optimum grouping of different parts of the mill liners and the optimal improvement in lifetimes for the liner components (represented by different geometric shapes in Figure 11).

In Figure 11, the vertical dashed lines show mill stoppages for the replacement of different mill liner components. The figure shows that the mill needs to stop on 11 occasions for the present scenario, whereas the optimum scenario suggests 3 stoppages after rescheduling and life improvement of the mill liner components. A comparison between the various cost parameters, such as the production loss cost, labour cost, liner cost and LCC, has been carried out. For this specific case, there is a reduction of 32% in the production loss cost due to a reduction in the number of mill stoppages and a 6% increment in the lining cost due to improvement in lifetime (see Figure 12). The variation in the different cost components due to the changes in the maintenance policy are shown in Figure 12 and represented by columns of different shades. The figure clearly shows a reduction in the LCC, production loss cost and labour cost, whereas an increment in the lining cost for the case of the optimum scenario is apparent.

### 4.2 Maintenance schedule options

The demonstrator also provides various maintenance schedule options, along with the improvement in lifetime at different levels of LCC. The main objective of considering various
maintenance schedule options is to synchronize the periodic maintenance overhaul and other maintenance activities with liner replacement activities. Figure 13 shows four different maintenance schedule options at different levels of LCC. The analysis shows that a slight increment in the LCC provides a better maintenance option which is technically more feasible concerning synchronization with the other maintenance activities performed on the grinding mill.

4.3 Sensitivity analysis for improvement in lifetime

A sensitivity analysis was carried out on the improvement in lifetime in order to validate the logical expectations of the proposed algorithm for hypothetical cost inputs. Figure 14 shows different cost curves, with the vertical dashed line showing the zone of optimum improvement in lifetime. In this figure, the lining cost (including the improvement cost) increases when the improvement in lifetime increases due to an increment in the lining cost, whereas the down time cost (including the labour cost) decreases due to a reduction in the number of mill stoppages. Therefore, the minima of all the LCC have been observed at the optimum improvement in lifetime. Figure 15 shows the same LCC curve as that presented in Figure 14, presented on a different scale for better visibility of the minima.
5. CONCLUSION

The results of the present research show that (i) a premature replacement, (ii) extending the replacement by improvement of the lifetime, or (iii) an optimal combination of both (i) and (ii) can significantly reduce the total life cycle cost of a system with different components of a pre-determined age. An optimum grouping for combined replacement and optimal improvement in lifetime of parts of mill liners can lead to a reduction in the production loss cost by up to 32% and a reduction in the LCC by 25% for this specific case study. The proposed optimization approach can be useful for the mill liner user in optimizing the LCC of mill liners, and it can be useful to the manufacturer of mill liner components in the design of new components to achieve an optimal maintenance strategy.

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7. REFERENCES


BIOGRAPHICAL SKETCH

Mr. Rajiv Dandotiya obtained his B. Tech and M. Tech in Industrial Engineering and Management at Indian Institute of Technology Kharagpur. He joined for PhD degree in the division of Operation and Maintenance engineering, Luleå University of Technology, Sweden. His main area of research is replacement decisions, maintenance and cost optimization. He is working on PhD project entitled “Decision support models for the Maintenance and Design of Mill liners” for a mining industry located in Sweden. The aim of the project is to develop decision support methodologies and tools for the mill liners of ore dressing plants, in order to facilitate and enhance the capability of making cost effective maintenance decisions on mill liners thereby increase the profit of the mill owners.

Jan Lundberg is professor of Machine Elements at Luleå University of Technology since the year 2000. During the years 1983-2000, his research concerned mainly about engineering design in the field of machine elements in industrial environments. During the years 2000-2006, his research concerned mainly about industrial design, ergonomic and related problems as cultural aspects of design and modern tools for effective industrial design in industrial environments. From 2006 and forward, his research is completely focused on maintenance issues like methods for measuring failure sources, how to do design out maintenance and how to design for easy maintenance.