A condition based maintenance approach for a rotary drum crop shear

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It all starts here ™

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Abstract

An alternative solution was proposed to the current replacement strategy employed to maintain the rotary drum crop shear at ArcelorMittal South Africa (AMSA) Vanderbijlpark Hot Strip Mill (HSM). Process and production characteristics were also considered in an attempt to optimise the expected crop-shear blades' lifetime.

Ineffective management of assets led to unpredictable performance and costly cessations in the production. Focus was placed on improving the reliability of the crop shear while mitigating the maintenance and operating costs, and thus striving towards a more efficient way to produce flat steel products at the HSM.

A universally applicable condition based maintenance (CBM) approach was considered as an alternative replacement strategy for the rotary drum crop shear at the HSM. The impact of current process and production methods was also analysed, identifying areas in the operation that lack sustainability. The execution of the proposed remedy strategies was monitored thoroughly to assess and validate its effective outcomes.

Replacements of crop shear cartridges yielded an extremely erratic trend; hence the unpredictability noticed early in the present study. The volatile performance often resulted in a reactive strategy to replace the cartridges. The proposed CBM approach was favoured for its ability in maximising the life duration of the crop-shear blades and eliminating the occurrence of breakdown replacements. The offsets of the crop shear cuts, speed configuration of the crop shear and the practice of making manual cuts, were indicated as factors contributing to the current poor performance of the crop shear. The modification of these components prolonged the life expectancy of the crop-shear blades.

The validated findings of the crop shear performance yielded the best-ever recorded performance at the HSM. A reduction in operating and maintenance costs of the crop shear, improved reliability of the crop shear's operation and thus also of the plant, are the major actual benefits initially anticipated. The topic of the study was considered to be a globally familiar application and, therefore, contributed to the body of knowledge in this field, from which other operators and maintenance consultants may benefit.

Keywords

Burr length

Condition based maintenance

Rotary drum crop shear

Standard operating procedure

Sustainability

List of abbreviations

AMSA	ArcelorMittal South Africa
CBM	Condition Based Maintenance
CCTV	Closed-loop Circuit Television
DMC	Digital Media Controller
HMD	Hot Metal Detector
HSM	Hot Strip Mill
KPI	Key Performance Indicator
OEM	Original Equipment Manufacturer
SOP	Standard Operating Procedure
V&V	Verification and Validation
YTD	Year to Date

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Chapter 1: Introduction

1.1. Problem statement and substantiation

I began working at ArcelorMittal South Africa (AMSA) Vanderbijlpark Works, in the Hot Strip Mill (HSM) department as a graduate in training in 2013. As part of HSM's reliability progress team I was particularly responsible for the area of the finishing mill. My responsibility was to focus on the reliability of the finishing mill with the aim to maximise the plant's availability.

I soon became aware that the reliability of the rotary drum crop shear yielded an erratic performance. This observed problem required an in-depth analysis to determine the causes and required appropriate remedies. It appeared to me that the unplanned downtime caused by failures of the crop shear blades was impacting the plant performance negatively. As a consequence, the production's output and financial losses could be severe.

I decided to present this problem as the topic for my Master's dissertation, which would enable me to build an in-depth research study around the mentioned problems as well as their root causes. My aim was to find possible remedies for the problems, and thereby benefit the company where I was employed.

The research started off by providing background information about the plant and the problems experienced with the rotary drum crop shear. At AMSA Vanderbijlpark Works, the HSM utilises a rotary drum crop shear to cut irregular front and rear end shapes off the flat steel transfer bar that enters the finishing mill in its process of manufacturing flat steel products.

My initial impression was that the crop shear failed to deliver consistent and predictable performance and was deemed unreliable by the production team. The resulting cobbles, plate shears, equipment damage and loss of production had become the norm, and were thus accepted as inevitable. In the process, the problem did cost AMSA unnecessary millions annually (ArcelorMittal South Africa, 2015). Therefore, I decided to set out to try and find a remedy for this situation and thus make a contribution, however small it may be, to help alleviate the financial set-backs that AMSA was enduring at that time.

I reasoned that the reoccurring failures that affected the plant's availability may be the result of crop shear blades that were maintained incorrectly and/or was subjected to incorrect operating conditions. Initially it was unclear to me whether these factors, singly or simultaneously caused the poor performance. I initially observed irregular wear rates between blade circulations; in other cases the blades were fractured when removed from the cartridge. The plant personnel who attempted to deal with this situation were left in the dark due to a lack of readily available information. At this stage, a lack of interest to monitor and record the performance of the crop-shear blades was prevalent.

An article in City Press confirmed that AMSA Vanderbijlpark Works had been struggling to turn around their losses over the previous few years (Klein, 2014). I realised that the crop shear losses only contributed a fraction of the total operating results of the company. However, every section of the company had to lower its costs in order to restore the profitability of the company as a whole.

After considering the actual problem, I found that the crop shear was bound to fail unexpectedly causing the plant to be inoperative, after which the shear had to be replaced on a breakdown basis and thus putting pressure on the maintenance teams. I postulated that such pressure could result in substandard quality maintenance work being performed. This, in turn, would feed back into a negative loop, resulting in further failures and downtime. I realised that the crop shear cartridges were actually being run to failure, seeing that there was no way to predict when these cartridges were on the point of failure. Thus my contention was that the ideal situation would be to run the crop shear to just before the point of failure, in order to acquire the maximum number of cuts from a crop shear cartridge, without the issues and cost of a failure.

While attending to a problem in the scrap area of the plant I noticed that the remaining burr on the cropped end differed from another in the vicinity set aside earlier the month for sampling purposes. It was brought to my attention that the burr tended to grow larger as the blades wore down. Therefore, I formulated the following supposition: “If it could be proven that there was a specific burr length with which an imminent blade failure could be predicted reliably, then we would be able to apply a condition based approach to the maintenance of the blade cartridges, instead of running them to failure. We would be able to replace the blades based on a measurable indication of their condition in terms of burr length.”

The supposition led to the development of my research aim and objectives, which are described in the following section.

1.2. Research aim and objectives

1.2.1. Aim

The aim of the research was to propose a validated condition based maintenance (CBM) approach for a rotary drum crop shear at AMSA Vanderbijlpark Works HSM.

1.2.2. Research objectives

To accomplish the aim of the study, the following objectives had to be met:

1. Using existing maintenance records, verify that we actually had as serious a problem as I foresaw and that we did indeed need a different maintenance approach.
2. Utilise the wealth of information, knowledge and practical experience of the HSM personnel to assist me in developing the proposed maintenance approach.
3. Find a relationship between the burr length on the crop offcuts and the crop shear blades' condition in order to specify a maximum allowable burr length at which the blade cartridge should be replaced.
4. Apply the specified targeted maximum allowable burr length in production, to validate the applicability of this parameter as an indicator for a CBM approach.
5. Propose a validated CBM approach for the crop shear.

1.3. Expected benefits

My expectation was that the results of this study should lead to reduced operating and maintenance costs of the crop shear, improved plant reliability and reliability of the crop shear operation. I also expected to contribute to the body of knowledge on the operation, maintenance and management of a crop shear as I considered many of the principles utilised in this research to be universally applicable.

1.4. Chapter division of dissertation

Chapter 1 – Introduction

The introduction enlightens the reader about the identified problem. The aim and objectives of the study is also discussed, broadly explaining the process followed throughout the study.

Chapter 2 – Literature review

This chapter provides information, derived from the literature and internal AMSA documents, which support the following requirements of the research:

- the application of a rotary drum crop shear;
- the functionality of the rotary drum crop shear at the HSM;
- the various maintenance approaches utilised in the industry for the maintenance of a rotary drum crop shear;
- the theory of CBM principles;
- the importance and application of verification and validation (V&V) in a research project;
- an evaluation of the current HSM's standard operating procedure (SOP) for the crop shear and a general outline of the information expected in a SOP;

- general outline of the structure and expected approach of questionnaires and interviews in a research-based project.

Chapter 3 – Experimental design

The experimental design is discussed, elaborating on the various quantitative and qualitative experimental components that were implemented. Consequently a layout is provided of the experimental components that were implemented.

1. *Experimental component 1:* An analysis of the history of the crop shear's performance at the HSM from the period 2008 to 2014.
2. *Experimental component 2:* A questionnaire distributed to gather input to enhance the research from the knowledgeable and experienced HSM personnel.
3. *Experimental component 3:* The measurement approach for the burr length aimed at finding a relationship between the burr length on the crop offcuts and the crop shear blades' condition, and thereby to specify a maximum allowable target for the burr length at which the crop-shear cartridge should be replaced. The process and production involvement was also analysed to introduce the best suited configuration that would prolong the life-cycle expectancy of the crop shear blades.
4. *Experimental component 4:* A Why-Why diagram was used to determine the problems surrounding the operating and maintaining of the crop shear at the HSM, prior to the revision of the SOP.
5. *Experimental component 5:* An interview held with an international maintenance expert to validate the proposed solution presented to the HSM on how the crop shear should be maintained and operated effectively.

The methods used to verify and validate the data are also discussed, before introducing the experimental results.

Chapter 4 – Experimental results

This chapter focuses on calculating and summarising the data obtained from the experimental approach discussed in Chapter 3. The immediate conclusions of the demonstrated findings are also drawn in this chapter.

Chapter 5 – Discussion and interpretation

Chapter 5 interprets the related findings that were deduced from the different experimental approaches and the previous chapters. The revised SOP, capturing the practical findings from the research study, are proposed and explained in this section.

Chapter 6 – Conclusion and recommendations

This chapter emphasises the conclusions of the research objectives, by discussing the inferences related directly to the research aim and objectives. Recommendations are also made as preparation measure when implementing the CBM approach at the HSM. Factors that are not included in the present research's scope, but help to develop the wealth of literature, are also recommended for purposes of future research.

Chapter 2: Literature review

The literature review discusses the application and functionality of the rotary drum crop shear. The focus will be on maintenance of the crop shear in light of previously utilised methodologies, similar type shear applications as well as the proposed condition based maintenance (CBM) approach. Finally, the tools will be discussed that was utilised throughout the study, for example verification and validation, in working towards a reliable and effective solution.

2.1. The application of a crop shear

A crop shear can be found in almost any Hot Strip Mill (HSM). The layout of a typical HSM is demonstrated in Figure 1 below. Various types of shears are presently available on the market, of which the rotary drum crop shear is seemingly the most common type (Mitsubishi-Hitachi Metals Machinery, Inc., 2014), illustrated in Figure 2 below.

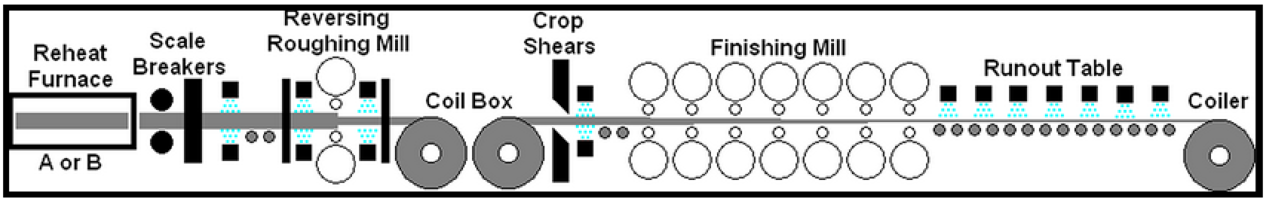

Figure 1: Typical layout of a HSM, (Evans, et al., 2012)

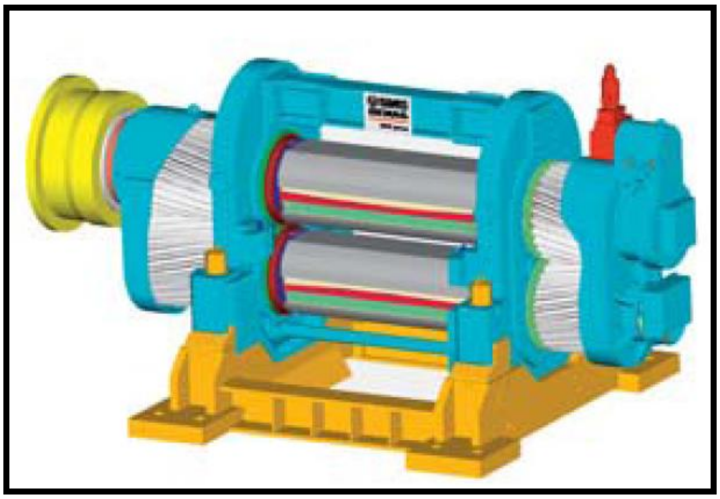

Figure 2: Rotary drum crop shear (Mitsubishi-Hitachi Metals Machinery, Inc., 2014)

Positioned on the entry side of the finishing stands, the crop shear is used to remove non-square, fishtail heads and rear ends on the transfer bar that is received from the roughing mill. Figure 3 below demonstrates the fishtail on the head end of the transfer bar before it is being cut.

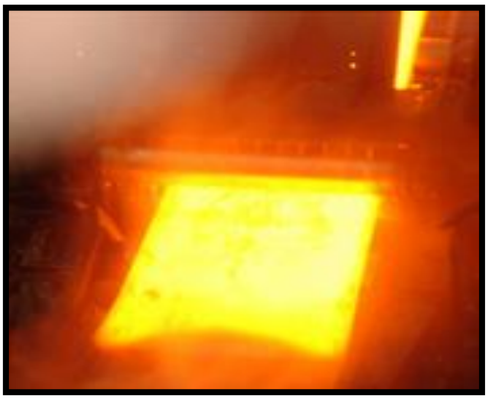

Figure 3: Head-end fish tail (Tata Steel, 2011)

Figure 4 below provides a picture of a typical hot metal transfer bar when it is received from the roughing mill before being cut; Figure 5 depicts the end result. The dark red coloured areas that can be seen in Figure 4 indicate the cold area on the transfer bar. Cutting through these cold areas should be avoided to make cutting through the metal easier, and to maximise the blades' life expectancy. The line drawn across the width of the transfer bar indicates the preferred cutting position on the bar.

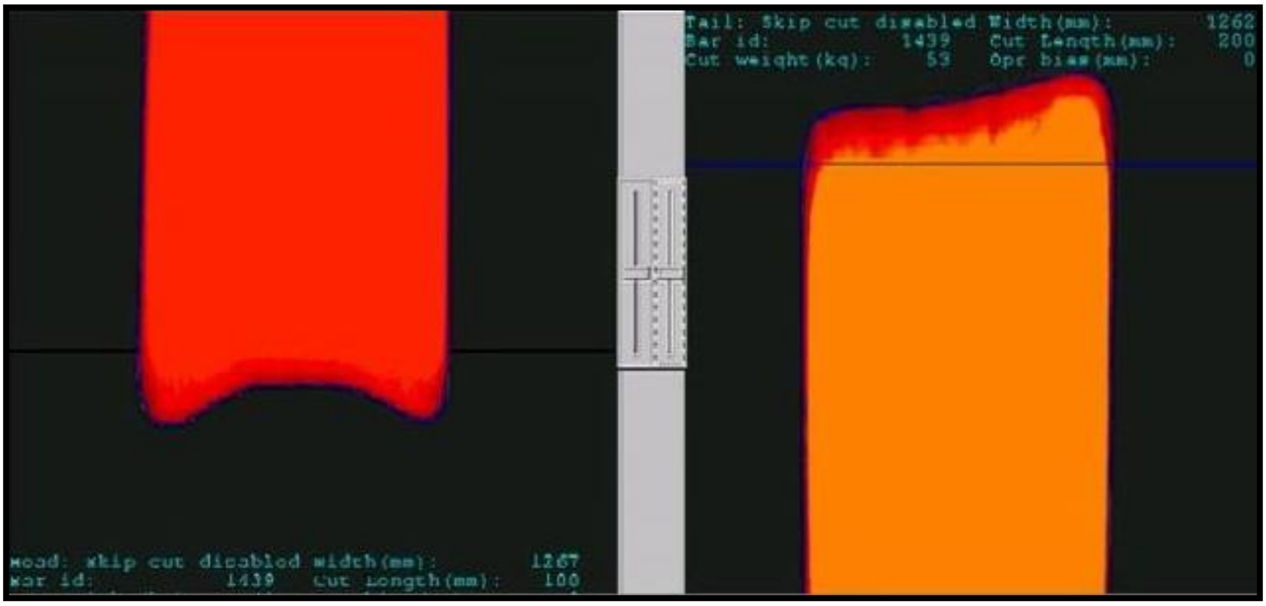

Figure 4: Transfer bar from the roughing mill. Left: Head end; Right: Tail end (Delta USA Inc., 2015)

Figure 5: Cropped transfer bar

The head end of the transfer bar is cut with a curved blade configuration, which benefits the load of the crop shear's drive as well as the earlier stands of the finishing mill (Iron and Steel Engineers Group, 1969). The curved edge enters the bite of the finishing mill more gradually with the middle portion of the head end (Charles, 1967). Continued movement into the bite allows the work rolls to grasp and reduce the work across the width of the front edge (Charles, 1967). Previously, a square cut was the norm, but it caused unnecessary shocks on the work roll and bearings due to the instant bite (Charles, 1967). The tail end is, however, still cut with a straight blade configuration. It is crucial to cut these head and tail ends to ensure stable threading conditions throughout the finishing mill and thereby avoid any cobbles from occurring (Mitsubishi-Hitachi Metals Machinery, Inc., 2014).

Cobbles tend to occur most frequently when producing thin gauge material that is difficult for operators to keep in the centre position throughout the mill (Eichert & Devorich, 2013). In unsuccessful cases the strip head collides with some or other object in the mill (Eichert & Devorich, 2013). Cobbles generated by the crop shear occur mainly because the shear is either incapable to cut the hot metal strip, or is unable to dispose of the cut-off piece effectively. Consequently, for the latter scenario, the cut-off drops onto the top of the metal strip, which results in operating disturbances. Figure 6 below illustrates a typical cobble. The photograph was initially taken by Tim Hadley at Bilston Steel Works in 1947.

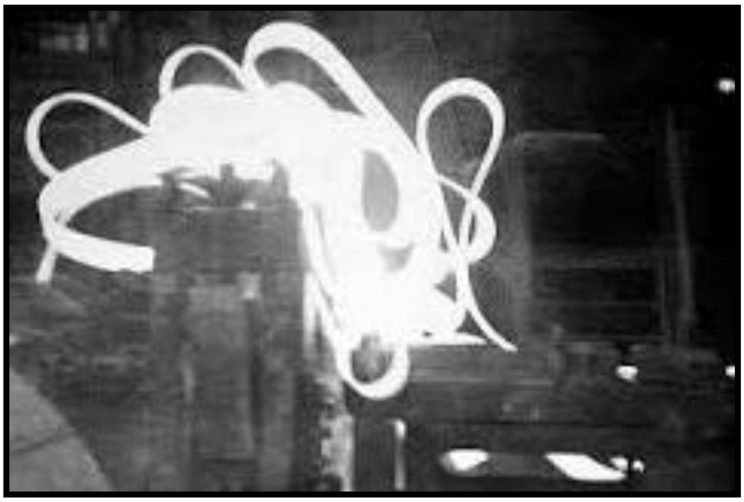

Figure 6: Cobble (Sharman, 2012)

The process, according to which the rotary drum crop shear cuts the head and tail end of the transfer bar, is demonstrated in Figure 7 below. The action of the drum and blade configuration is emphasised in the depiction, showing various characteristics of both the blades' assembly and the profile of the sheared crop piece. The offcuts are scrapped from the process and recycled later. Two types of crop shears are depicted in Figure 7. It should be noted that the present study focused on the conventional type of crop shear, of which the process is illustrated on the bottom half of Figure 7.

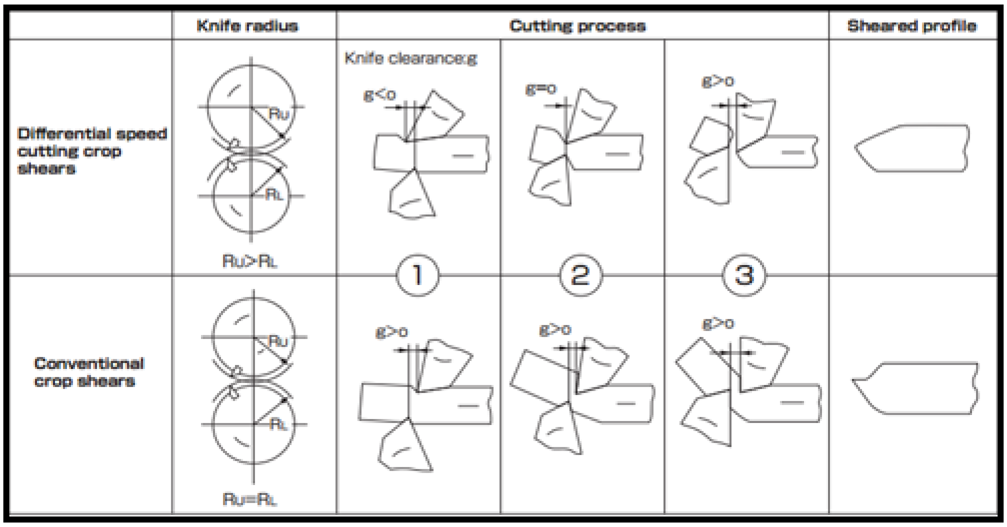

Figure 7: Rotary drum crop shear cutting process (Mitsubishi-Hitachi Metals Machinery, Inc., 2014)

Figure 8 below provides a picture of the typical crop-shear blades utilised in the steel manufacturing industry. The shear blades differ in shape, depending on the application.

Figure 8: Crop-shear blades (Knifemaker.com, 2015)

Referring to Figure 8 above, it is clear that the blade's face is curved. Previously the crop shear blades were only available in straight profiles, which meant that the head-and tail ends of the transfer bar were cut squarely across the width of the strip (Charles, 1967). The inventor Wesley Murray Charles found that the squarely cut strip caused undesirable shocks on both the roll configuration in the mill and both components' bearings. Thus he introduced the curved blade design, which allows for a more gradual strip entry into the mill (Charles, 1967).

2.2. The functionality of a rotary drum crop shear

The rotary drum crop shear at ArcelorMittal South Africa (AMSA) Vanderbijlpark HSM consists of a 281kW DC motor that powers two rotating drums within a cartridge, each with a set of shear blades fixed to the rotating drum. The AMSA operating unit has three crop-shear cartridges in stock. When one cartridge is in use, the second one is constantly available as a standby while the third cartridge is serviced. The crop shear blades are removed from the drum when needed to be replaced. Unfortunately the HSM crop-shear cartridges did not have advanced hydraulic blade clamping equipment. This meant that the replacement of the blades required extensive manpower and time. The blades are available in various shapes and sizes, of which the AMSA Vanderbijlpark HSM uses a curved blade for head-end cuts, and a straight profile blade for rear-end cuts.

The crop shear is capable of cutting hot transfer bars with a maximum thickness of 55 mm. The normal cropping operation is done automatically by means of either the KELK shear control system, or the hot metal detector (HMD). The KELK system uses a laser to determine the transfer bar's speed, in order to calculate the position of the cut (Ricciatti, 2009). The HMD system requires a pre-set crop length by the operator and the cut is initiated by the HMD that is located above the delay table (Roberts, 1983). Both of these automatic systems consider the speed of the transfer bar when determining the cut position on this bar. When needed, operators are able to intervene and override the mentioned systems. The operators are, therefore, able to adjust the crop shear's speed and the cutting length in situations where the automatic systems are unable to do so effectively, or operators have to perform manual cuts. This is ideal to ensure that the peripheral speed of the shear blades is equivalent to the speed of the transfer bar, which ultimately depends on the speed of the delay table.

The author of *Hot Rolling of Steel* (Roberts, 1983) created the idea that these process-control characteristics are common across the HSM plants globally. Unfortunately the researcher could find no guideline to help optimise the application of these controls according to specific production conditions.

2.3. Shear-blade maintenance practices

There is limited literature of value on the results of verified and validated maintenance approaches for crop shear blades. This stresses the need for such a study to at least narrow the gap of literature available on these types of industrial applications. In the present study's literature review two sources were analysed and critically reviewed. Both of these sources elaborate on considered attempts to describe how crop shear blades should be maintained.

Firstly, Robert Kotynski, in his article (Kotynski, 2001), proposed a number of guidelines that may be considered to improve the performance of high-production shear blades. Kotynski did not particularly focus on the maintenance aspects of a crop-shear application, but rather on a more general approach to various shear-blade applications in the industry. The proposed actions can be summarised into the points that are expounded below.

1. **Know the requirements and limitations of the equipment**
   Kotynski emphasises the importance of a good understanding of the equipment that is used. Kotynski makes a valid point in also mentioning the importance of understanding the original equipment manufacturer's (OEM) specifications keeping in mind the equipment's capabilities as well as the recommended maintenance requirements and to adhere to these guidelines (Kotynski, 2001).

2. **Execution of inspections and data capturing**
   Kotynski suggests that frequent inspections should be conducted on the equipment and the findings documented for future references (Kotynski, 2001). The equipment, which according to Kotynski should be inspected, is only mentioned with regard to a high level and thus, insufficient detail. Kotynski does not elaborate on a preferred procedure describing how the inspection should be done. Emphasis is also placed on the importance of considering the global perspective of the equipment at hand.

3. **Review documentation**

   After inspection has been done and the data captured, Kotynski explains the necessity to review the captured data and to conclude on the condition of the equipment (Kotynski, 2001). The life-cycle prediction of the equipment can be improved and be reacted on possible abnormal discrepancies, and thus supporting a preventive method to maintain the equipment (Kotynski, 2001).

4. **Blade installation**

   Satisfactory results cannot be expected if the equipment has been installed incorrectly in the first place. The clearances specified by the OEM are important when aiming to avoid unnecessary wear and unexpected failures (Kotynski, 2001).

5. **Maintaining the correct blade clearance**

   The blade clearances and accuracy of both the installation and maintenance should be ensured for optimal shear-blade usage and to avoid unplanned downtime (Kotynski, 2001).

6. **Isolate and level the machine**

   An improved life span can be expected when ensuring that the equipment is level and free from vibrations (Kotynski, 2001).

7. **Conducting maintenance according to a plan**

   A specific type of shear equipment or shear application was not mentioned in Kotynski's discussion. Thus, the critical components that, according to Kotynski, should be maintained properly may not be applicable to all shear applications (Kotynski, 2001). Kotynski suggests paying close attention to the mechanical drivetrain, lubrication requirements and pneumatic systems (Kotynski, 2001). The researcher of the present study found that the application of the HSM on which the study focuses does not have all the mentioned equipment. The information that Kotynski has shared is the type that can be expected from the specifications of the OEM.

8. **Rectify unideal operating conditions as soon as possible**

   When the equipment shows signs of degradation in wear, lack of basic conditions and damages, it is replaced immediately or corrected. This is done to ensure a safe working environment, avoid unnecessary damage and to save costs (Kotynski, 2001).

Although Kotynski's article focuses on a relatively general approach that can be expect from that particular study, he did make some valid points that contributed to the success of the present study. The next book section from *ASM Speciality Handbook: Tool Materials* (Davis, 1995) focuses on choosing the best type of shear-blade material for a specific shear application. Davis provides a detailed approach on how the life-cycles of shear blades were monitored when determining the wear rates between blades of different material specifications in various shear applications.

Davis focuses on shearing practices in general for hot and cold rolling operations in the steel-making industry. Although published in a specialised handbook, the author was unable to provide a detailed analysis of the findings on the discussed topics. This is due to the lack of data in the literature covering specific applications (Davis, 1995). Davis recommends that the following three factors should be considered when selecting a blade-material specification for a hot rolling application (Davis, 1995):

1. the thickness of the material to be cut;
2. the temperature of the material to be cut;
3. the type of equipment used to cut the steel as well as the condition of these equipment.

In order to evaluate the performance of the blades, the number of cuts made was monitored between blade replacements. This practice seems to be the most common means of monitoring shear blades' performance in the industry. However, it is not primarily employed as a preventative means to predict when the blades should be replaced (Davis, 1995). Other means of measuring performance are as follows (Davis, 1995):

1. steel tonnage produced between blade replacements;
2. duration between blade replacements;
3. cumulative wear of the blades established by measuring the blade itself and calculating the abrasive wear that has occurred.

The first two points are a quantitative means of measuring the shear blades' performance as related to the production throughput. Time-based replacements are not as effective when daily production rates differ. Therefore, the first point mentioned above seems the better option as it is directly related to actual throughput. Measuring the actual abrasive wear that has occurred on the shear blades is a much more effective means of determining the wear rate on these blades. Figure 9 below, provides an illustration of a rotary drum crop shear blade, indicating the OEM dimensions as well as the scrap dimensions of the blade. As the blade usage increases, the blades' wear increases accordingly. Although this method may seem very effective, it may also be unpractical in many cases, seeing that it is not always possible to measure the shear blades while in operation. This even applies to cases where the crop shear is not operational but in position on plant, and it may be difficult to measure the shear blades.

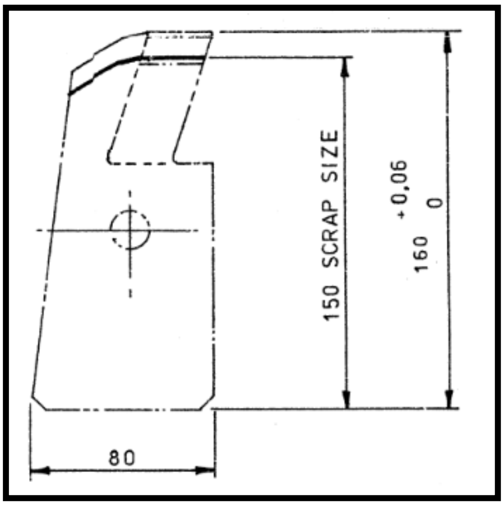

Figure 9: Influence of wear and grinding on blades

Results from different shearing applications cannot be compared with each other (Davis, 1995). The author also mentioned cases where a similar shear application is used. Under exactly the same operating conditions results may differ between blades that are replaced (Davis, 1995). The following graph demonstrated in Figure 10 illustrates these different results:

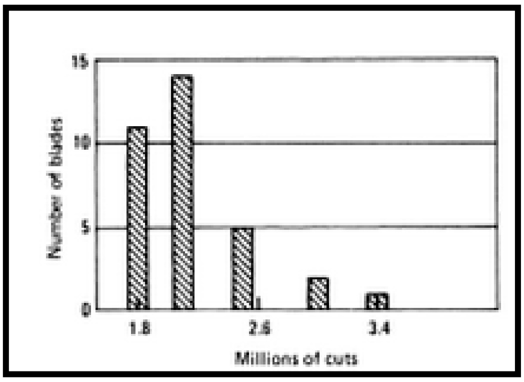

Figure 10: Blade usage vs. number of cuts under similar operating conditions, (Davis, 1995)

The researcher used 33 blades that were identical in comparison and installed in the same operating conditions. After this process, the result of the blades' performance led to the conclusion that, in certain cases, 3.4 million cuts could have been delivered by one blade, whereas other cases required 11 blades to accomplish only 1.8 million cuts (Davis, 1995). Davis, however, does not specify the conditions under which the blade replacements were done in the study from which the graph is generated. Two alternatives should be considered. Either the blades were replaced due to the fact that they had failed, or the blades were replaced as a preventative measure. If the blades had failed and thus needed to be replaced, it can be deduced from the graph that the shear blades' life-span between replacement cycles is inconsistent and unpredictable. On the other hand, the shear blades may have been replaced as preventative measures. For example, if the shear blades were replaced during every shut down, no matter what its condition were, the graph depicts an inefficient method to manage and utilise assets. In the opinion of the researcher, this is the case in many present industrial applications that may turn out to have high costs. This view is supported by Davis, who commented on the means in which most high production mills maintain their shearing operations. The discussion emphasises how shear blades are replaced on a fixed frequency, without even inspecting the condition of the blades before replacing it (Davis, 1995).

The literature that was investigated did not focus specifically on the rotary drum crop shear application, and in some cases more detail would be recommended. However, the researcher did gain relevant information from the review. This entails, for example, a better understanding of the factors involved when referring to shear blade usage and methods that already are applied to measure such usage. The measurements were, however, only finalised after the shear blades were replaced. Measurements could not be applied while the blades were in its operating position thus, unable to enforce a CBM strategy that could improve on the use of equipment by predicting the best replacement times.

2.4. Condition based maintenance

The proposed maintenance approach to improve current crop-shear maintenance practices is based on the CBM approach. Therefore the focus will be on a better understanding of the technicalities involved in applying the CBM approach and to review the benefits provided from the approach.

2.4.1. Definition of CBM

CBM is a preventative means of doing maintenance by predicting when an *unideal* situation may arise, and thus allowing people to act accordingly (Van Puyvelde & Pintelon, 2006). Defined in a more practical sense, CBM is maintenance based on the collecting, processing and transmitting of data from a condition survey (Olanrewaju & Abdul-Aziz, 2014). The predictive techniques employed to collect data or to measure a system's parameters may differ from very simple to relatively complicated. A few techniques are listed below (Van Puyvelde & Pintelon, 2006):

1. Checklist
2. Visual inspections
3. Vibration monitoring
4. Tribology
5. Thermography
6. Electrical testing

According to (Van Puyvelde & Pintelon, 2006) the simplest means of measuring relevant parameters may lead to a successful implementation of the CBM strategy. Numerous industrial applications may require relatively technically complex methodologies to conduct CBM in order to deliver effective results. Nevertheless, simple methodologies such as measuring the crop offcuts' burr length with a digimatic caliper may be just as effective.

2.4.2. Benefits of CBM

According to Olanrewaju & Abdul-Aziz (2014), the following advantages have been noted when applying the CBM technique:

1. The execution is optimised by only doing maintenance when it is really required.
2. It provides an early means of detecting failures in order to improve on the equipment's availability and thereby save on unnecessary expenditures and downtime.
3. It continuously improves and develops the managing of work flow.
4. This provides a means of easy access to assets' information for those who need such information, for example, maintenance and engineering departments.
5. It integrates various disciplines.
6. It enables organisations to utilise data on assets to improve expenditures and throughput.
7. It makes tracking, history keeping and statistics of assets simpler, where previously it would typically not be trended.
8. Data that is generated can be captured and stored along with strategic knowledge for future reference and may benefit those who are new to the environment in their decision-making.

The CBM technique holds various advantages when implemented. Another aspect was not mentioned by Olanrewaju & Abdul-Aziz (2014), but in the researcher's opinion provides a significant advantage to any similar scenario. This is the fact that once, the above-mentioned advantages have been noticed, the maintenance team gets a sense of being successful in managing their equipment, which makes their work more effective as well. The advantages mentioned above rectify many of the shortages noticed in this particular study. Therefore, it was evident that the CBM technique would be an effective implementation to improve the current conditions regarding the rotary drum crop shear.

2.4.3. The CBM approach in a similar-shear application

An approach similar to the one proposed for the HSM was not found in the literature review on CBM, even though the crop shear's operation is similar throughout the steel industries globally. The contribution of *Kotynski* and *Davis* discussed in the literature review was, however, considered to develop the proposed CBM approach and adapt it for the HSM. The proposed adapted CBM approach will, therefore, be a distinctive contribution to the body of knowledge in literature and should be universally applicable to other operations involving rotary drum crop shears.

2.5. Verification and validation

The principles of verification and validation (V&V) are discussed in this section. The application of V&V has been considered for the present study. Therefore, it is first necessary to get a clear understanding of the two concepts and its application.

2.5.1. Definition of the concepts

Various definitions for V&V exist, depending on the application. The absence of a consensual definition raises uncertainties, which leads to the improper use and a misunderstanding of V&V (Debbabi, et al., 2010).

Avner Engel, in *Verification, Validation and Testing of Engineered Systems: Assessing UML/SysML Design Models* (Engel, 2010) defines the term ‘verification’ as “the process of evaluating a system or component, to determine whether the products of a given development phase satisfy the conditions imposed at the start of that phase.” (Engel, 2010). Engel continued to mention that the term ‘validation’ is a method utilised to assess a system and determine whether it fulfils the expectations of its stakeholders (Engel, 2010). It should be noted that these definitions do not only apply to a system.

Myer Kutz, in *Mechanical Engineers’ Handbook, Manufacturing and Management* (Kutz, 2015) explains the definition of validation in terms of a product/process. It is the stage where the team revises a finished design and ensures that both the engineering needs are met and that the product/process performs as it was intended to initially (Kutz, 2015). Ensuring that the product/process meets the requirements of the customer requires of the team to validate the product or process properly (Kutz, 2015).

The researcher concurs that these definitions and applications of V&V can be confused easily. The vague description of keywords in the definitions discussed above, provide a multi-disciplinary definition that may lead to confusion. Therefore, it is necessary to establish the application of V&V in the present study, in order to explain the manner in which V&V was intended to be used for this study. The following criteria reflect the intended usage:

- *Verification* refers to the measures implemented, which ensure that the experiments are executed successfully.
- *Validation* refers to the measures implemented, which ensure that the experiments successfully fulfil their purpose in the study.

2.5.2. The importance of the technique

To demonstrate the importance of V&V, the researcher reviewed an article: "Understanding the importance of Data Verification and Validation" (Effective Intelligence, 2014). Although the article focused primarily on data management, it evidently provides the essence of V&V.

Large decisions in the industry, for example, are often made by using figures and other forms of data, all but making the success of the company dependent on the figures used when driving processes or strategies. The quality of the data utilised in such decision making is, therefore, essential when decisions can cause large repercussions (Effective Intelligence, 2014). Poor data lead to poor decisions, which could end up being extremely costly. V&V of data/processes are two significant quality tools available to ensure accurate and logical data (Effective Intelligence, 2014). Seeing that effective V&V allows for quality data, the frequency at which data is captured, updated and verified, will have a significant impact on the outcome of any study, investigation or strategy. (Effective Intelligence, 2014).

Even though the mentioned article focused specifically on the V&V of data, the review has benefitted the present study. This is, firstly, because the article's experimental investigation in Chapter 3 focused on capturing and analysing the data. Secondly, the general emphasis was to ensure the research approach was done properly in order for the study's outcome on validation to benefit the literature domain. The article did, however, fail to provide a thorough overview of simple tools or methodologies that could be implemented when attempting to verify the captured and analysed data, and thereby validate the study as a whole.

2.5.3. Verification and validation tools/techniques

V&V can be executed by using various tools. Verification can, for example, be done by proofreading methods and double-entry checks (Effective Intelligence, 2014). Proofreading methods recommend that two sets of work are available and data is checked manually by comparing the work with an original document (InfoCheckPoint, 2012). Double-entry check requires two of the same inputs in order to verify the differences between the inputs. The latter method may, however, be more time consuming when done manually without the available software to assist the process (InfoCheckPoint, 2012). When validating data, information is assessed to ensure that it is logical and transfer meaning. The following techniques of data validation are available (mrmwood, 2011):

1. Presence check: Ensuring that an input has been given.
2. Range check: Ensuring data received is within a preferred expected parameter.
3. Format check: Ensuring that data follows an expected pattern.

4. Length check: Examining the inputs given, and thereby ensure that all the inputs does, for example, have the same amount of digits or characters.
5. List or lookup check: Ensuring that the retrieved data correlates with a list of expected data.
6. Cross-field check: Validating by setting up two similar input points, thus making sure that the input is identical.
7. Digit check: Ensure that no digits are missing.

The V&V techniques mentioned thus far, primarily focused on verifying and validating data. By applying some of these techniques when measuring the crop-end burrs and analysing the data, the researcher could ensure that good-quality data was captured and analysed. Although these techniques function well in data-related scenarios, they are not applicable to the general approach of the present study. It was, therefore, necessary to implement other methods to ensure a quality approach throughout the study.

In order to verify and validate the need for the present study as well as the proposed solution to address the stated research problem, a different approach was needed. By evaluating AMSA's works procedure and allowing the staff the opportunity to complete a questionnaire, the mutual problems and requirements for relevant personnel could be determined and verified along with the study's aim and objectives. At a later stage, the formal interview meant that the proposed approach could be validated by ascertaining how effective the study was.

2.6. Evaluation of AMSA's works procedure

The standard operating procedure (SOP) used by the HSM personnel to operate and maintain the crop shear was critically evaluated and compared to the expected standard from educational as well as practical literature. Both webGURU (webGURU, n.d.) and EPA (United States Environmental Protection Agency, 2015) have a similar purpose and methodology regarding why and how an effective SOP can be written.

The HSM utilise three internal documents, as listed below, to demonstrate how the crop shear works and should be operated:

1. WWNPWA0000043 ver. 01, Title: *Correct Proc: Use of the Crop Shear*
2. HSMFMCM000003 ver. 00, Title: *Crop Shear*
3. HSMFMWPC00004 ver. 00, Title: *Section C: Zeroing the Crop Shear*

The first document mentioned, WWNPWA0000043, contains the current works procedure that all the relevant HSM personnel were supposed to consult for guidance when operating the crop shear. The two-page document only discusses the zeroing procedure for the crop shear hot metal detector (HMD) system.

The second listed document, HSMFMCM000003, contains training material and was only referred to when educating personnel on the functioning of the equipment. Only three pages of the ten-page document contained meaningful information about the crop-shear operation. The document discusses the operation of the crop shear itself as well as the crop shear's side guides.

HSMFMWPC000004 is very similar to the previous document, as it is also a training document. The document contains a highly detailed and effective procedure on how the crop shear should be calibrated.

The general format and process used in the HSM's SOP, conforms to the guidelines found in the literature. The procedure used by the HSM, although similar in the way it explains the scope and definitions, differs from the more detailed approach recommended in the literature. The inadequacies of the HSM SOP in comparison with the guideline the EPA suggests, (United States Environmental Protection Agency, 2015) are as follows:

1. Data and records management: The HSM did not include a section in the SOP to ensure that data is captured accurately and stored for future purposes. Making sure that reports, calculations and relevant data are analysed and captured is critical for an effective technical SOP (United States Environmental Protection Agency, 2015)
2. Health and safety: In most cases, and found in these instances, the HSM did not include a section that elaborates on safety and health. In cases where the HSM have considered the factors regarding safety and health, it is generally found in other, more safety-specific type documents or in an attachment to the SOP (United States Environmental Protection Agency, 2015).
3. Interferences: It is recommended to ensure that the personnel are aware of the specific factors that may impact the effectiveness of the task (United States Environmental Protection Agency, 2015).
4. Cautions: The SOP should include elements of inspection and communication that can determine events, which may lead to equipment damage or unexpected results, and then set out the procedure by which to address the situation effectively (United States Environmental Protection Agency, 2015).

Focussing on these inadequacies when revising the HSM's SOP, should clearly improve the quality of the SOP and have the potential to make a difference in the plant. However, it will require management to enforce staff's adherence to the SOP. EPA emphasises that the best written SOP will fail if not adhered to (United States Environmental Protection Agency, 2015). WebGURU recommends that the roles and responsibilities of each individual in the team are included in the SOP (webGURU, n.d.). This allows management to enforce the needed inadequacies of the SOP effectively – with the responsible individual in mind.

2.7. Questionnaire

The following recommendations are made by Gould (2011) on how to approach a questionnaire and actualise its general purpose, considering the types of questions, and the administering of the questionnaire to the relevant participants:

1. Keep the questionnaire as short as possible.
2. Target the sample sensibly by considering the correct participants and addressing the request to them.
3. Include a sense of confidentiality by assuring participants of anonymity in their response.
4. Give participants something in return as a means of gratuity for their time spent completing the questionnaire.
5. Language should remain comprehensive, yet simple.
6. Keep the balance between formal-and informal style.
7. The interest of the participant should be captured in the early stages of responding to questions, therefore, the questions should be interesting.
8. Avoid leading and open-ended questions.
9. Use simple rating scales and clear options.
10. Ensure that questions are presented in a logical order.
11. Do as many trials necessary prior to the distribution to ensure that the questionnaire complies with the above-mentioned guidelines.
12. When distributing the questionnaire make sure that it is properly introduced to the participant. The following aspects should be available on the document:
    a. The purpose of the questionnaire.
    b. Comprehensive details of contact information.
    c. The importance of the questionnaire and the topic at hand to all parties involved.
    d. The expected time needed to complete the questionnaire.
    e. The purpose of the results from the questionnaire explained.
    f. The final date or opportunity for the participants to reply.

2.8. Formal interview

A formal interview was planned with an expert in the steel industry to validate the proposed CBM solution. The fundamentals of a formal interview are discussed in this section.

The most common type is a job interview where one or more persons query, consult, or assess another person (Dictionary.com, 2010). There is, however, other means of conducting interviews, which is akin to formal meeting namely, an informational interview. This entails a two-way conversation with an expert in the field with the intention to gather information on a specific topic (Brandeis University, 2010). The structures of the different type of interviews are very similar.

2.8.1. Interview structure

Before the interview takes place the interviewer beforehand should know what information needs to be collected from the session (Information Services and Technology, 2009)

According to Lloyd (Information Services and Technology, 2009) a typical formal interview can last either 30 or 60 minutes and can be structured accordingly:

- 30 minute-interview structure:
  - Opening the session: 3 minutes
  - Providing information: 5-10 minutes
  - Gathering information: 15-20 minutes
  - Closing the session: 2 minutes
- 60 minute-interview structure:
  - Opening the session: 5 minutes
  - Providing information: 10-20 minutes
  - Gathering information: 30-40 minutes
  - Closing the session: 5 minutes

Throughout the process the interviewer should control the proceedings and guide the conversation according to the so called “20/80” rule. The interviewer should contribute approximately 20% to the conversation and thus, approximately 80% is expected from the interviewee (Information Services and Technology, 2009). Except for the opening and closing of sessions, the topic of discussion should be linked specifically to the purpose of the interview.

Chapter 3: Experimental design

This chapter accentuates the aim and design of the experiments that was conducted; elaborating on the experimental components as well as on the verified and validated methods that were implemented.

3.1. Experimental aim

The aim of the experimental design was to plan and thereafter execute the required quantitative and qualitative experimental approaches thus, delivering validated results that support the objectives mentioned in Chapter 1, paragraph 1.2.2.

3.2. Experimental design

The qualitative and quantitative approach consisted of certain experimental components as illustrated in Figure 11 below. Firstly, to have verified the need for this research topic as accentuated in Paragraph 1.2.2, research objectives 1 and 2, an assessment was required to determine the real impact of the problem and to gain input from the Hot Strip Mill (HSM) personnel on the topic. A quantitative approach was considered to verify the effectiveness of the burr-length measurement as a primary means of evaluating the crop-shear blades' condition and the impact of process parameters. Frequent burr-length measurements were taken and analysed throughout the circulation period of each crop-shear cartridge. Thereafter a database was developed comprising the measurements and process readings. The expected results would conclude that this means of evaluating condition of the crop-shear blade was feasible, seeing that the researcher noticed a progressive increase in burr length throughout the life-span of the blades.

Furthermore, a Why-Why diagram was developed to consider the problems related with the operation and maintenance of the crop shear in order to make the proposed solution more effective before having it validated by an international maintenance expert.

For each of these experimental components, a verification and validation (V&V) element was designed in Paragraph 3.2.6 and 3.2.7. The layout of these is depicted in Figure 11 below.

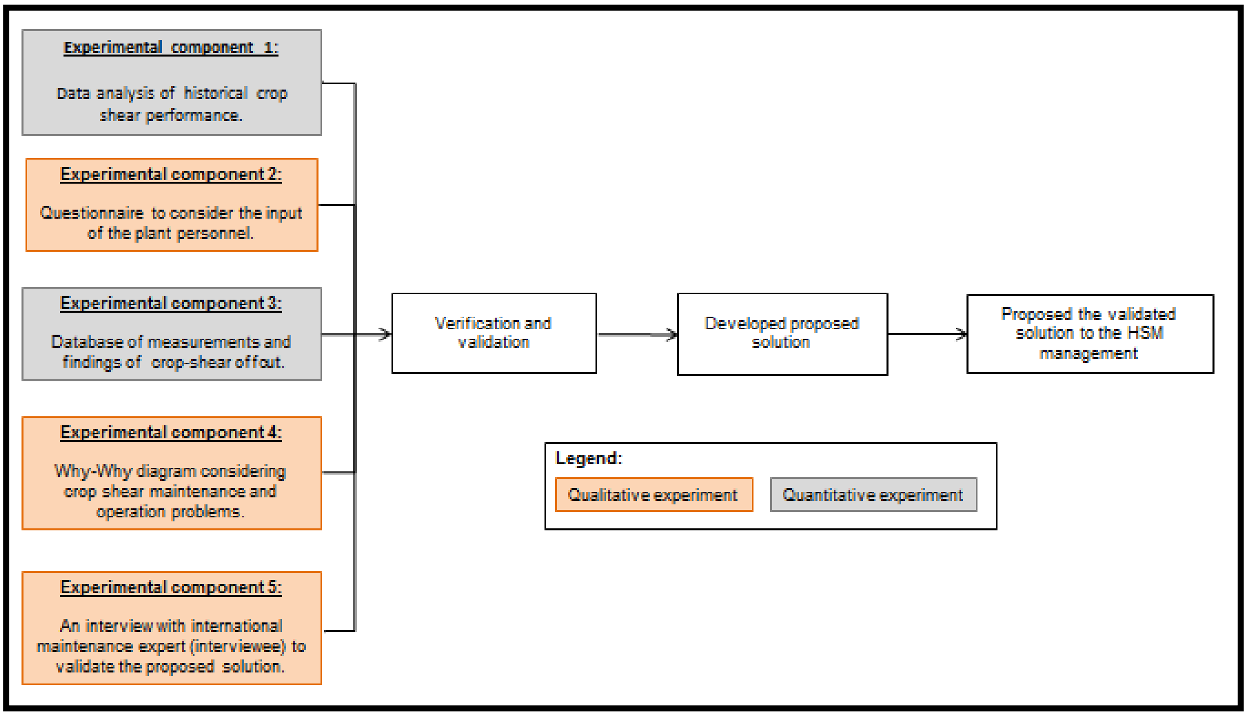

Figure 11: Layout of experimental design

Executing the above-mentioned experimental components helped determine the HSM personnel's influence on the life-cycle of the crop-shear blades and eventually lead to the proposal of a validated remedial solution for the HSM management to consider.

A standard operating procedure (SOP) revision of the proposal was needed to assist the HSM personnel with a procedure on adapting the maintenance and operating practices to ensure optimal life-cycle usage extracted from the crop shear blades. The proposal focused on maximising the plant's availability and improving mechanical yield. The revised SOP is discussed in Chapter 5.

The approach illustrated in Figure 11 is discussed below, expounding each individual experimental component in further detail.

3.2.1. Experimental component 1: Historical performance of the crop shear's data analysis

The crop shear's performance was previously monitored by means of two key performance indicators (KPIs):

- Unplanned downtime, a unit that measures the unproductive time of the plant in case of malfunctions that cause the plant to stop production temporarily, in order to rectify the problem.
- Trending the number of cuts that the crop-shear cartridge has made since its replacement.

To support research objective 1, this data was collected for an empirical analysis of the crop shear's recent failing performance. The following constraints were shown by the data:

1. Unplanned downtime could only be captured as far back as 2008.
2. Trending the number of cuts before replacing each crop-shear cartridge only began in 2009.

Considering the constraints indicated by the empirical data, the data was verified and validated once results were generated. Refer to Paragraph 3.2.6.1 and 3.2.7.1 for the verification and validation of Experimental component 1 in particular.

The data was analysed and discussed as presented in Table 1 below (and is provided in Appendix A):

Table 1: Raw data description of crop-shear utilisation

Description of data	Data unit	Frequency of data
Crop shear's unplanned downtime	Percent	Per failure/occurrence of failures
Crop-shear cartridge's cut count	Number of cuts	Per crop-shear cartridge's replacement

The data was analysed and illustrated in the utilisation graphs. These graphs had to be planned and designed to give a clear illustration of the following characteristics from the obtained data:

1. The usage in terms of unplanned downtime and number of cuts.
2. The time/period related to the unplanned downtime and data regarding the number of cuts.
3. Possible correlation between the unplanned downtime and data of the number of cuts.
4. The average characteristics of the unplanned downtime and number-of-cuts data.

The results of these graphs are reported in Chapter 4.

3.2.2. Experimental component 2: Questionnaire

In support of research objective 1.2, to gain the beneficial information regarding HSM personnel's knowledge and practical experience, a questionnaire was distributed. The aim was to verify by qualitative means whether a different maintenance approach was needed. The input from the HSM personnel was also considered in Experimental component 3 to maximise the effectiveness of the proposed condition based maintenance (CBM) approach.

A list was drawn up of 31 suitable candidates, based on their knowledge and experience of the crop shear at the HSM, to complete the questionnaire successfully. The questionnaire was only distributed to the selected 31 candidates, to ensure an effective outcome and avoid potentially invalid responses.

Prior to developing the questionnaire effectively, insight from Chapter 2 on questionnaires (see Paragraph 2.7) was utilised. The following characteristics were considered:

1. A gift was offered as gratuity after completing the questionnaire to encourage the HSM personnel to participate in the questionnaire.
2. The estimated time required for detailed completion was 20 minutes. This included 10 working days to complete the questions, before the questionnaire would be collected. The participants were also reminded two days before the set collection date.
3. The participants' identity was to remain anonymous when completing the questionnaire. Hence, no questions were included that could possibly expose their personal details.
4. A simple, yet formal, language style was considered as well as image illustration, to allow for an interesting and reader-friendly questionnaire.
5. The questionnaire consisted of yes-no questions as well as multiple-choice questions, designed to simplify the completing and evaluation of the questionnaire.
6. The questions were arranged in such a manner that the participants were not coerced into giving a specific answer.
7. Deviating from the question style used earlier, towards the end of the questionnaire a question was included asking extensive feedback on relevant information the participant wished to share regarding the crop-shear topic.

Appendix B provides an example of the questionnaire distributed to all the participants.

A hardcopy of the questionnaire was distributed to the sample group, made up of ArcelorMittal South Africa (AMSA) HSM personnel who work with the crop shear. These employees consisted of the following participants:

- 4 x Maintenance managers
- 4 x Mechanical-and electrical engineers
- 3 x Process engineers
- 3 x Technologists and technicians
- 3 x Production specialists
- 1 x Senior production operator
- 5 x Maintenance-and production superintendents
- 8 x Artisans

Once the deadline was approached and the questionnaires had to be collected, the following approach was used when analysing the received feedback:

1. The summary sheet for feedback, attached to each of the questionnaire, was completed and transfers of the results verified through double checking of the data, to avoid miscalculations when processing the data.
2. After the summary sheets were completed, each sheet was verified along with the criteria set out in Paragraph 3.2.7.2. The summary sheets that did not comply with the verification criteria were rejected, assumed unreliable and no longer considered for further data analysing.
3. The details of the approved summary sheets were then transferred to a master evaluation sheet. Again the data processing was verified by double checking to avoid oversight and miscalculations.
4. The master evaluation sheet (provided in Appendix C), was designed to accumulate and count the results for each question within the questionnaire. The feedback from the summary sheets on specific questions was collected in one line on the master evaluation sheet, after which the distribution of the results was calculated. For example, if 20 questionnaires were still considered after the verification process, question 1 would have 20 responses. The distribution of the various options was calculated in terms of percentages. For example, if 10 participants agreed with question 1, then it was recorded that 50% of the participants agreed with the statement made in question 1.
5. Pie charts were also developed for the results of each question, in order to depict the outcomes graphically, making it easier to understand and synthesise the results.
6. The master evaluation sheet also contained the qualitative text data, where participants could share a response on aspects that were not covered in the questionnaire.

The results of the questionnaire are reported in Chapter 4.

Along with data on the crop shear’s usage, the two experiments were designed to ultimately determine the history of its usage and whether the inputs of the sample group correlates with these results on the usage history. Conclusions were drawn from the results of these two experimental approaches, in order to find a means of assisting the personnel in improving the crop shear’s usage – hence measurement experiments regarding its burr-length.

The correlation of results between the two experiments and its outcome is investigated and discussed in Chapter 5.

3.2.3. Experimental component 3: Burr-length measurement

Research objective 3 in chapter 1 reads as follows: "Find a relationship between the burr length on the crop offcuts and the crop shear blades' condition in order to specify a maximum allowable burr length at which the blade cartridge should be replaced." Consequently frequent measurements were taken in the period February 2014 – August 2015, ensuring for a large enough empirical data base of findings, which could later be analysed.

The layout of Experimental component 3 is demonstrated in Figure 12 below, which provides a concise view of the layout and means of execution of the burr-length measurement experiment.

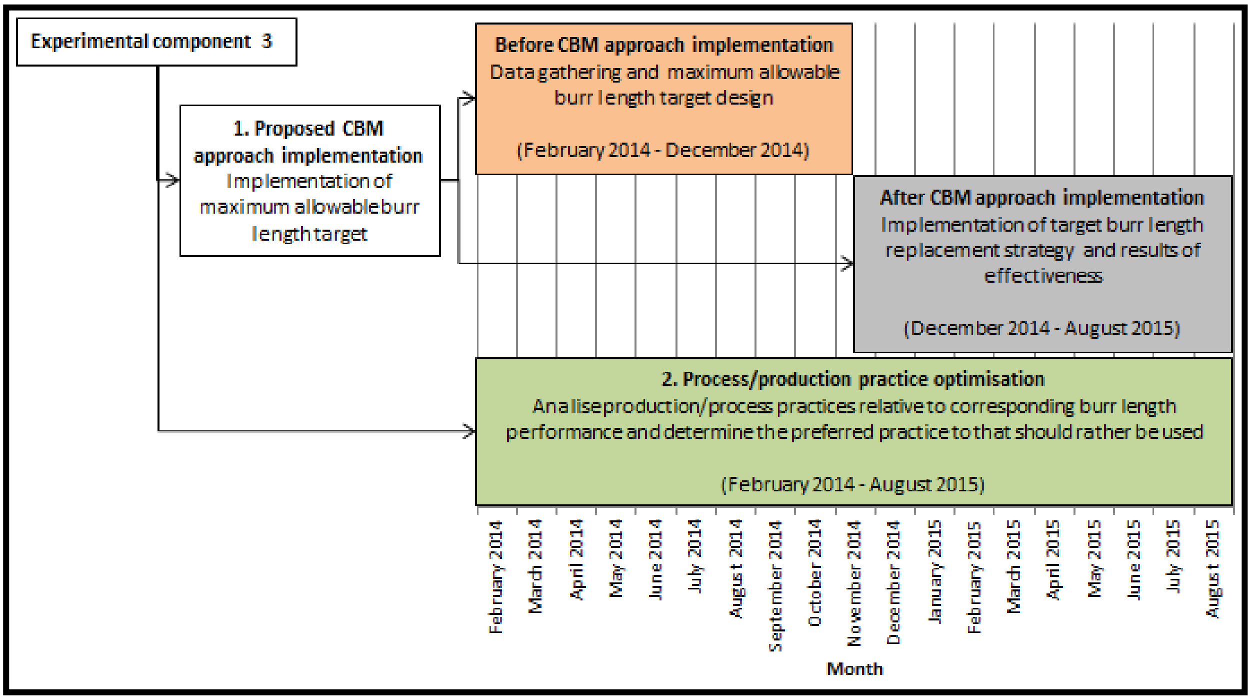

Figure 12: Experimental component 3 – layout and timeline

The layout and timeline of the burr-length measurement experiment is Illustrated in Figure 12 above. The experiment consisted of 2 sub-components, namely: proposed implementation of the CBM approach and optimisation of the process/production practice.

The first sub-component, referred to as the proposed implementation of the CBM approach, focused on designing the maximum allowable burr-length target for the CBM approach, assess the approach and then determine its effectiveness. The aim was to maximise the life expectancy of the crop-shear blades while avoiding production problems. Before implementing the CBM approach, as illustrated in Figure 12 above, a database was first developed from which a maximum allowable burr-length target could be determined that signals when a crop-shear cartridge should be replaced. After implementing the CBM approach in December 2014, the crop shear was maintained accordingly until August 2015. The resulting effectiveness of the proposed CBM approach was then determined for the duration of the experiment, throughout the period of August 2015.

The second sub-component focused on the practices of the crop shear process and production teams. Throughout the period for Experimental component 3, from February 2014 – August 2015, the related factors were analysed to determine the preferred practice of the crop shear's operation. The aim was to improve the performance of the crop shear and also maintain a burr length that is as short as possible. The current practice was then revised in accordance with the findings and introduced to the revised SOP in August 2015.

Below is a list of the factors related to the process and production of the crop shear:

1. Determining the effect of the cut values for head and tail offset on both the reliability and mechanical yield of the crop shear.
2. Determining whether there is a noticeable difference when operating the crop shear on automatic and manual mode.
3. Determining whether a difference in performance was noticed when comparing the different crop-shear cartridges used in succession.
4. Determining whether the lead-and lag speed of the delay table relative to the crop shear had an effect on the crop shear's offcut burr length.

Table 2: Execution of Experimental component 3.1

<table>
<tr><th colspan="2">Execution of Experimental component 3.1.</th></tr>
<tr><th>Description</th><th>Experimental approach</th></tr>
<tr><td>Before CBM approach implementation</td><td>A database was compiled from frequent burr-length measurements taken whilst still utilising the crop shear according to the current 22 000 cut-replacement strategy. After analysing the data, the proposed targeted maximum allowable burr length was determined at which the crop-shear cartridge should be replaced for the proposed CBM approach. The following factors had to be considered regarding the circulation of each cartridge in this section:

• The crop offcut burr length relative to the production problems encountered. These problems included the following:
  ○ pulled through head and tail offcuts due to blunt blades;
  ○ fractured blades;
  ○ stalling of the crop shear when attempting to cut the transfer bar;
• The crop offcut burr length relative to the cumulative number of cuts made.
• The cumulative number of cuts and the crop offcut burr length relative to the condition of the blades after replacement.

The proposed maximum allowable burr-length target was then implemented towards the end of this section. From then onwards, the cartridge would be replaced according to the burr length, and no longer based on the number of cuts.</td></tr>
<tr><td>After CBM approach implementation</td><td>After introducing the CBM approach, the following measures were taken to determine the effectiveness of the new approach:

• The actual crop offcut burr length had to be examined frequently to ensure that the crop shear cartridges are replaced according to the preferred burr length that was determined earlier.
• To assess the effectiveness of the new CBM methodology, the cumulative number of cuts made and the unplanned downtime for 2015 was monitored to compare with the historic data.

Towards the end of this section the data was analysed to determine the feasibility of the proposed CBM approach.</td></tr>
</table>

The measurements were conducted with an Absolute Digimatic Caliper or better known as a vernier, illustrated in Figure 13 below:

Figure 13: Absolute digimatic caliper (Vernier)

As illustrated below in Figure 14, a measuring tape was also used to ascertain the width of the transfer bar.

Figure 14: Measuring tape (Stanley, 2015)

The following Figures 15, 16 and 17 below practically demonstrates how the vernier and measuring tape was utilised during the task of measuring the offcut burr length, as well as the transfer bar's thickness and width respectively.

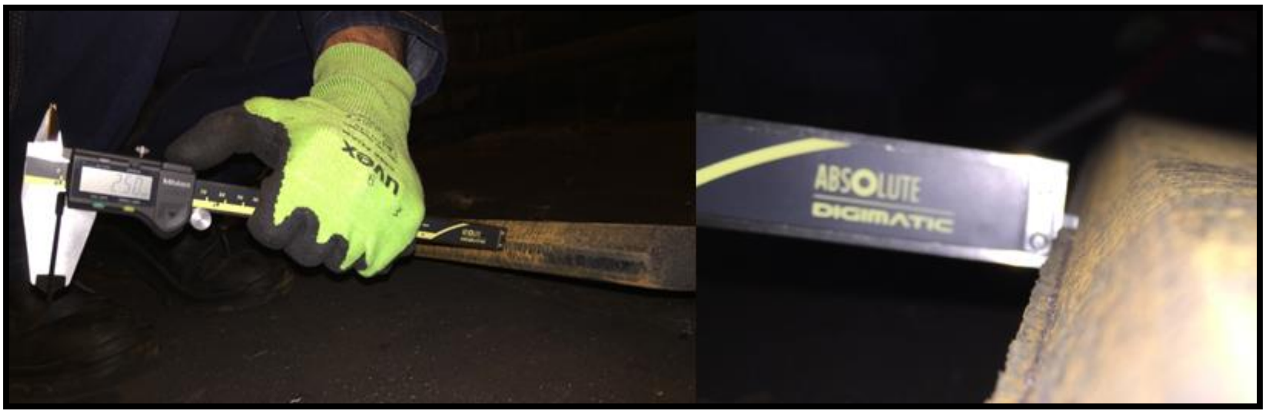

Figure 15: Photo demonstrating the measurement of the burr length with vernier

Figure 16: Photo demonstrating the measurement of the transfer bar's thickness with vernier

Figure 17: Photo demonstrating the measurement of the transfer bar's width with measuring tape

Due to the layout of the plant it was not possible to match a particular offcut with the data captured during a normal production operation. In cases where the offcut were required to match the data, intervention was needed. The means of production had to be altered in order to obtain the specific offcut directly after the crop shear had cut the transfer bar. Seeing that the researcher was unable to reach a specific offcut without influencing normal production, the following assumptions were made:

- When cutting transfer bars of any material classification, which falls within the accepted temperature parameters, the dimensional characteristics of the offcut's burr are similar.
- When cutting transfer bars of materials classified within the same product family, the dimensional characteristics of the offcut's burr are similar.

The width and thickness of the offcuts were, therefore, intentionally measured as these characteristics could reveal the product family from which the offcuts originated.

The following approach was used when measuring and reporting the findings:

1. The crop ends' burr length was measured on a regular basis, measuring at least three different crop ends for data-verification purposes.
2. Prior to each measuring session, the recommended procedure for the zeroing preparation of the vernier (as noted in paragraph 3.2.6.3) had to be completed.
3. With each measuring session the measurement report had to be completed to capture the data. (The template of the measurement report is provided in Appendix D.) Included in the measurement report are the dimensional characteristics of the offcuts that had to be measured and recorded accordingly.
4. Other readings were also obtained from the crop shear's control historian. This historian captures the user input and processes setup data during production, stores it and makes it available for future reference. These readings include the following:
    a. cut position's offset values;
    b. the lead and lag speed of the crop shear relative to the delay table;
    c. the number of automatic cuts made;
    d. the number of manual cuts made;
    e. the mechanical yield observed;
5. The measurement findings and readings were then captured on a master burr-length result sheet. (Appendix E presents the obtained results.)
6. The verification procedure to ensure the data was accurately distributed and processed was then completed. The verification procedure that was utilised is discussed in Paragraph 3.2.6.3

The results and findings were analysed and illustrated graphically to simplify the means at which results were compared and discussed. These results are reported in Chapter 4.

3.2.4. Experimental component 4: Utilisation of Why-Why problem-solving technique

With the aim to assist research objective 3 the tool was utilised to capture findings made during the experimental phase. For example, during the experimental study it was found that the operator accidentally attempted to cut a transfer bar that was double the thickness which the crop shear is capable of cutting. These occurrences were introduced to the Why-Why diagram and investigated further to determine the root cause, in order to introduce the required preventative actions to the revised works procedure.

FreeMind, a free, downloadable mind-mapping software package, productive in generating categorised ideas, was used to develop the Why-Why diagram (FreeMind, 2014). The detailed Why-Why diagram is provided in Appendix F.

3.2.5. Experimental component 5: Interview

An interview of one hour was held with an international experienced maintenance expert with the intension to validate the proposed solution. The interview agenda in terms of the information dealt with and the questions that needed answers is provided by Appendix G. The interviewee was given the opportunity to deliver an input through recommendations before the final revision of the newly revised works procedure was published. The results of the interview are reported in Chapter 4.

3.2.6. Verification of experimental data

For each of the experiments a verification strategy was implemented to ensure accurate and thus reliable data. This section focuses on the design of verification strategies for each of the different experiments that were conducted.

3.2.6.1. Verification design: Historical performance of the crop shear – data analysis

The raw data collected for analysis purposes, discussed in Table 1 consisted of only two variables obtained directly from the source without the need for further analysis deemed useful. Due to the simplicity of the captured data and minimal user interference, the double-checking technique was sufficient to verify the accuracy of the data processing.

3.2.6.2. Verification design: Questionnaire

Before distribution, the questionnaire was proofread, making sure that the questions were interpreted correctly, as well as for verification purposes. While the researcher developed the questionnaire a colleague did the proofreading.

After the questionnaires were distributed, completed and collected, the feedback was summarised. To ensure that the data was managed correctly and preventing any miscalculations from affecting the data, the following measures were followed:

1. A questionnaire-specific summary sheet was attached to each of the questionnaires on collection. The data could then effectively be summarised on the summary sheet minimising any confusions or miscalculations that could have taken place. The data was thereafter imported to a master evaluation sheet where the information of the entire sample group was collected and analysed.
2. Whenever data had to be imported from one document source to another, the data was double checked to ensure that it was processed correctly.

3.2.6.3. Verification design: Burr-length measurement experiment

Both the measuring equipment and the means of data processing had to be verified for this experimental component in order to ensure reliable data.

Firstly, the equipment used to measure the characteristics of the transfer bar’s offcuts had to be verified before use. The following measures were followed to verify the equipment:

1. A certified vernier was compulsory for the experiment. As demonstrated in Figure 18 below, a certified vernier that was still in a good condition, along with the corresponding documents, was used to measure the burr length.

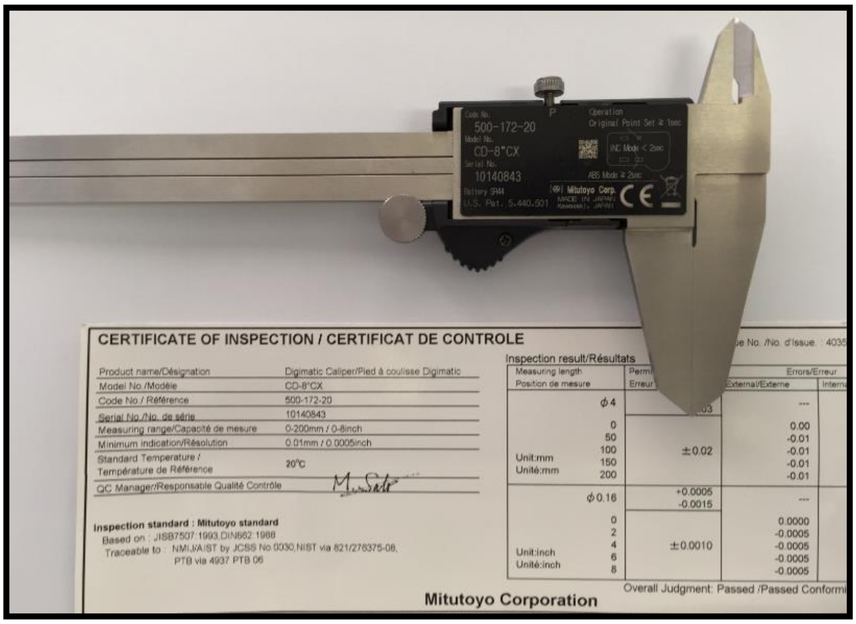

Figure 18: Illustration of vernier calibration certificate

2. Before each measurement session, the vernier was zeroed. The vernier had to be fully closed before the dimensional feedback was reset to a value 0.00 mm. Figure 19 below illustrates the zeroing practice visually for better interpretation.

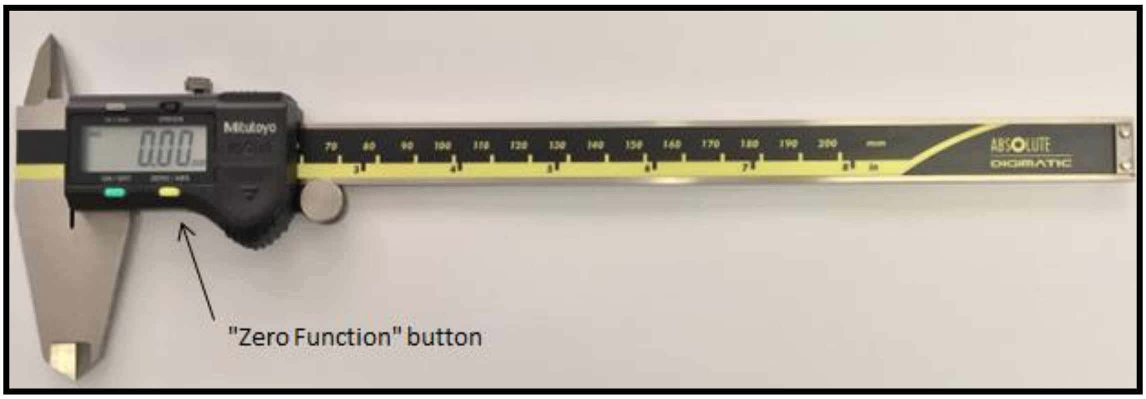

Figure 19: Zeroing of the vernier

3. A verification test-piece measuring 30mm was used prior each measuring session to conclude the accuracy of the vernier. This was done as a last means to verify the equipment, before measuring the burr length.

No verification measures were needed for the measuring tape due to the simplicity of the equipment.

After the vernier has been verified with the test-piece measurement, the crop ends could be measured. In developing the database for the measurements, a means of data verification was also needed to deliver accurate data. The following measures were implemented to verify the data:

1. At least three different crop-end pieces were measured at each measuring opportunity. The average between the various pieces could then be calculated for data-analysis purposes.
2. By using the measurement report for each cartridge, the data could be trended. In cases where the later measurement delivered results with a shorter burr length than an earlier measurement, the data would be flagged. The burr length for the later measurement would be re-measured to verify the results.
3. When exporting data from the measurement report to the master result sheet, the data was double checked to ensure that no miscalculations took place while processing the data.

3.2.6.4. Verification design: Why-Why diagram

After completing the Why-Why diagram, the HSM's Reliability Progress Manager verified and approved the document as an effective trouble-shooting solution for the crop shear and its operation.

3.2.6.5. Verification design: Interview

For verification purposes the interview was recorded. When needed to verify the notes and statements made in the interview, the recording allowed the benefit to revisit the particular discussion.

3.2.7. Validation of experimental data

3.2.7.1. Validation design: Historical performance of the crop shear – data analysis

The potential of the historical performance data to be used as platform to motivate the purpose of the present study and be an appropriate means of reference to compare the actual performance achieved from the experimental study was validated. The detailed approach considered should also have identified possible problem areas that could be focussed on further in the study.

3.2.7.2. Validation design: Questionnaire

To ensure that reliable data was obtained from the questionnaires, the participants' feedback had to be trustworthy. In order to validate the questionnaires' trustworthiness the researcher had to determine whether the participants did read the questions thoroughly before answering them. To enhance this process, two validation techniques were incorporated into the questionnaire.

Validation technique #1: The first question of the questionnaire gave the participant the opportunity to share his/her knowledge on the basics of the crop shear by means of a "Yes" or "No" answer. Questions 18 and 20 are very simple assessing the basic operation of the crop shear – knowledge that participants should have if they know what a crop shear is. If one of the following scenarios occurred, the feedback would be flagged as unreliable and the questionnaire, therefore, rejected:

- If Question 1 was answered "Yes", implying that the participant had a basic understanding of the crop shear, but Question 18 was answered "No" (since a "Yes" answer is expected if question 1 is answered "Yes").
- If Question 1 was answered "Yes", assuming a basic understanding of the crop shear, but Question 20 is answered "Yes" (since a "No" answer is expected if question 1 is answered "Yes").

Validation technique #2: In the same format as the other questions, question 25 was an instruction to refrain from answering a given option. If an option was answered nevertheless, the feedback would be flagged as unreliable and the questionnaire would therefore be rejected.

3.2.7.3. Validation design: Burr length measurement experiment

The potential of the burr-length measurement experiment being an effective tool in developing the proposed CBM approach was validated using the input of an international maintenance expert. The results are discussed in Paragraph 4.5.

Chapter 4: Experimental results

The results for each of the experimental components defined in Chapter 3 are discussed in the present chapter. To simplify the interpretation of the results the discussion and conclusions follows directly after stating the results.

4.1. Results: Data analysis of historical performance of the crop shear (Experimental component 1)

The researcher had to verify his initial workplace observations, which indicated the appearance of a serious and consistent lack of reliability of the crop shear at the Hot Strip Mill (HSM).

For this verification, performance data for the period 2008 – 2014 was analysed using two metrics, namely:

1. **Unplanned downtime:** Taken as an indication of a lack in reliability.
2. **Number of cuts:** Taken as an indication of the consistency in the performance of the crop-shear cartridges.

The data reflecting these findings can be referred to in Appendix A.

4.1.1. Crop shear unplanned downtime for the period 2008 – 2014

Figure 20 below illustrates the unplanned downtime that was recorded for the crop-shear split between three cause categories as recorded by the plant personnel. The cause categories are as follows:

- poor blade condition;
- mechanical and electrical equipment failures;
- process/production-related problems.

It was found that the crop shear’s unplanned downtime had averaged at 0.32% per year for the years 2008 – 2014.

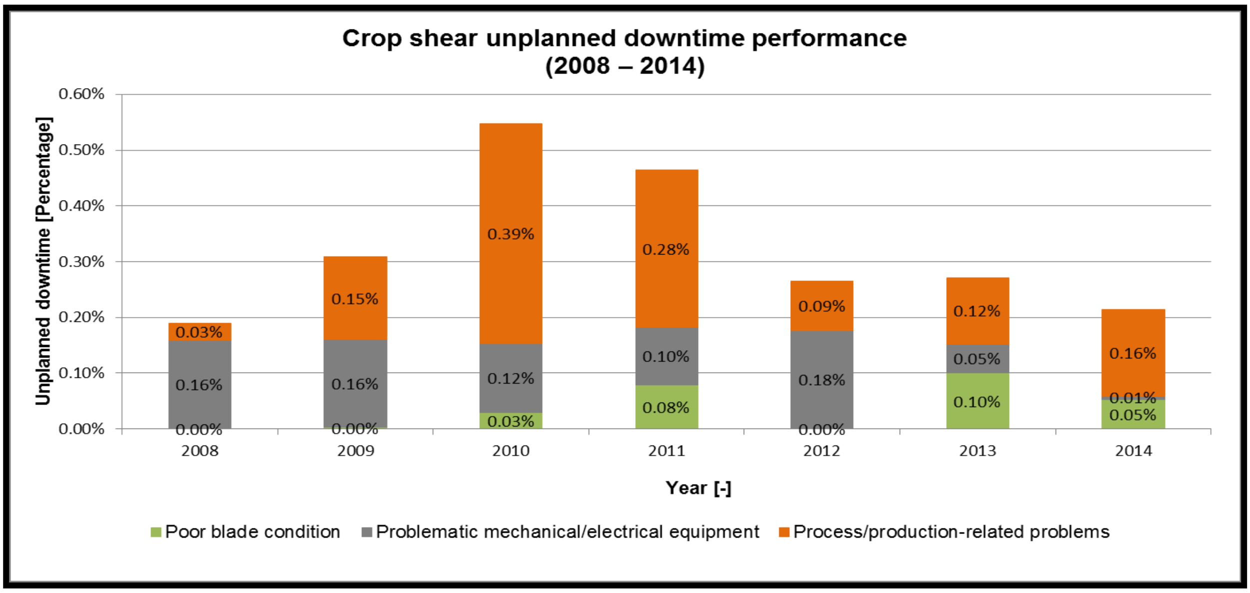

Figure 20: Crop-shear unplanned downtime performance 2008 – 2014

There was a noticeable increase in the unplanned downtime from the period 2008 to 2010. The crop shear's availability performance for 2010 was the worst ever recorded performance, indicating an unavailability of 0.55% for the year. A significant improvement of 52% was recorded when proceeding from 2011 to 2012. The unplanned downtime has remained more consistent from the period 2012 – 2014.

As represented in orange in the graph below (Figure 21), the unplanned downtime originating from process-/production-related problems improved by 0.19% from 2011 to 2012 after management simply enforced a better performance. According to the production specialist, the following implementations contributed to the improved performance (Williams, 2015):

1. A production specialist was appointed to coach the production operators and superintendents with the aim to improve the overall quality of production and reduce unplanned downtime.
2. Emphasis was also placed on the poor performance of mechanical yield and the production specialist was expected to ensure that crop-shear operators considered the proposal of improving the mechanical yield.
3. The largest problem contributing to the high process/production-related, unplanned downtime in 2011, was the occurrences where cropped tail-ends were pulled through. This resulted in cobbles when the transfer bars enter the finishing mill or plate shears if the tail-end got stuck in the descaler box. Closed-circuit television (CCTV) was then considered, and cameras were installed in the vicinity of the crop shear giving the operators the required vision, which was not possible from the operating room. This enabled the operators to see whether a tail-end has pulled through, giving them the

opportunity to act preventatively in avoiding a cobble or plate shear from occurring, and as a consequence, reducing the unplanned downtime as well.

Represented in grey in the graph below (Figure 21), another significant improvement of 71% in the year 2013 was the result of a reliability-improvement initiative the HSM implemented in the year 2011. According to the HSM plant manager the initiative was based on a methodology in which problematic equipment was listed on a reliability program. Thus the replacement of the equipment was planned with the aim to return the plant equipment back to its basic conditions and improve the reliability of the plant. The problematic equipment were those in need of replacement for the following reasons:

1. It was not/no longer effective to fulfil its purpose, and had to be replaced with other, more effective equipment.
2. It was in need of a service, due to age and a deteriorating condition, and was thus systematically rotated to have it reconditioned.

According to the finishing mill's reliability program the following actions were taken regarding the crop shear equipment:

1. The crop shear motor tachometer was replaced with an incremental encoder.
2. The crop shear spindle was replaced and a three-year replacement frequency was implemented.
3. The scrap-bucket trolleys were replaced and a one-year replacement frequency was implemented.
4. The crop-shear chute was replaced.
5. The crop-shear cartridges were placed on a three-year reconditioning frequency.

The production throughput was also considered when considering the improvement in the availability of the crop-shear equipment. *Mitchell* explains that, driven by throughput, the operation function of manufacturing plants provide limited opportunities for maintenance when an increase in production rate is experienced (Mitchell, 2015). *Mitchell* concluded in mentioning that increasing the throughput and making a system work harder to increase the throughput will increase maintenance costs and may result in limited availability of the asset (Mitchell, 2015). There is thus less time available for planned maintenance, which may lead to an increase in unplanned stoppages.

The following Figure 21 below comparatively illustrates the HSM unplanned downtime and the annual tonnage of hot-rolled coils produced by the HSM for the years 2008 to 2014. The grey column data in the graph demonstrates the unplanned downtime percentage. The overlaying orange scatter plot points out the correlation between the unplanned downtime and the production throughput.

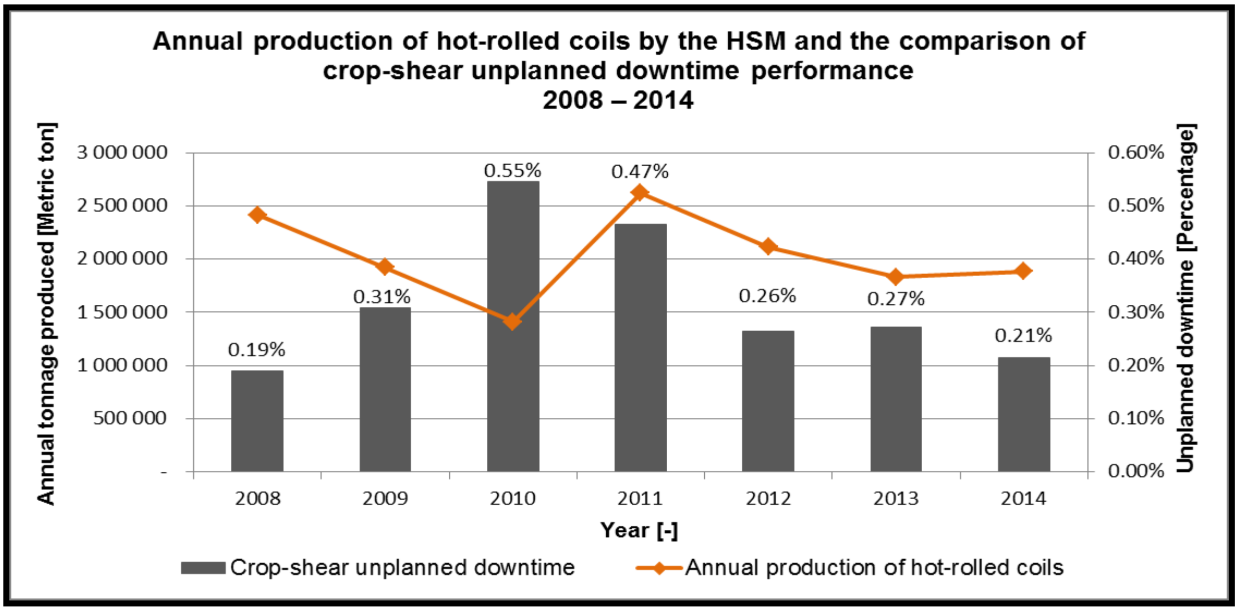

Figure 21: Annual production of hot-rolled coils by the HSM and the comparison of crop-shear unplanned downtime performance 2008 – 2014

A contradiction to the statement made by *Mitchell* is noticed in Figure 21 above when analysing the performance of the period 2008 to 2010. An increase in unplanned downtime is noticed along with a decrease in production. Although more time was available for inspections and maintenance, the crop shear's unplanned downtime performance kept worsening from 2008 to 2010. This finding questions the effectiveness of the process and production practices.

For the period 2012 – 2014, an improvement in crop shear's availability is noticed along with a decrease in production in Figure 21 above but, the result of the initiative to improve reliability implemented in 2011 also has to be considered. The result of this initiative and the enforcement of improved operating practices contributed considerably to the recorded improvement in the crop shear's performance from the year 2011 onwards.

4.1.2. Performance in number of cuts

The number of cuts produced per cartridge circulation is illustrated in Figure 22 below. By using all three cartridges a total of 65 cartridge replacements occurred between the period 2009 and 2014, with a total average of 15 887 cuts per circulation.

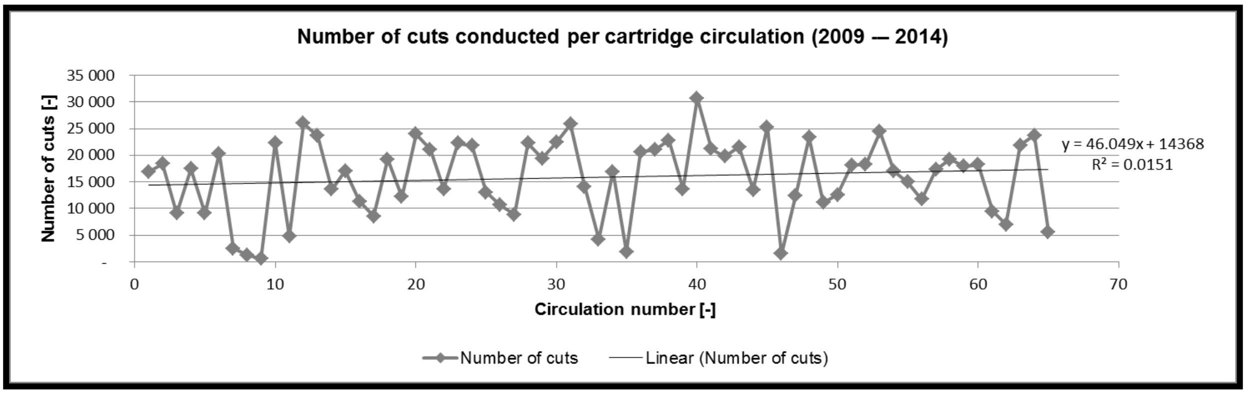

Figure 22: Number of cuts conducted per cartridge circulation (2009 – 2014)

Figure 22 illustrates how erratic the crop shear's performance was over the period 2009 to 2014. The percentage in variance value from the regression analysis conducted on the data was 0.0151. A value of 0 specifies that the regression is non-existent, and a value 1 indicates a perfect linear relationship (Freund, et al., 2006). A value of 0.0151 thus signifies a poor linear relationship, which leads to the observation that the crop shear's blade life would be unpredictable with any level of certainty from this data.

Searching for trends between the three crop shear cartridges, the data of each cartridge was plotted on the same axis, as indicated in Figure 23.

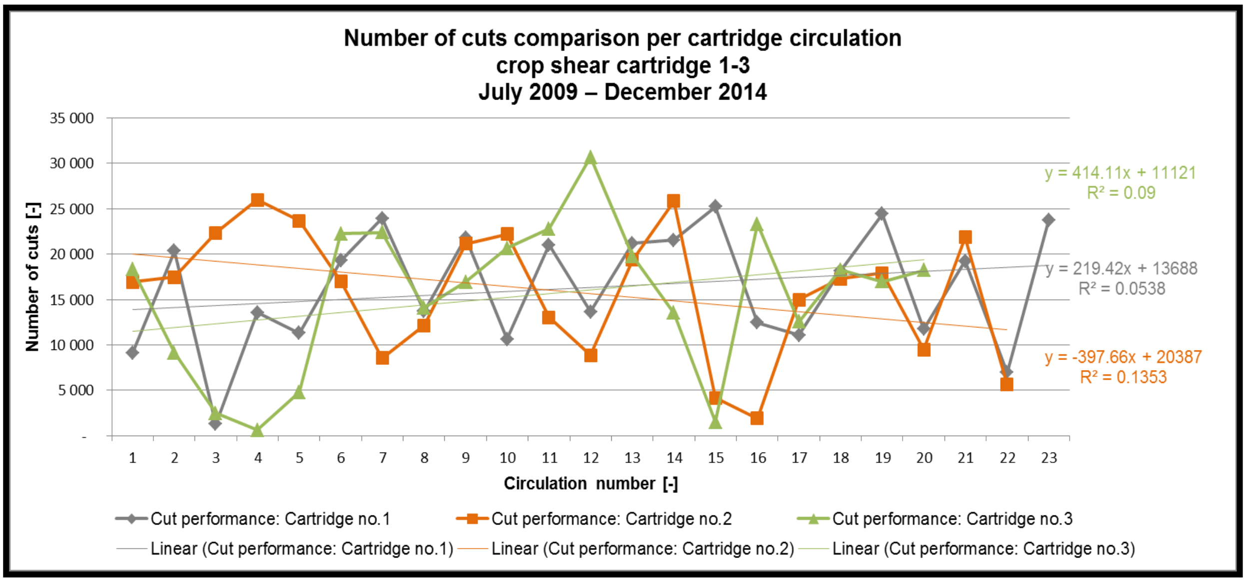

Figure 23: Number of cuts conducted per cartridge circulation (2009 – 2014)

The linear regression analysis concluded a percentage in variance value of 0.0538, 0.1353 and 0.09 for crop shear cartridge 1, 2 and 3 respectively. All three of the cartridges indicated a poor linear relationship. Considering the diminutive variance in the regression analysis results, no certain cartridge(s) can be linked directly to the cause of the erratic results seen in Figure 22. The same erratic performance is noticed on each of the individual plots. The average in the number of cuts per circulation was 16 322, 15 814 and 15 469 for cartridge 1, 2 and 3 respectively.

The following histogram, utilising the same data as explained in Figure 24 illustrates the distribution of the number of cuts obtained with each cartridge circulation.

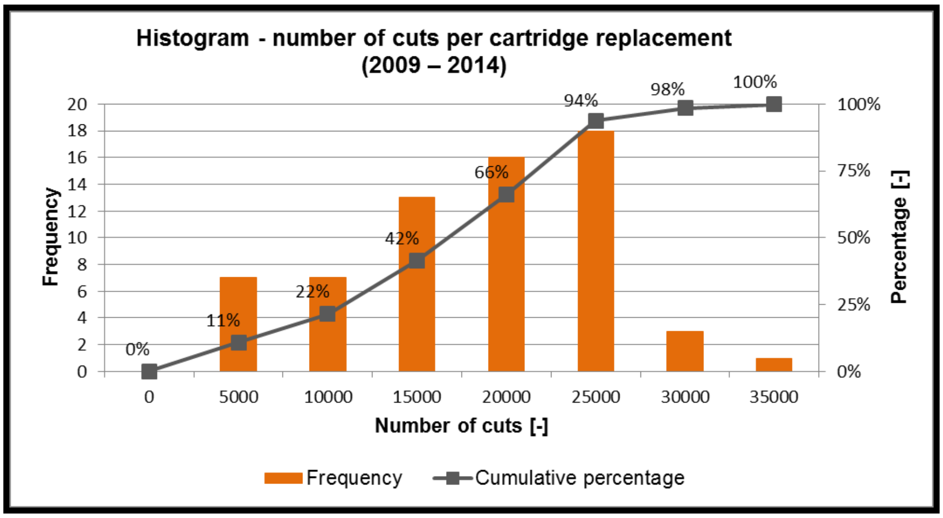

Figure 24: Histogram – number of cuts per cartridge replacement (2009 – 2014)

The horizontal axis of the histogram can be divided into the following ranges, which is explained in Table 3 to simplify the discussion of the results.

Table 3: Histogram – range description

Range description	
Description	**Number of cuts**
Lower Range	0–5 000 & 5 000–10 000
Centre Range	10 000–15 000, 15 000–20 000 & 20 000–25 000
Higher Range	25 000–30 000 & 30 000–35 000

Figure 24 above shows a wide variation in results for the period 2009 to 2014 when referring to the lower as well as higher range in number of cuts accomplished with each cartridge circulation. The lower range with a frequency of 14 occurrences represents 22% of the total number of circulations and thus signifies an extremely poor crop-shear performance.

As many as 72% of the cartridge circulations are located in the centre range showing a distribution of 20%, 24% and 28%, respectively. Only 4% of the total cartridge circulations represent the higher range. It, therefore, rarely occurred that such a significant number of cuts were obtained. The HSM anticipated definite blade failure when using the crop shear blades beyond 22 000 cuts. This ensured that the blades were replaced according to a 22 000-cut target, hence the dense population in the centre range. Poor adherence to the current practice resulted in 25% of the cartridge replacements occurring after exceeding the 22 000-cut target.

Due to a lack of resources it was unclear how 4% of the cartridge-replacement occurrences exceeded 25 000 cuts prior to the replacement. It can be assumed that the 4%, consisting of three occurrences of cartridge replacement, was run to failure but only one of the three occurrences resulted in a blade failure that forced a replacement. The other two occurrences, although above the anticipated 22 000-cut target, were replaced before a problem ensued.

Unfortunately the approach in successfully achieving a blade life span exceeding 25 000 cuts was unknown, emphasising the importance of keeping maintenance history effectively.

4.1.3. Preventative vs. reactive cartridge replacements

This section elaborates on the type of cartridge-replacement occurrences throughout the period 2009 to 2014, whether it was preventative or reactive. Preventative type replacements refer to those occurrences where the crop-shear cartridge was replaced without experiencing a blade failure. Reactive replacements refer to forced occurrences of replacements only after a blade failure had occurred.

Of the 65 cartridge-replacement occurrences, 31 cartridges were replaced reactively. Thus, 48% of the total replacements were done after a problem had occurred. Figure 25 below illustrates the data by means of a pie chart.

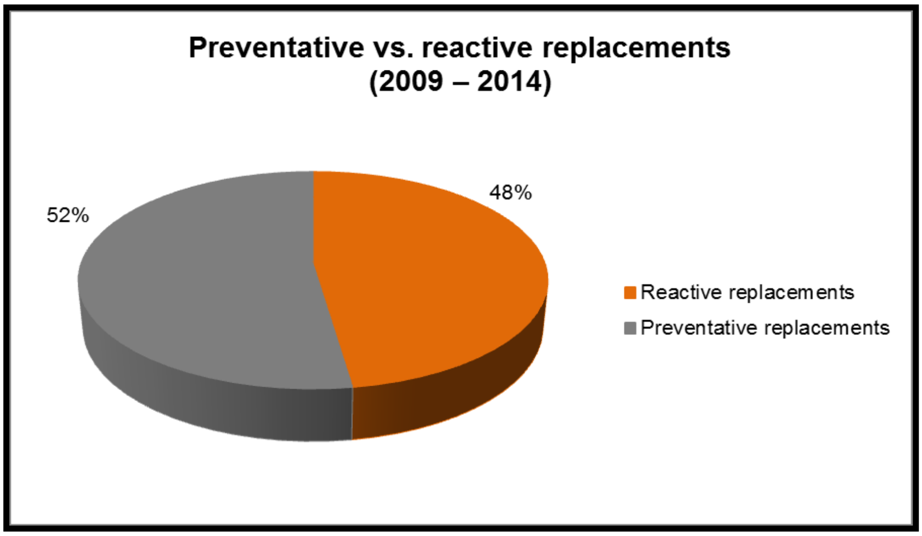

Figure 25: Preventative vs. reactive replacements (2009 – 2014)

Figure 26 below demonstrates two histograms that compare the performance of the cartridges in terms of the number of cuts made before the cartridges were replaced reactively and preventatively, respectively.

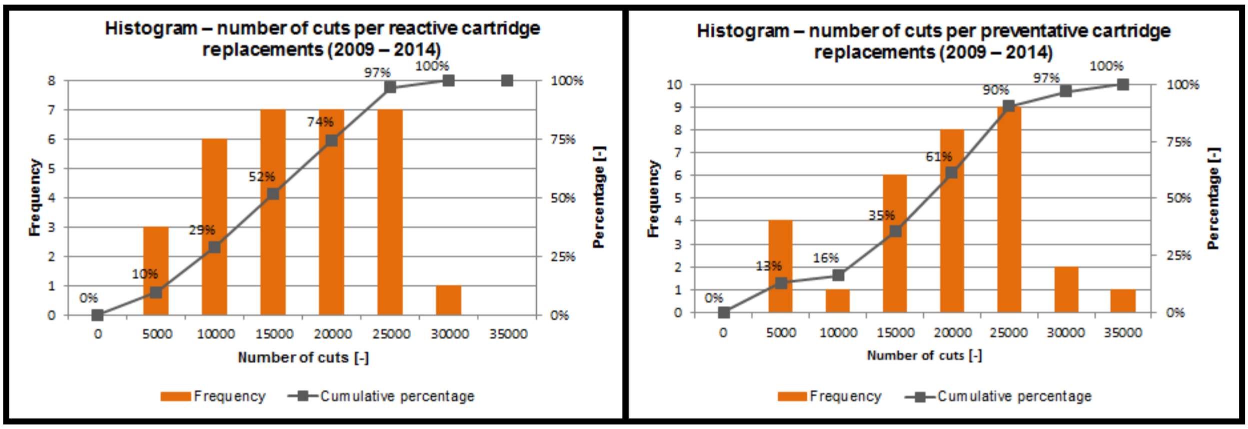

Figure 26: Histogram – number of cuts per reactive (left) and preventative (right) cartridge replacement (2009 – 2014)

Table 4 below summarises the data in Figure 26 above for each of the type of replacements and the percentage of contributions per range of cuts made.

Table 4: Contribution per range for reactive-and preventative cartridge replacements 2009 – 2014

Range description	Reactive replacement	Preventative replacement
Lower Range	29%	16%
Centre Range	68%	74%
Higher Range	3%	10%

The summary of results in Table 4 draws the following findings:

1. Poor adherence to the replacement rules resulted in exceeding the current target of 22 000 cuts. As little as 10% of the preventative replacements occurred in the higher range and the cartridge was thus only replaced after exceeding 25 000 cuts. Only 3% of the reactive replacements occurred after exceeding the 22 000-cuts target.
2. A total of 16% of the preventative replacements occurred in the lower range for the number of cuts, therefore, the HSM personnel were able to detect malfunctions before there were major disturbances in production and thereby address the problems before it resulted in a blade failure.
3. More cartridges were replaced after succeeding in reaching the centre or higher range of cuts before being replaced for preventative reasons.

The cartridges that were replaced reactively were done so for either of the following reasons:

1. Unexpected equipment failure occurred early in the circulation period.
2. Abnormal increased wear rate caused the blades to be blunt sooner than usual.

4.1.4. Conclusion of Experimental component 1

The period 2012 – 2014 have demonstrated a slow rate of improvement with the latest unplanned downtime figure of 0.21% for the year 2014. With only 52% of the cartridge replacements done preventatively, there was ample opportunity to improve on the number of preventative replacements, which would increase the availability performance significantly. To be able to improve on the number of preventative replacements, much attention had to be given to the maintenance and operation methodologies used at that time. The following findings support the proposal:

1. It was determined that no single cartridge contributed to the poor performance at that time since a similar erratic performance was found across all three of the utilised cartridges. The problem impeding the desired performance was the manner in which the crop shear equipment was managed and utilised.
2. The initiative to improve reliability only focused on replacing problematic equipment that has exceeded their recommended lifecycle. The HSM management team did not apply the maintenance and operation methodologies used at that time.

A more stable and less unpredictable crop-shear performance should benefit the preventative means of cartridge replacement. A more dense population can then be expected in the centre range for the distribution of cut performance.

4.1.5. V&V results and critical review of Experimental component 1

The double-checking verification method was successfully applied, ensuring that possible human errors were corrected as early as possible in the process. No miscalculations were, however, made whilst processing the data.

The outcomes of the experiment proved to be effective in determining the current condition of the crop shear's utilisation at the HSM. The findings from the various approaches in the experiment complimented each other well by identifying the problem areas that needed to be addressed in order to improve further on the crop shear's general performance.

The following section discusses the results of Experimental component 2, which entails the questionnaire distributed to the HSM personnel. The knowledgeable feedback received from the experienced personnel was captured and used to develop a strategic approach that would address the identified problem areas properly. In addition, this feedback was also used to correlate the results with that of Experimental component 1, in order to verify the need of the present study.

4.2. Results: Questionnaire

A hard copy of the questionnaire was distributed to 31 individuals employed at the HSM. This was done to gather input from the personnel regarding the crop shear's performance, with the intention to improve this performance. Of the 31 questionnaires distributed, 23 completed ones were returned. The following section only elaborates on the raw data obtained from the completed questionnaires. (Chapter 5 provides the interpretation of these results.)

4.2.1. Questionnaire's sample group

The sample group for the questionnaire consisted of the following personnel:

- 1 x Mechanical maintenance manager
- 1 x Electrical maintenance manager
- 2 x Systems maintenance managers
- 2 x Mechanical reliability engineers
- 1 x Electrical reliability engineer
- 2 x Metallurgical process engineers
- 1 x Metallurgical process technologist
- 3 x Production specialists
- 1 x Mechanical maintenance superintendent
- 3 x Production superintendents
- 6 x Mechanical maintenance artisans

4.2.2. Questionnaire's verification results

Before the questionnaire was distributed, a final draft proposal was proofread as verification tool. The following amendments were introduced to the final questionnaire before being distributed:

1. Information of the questions that expected an assessment from the participant regarding the current standard operating procedure (SOP) and the unplanned downtime figures, was supplied as appendix documents.
2. The complexity of the language was evaluated and improved on to best accommodate the preferred language style of the majority of the sample group.

4.2.3. Questionnaire's validation results

Of the 23 completed questionnaires that were collected, 22 were found to be reliable enough for further analysing purposes. One questionnaire was rejected for the following reasons:

1. The questionnaire did not comply with the validation criteria as mentioned in Paragraph 3.2.7.2.
2. Additionally, multiple questions were left unanswered meaning that the individual had either not paid sufficient attention to the questionnaire, or the integrity of the agreement that the individual needs to be familiar with the crop shear, had to be questioned.

4.2.4. Accepted questionnaire results

The following section elaborates on the 22 questionnaires that were accepted – focusing on the process of acceptance or rejection. The data is discussed in the same numerical order as the questions were posed in the questionnaire.

4.2.4.1. Knowledge of the crop shear at the HSM

Question 1:

Are you familiar with the crop shear utilised at the HSM (Hot Strip Mill)?

Yes	100%
No	0%

Question 2:

Please rate your detail of experience regarding the crop shear (If applicable, more than one option may be selected with a X):

You have **only** heard of and seen the crop shear in operation	18%
You have physically conducted maintenance on the crop shear before	64%
You have operated the crop shear before	55%
You have been involved in trying to improve the reliability of the crop shear	64%

Question 3:

Please rate your detail of technical knowledge related to each of the disciplines listed below regarding the crop shear (Give a rating for each one of the disciplines):

Discipline	Very good	Fair	Not good
Your knowledge from a **systems** point of view	18%	46%	36%
Your knowledge from a **mechanical** point of view	50%	45%	5%

You knowledge from an **operating** point of view	63.6%	31.8%	4.6%
Your knowledge from a **reliability** point of view	50%	36%	14%

Question 4:

Have you undergone any form of training on the crop shear before? If yes, please briefly elaborate.

Yes	59%
No	41%

The training to which the participants have referred is mentioned below. The received training focused on:

- most predominantly, the reconditioning of the crop shear;
- control of the crop shear and its optimisation;
- the cutting position of the crop shear on the head and tail end of the transfer bar.

4.2.4.2. Utilisation and effectiveness of the crop shear's works procedure

Question 5:

Have you had the opportunity to read the crop shear works procedure before?

Yes	73%
No	27%

Question 6:

Attached to Appendix 1 of the questionnaire is the latest revised crop shear works procedure. Do you think the latest revision is effective in elaborating on operating and maintenance principles of the crop shear?

Yes	18%
No	82%

Question 7:

If your answer to the above question is no, please select the possible aspects listed below you agree with (If applicable, more than one option may be selected). Please elaborate below if felt needed.

Insufficient detail related to process introduction	73%
Insufficient detail related to process parameters	77%
Insufficient detail related to preferred maintenance strategies	73%
Insufficient detail related to maintenance execution	73%
Insufficient detail related to trouble shooting manual	77%

Furthermore, the participants elaborated on and recommended the following:

- The current works procedure only accommodates the production discipline by discussing the zeroing function, one of the many functions actually used by the process/production personnel.
- The use of pictures of the HMI interface along with instructions to do so, should also be considered in the works procedure.

4.2.4.3. Crop-shear performance/utilisation figures

Question 8:

Are you aware that the crop shear performance/utilisation is being monitored by HSM personnel?

Yes	95%
No	5%

Question 9:

If your answer to the above question is yes, please indicate from options below how the performance/utilisation is being monitored. (If applicable, more than one option may be selected.)

Number of cuts conducted per cartridge	100%
Number of days the crop shear cartridge is in operation	52%

Unplanned downtime	86%
Mechanical yield	100%

Question 10:

From your selection in the above question, do you know what the condition of current performance/utilisation figures of the crop shear is?

Yes	48%
No	52%

Question 11:

If your answer to the above question is no, would you be interested in receiving monthly feedback regarding the crop shear performance/utilisation figures?

Yes	91%
No	9%

Question 12:

In terms of the crop shear performance/utilisation figures, what do you think the result thereof has been since the year 2008 up until now?

The performance/utilisation has improved	86%
The performance/utilisation has remained more or less the same	5%
The performance/utilisation has become worse	9%

Question 13:

Please refer to the actual crop shear performance/utilisation graphs in Appendix 2 of the questionnaire. Do you think it is possible to improve on current crop shear performance/utilisation? If not, please elaborate why you believe so.

Yes	91%
No	9%

4.2.4.4. Attitude of the relevant team to improve on the crop shear performance/utilisation

Question 14:

Do you think the relevant personnel/teams listed below have the required attitude to improve the performance/utilisation of the crop shear? Please give a rating for each of the responsible teams.

Responsible Teams	Strongly agree	Agree	Disagree	Strongly disagree
Maintenance execution team (Artisans)	64%	32%	4%	0%
Mechanical reliability team (Supt. and engineer)	91%	9%	0%	0%
Systems reliability team (Technicians and technologists)	18.2%	54.5%	22.7%	4.6%
Production team (Operators and production specialists)	9%	36%	55%	0%

4.2.4.5. Skill of the relevant team to improve on the crop shear performance/utilisation

Question 15:

Do you think the relevant personnel/teams listed below have the required skills to improve the performance/utilisation of the crop shear? Please give a rating for each of the responsible teams.

Responsible teams	Strongly agree	Agree	Disagree	Strongly disagree
Maintenance execution team (Artisans)	73%	27%	0%	0%
Mechanical reliability team (Supt. and engineer)	91%	9%	0%	0%
Systems reliability team (Technicians and technologists)	45.4%	36.4%	18.2%	0%
Production team (Operators and production specialists)	27%	50%	18%	5%

4.2.4.6. Knowledge regarding the maintenance method currently being used

Question 16:

Do you know what maintenance method is being used to maintain the crop shear blades?

Yes	86%
No	14%

Question 17:

If your answer to above question is yes, please indicate which method you think is being used:

Condition based maintenance	11%
Run-to-failure maintenance	0%
Predictive maintenance	21%
Preventative maintenance	68%

4.2.4.7. Proposed maintenance approach

Question 19:

The mechanical reliability team is considering using the crop shear off cuts' burr length (as demonstrated in images below) as a measurement to determine the condition of the crop shear blades. Do you think this approach will be effective in trying to improve the crop shear performance/utilisation? If no, please elaborate why you believe so.

Yes	91%
No	9%

Two of the participants were of the opinion that the proposed approach would not be effective in improving the crop shear's performance/utilisation due to the following reasons:

- All the factors should have been considered such as the condition of the blade, the shear speed, material type and the occurrences of tail-ends being pulled through.
- The effectiveness of the approach was criticised due to the opinion that the burr length of the offcuts is the wrong parameter to monitor.

4.2.4.8. Quality of reconditioning work executed on the crop-shear cartridges

Question 21:

The HSM has 3 crop shear cartridges in their possession. One in operation, one as an available standby on site and the other sent out for reconditioning. Do you think there is a difference in the performance/utilisation when comparing the cartridges with one another?

Yes	41%
No	59%

Question 22:

If your answer to above question is yes, please elaborate on why you believe there is a difference in performance/utilisation amongst cartridges.

The participants indicated that the crop shear cartridges perform differently when compared to one another, due to the following claimed reasons:

- The wear associated with each of the components, such as the liners and gear teething, contribute to the rate of deterioration.
- Different reconditioning approaches were used on the three different crop shears.
- The product mix that is produced differs in steel grade and dimensions throughout production and, therefore, would cause different wear rates on the various cartridges.

Question 23:

Do you think the crop shear cartridges are reconditioned according to the required quality specification? If yes, please motivate your answer.

Yes	84%
No	16%

Of the 19 participants who gave an input on question 23, as many as 16 participants believed that the crop shear is being reconditioned according to the required specification. Their claimed reasons are as follows:

- The crop shears perform relatively well prior to replacement, which induces the believe that the reconditioning is, therefore, done properly.

- The participants trust that the effort spent to ensure the crop shear quality control, reliability and performance, is monitored adequately and thus effective enough to ensure that the crop-shear cartridges are reconditioned to an appropriate standard.
- All the cartridges are supposed to be reconditioned according to a specification (i.e. technical drawing).
- In many cases the cartridges are reconditioned by the same reconditioning firm, hence have the experience to guarantee the quality of the delivered product.

4.2.4.9. Technical feedback/commentary

The questionnaire was designed for respondents to make free-form remarks and comments which are summarised below:

- The effect of cold ends being cut should also be considered in the study as it evidently have a significant impact on the blade's life span.
- Vector cutting, a blade with a sharper attack angle could be considered in the study as an alternative to the current design.
- The effect of manual cuts being made should also be incorporated into the analysis when monitoring the number of cuts.
- The cut control – Digital Media Controller (DMC) allows for too many control inputs, which is not appropriately managed between the personnel. DMC replacement with fewer inputs should be considered for a more consistent operation of the crop shear.
- The control-input parameters should be optimised to allow for optimal lifetime for the crop-shear blades.
- Improved environmental conditions should be considered such as steam, which could diminish the accuracy of the measuring equipment used to calculate the position of the crop shear's cut.
- The HSM should consider investing in a larger crop shear, which suits the material specification better, in order to increase the crop shear's performance and reliability.

4.2.4.10. Effectiveness of the questionnaire

All of the participants found the questions in the questionnaire to be meaningful and applicable to the topic at hand. They understood all the questions and were truly able to demonstrate their insight and opinion by following the available options.

One participant indicated a concern about certain questions that may have been too technical. These questions focused on the crop shear's maintenance, and personnel who are not as involved in and associated with the crop shear operation would find it difficult to answer the question based on certain assumptions.

4.2.4.11. Conclusion of questionnaire results

The selection of the questionnaire participants, prior the questionnaire's distribution, was successful since the response concluded that all of the participants were familiar with the crop shear. The majority of the participants (64%) have done maintenance on the crop shear previously and have been involved in attempts to improve the reliability of the crop shear. The participants also had a clear understanding of the various disciplines' details concerning the crop shear, excluding that of the systems discipline. Only 30% of the participants indicated a sufficient understanding of the system's discipline involvement with the crop shear. Apart from past experience, training has also benefitted many of the participants in their knowledge of the operation of the crop shear at the HSM.

The current works procedure (2nd revision) was assessed, and 82% of the participants mentioned that this document was still ineffective and in need of improvement in all of the available options provided in the questionnaire.

It was also concluded that there is insufficient communication since only 73% of the participants were aware of the contents of the works procedure before completing the questionnaire, and 48% were aware of the current performance of the crop shear.

The high level of work engagement and the motivation to deliver work of high quality could be inferred amongst the HSM personnel. As many as 91% of the participants would wish to be informed of the crop shear's performance. This finding demonstrated a significant amount of interest in the crop shear's operation.

The participants were also keen to see improvements since 91% of the participants believed that the crop shear's performance could be improved and that the proposed CBM approach should be effective in doing so.

The remaining 9% of the participants, who disagreed that the proposed CBM approach wouldn't be effective, motivated their doubts by alluding to the following factors that limit the potential in improvement:

- the lack of clarity on the preferred crop-shear speed settings;
- the condition of the crop shear blades;
- the diverse types of material produced, which will hinder the success of the approach;

- the continuous occurrence of tail-ends that are pulled through the crop shear and the finishing mill.

These remarks were considered in Experimental component 3 in an attempt to address the concerns of the participants and to enhance the proposed CBM approach. Along with the feedback all of the participants mentioned that the questionnaire was of a high-quality standard. This feedback did not only verify that Experimental component 2 was well planned and executed. It also confirmed that the results obtained were valid by which to develop an effective CBM approach for the HSM.

4.3. Results: Burr-length measurement

The objective was to establish a relationship between the burr length on the crop offcuts and the crop shear blades' condition in order to specify a maximum target for the burr length at which the crop-shear cartridge should be replaced.

In this section the results are discussed in a similar order to the introduction of the experiments in Chapter 3, Figure 12. The results found before implementing the CBM approach is discussed first before assessing the results that were concluded after implementing the CBM approach. The results before and after the implementation is then compared, before reporting on the results found during the analysis of the process or production practices.

The experiment was executed from February 2014 to August 2015. Within this period only cartridge 1 and 2 was available. A total of 16 circulations of crop-shear cartridges took place, where each cartridge's performance was examined closely. The experiment focussed on frequently measuring the burr length of the crop shear's offcuts with the aim to develop a comprehensive database of the findings. Appendix E presents the raw data that was gathered through this experiment.

While still operating according to the 22 000-cut replacement strategy, 10 crop shear cartridge circulations were analysed and a database was developed to record burr-length measurements. The database helped determine the maximum allowable burr-length target to be implemented for the following six cartridge circulations.

4.3.1. Crop shear performance – before implementing the CBM approach

This section discusses the results found when analysing the first ten cartridge circulations that occurred before the implementation of the proposed CBM approach was planned.

Figure 27 below represents more than one data series to demonstrate collaboratively the crop shear performance in terms of the number of cuts and the corresponding burr-length specifications for the final head and tail offcuts when each cartridge should be replaced.

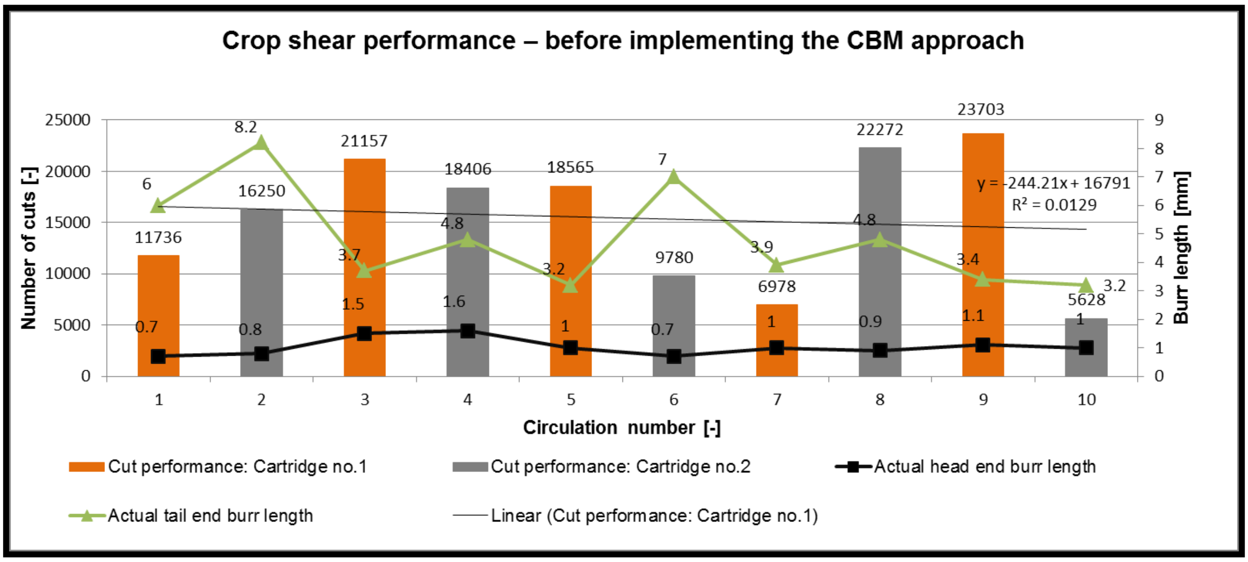

Figure 27: Crop shear performance – before implementing the CBM approach

Data represented in orange and grey in the graph above, illustrate the number of cuts that cartridge 1 and 2 delivered per circulation, respectively. Utilising the secondary y-axis, the burr length for the head and tail offcuts is represented by the black and green data series, respectively.

The results display an erratic performance regarding burr length for the cuts and tail-end offcuts. The percentage in variance value from the regression analysis done on the cuts' performance data was 0.0129, which demonstrates a poor predictability and consistency.

The erratic performance for the tail-end's burr length was expected since it was then not yet restricted to a specific allowable length for observation purposes, and still replaced according to the original target of 22 000-cuts. The instances where the actual cut performance indicated less than the expected performance of 22 000 cuts, were due to early cartridge replacements. Signs of possible fractured/blunt blades causing a delay in productive time would cancel out the preventative replacement rule, and thus force an early replacement for the cartridge. Figure 20 depicts the occurrences of replacements below 22 000 cuts and the unplanned downtime thereof for 2014. Only two of the ten circulations in that period occurred where the expected performance of 22 000 cuts was achieved, without impacting production. The performance of the crop shear regarding the number of cuts delivered per circulation from before implementing the CBM approach delivered a wide spread in results, more specifically demonstrated below by the following histogram:

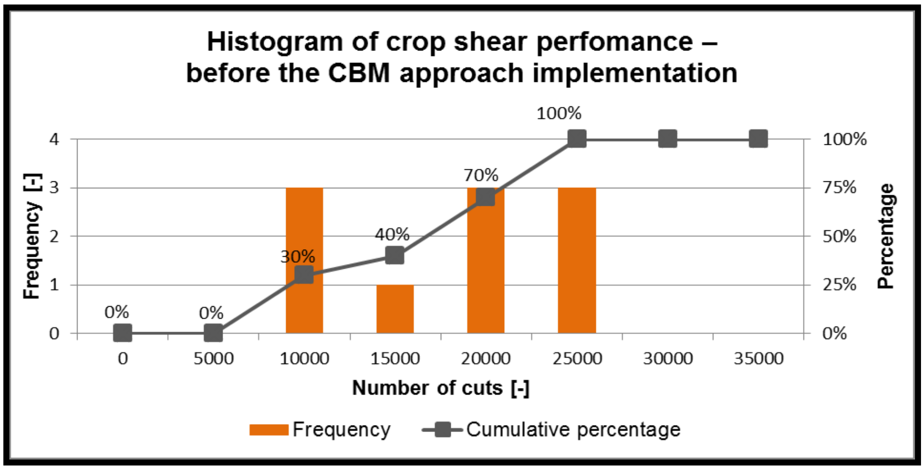

Figure 28: Histogram of crop shear performance – before implementing the CBM approach

4.3.2. Determining the burr-length target for replacing the crop-shear cartridge after implementing the CBM approach

Before implementing the CBM approach, the maximum allowable burr length target had to be determined. This target would then be used as reference to predict the future replacements of the crop-shear cartridge in a preventative manner, and thereby revise the 22 000-cuts rule. In this way the following factors were considered before implementing the CBM approach:

- the average final burr length of the circulations;
- the condition of the blades after cartridge circulations;
- the performance of the cartridges in terms of the number of cuts compared to the obtained burr length.

4.3.2.1. The average final burr length of the circulations that occurred before implementing the CBM approach

The head-and tail end burr length maintained an average length of 1 mm and 4.7 mm respectively prior to replacing the cartridge. The following two figures each demonstrate the spread in the final burr length of the circulations for the head and tail end, respectively.

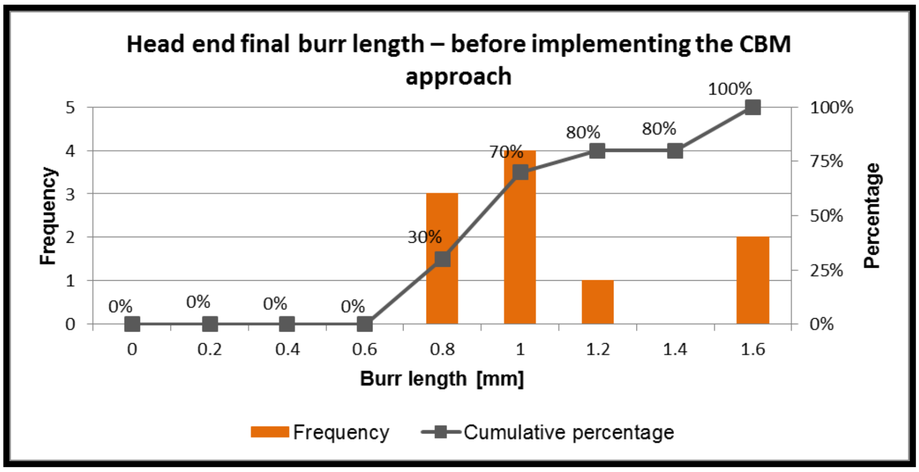

Figure 29: Head end final burr length – before implementing the CBM approach

Figure 29 above illustrates that 30% of the final head end burr lengths was within the 0.8 – 1 mm range. A further 40% of the data populated the 1 – 1.2 mm range. These two ranges were the most dense data ranges for the head end cuts.

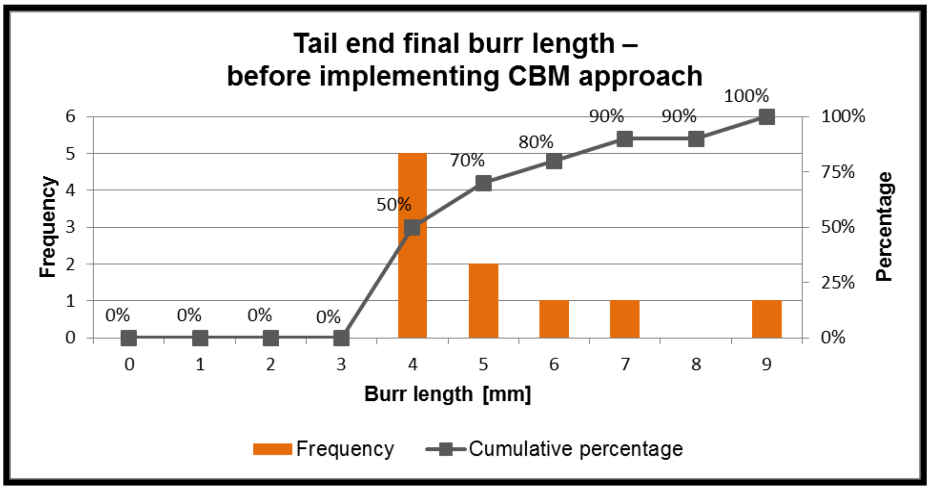

Figure 30: Tail end final burr length – before implementing the CBM approach

The range 4 – 5 mm was in this case the densest range for the tail-end burr lengths indicating a 50% population.

4.3.2.2. The condition of the blades on cartridge circulations before implementing the CBM approach

In some instances a long burr length was maintained before replacing the cartridge, for example during circulations 2 and 6. These cartridges were only replaced after the tail-end burr length accumulated to 8.2 mm and 7 mm respectively. Utilising the blades to such an extent obviously increased the risk of a production disturbance, but evidently also influenced the integrity of the blades' condition. The blades in these two occurrences were found to be fractured severely into several segments when it was replaced. Figure 31 below provides an example of the fractured blades.

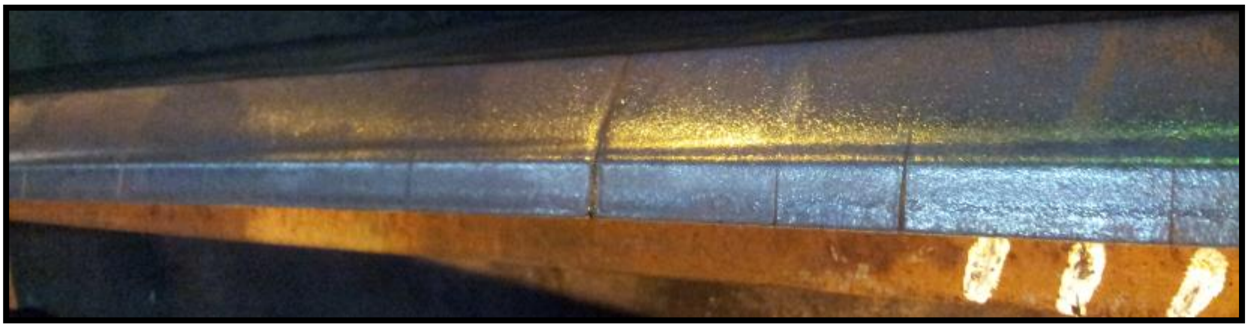

Figure 31: Fractured blade

The fractures originate at the sharp cutting edge and eventually propagate downwards, along the depth of the blade, and in some cases throughout the whole cross-section of the blade. These types of cracks, however, did not influence the shearing capability of a sharp blade assembly, seeing that it still made successful cuts. Unfortunately the fractured blades were often not reconditionable after being replaced and, therefore, had to be scrapped. The shortcoming of the need to scrap the blades meant less opportunity to save on funds where blades could have been reconditioned rather than purchasing new ones, which is clearly more expensive. The fractured blades either cracked so significantly that repairing them would need a machining depth beyond the scrap size of the blades, or the blades were totally fractured into two or more segments as illustrated below in Figure 32.

Figure 32: Top and cross-sectional view of the fractured blade

In one unique occurrence the cartridge used in circulation 10 only completed 5 628 cuts before the blades were no longer capable of shearing the transfer bar. After removing the cartridge a blade fracture was found that had propagated from a downward vertical direction to a horizontal direction, which disintegrated the blade section. The failure mode is demonstrated below in Figure 33.

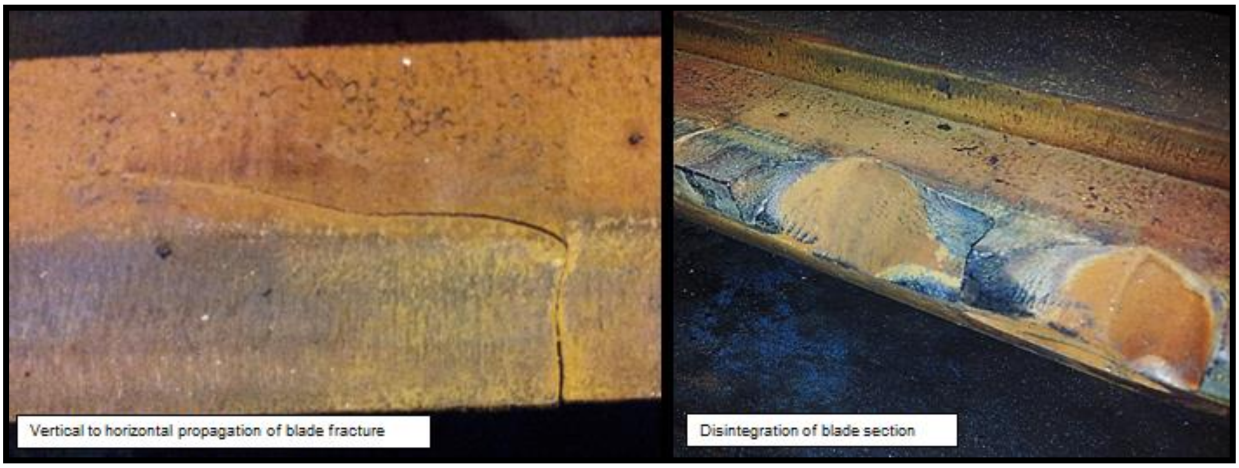

Figure 33: Blade section disintegration due to horizontal fractures

The clamping load that was exerted on the blades when they were wedged into position in the drums of the cartridge meant that the straight type of fracture did not influence the blades' shearing capability. The mentioned failure mode did, however, result in an immediate breakdown if a blade section had disintegrated. These type of failures were not preventable and the blades, therefore, required frequent inspections to replace the cartridge preventatively.

Table 5 below summarises the results of the blades' conditions when the cartridges were replaced. The blades' condition defined as "*scrapped*" meant that a blade was so severely damaged that it had to be replaced. The condition defined as "*reusable*" meant that the blade was either not fractured at all, or the minor fractures could have been removed with minor machining.

Table 5: Condition of crop-shear blades on replacement – before implementing CBM approach

Condition of crop-shear blades on replacement – before implementing CBM approach							
Circulation number	**Number of cuts**	**Burr length**		**Blade condition per blade position**			
		Head [mm]	Tail [mm]	Head Top	Head Bottom	Tail Top	Tail Bottom
1.	11736	0.7	6	Reusable	Reusable	Scrapped	Scrapped
2.	16250	0.8	8.2	Scrapped	Scrapped	Scrapped	Scrapped
3.	21157	1.5	3.7	Scrapped	Scrapped	Reusable	Reusable
4.	18406	1.6	4.8	Scrapped	Scrapped	Scrapped	Scrapped
5.	18565	1	3.2	Reusable	Reusable	Scrapped	Scrapped
6.	9780	0.7	7	Scrapped	Scrapped	Scrapped	Reusable
7.	6978	1	3.9	Scrapped	Reusable	Reusable	Reusable
8.	22272	0.9	4.8	Scrapped	Reusable	Reusable	Reusable
9.	23703	1.1	3.4	Scrapped	Scrapped	Reusable	Scrapped
10.	5628	1	3.2	Scrapped	Scrapped	Scrapped	Scrapped

From Table 5 above it is clear that 40 blades were utilised during the circulation of 10 cartridges before implementing the CBM approach; and only 14 blades were in a reusable condition when the cartridges were replaced. Therefore, 65% of the blades were fractured in such a manner that they had to be scrapped. The fact that contributed the most to the poor reuse of the blades was the use in the head-end position of the cartridge assembly. As many as 70% of the blades in the head-end position were scrapped, due to severe fractures. In order to minimise crop losses, it should be noticed that the crop's offset cut position caused the poor head-end performance. Reducing the offset length from the true head-end ensured that less material is cut from the head-end of the transfer bar. Although this implementation improved the crop yield as demonstrated in paragraph 4.3.5.1, the crop shear was forced to cut on colder areas of the transfer bar, which made it more difficult to shear through the material. The increased difficulty to cut the transfer bar resulted in increased wear rates and more fractured blades.

4.3.2.3. The performance of the cartridges in terms of the number of cuts compared to the burr length obtained before implementing the CBM approach

Referring back to Figure 24, the 20 000 – 25 000 cut range had the highest frequency population and represents 28% of the data for the period 2009 – 2014. Referring to the same range (20 000 – 25 000 cuts) for the data collected from the first 10 circulations of cartridges of Experimental component 3, the corresponding data's average head- and tail-end burr length was found to be equivalent to 1.03 ≈ 1 mm and 4.82 ≈ 5 mm, respectively. Although an average of 1 mm was obtained, a head-end burr length of 1.5 mm was suggested, provided the cutting of cold transfer bars would be avoided in future. The spread of the tail-end burr length results were the densest between the 4 mm and 5 mm range. The blades obtained from circulation occurrences 3, 7 and 8, replaced at an average final burr length of 4.1 mm, delivered tail-end blades that were still in a good condition and reusable.

4.3.2.4. Conclusion on determining the maximum allowable burr length

Based on the above-mentioned findings a specification for a preferred cartridge replacement of head- and tail-end burr length was determined at 1.5 mm and 4.5 mm, respectively – the length which would most likely deliver adequate life-cycle expectancy. Using the CBM approach along with the determined specifications for cartridge replacements the expected benefits were as follows:

1. Improve on the current unpredictable and erratic trend of crop-shear cartridge replacements.
2. Decrease the number of fractured blades when it is replaced.
3. Improve on the current performance of the plant's availability.

The consideration of the various performance-affected factors associated with the utilisation of the crop shear at the HSM, has confirmed the integrity of the results and, therefore, of the conclusion that was made from the findings.

The results of utilising the proposed CBM approach along with the target for maximum allowable burr length on the last six cartridge circulations of Experimental component 3 are discussed in the following section.

4.3.3. Crop-shear performance – after implementing the CBM approach

This section investigates how effective the CBM approach was implemented for the period December 2014 – August 2015. The experiments similar to those done earlier in Experimental component 3, before the implementation of the CBM approach, allowed for the opportunity to compare the results of before and after the implementation of the CBM approach.

The crop-shear performance is demonstrated below in Figure 34 for the six cartridge circulations that were analysed after implementing the CBM approach. These cartridge circulations were the last 6 of the 16 circulations considered for Experimental component 3 and, therefore, referred to as circulation number 11-16 in the figure below.

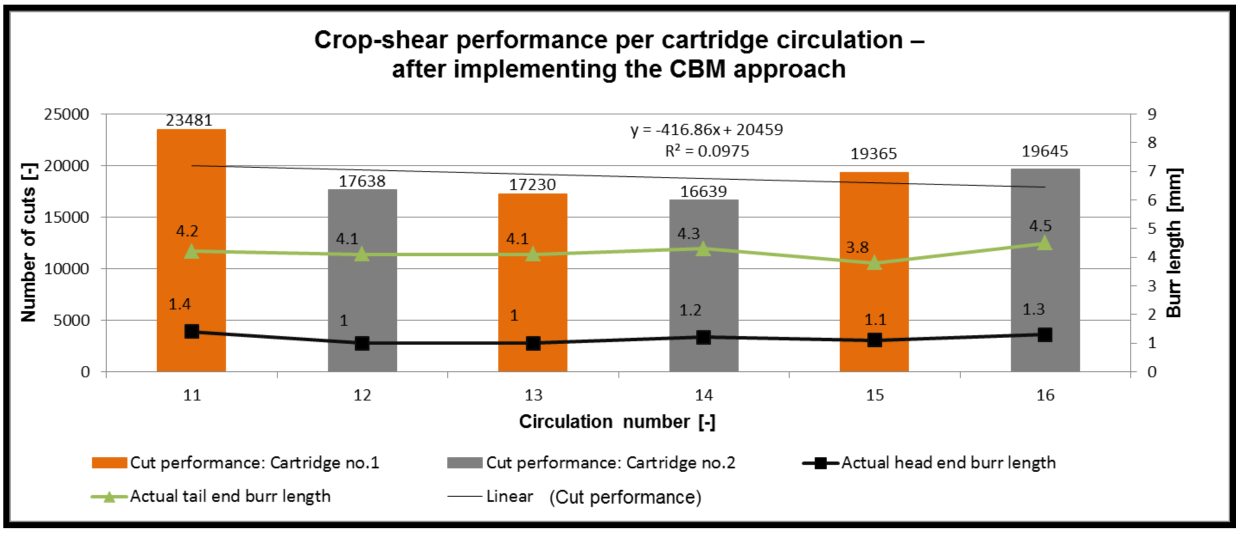

Figure 34: Crop-shear performance per cartridge circulation – after implementing the CBM approach

Similar to the format and layout utilised in Figure 27, the number of cuts completed and the final burr-length dimensions for the circulation of each cartridge is depicted above in Figure 34. After implementing the burr-length specifications for the cartridge replacements, the head and tail offcut values only indicated a small variation. The average of the number of cuts for the six circulations that occurred was 19 000 cuts with a percentage in variance value of 0.0975 for the cuts' performance data. An alternative representation of the spread of the data is provided in the histogram (Figure 35) below.

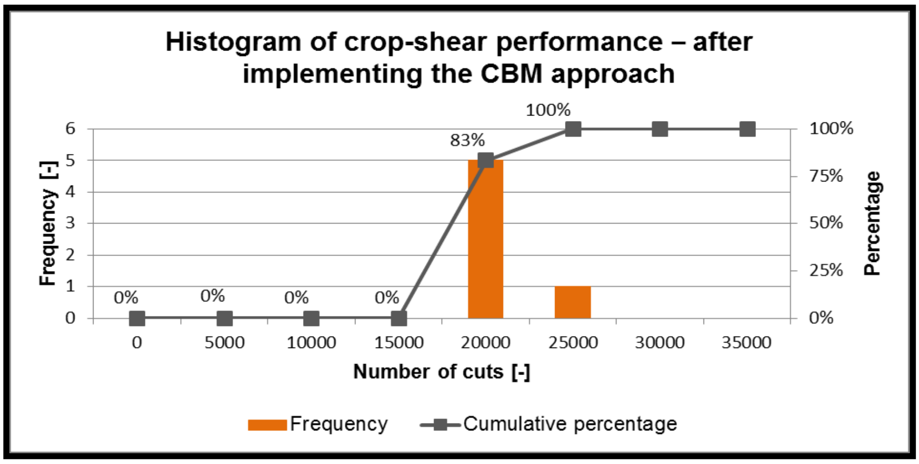

Figure 35: Histogram of crop-shear performance – after implementing the CBM approach

According to the graph above, only the centre ranges of the histogram is populated. The 15 000 – 20 000 and 20 000 – 25 000 range is populated with 83% and 17% respectively.

The following table summarises the results of the blades' conditions when the cartridges were replaced after implementing the CBM approach.

Table 6: Condition of crop-shear blades on replacement – after implementing the CBM approach

Condition of crop-shear blades on replacement – after implementing the CBM approach							
Circulation number	**Number of cuts**	**Burr length**		**Blade condition per blade position**			
		Head [mm]	Tail [mm]	Head Top	Head Bottom	Tail Top	Tail Bottom
11.	23481	1.4	4.2	Scrapped	Scrapped	Scrapped	Reusable
12.	17638	1	4.1	Scrapped	Reusable	Scrapped	Reusable
13.	17230	1	4.1	Scrapped	Reusable	Scrapped	Reusable
14.	16639	1.2	4.3	Reusable	Reusable	Reusable	Reusable
15.	19365	1.1	3.8	Reusable	Reusable	Reusable	Reusable
16.	19645	1.1	4.5	Scrapped	Scrapped	Reusable	Reusable

A total of 24 blades were utilised throughout the six circulations of the cartridges, after implementing the CBM approach. From the results, 62% of the blades were still reusable after replacement; 38% were fractured to such an extent that they had to be scrapped; 67% came from the head-end position of the cartridge; the remaining 33% of scrapped blades came from the tail-end position.

4.3.4. Comparison of results before and after implementing the CBM approach

Similar to the layouts of Paragraphs 4.3.1 – 4.3.3, this section compares the results before and after implementing the CBM approach. From the comparison, the effectiveness of the proposed CBM approach was confirmed. This section also concludes the sub-component of the experiment that measures the burr length.

The general performance of the crop shear, measured in actual burr lengths and the number of cuts made when the cartridge was replaced, is demonstrated below in Figure 36.

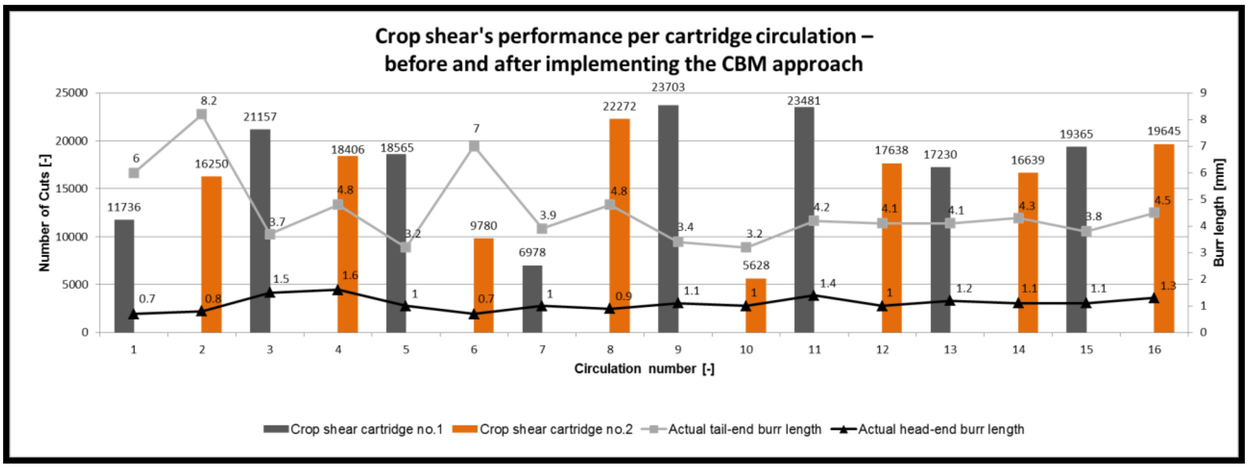

Figure 36: Crop shear's performance per cartridge circulation – before and after implementing the CBM approach

The performance of both phases, before and after implementing the CBM approach, is included in Figure 36 above, which thus indicates 16 circulation occurrences. When observing the graph it should be kept in mind that circulation numbers 1 to 10 represents the data of before CBM implementation and circulation numbers 11 to 16 represents the data of afterwards. After these observations a few deviations can be pointed out when comparing the data.

An expected deviation concerned the actual burr length for the head and tail ends. By applying the maximum allowable burr length when cartridges should be considered to be replaced led to a more consistent head- and tail-end burr length. The percentage in variance increased from 0.0129 to 0.0975 for the data of the number of cuts also indicates an improvement in the consistency of the data. Figure 37 below illustrates the comparative distribution of the data for both phases, before and after the CBM approach was implemented, and thus explaining the improved consistency which was pointed out when discussing Figure 36.

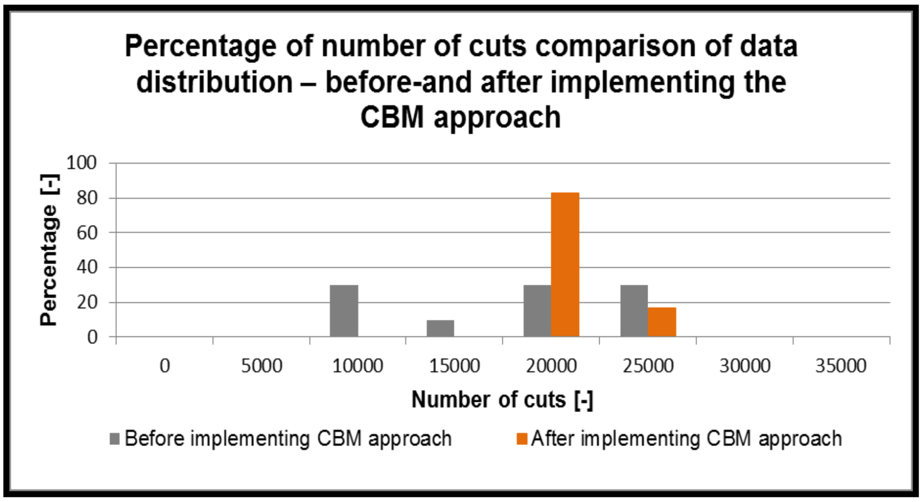

Figure 37: Percentage of number of cuts comparison of data distribution – before-and after implementing the CBM approach

Figure 37 indicates that the data obtained after implementing the CBM approach is more concentrated in the centre range of the graph. Although the results prior to the implementation also populate the centre range of the graph, 40% of the results represent the lower range of the graph, which is considered a poor performance. Abnormal/excessive wear rates and horizontal propagating blade fractures resulted in the inability to perform adequate cuts, which caused the mentioned breakdowns. The CBM approach has, therefore, been able to curb the occurrence of these type breakdowns. The approach thus in effect did not only improve the consistency in the number of cuts completed per cartridge, but also increased the time the crop shear is available. Figure 38 below demonstrates the availability performance of the crop shear before and after the CBM approach was implemented.

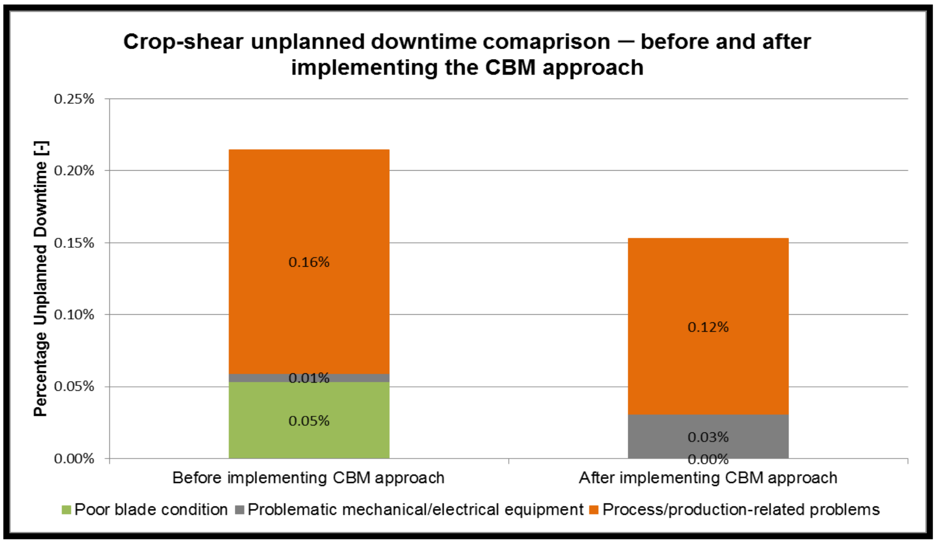

Figure 38: Crop-shear unplanned downtime comparison – before and after implementing the CBM approach

The unplanned downtime decreased from 0.22% to 0.15% after implementing the CBM approach. More significantly, the CBM approach has managed to eliminate breakdown occurrences resulting from poor crop-shear blades. The unplanned downtime related to the process/production also decreased by 25%, from 0.16% to 0.12%.

Referring to Figure 39 below the general condition of the crop-shear blades after its replacement has also improved since the CBM approach.

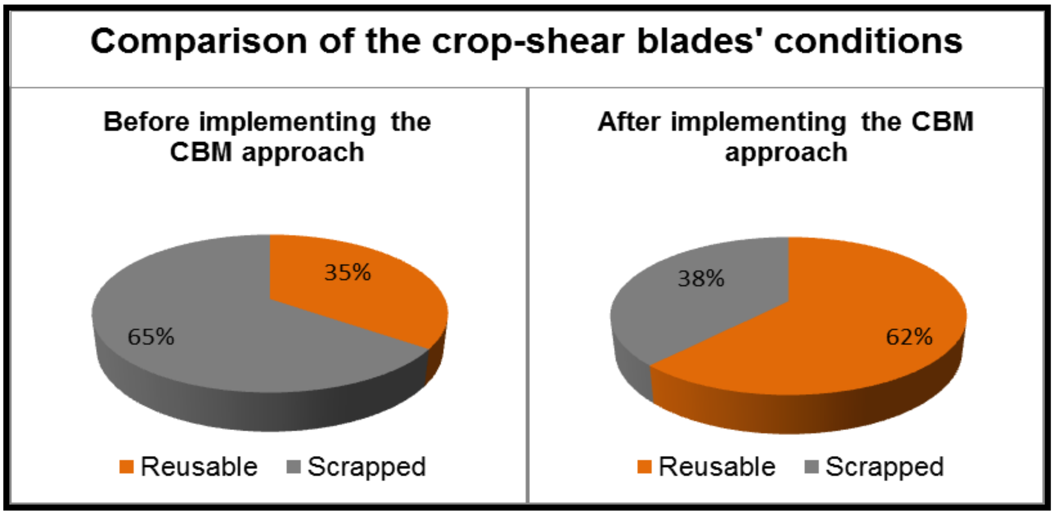

Figure 39: Comparison of the crop-shear blades' condition – before and after implementing the CBM approach

The quantity of scrapped blades decreased from 65% to 38% after implementing the CBM approach. This occurred even though the average number of cuts completed for the circulation of each cartridge increased from 16 539 to 19 000 cuts. Although the new CBM approach led to a noticeable improvement in the condition of the used blades, there is still room for improvement on these results. The majority of the scrapped blades utilised before and after the CBM implementation came from the front-end position. Only a minor improvement in percentage of scrapped front-end blades could be indicated since the CBM improvement, decreasing from 70% to 67% scrapped blades. One of the claimed causes for the high number of scrapped blades on the front end was pointed out as the small offset lengths of the cuts when operating the crop shear. The results worsened when small offset lengths were followed and because too cold transfer bars were being sheared. Paragraph 4.3.5 provides more detail on this matter.

All the results obtained since implementing the CBM approach has validated the experiment. The average usage cycle duration of the crop shear cartridges increased without having a negative impact on the condition of the blades. More importantly, the improved manner of maintaining the crop shear has increased the time that the crop shear is available. A more consistent replacement frequency has also created a sense of being in control. The new CBM approach has thus effectively provided the answer regarding the method to maintain the crop shear. Improving the means in which the crop shear is operated would not only increase the general usage of the crop shear but, as noticed in the case of the scrapped front end blades, also enhance the crop shear's maintenance. The second sub-component of the experiment measuring the burr length, entailed optimising the process/production practices. The following sections elaborate on process methods employed to operate the crop shear at the HSM and the actual impact it has on maintaining this equipment.

4.3.5. Effect of the head and tail offset cut position values on the crop yield and reliability of the crop shear

One of the most noticeable process parameters that influenced the reliability of the crop shear blades was the values establishing the offset position of the head and tail. These values were used to control the position of the cut on the head and tail end of the transfer bar. In cases where an abnormal head end approached the crop shear, the values for the offset position could be altered to ensure a proper cut was made before the transfer bar entered the finishing mill. In order to minimise costs, losses had to be reduced and the crop yield, therefore, had to be minimised. The offset values were decreased, which resulted in a cut much closer to the edge of the transfer bar.

4.3.5.1. Effect of the head-and-tail offset values on the crop yield

Figure 40 below represents three series of scattered data plots. The values for the head-and-tail -end offset position are depicted in orange and grey, respectively, using the primary vertical axis. The crop yield, depicted by the black, scattered data, uses the secondary vertical axis. Day 1 to 315 represent the period of data gathering and analysis, before the CBM approach was implemented, and the remaining days display data after the CBM approach was implemented.

From day 1 to 30 the head-and-tail-end offset values were set to 85 mm with a minor variation that occurred in that period. From day 31 to 151, when referring to the crop yield data, a noticeable downward trend can be seen. The frequent changes in the offset values gradually got lesser until day 255, when the offset values predominantly remained fixed to 85mm. From day 421 onwards, the attempt to improve on crop losses was considered, hence the noticeable decrease in the offset value to 45 mm. An almost instant improvement in the crop yield was noticed after the change in offset values.

The noticed rapid increase in the crop yield along with unchanged offset values signifies occurrences where manual cuts were required in order to create a satisfactory head end before entering the finishing mill. Figure 41 focuses especially on the manual cuts made before and after the CBM approach was implemented. It was found that excessive manual cuts were made before the CBM approach. An average of 16.5 manual cuts per day, resulting in an average crop yield of 0.032% was calculated for the duration of the period under investigation. The roughing mill, therefore, had to ensure efforts are put in to minimise the excessive edging on the material where possible. Finishing mill operators were also informed on the consequences of excessive manual cuts and trained to eliminate the occurrences of performing unnecessary manual cuts.

The result was noticed immediately after implementing the CBM approach. An average of 1.83 manual cuts per day, resulting in an average crop yield of 0.00141%, was calculated for this duration. Reducing the significant number of manual cuts not only improved the crop yield as demonstrated in Figure 41 but, also helped the HSM to use the crop shear more effectively. Fewer manual cuts resulted in saving on costs but also on unnecessary wear on the crop shear blades.

4.3.5.2. Effect of the head-and-tail offset values on the reliability of the crop shear blades

In a few incidents it was noticed that a transfer bar processed slightly below the preferred target temperature and low values for the crop shear's offset caused a loud shearing. The drumming noise only occurred in instances where small offset values were used and abnormally cold material was sheared, when the crop-shear blades made contact with the transfer bar's surface. An investigation was therefore launched to prove that these process parameters truly had an effect on the reliability of the crop-shear blades.

The crop shear's performance before and after implementing the CBM approach was compared to the offset values for the head and tail ends, which is depicted in Figure 42. Similar to Figure 40, the graph represents three series of scattered data plots. The values for the offset position of the head and tail ends are depicted in orange and grey, respectively, using the primary vertical axis. The crop shear performance indicating the number of cuts made prior to its replacement is depicted by the green scattered data and uses the secondary vertical axis. Additionally, without an allocated scaled axis, the burr lengths for the head-and tail ends are included in the form of a data label.

When referring to the data displayed in the period from day 222 to 416, a fairly consistent offset value of 85 mm was used. On the left-hand side, for day 1 to 221, the data is less consistent due to regular variations in the offset values for the tail end that predominantly featured at the 65 mm mark. On the opposite side, the data on the right-hand side, more specifically day 416 to 555 indicate less inconsistency but in this case the offset values for both the head-and tail ends prominently featured at the 45 mm mark.

The results on the right-hand side revealed that the burr lengths for both the head and tail ends are larger than those found in the period from day 222 to day 416 even though the cartridges made fewer cuts. This conclusion, therefore, supports the hypothesis that the smaller offset values forced the crop shear to cut closer to the edge of the transfer bar, and in effect was cutting colder areas of the transfer bar, and thus the increased wear rate that was noticed on the crop-shear blades.

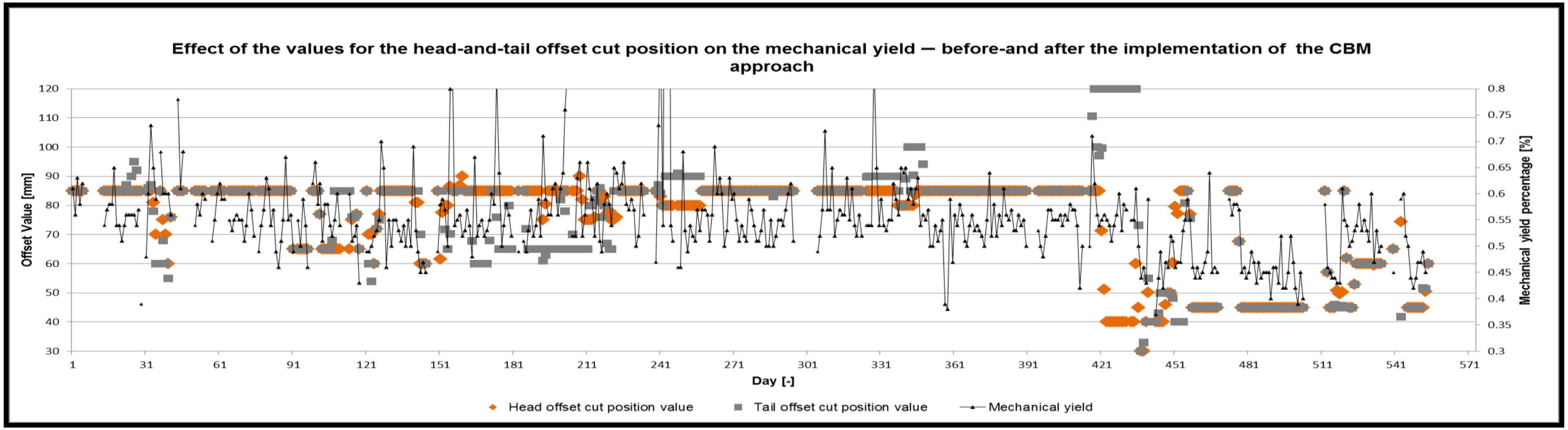

Figure 40: Effect of the values for the head-and-tail offset cut position on the crop yield – before and after implementing the CBM approach

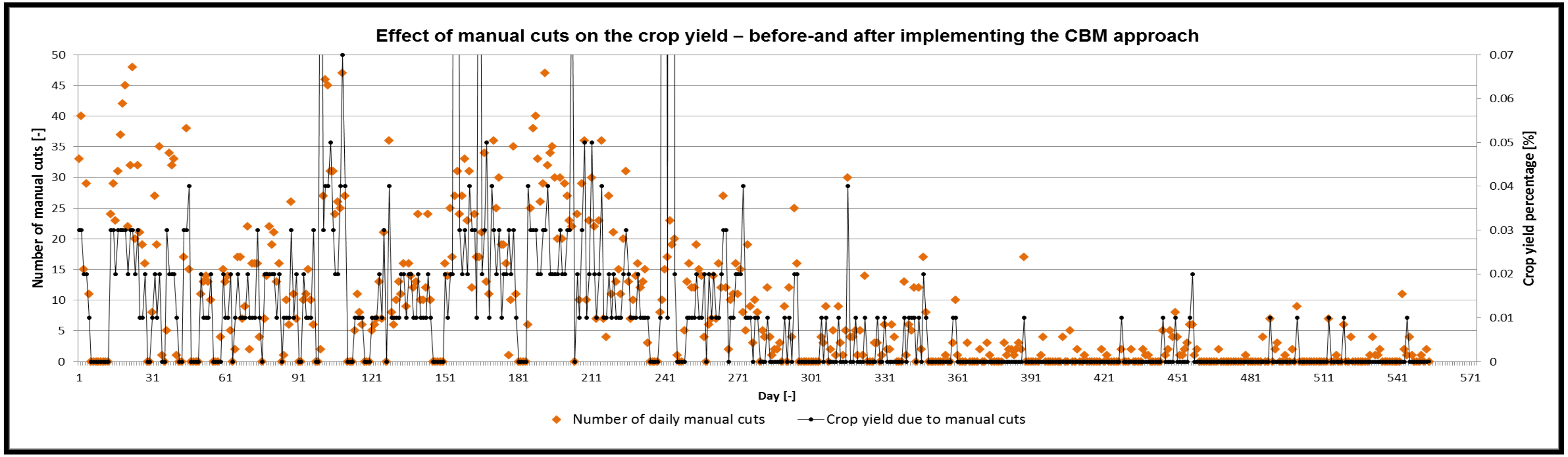

Figure 41: Effect of manual cuts on crop yield – before and after implementing the CBM approach

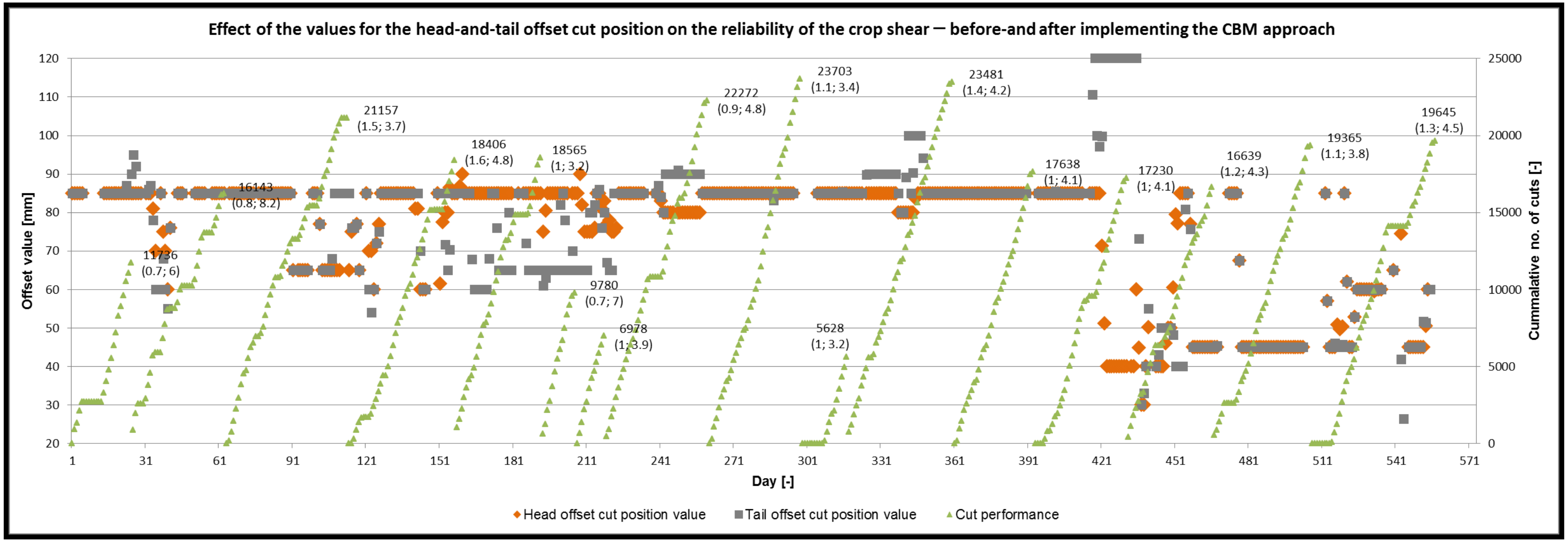

Figure 42: Effect of the values for the head-and-tail offset cut position on the reliability of the crop shear – before and after implementing the CBM approach

4.3.6. Difference between cutting on automatic and manual modes

It was necessary to determine whether a difference in the burr length was noticed when using the different cutting modes. Therefore, an experiment was undertaken in which the burr length was compared with occurrences of similar conditions, except for the change between the automatic and manual cutting mode.

Figure 43 below represents the data captured from 10 manual and automatic cuts that were made. Sample 1, for example, provides a comparison on the resulting burr length for both the head and tail end when applying the manual and automatic mode.

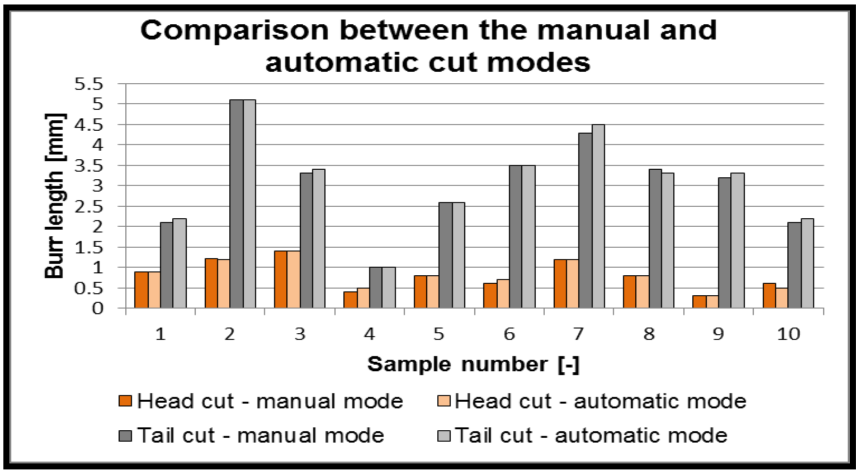

Figure 43: Comparison between the manual and automatic cut modes

In Figure 43 above, the darker shades of orange and grey indicates the resulting burr lengths of the head and tail cuts under the manual cutting mode. In comparison with the darker shades, the lighter orange and grey shades depict the burr lengths of the cuts made by using the automatic mode.

When comparing the burr lengths of an automatic cut with those of a manual cut, no significant difference was found. The manual cuts were only made as intervention in the normal operation when additional cuts were required. Therefore, the manual cuts only led to an increase in crop yield – as demonstrated previously (Figure 41).

4.3.7. Effect of the lead-and-lag speed of the delay table relative to the crop shear on the burr length of the offcut

In order to determine whether the lead/lag speed of the crop shear influenced the burr length of the offcuts, ten different samplings were done where the burr length could be measured for different speed settings. For each sampling the lead/lag speed of the crop shear was set to -3, 0, +3 and +5 respectively, and the tail end's burr length was measured on each speed setting.

Comparatively demonstrated in Figure 44 below the burr lengths for each sampling is categorised according to each speed setting.

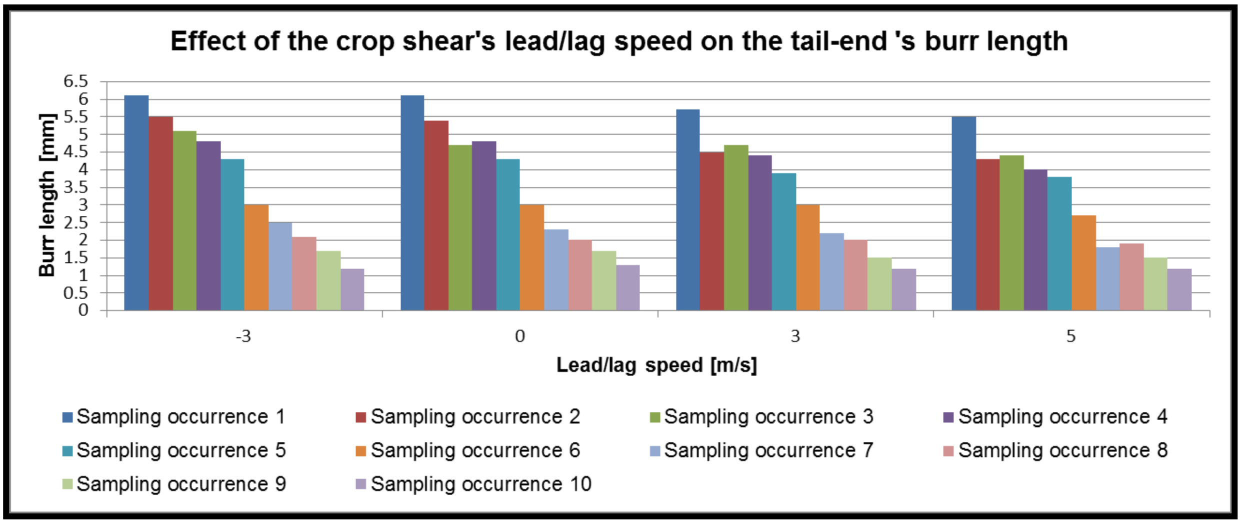

Figure 44: Effect of crop shear's lead/lag speed on the tail-end's burr length

In all the sampling a decreasing tail-end burr length was found with an increasing lead/lag speed of the crop shear. For example, sampling 2 resulted in a 5.5 mm tail-end burr length at a lag speed setting of -3. For a lead/lag speed setting of 0, +3 and +5, the burr length decreased with each increment in the speed setting.

To ensure for the maximum duration of a cartridge's lifecycle, a crop shear lead speed of +5 was thus recommended.

4.3.8. Compared performances between the three different crop-shear cartridges

The different performances of the three crop shear cartridges were compared and similar results were concluded. Figure 45 below demonstrates the number of cuts each of the three crop shear cartridges had completed before each was replaced during the period July 2009 to August 2015.

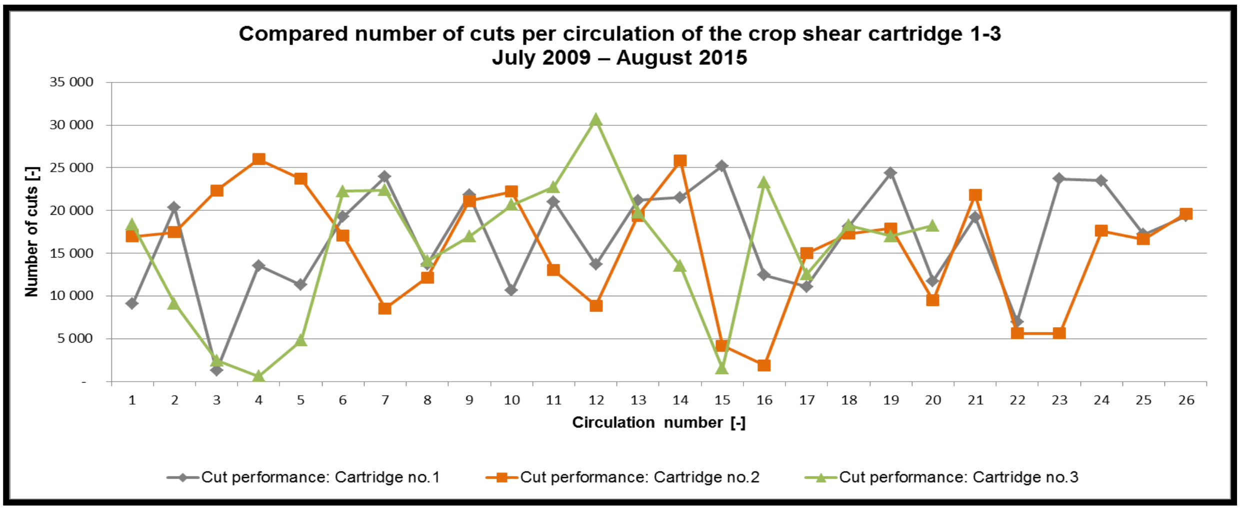

Figure 45: Compared number of cuts per circulation of crop-shear cartridge 1-3 July 2009 – August 2015

From the 26 circulation occurrences that crop-shear cartridge 1 was used, the average number of cuts made was 16 749. Crop-shear cartridge 2 was used on 26 occurrences and delivered an average of 15 671 cuts. With similar results, crop-shear cartridge 3 delivered an average of 15 469 cuts from the 20 times it was used.

The circulations of the last six crop shear cartridges after the CBM approach was implemented, delivered a total average of 19 000 cuts. Not only was the average number of cuts since the CBM approach implementation higher than the achieved total average of 15 963 cuts for the period 2009 – 2014. As demonstrated in Figure 36 but for the last six circulations the cuts were also more consistent.

Although the average number of cuts achieved per cartridge differed, the trend of each cartridge's operation was similar. Each cartridge demonstrated an erratic performance prior to the CBM approach implementation. Thus it can be concluded that each cartridge is equally reliable, seeing that no obvious difference in performance was noticed when the cartridges were compared. The average number of cuts achieved per circulation for each cartridge could not have been used as a KPI by which to compare the performance of the cartridges.

In many cases the cartridges were not used up until the exact targeted number of cuts or burr length. Therefore its performances were restricted to shutdowns shortly before the target was expected to be met. It was good practice at the time to use a shutdown for replacing the cartridges in cases where the actual performance had almost reached the targeted rate, rather than causing another production delay by isolating the equipment only to replace the crop-shear cartridge.

4.3.9. V&V results of the burr-length measurements

No incorrect measurements were found when measuring the verification test piece after zeroing the vernier. It can, therefore, be concluded that the dimensions obtained from the experiment was highly effective in fulfiling its purpose.

The aim of determining the condition of the crop-shear blades by measuring the dimensional characteristics of a crop-shear offcut was found to be successful. An increased usage of the blades linked to a progressively increasing burr length was found. This finding helped the researcher to draw valid conclusions from the various experimental approaches.

The findings according to the opinion of a maintenance expert on whether the correct experimental approach was considered in the experiment measuring the burr lengths are discussed in section 4.5.

Chapter 5 provides the interpretation of these results.

4.4. Results: Why-Why diagram

The Why-Why diagram focused on 14 major problems related to the crop shear equipment and its operation. (The Why-Why diagram is presented in Appendix F). The entire mind-map consists of 96 entries that elaborate on the root cause for the unreliable conditions of the crop shear. The mind-map includes problems detected prior to the present study as well as during the experimental period. Approved by the Reliability Progress Manager, the detailed Why-Why diagram did not only help offering effective solutions during the course of the present study. It also identified other possible malfunctions that may occur in the future. Therefore, the analysis can either be referred to when needing to improve the unplanned downtime, or used as a troubleshooting manual.

4.5. Results: Interview

A 30 minute interview was held with a maintenance expert to validate the proposed CBM approach and its results thus far. Dominique Cosset was the interviewee, a French engineer and maintenance expert with 40 years' experience, of which 36 years were related to the steel industry. Dominique provides consultation to various steel-producing plants across the world, including Belgium, USA, Italy and India, to assist with methodological approaches aimed at improving maintenance, production and reliability.

Working through the present study with Dominique prior to the interview, he was given the opportunity to acquaint himself with the proposed CBM approach. Any misunderstandings were thoroughly cleared up beforehand with the interviewee.

The following remarks were made in the interview:

1. There was consensus that the crop shear's availability, discussed in Experimental component 1, represents the improved results that was expected after implementing the reliability program in 2011. Dominique commented on the contribution of the mechanical equipment (i.e. crop-shear housing, power transmission and motor) towards the unplanned downtime in the years 2012, 2013 and 2014. He confirmed that this indicates the need to deal with other factors causing unplanned downtime, before a significant improvement could be expected in the future. The factors to which he referred are the involvement of the production and process teams, the methodologies they follow to operate and control the crop shear, as well as the frequency with which the cartridge is replaced.
2. Dominique valued the questionnaire and the approach followed to involve the other HSM personnel in gaining their input, especially the artisans and the operators. He emphasised that a team effort was needed to sustain the improvements successfully. The involvement of all the relevant personnel, from the initial stages of the project, would thus only make it easier to implement the required corrective actions.
3. This was the first time that Dominique had heard of and seen that a CBM approach is implemented to maintain a crop shear cartridge, especially by using the burr length on the offcuts. Dominique said that all the other HSM plants he had been acquainted with use a systematic approach and are able to sustain 100% availability. A fixed frequency for replacements in terms of tonnage or days was used, for example, the cartridge would be replaced with every 100 000 tons of steel produced. Dominique also added that, although the proposed CBM approach was very effective, the approach was more time-consuming, more complicated and labour intensive in comparison with the systematic approach that he mentioned.

4. Dominique commended the fact that sub-component 3.2 addressed the factors involved in the process/production. He mentioned that it was extremely important that the lead/lag speed of the crop shear was included. Dominique commended the fact that the results of the experiment presented to him were similar to his expectations.
5. When referred to the current crop-shear works instruction, Dominique confirmed that the document was not comprehensive enough and, therefore, ineffective. An example was mentioned where the production personnel attempted to cut a cold transfer bar. Although the production personnel were aware of the risks involved, they were not definitely sure whether the crop shear would be able to perform the task. Unfortunately the transfer bar was too cold and thus damaged the blades. Dominique argued that a standard should be designed and incorporated into the works instruction. This would provide the relevant personnel with a reference to the preferred means of operating and maintaining the crop shear. This especially applies to the operators, that they will be able to avoid such occurrences in the future. Dominique also stressed the importance to educate the personnel, not only by supplying them with a detailed works instruction but also to monitor their performance and communicate with them continuously. Dominique placed high emphasis on communication and its effective execution.
6. Dominique also suggested that the integrity of the workmanship practiced when installing the blades should be investigated. He points out that it is vital that the blade setup is installed perfectly otherwise increased wear and premature blade failures can be expected. In some of the other plants the shear-blade services are not only responsible to recondition the blades but also to assemble the crop-shear cartridge. Dominique also stressed the importance of using good grinding practices.
7. Towards the end of the interview, it was agreed that the proposed CBM approach was highly effective although it was extremely labour intensive. Even though the CBM approach could turn out too labour intensive and over-stress the resources, this approach could be used until acceptable performance has been maintained and the contributing factors hampering sustainable performance have been eliminated. Then a systematic approach could be implemented. Although less labour intensive, a systematic approach will no longer allow the asset manager to maximise the usage of the crop-shear blades.

With the assistance of Dominique, the interview concluded the experimental approach that was followed. Dominique highlighted the importance of some basic principles in the interview that should assist the implementation of the proposed CBM approach and deliver the anticipated results. The basic principles and methods which Dominique has pointed out, has allowed him to assist numerous other plants in delivering outstanding results.

4.6. Results: Conclusion

The worst recorded unplanned downtime for the crop shear was found to be 0.55% in the year 2010. In comparison with the recorded improvement noticed in the year 2012 the crop shear's availability performance has remained relatively stable at 0.26%, 0.27% and 0.21% for the period 2012, 2013 and 2014, respectively. Not only did the results of the questionnaire reaffirm the need for an improved approach for the HSM personnel it also brought to light several other contributing factors that were initially not anticipated. The questionnaire's results led to the conclusion that the attitude of the production personnel had to be addressed and that the SOP material that was made available to the personnel was ineffective. As many as 91% of the participants anticipated that the proposed approach would help reduce unplanned downtime. Feedback received from the participants also led to the experiments conducted in the second sub-component that measured the burr length. This experiment focused on the process/production practices and its optimisation. A head-and-tail-end burr length of 1.5 mm and 4.5 mm respectively was determined to be the preferred means of indicating when a cartridge needs to be replaced. The previous methodology employed at the HSM to replace the crop-shear cartridge every 22 000 cuts proved to be ineffective.

The proposed approach led to a 50% improvement in the unplanned downtime of the crop shear and eliminated the unplanned downtime, due to poor blade conditions, from 0.05% to 0%. The average number of cuts also increased from 15 963 to 19 000 cuts, after the CBM approach was implemented. The results of the experiments regarding the process/production were beneficial to the process and production team by helping the members follow the preferred process and operation setups.

Although the experimental approach was extensive, a number of other problems were noticed that needed to be addressed. Unfortunately the workload could not permit the researcher to rectify those problems as well. However, by using a common problem-solving tool at the HSM, the Why-Why diagram, a detailed diagnostic framework was constructed, which highlights the root-causes to the additional problems confronted throughout the study. The maintenance consultant commended the extensive approach that was considered to improve the crop shear's performance. Although the proposed CBM approach is labour intensive it has proved to be highly effective in curbing the poor performance of the major KPIs.

The following chapter (Chapter 5) provides a more detailed analysis of the findings that were made throughout the study.

Chapter 5: Discussion and interpretation

The results of each experimental component in Chapter 4 have already been discussed within its own domain. The aim of Chapter 5 is to elaborate and conclude the results about the expected benefits and the deliverable of the study. Thereafter critical findings of the study are highlighted, introducing the newly revised standard operating procedure (SOP) and the proposed condition based maintenance (CBM) approach.

5.1. Discussion of the study's general results

Figure 46 below illustrates the crop shear's unplanned downtime for the years 2008 to 2015. The 2015 year to date (YTD) unplanned downtime of 0.15% is the best ever recorded results for the Hot Strip Mill (HSM). The average unplanned downtime for the crop shear was 0.32% for the period 2008 to 2014. The unplanned downtime due to damaged blades was eliminated from the period 2014 to 2015. The unplanned downtime of the disturbances in the process/production also improved from 0.16% to 0.12%.

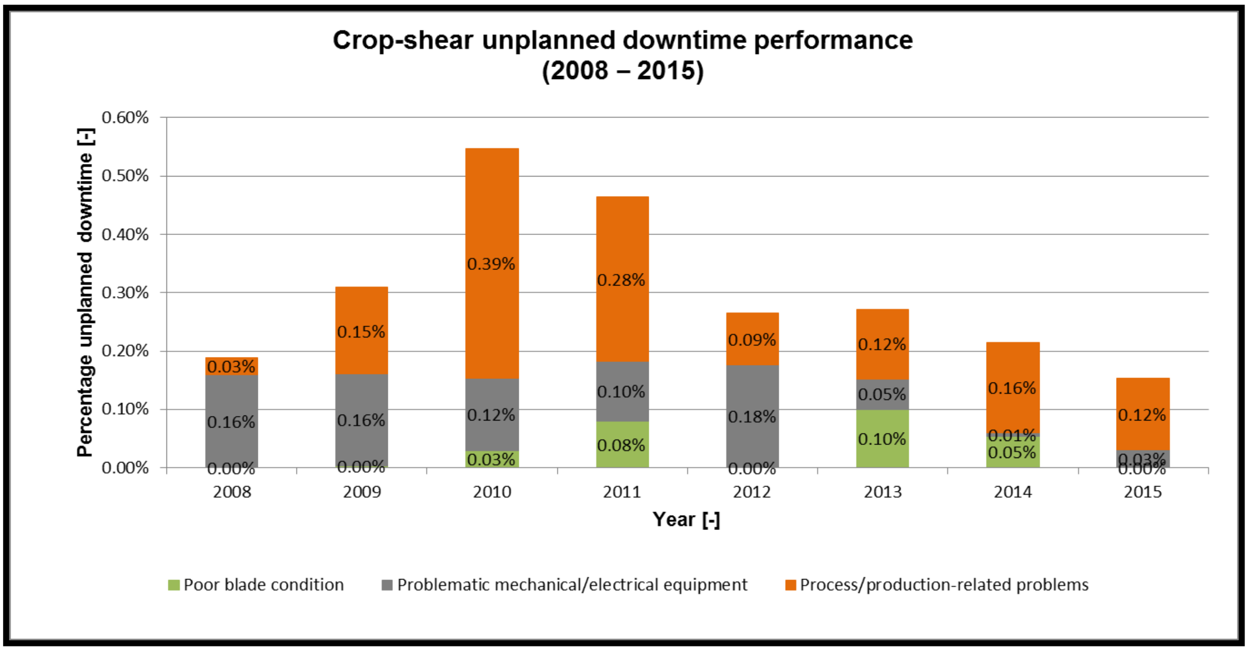

Figure 46: Crop-shear unplanned downtime performance 2008 – 2015

Figure 47 below compares the performance regarding circulation occurrence 1 to 65 and 66 to 71, to illustrate the impact of the implemented CBM approach. The regression analysis revealed an improvement in consistency and predictability of the crop shear's performance. The percentage in variance value increased from 0.0159 to 0.0975.

The blades' lifetime has also improved from an average of 15 963 cuts before the CBM implementation, to 19 000 in the last six circulation occurrences.

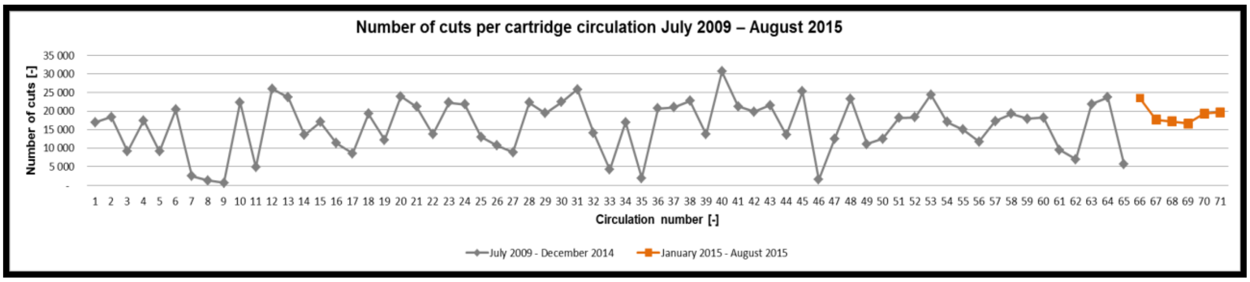

Figure 47: Number of cuts per cartridge circulation July 2009 – August 2015

It was deduced from the literature review that the proposed CBM approach for the crop shear at the HSM was not yet a commonly used practice throughout the global steel-making industry. The results corroborate these initial expectations of the study. The maintenance consultant, Dominique, also commented on the distinctiveness of the proposed approach in mentioning that he had never before come across this type of approach to maintain a crop shear.

5.2. Discussion of the questionnaire

The results from the questionnaire exposed the desperate need for an effective SOP for the crop shear at the HSM. The content of the current SOP was in need of improvement in certain areas mentioned below (Also mentioned per item, is the remedial actions considered in the newly revised SOP):

1. Process introduction

   A section in the revised SOP was meant to familiarise the reader/user with an effective introduction of the crop shear’s purpose and functionality.

2. Process parameters

   The process parameters determined in the study, and which provided the most effective means to operate the crop shear at the HSM, was introduced to the SOP. The operators were expected to work according to these specified process parameters at all times.

3. Maintenance strategies

   The procedure of the validated CBM approach was included in the revised SOP, ensuring that all personnel understood the new replacement strategy.

4. Maintenance execution

   The important specifications were included for the proper installation of the crop-shear blades and the insertion of the cartridge in the revised SOP, to ensure consistent basic conditions maintained for the crop shear. In cases where problems did occur, several possible causes could be eliminated if basic conditions are adhered to. This also led to more effective fault finding and the minimising of unplanned downtime.

5. Trouble shooting

   Reference to technical drawings of the crop shear was included in the SOP to assist with fault finding. The detailed Why-Why diagram compiled in Experimental component 4 was also included in the SOP to keep the reader/user informed of known problems associated with the crop shear's operation.

6. Communication and enforcement

   The specific communication methodology needed to be followed to ensure that all the personnel were aware of the current performance conditions. This methodology was included in the revised SOP. Furthermore, the methodology outlining how the revised SOP should be enforced and managed to remain effective was also included in the revised SOP.

5.3. Discussion of the burr length measurement experiment

The established head-and-tail-end burr length of 1.5 mm and 4.5 mm, respectively, was used as the maximum allowable reference to predict the replacement of the crop shear's cartridge. This reference was included in the section of the SOP dealing with the maintenance strategy.

The preferred parameters for the process/production as identified in the study were expected to deliver a more improved performance once officially rolled out in the revised SOP. The continual adjustments made throughout the study meant that the configurations determined to deliver the best results was not continually implemented throughout the year. Adherence to the proposed process parameters would allow for more stable operating conditions and easier fault finding.

The outcomes of the experiment to measure the burr length have demonstrated improved results at the HSM. Nevertheless, the maintenance consultant still critiqued the CBM approach for being too labour intensive. He suggested that a systematic approach would make maintaining the crop shear easier and be more sustainable in the future. The consultant has witnessed other HSMs use a systematic approach and as a result, they maintain a crop-shear availability of 100%. Unfortunately it is expected of any general CBM methodology to be more labour intensive due to the constant record keeping and analysing needed to make the methodology effective (Barron, 1996).

In favour of the consultant's opinion and for future executors of the proposed CBM approach, a systematic approach could be considered once the application of the revised SOP has provided near-perfect (100%) operating conditions. For a systematic approach to be effective at the HSM, abnormal operating conditions have to be avoided such as cutting cold edges, which would affect the reliability of the crop-shear blades.

5.4. Discussion of the Why-Why diagram

A Why-Why diagram was compiled, which included the problems that were identified previously and were overcome. The SOP would thus not only be effective in guiding the personnel in the most effective way to operate and maintain the crop shear, but also function as a vital tool during fault-finding exercises. It was a unique venture for a HSM SOP to include a Why-Why diagram as troubleshooting manual in the content of the SOP at that time. In this light, the maintenance consultant approved of the fresh approach. The inclusion of the detailed troubleshooting manual therefor added value to the SOP.

5.5. Responsibilities of HSM management

The attitude and knowledge of the teams managing the production and systems' reliability were also concluded to be a major problem, which impeded the performance of the crop shear at the HSM. In these cases, solely relying on the SOP and expecting a significant improvement, may have set the bar too high. It is thus recommended for management to ensure that training sessions are made available to address these deficiencies, which would allow the team to work effective in deliver the required results.

The sustainability of the CBM approach and the related results depends on the manner in which the HSM management enforces the SOP. The initial SOP used as a platform to improve the revised version was maintained incorrectly and enforced poorly. Although the initial SOP had been previously revised by management, it still was ineffective in aligning the HSM personnel. Again the concept of teamwork is emphasised. From webGURU and the interview with the maintenance consultant, the importance was underlined that management should enforce the use of the SOP. The best SOP will be ineffective if not managed and enforced properly. The HSM management, therefore, have to accept the responsibility of maintaining effective and valid SOP if they expect efficient results from the HSM personnel.

By considering the input of the HSM personnel when the newly revised SOP was developed demonstrates the advantages of incorporating all the HSM personnel. Management should take constant note of personnel's requests and input. Then if necessary, the SOP should be revised to maximise its applicability and thus ensuring that the SOP remains a reliable tool in the operation.

The importance of management supporting the maintenance and operating personnel was also emphasised by the maintenance consultant. The personnel should, therefore, be encouraged to challenge the management teams when noticing a lack of assistance.

The newly revised SOP is attached to Appendix H. The indications are that the application of the revised SOP should maintain the results noticed in the last six circulation occurrences and allow the HSM to improve further on the unplanned downtime flowing from the process/ production.

Chapter 6: Conclusions and recommendations

6.1. Conclusions

The proposed condition based maintenance (CBM) approach yielded the expected result of improving the reliability of the crop shear's operation, providing a solution to reduce operational and maintenance costs of the crop shear at the Hot Strip Mill (HSM). The alternative solution was unique from both a literature and practical point of view; hence the prescribed requirements for validation to assess the feasibility of implementing the proposed CBM approach as preferred practice at ArcelorMittal South Africa (AMSA) Vanderbijlpark HSM.

Maintenance records verified the anticipated that the use of the crop shear at the HSM was unreliable. The discipline-specific approach was favoured seeing that it provides a prognosis of the various attributes for the crop shear's reliability. The experimental component could thus be designed accordingly, considering each of the disciplines to ensure that effective remedial measures were put in place.

The input received from the informed HSM personnel verified, from a different perspective, the need for the study as well as the non-ideal operating conditions that existed. The wealth of knowledge and practical experience was employed to the benefit of the study, to reaffirm that the personnel too, desire improved reliability in the operation of the crop shear. The input and suggestions received added to the detail considered in the experimental component design, especially regarding the attributes of the process and production.

Analysing the characteristics of the burr length helped establish a relationship between the crop shear offcuts' burr length and the actual wear condition of the crop-shear blades. It was determined that the gap between the crop-shear blades and the offcuts' burr length was indeed related. The longer the crop shear blades were in operation, the blades' wear increased, thereby widening the gap between the two shearing blades. By determining the maximum allowable burr-length target at which the crop-shear cartridge should be replaced meant all future cartridges could be managed preventatively before encountering cutting problems. This also reduced unplanned downtime. The CBM approach proved to be a valid alternative to the existing maintenance strategy, seeing that the former delivered the least unplanned downtime ever recorded at the HSM in 2015.

The burr length was later also used to determine the impact of the different control parameters on the offcuts' burr length for the crop shear. In order to minimise the offcuts' burr length, and thus maximise the operational blades' lifetime, the preferred control configuration was determined and also implemented, which delivered more reliable operating conditions.

With a view to sustain the CBM approach and the results obtained in the study for future purposes, the current standard operating procedure (SOP) was revised. Amendments included the procedure for the CBM approach, the specification for a maximum allowable burr-length target, and the other control configurations for the process and production – all intended to enhance the crop shear's performance at AMSA Vanderbijlpark HSM.

The study thus successfully covered the operation, as well as the maintenance and management principles of a rotary drum crop shear application. The validated study, therefore, also contributed to the body of knowledge in this field because of the similarity of the shearing application across HSMs globally.

6.2. Recommendations

Even though the proposed CBM approach implemented at the HSM was universally applicable, the exact findings would most probably not be as effective in a different application. The same experimental procedure will have to be followed to determine the maximum allowable burr-length target as well as the preferred configuration to control the process and production that would be viable for that particular application. Each process can, therefore, be considered unique although the fundamentals of the proposed CBM approach are valid for all shearing applications.

Process and material specifications differ amongst the various steel producing plants, and have to be factored in when considering implementing the exact findings drawn from the present study, for a different shearing application. The difference in transfer bars' width and thickness, and the metallurgical composition of the material that is sheared, are some of the variables that have to be considered.

It is recommended that, if possible, the relevant material specification measured per offcut is also captured. The crop-shear blades' wear rate can then be linked to a particular material specification. Whether the interest lies in a more detailed performance analysis, or opting for a particular specification for the material, in order to maximise the crop-shear blades' lifetime, the additional data may be beneficial to the user or operator.

From the validated findings it was concluded that the proposed CBM approach is a high labour-intensive methodology. Although more time and effort was required, the CBM approach was successful in maximising the crop shear's blades' lifetime. No further production disturbance was reported after implementing the approach, even though production abnormalities occurred.

Other methodologies may be considered, however these hold the risk of production disturbances by not considering the condition of abnormalities occurring during production. Such abnormalities include cold transfer bars, double front ends and camber from the roughing mill, all which undermine the blades' reliability. If these abnormalities are not dealt with proactively, it may result in premature failure of the blades and thus cause significant unplanned downtime.

With the aim to maximise the crop-shear blades' life duration, the other methodologies mentioned above only seem feasible if stable production conditions are maintained and no, or very few, production abnormalities occur.

The CBM approach proposed in the present study could, however, also be implemented temporarily to determine the maximum allowable burr-length target as well as the other configurations to control the process and production. This strategy would yield more stable operating conditions without any or very few production abnormalities. By applying the methodology of the burr-length measurement, the user/operator will in time develop insight into the number of cuts usually made before a preventative cartridge replacement occurred. Although it is not as efficient as the CBM approach, the usage-based replacement methodology could then be considered if it was able to maintain stability in production and avoid abnormalities in the operation.

I believe that I have achieved a personal goal in contributing to the “bottom line” of my employer with this work, and if fully implemented and supported by management, will make a material difference to the operational efficiency of AMSA HSM.

My next objective would be to share the results of my research with the broader maintenance community, by publishing in an international journal or presenting a paper at an international maintenance conference.

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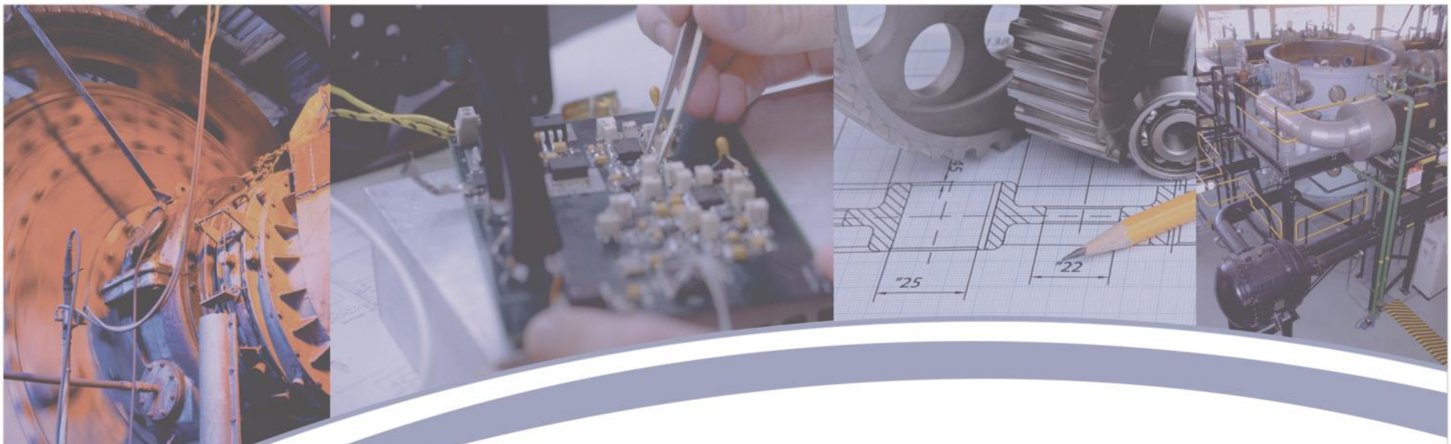
Appendix A (Unplanned downtime and number of cuts data)

Crop shear unplanned downtime and availability data								
Description	**Year**							
	2008	2009	2010	2011	2012	2013	2014	2015
Crop shear unplanned downtime data (minutes)								
Unplanned downtime: Poor blade condition	0	16	129	339	0	350	206	0
Unplanned downtime: Mechanical equipment	684	660	532	441	633	182	23	83
Unplanned downtime: Process / production related problems	128	627	1693	1211	314	418	601	330
HSM plant availability time	429676.2	421804.8	430615.8	428140.8	357888	349716	386860.2	269799
Crop shear unplanned downtime data (percentage)								
Unplanned downtime: Poor blade condition	0	0.004	0.03	0.079	0	0.1	0.053	0
Unplanned downtime: Mechanical equipment	0.159	0.156	0.124	0.103	0.177	0.052	0.006	0.031
Unplanned downtime: Process / production related problems	0.03	0.149	0.393	0.283	0.088	0.12	0.155	0.122
Annual HSM production								
Hot rolled coil production (metric ton)	2419477	1922706	1411388	2613472	2116224	1831705	1886954	-

Crop shear cut performance											
Occurrence No.	Date In	Date Out	No. of cuts	Cartridge No.	Type of Replacement	Occurrence No.	Date In	Date Out	No. of cuts	Cartridge No.	Type of Replacement
1	01-Jul-09	27-Jul-09	16 946	2	Preventative	**36**	11-Nov-11	20-Dec-11	20 666	3	Reactive
2	27-Jul-09	09-Sep-09	18 350	3	Reactive	**37**	20-Dec-11	23-Jan-12	21 034	1	Preventative
3	09-Sep-09	22-Sep-09	9 080	1	Reactive	**38**	23-Jan-12	01-Mar-12	22 772	3	Preventative
4	22-Sep-09	21-Oct-09	17 448	2	Reactive	**39**	01-Mar-12	26-Mar-12	13 672	1	Preventative
5	21-Oct-09	03-Nov-09	9 120	3	Preventative	**40**	26-Mar-12	25-May-12	30 686	3	Preventative
6	03-Nov-09	02-Dec-09	20 344	1	Preventative	**41**	25-May-12	24-Jul-12	21 210	1	Preventative
7	02-Dec-09	08-Dec-09	2 484	3	Reactive	**42**	24-Jul-12	12-Sep-12	19 788	3	Preventative
8	08-Jan-10	25-Jan-10	1 276	1	Preventative	**43**	12-Sep-12	17-Oct-12	21 543	1	Preventative
9	25-Jan-10	26-Jan-10	604	3	Preventative	**44**	17-Oct-12	10-Dec-12	13 522	3	Preventative
10	26-Jan-10	03-Mar-10	22 338	2	Reactive	**45**	10-Dec-12	18-Mar-13	25 242	1	Preventative
11	03-Mar-10	09-Mar-10	4 788	3	Reactive	**46**	18-Mar-13	26-Apr-13	1 527	3	Reactive
12	09-Mar-10	08-Apr-10	25 996	2	Reactive	**47**	26-Apr-13	17-May-13	12 446	1	Reactive
13	09-Apr-10	17-May-10	23 688	2	Reactive	**48**	17-May-13	18-Jun-13	23 335	3	Reactive
14	17-May-10	03-Jun-10	13 570	1	Reactive	**49**	18-Jun-13	04-Jul-13	11 089	1	Reactive
15	03-Jun-10	27-Jun-10	17 036	2	Reactive	**50**	04-Jul-13	30-Jul-13	12 550	3	Reactive
16	27-Jun-10	14-Jul-10	11 312	1	Preventative	**51**	31-Jul-13	05-Sep-13	18 123	1	Preventative
17	14-Jul-10	24-Jul-10	8 564	2	Reactive	**52**	06-Sep-13	01-Oct-13	18 267	3	Preventative
18	24-Jul-10	07-Aug-10	19 272	1	Reactive	**53**	01-Oct-13	11-Nov-13	24 421	1	Preventative
19	07-Aug-10	26-Aug-10	12 162	2	Reactive	**54**	20-Nov-13	18-Dec-13	17 000	3	Reactive
20	26-Aug-10	30-Sep-10	23 958	1	Reactive	**55**	18-Dec-13	27-Jan-14	15 004	2	Reactive
21	30-Sep-10	28-Oct-10	21 130	2	Reactive	**56**	05-Feb-14	02-Mar-14	11 736	1	Preventative
22	28-Oct-10	18-Nov-10	13 684	1	Preventative	**57**	02-Mar-14	10-Apr-14	17 310	2	Preventative
23	18-Nov-10	04-Jan-11	22 230	2	Preventative	**58**	10-Apr-14	26-May-14	19 241	1	Preventative
24	04-Jan-11	02-Feb-11	21 800	1	Preventative	**59**	26-May-14	09-Jul-14	17 914	2	Preventative
25	02-Feb-11	03-Mar-11	13 012	2	Preventative	**60**	09-Jul-14	13-Aug-14	18 227	3	Preventative
26	03-Mar-11	21-Mar-11	10 660	1	Reactive	**61**	13-Aug-14	26-Aug-14	9 478	2	Reactive
27	21-Mar-11	03-Apr-11	8 884	2	Reactive	**62**	27-Aug-14	08-Sep-14	6 979	1	Reactive
28	03-Apr-11	03-May-11	22 264	3	Reactive	**63**	08-Sep-14	21-Oct-14	21 850	2	Preventative
29	03-May-11	30-May-11	19 388	2	Preventative	**64**	21-Oct-14	26-Nov-14	23 703	1	Preventative
30	30-May-11	29-Jun-11	22 386	3	Preventative	**65**	26-Nov-14	15-Dec-14	5 628	2	Reactive
31	29-Jun-11	12-Aug-11	25 834	2	Preventative	**66**	15-Dec-14	27-Jan-15	23 481	1	Preventative
32	12-Aug-11	11-Sep-11	14 100	3	Reactive	**67**	27-Jan-15	05-Mar-15	17 638	2	Preventative
33	11-Sep-11	11-Oct-11	4 182	2	Preventative	**68**	05-Mar-15	08-Apr-15	17 230	1	Preventative
34	11-Oct-11	07-Nov-11	16 948	3	Reactive	**69**	09-Apr-15	15-May-15	16 639	2	Preventative
35	07-Nov-11	11-Nov-11	1 886	2	Preventative	**70**	15-May-15	01-Jul-15	19 365	1	Preventative
						71	01-Jul-15	12-Aug-15	19 645	2	Preventative

Appendix B (Questionnaire)



As partial fulfilment of my Master's degree in Engineering Development and Management I have decided to adopt the current situation regarding the poor crop shear performance at the ArcelorMittal HSM plant as the topic for my Master's dissertation, namely: "*A conditioned based maintenance approach for a rotary drum crop shear*".

This questionnaire is aimed at obtaining your valuable input and utilising the data as part of my experimental research with the hope to determine the need for an alternative approach in the way we operate and maintain the crop shear at the HSM

Questionnaire collection date: 17th July 2015

Evo Ribeiro

I would like to thank you for participating in the survey, your much appreciated time and valuable input. I am looking forward to the results and the anticipated benefits from this survey.

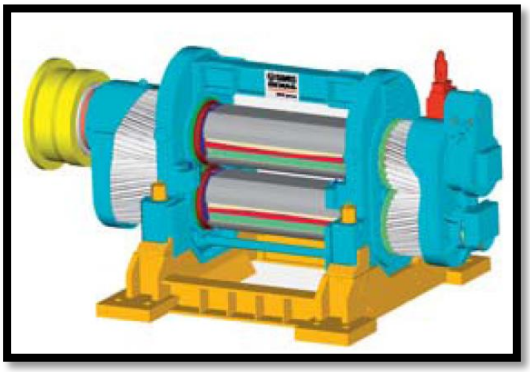
North-West-University Potchefstroom Campus

Innovation through diversity ®

NORTH-WEST UNIVERSITY ®
YUNIBESITI YA BOKONE-BOPHIRIMA
NOORDWES-UNIVERSITEIT
POTCHEFSTROOM CAMPUS

1. Are you familiar with the crop shear utilised at the HSM (Hot Strip Mill)? If not, please indicate so in the selection box below by marking the relevant option with a X. It is then also no longer necessary to complete the remaining questions within the questionnaire if you have answered no.

Yes	No



2. Please rate your detail of experience regarding the crop shear (If applicable, more than one option may be selected with a X):

You have **only** heard of and seen the crop shear in operation	
You have physically conducted maintenance on the crop shear before	
You have operated the crop shear before	
You have been involved in trying to improve the reliability of the crop shear	

3. Please rate your detail of technical knowledge related to each of the disciplines listed below regarding the crop shear (Give a rating for each one of the disciplines):

Discipline	Very good	Fair	Not good
Your knowledge from a **systems** point of view			
Your knowledge from a **mechanical** point of view			
You knowledge from an **operating** point of view			
Your knowledge from a **reliability** point of view			

4. Have you undergone any form of training on the crop shear before? If yes, please briefly elaborate.

Yes	No

____

____

____

5. Have you had the opportunity to read the crop shear works procedure before?

Yes	No

6. Attached to Appendix 1 of the questionnaire is the latest revised crop shear works procedure. Do you think the latest revision is effective in elaborating on operating and maintenance principles of the crop shear?

Yes	No

7. If your answer to the above question is no, please select the possible aspects listed below you agree with (If applicable, more than one option may be selected). Please elaborate below if felt needed.

Insufficient detail related to process introduction	
Insufficient detail related to process parameters	
Insufficient detail related to preferred maintenance strategies	
Insufficient detail related to maintenance execution	
Insufficient detail related to trouble shooting manual	

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Throughout the questionnaire the term performance/utilisation is frequently used. The term refers to the following aspects of the crop shear:

- Maximising the life cycle duration of the crop shear blades.
- Minimising the mechanical yield.
- Minimising the unplanned down time of the crop shear.

8. Are you aware that the crop shear performance/utilisation is being monitored by HSM personnel?

Yes	No

9. If your answer to the above question is yes, please indicate from options below how the performance/utilisation is being monitored. (If applicable, more than one option may be selected.)

Number of cuts conducted per cartridge	
Number of days the crop shear cartridge is in operation	
Unplanned downtime	
Mechanical yield	

10. From your selection in the above question, do you know what the condition of current performance/utilisation figures of the crop shear is?

    For example, if you have chosen “number of cuts conducted per cartridge” do you know the approximate number of cuts that are conducted by a crop shear before being replaced?

Yes	No

11. If your answer to the above question is no, would you be interested in receiving monthly feedback regarding the crop shear performance/utilisation figures?

Yes	No

12. In terms of the crop shear performance/utilisation figures, what do you think the result thereof has been since the year 2008 up until now?

The performance/utilisation has improved	
The performance/utilisation has remained more or less the same	
The performance/utilisation has become worse	

13. Please refer to the actual crop shear performance/utilisation graphs in Appendix 2 of the questionnaire. Do you think it is possible to improve on current crop shear performance/utilisation? If not, please elaborate why you believe so.

Yes	No

____

____

____

14. Do you think the relevant personnel/teams listed below have the required attitude to improve the performance/utilisation of the crop shear? Please give a rating for each of the responsible teams.

Responsible Teams	Strongly agree	Agree	Disagree	Strongly disagree
Maintenance execution team (Artisans)				
Mechanical reliability team (Supt. and engineer)				
Systems reliability team (Technicians and technologists)				
Production team (Operators and production specialists)				

15. Do you think the relevant personnel/teams listed below have the required skills to improve the performance/utilisation of the crop shear? Please give a rating for each of the responsible teams.

Responsible Teams	Strongly agree	Agree	Disagree	Strongly disagree
Maintenance execution team (Artisans)				
Mechanical reliability team (Supt. and engineer)				
Systems reliability team (Technicians and technologists)				
Production team (Operators and production specialists)				

16. Do you know what maintenance method is being used to maintain the crop shear blades?

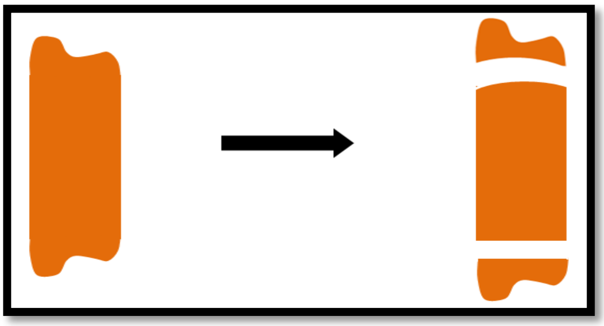
Yes	No

17. If your answer to above question is yes, please indicate which method you think is being used:

Condition based maintenance	
Run-to-failure maintenance	
Predictive maintenance	
Preventative maintenance	

18. Please study the images below and verify if the crop shear process illustrated below is correct.

Yes	No



19. The mechanical reliability team is considering using the crop shear off cuts' burr length (as demonstrated in images below) as a measurement to determine the condition of the crop shear blades. Do you think this approach will be effective in trying to improve the crop shear performance/utilisation? If no, please elaborate why you believe so.

Yes	No

____

____

____

20. Do you agree that the crop shear is used to heat up the transfer bar to a temperature of 1100˚C at the HSM?

Yes	No

21. The HSM has 3 crop shear cartridges in their possession. One in operation, one as an available standby on site and the other sent out for reconditioning. Do you think there is a difference in the performance/utilisation when comparing the cartridges with one another?

Yes	No

22. If your answer to above question is yes, please elaborate on why you believe there is a difference in performance/utilisation amongst cartridges.

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23. Do you think the crop shear cartridges are reconditioned according to the required quality specification? If yes, please motivate your answer.

Yes	No

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____

24. If felt needed, please give some technical feedback/commentary which could benefit the study.

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25. Please tear off the square on the last page, beneath question 29. Fill in the required detail and submit along with the completed questionnaire (It is not needed to fill in your name if you would like to remain anonymous) in order for you to qualify for a free cold drink. Please **do not** select one of the options below.

Yes	No

The following section of the questionnaire is intended to gain your input on the effectiveness of the questionnaire.

26. Did you find the questions to be meaningful and applicable to the topic at hand?

Yes	No

27. Did you understand all the questions asked?

Yes	No

28. Did the available options allow you to truly reflect your insight and opinions?

Yes	No

29. If felt needed, please give some feedback on the effectiveness of the questionnaire,

____

____

____

____

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____

Name:			
Designation:	☐ Artisan	☐ Technologist	☐ Operator
	☐ Superintendent	☐ Engineer	☐ Specialist
	☐ Technician	☐ Planner	☐ Manager
Date of submission:			
			Tag x of 30

Appendix 1 - (Crop shear works procedure)

ArcelorMittal

Centre	Vanderbijlpark Works	**Document Type**	KPR	**Effective Date**	29 March 2011
Document	WWNPWA0000043	**Version**	01	**Revision Date**	28 March 2016
Status	Released			**Approved By**	SAREL (SJ) NIEMANDT
Title	CORRECT PROC: USE OF THE CROP SHEAR				

This document replaces	WWNPWA000000043/00
Reason for revision	
Destination group	All FM Production Supt's and Process Controllers.

1. **PURPOSE**

To communicate the correct zeroing procedure for the crop shear HMD system and to address critical operational procedures.

2. **DEFINITIONS AND TERMS**

HMI – Human-Machine Interface
HMD – Hot metal detector
HMDCS – Hot metal detector, crop shear

3. **RELATED DOCUMENTS AND FORMS**

None

4. **METHOD OF CONTROL**

It is the Production Superintendent's responsibility to see that the crop shear is used according to this procedure.

5. **DESCRIPTION OF PROCEDURE**

5.1 **Calibration of the HMD system**

5.1.1 On the HMI screen, select SERVICE STATUS -> CROP SHEAR -> MANUAL.

5.1.2 Jog the crop shear with the help of the DAK (Direct Action Keyboard) until the calibration arrows on the drive side of the shear are exactly aligned. The straight blades of the shear (tail cut) are now aligned.

5.1.3 On the HMI screen, select "SELECT ZERO" = ON.

5.1.4 Select "ZERO REQUEST".

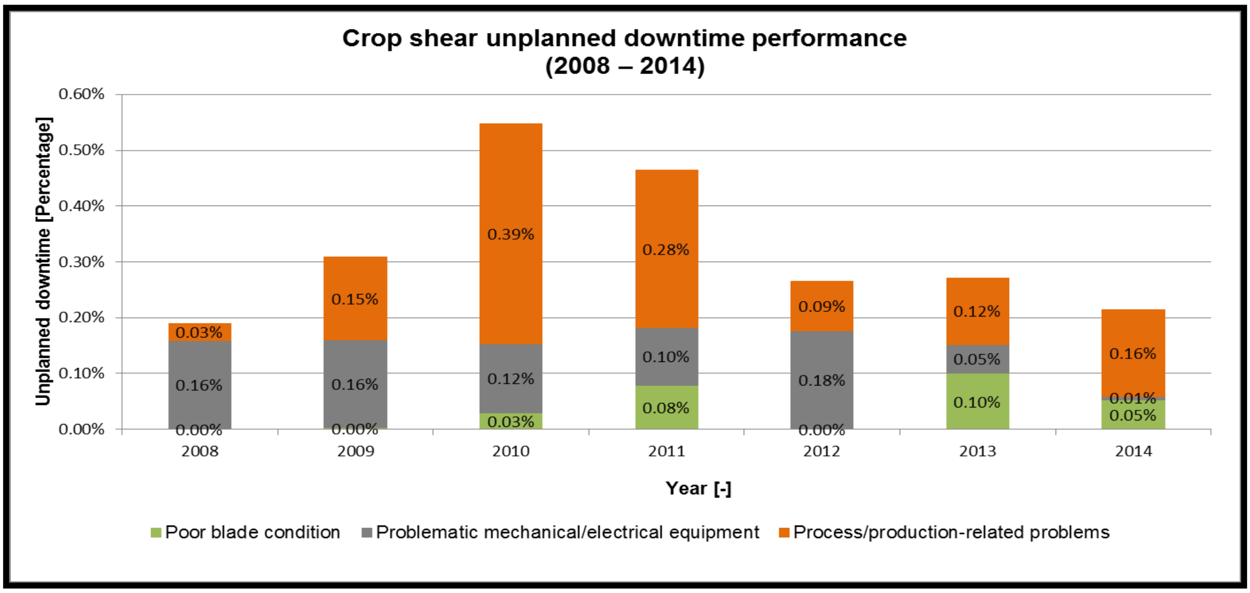
5.1.5 Select "SELECT ZERO" = OFF.

5.2 Conditions for the successful functioning of the crop shear.

5.2.1 There must never be two sequential slabs at the same time in the tracking zone of the crop shear. The tracking zone consists of HMDCS2 and HMDCS3.

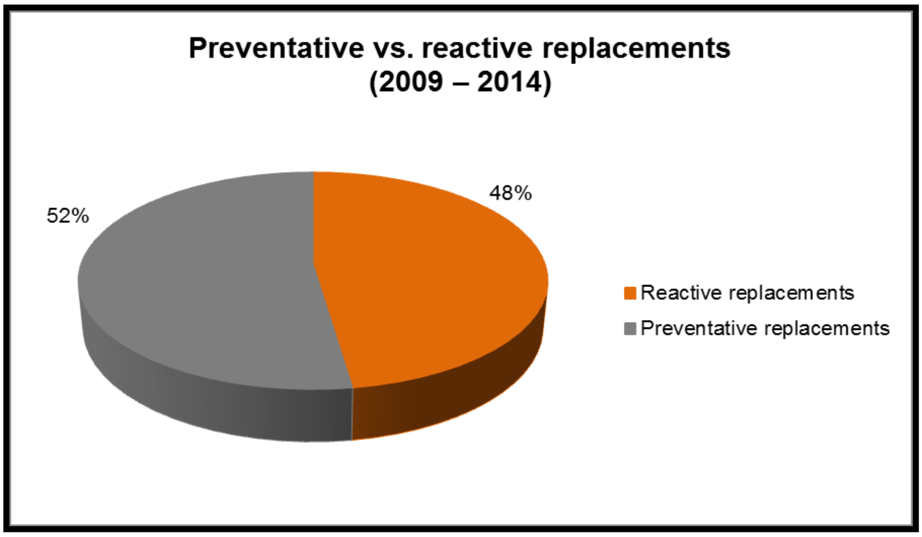
When a transfer bar enters the tracking zone of the crop shear and the delay tables are stopped, the slab must first be pulled back out of the tracking zone of the crop shear. After the process interruption has been resolved, the tables can be started and the crop shear will cut normally.

Appendix 2 - (Crop shear performance/utilisation)



The figure above illustrates the unplanned downtime in terms of minutes for the crop shear utilisation the previous 7 years.

Of the 65 crop shear cartridge replacements conducted between the year 2009 and 2014, the HSM personnel managed to only conduct 34 on-time preventative replacements. This means that only 52% of the total cartridge replacements were done before any production related problems occurred, forcing a reactive means of replacement. The figure below compares the number of preventative replacement-and reactive replacement events with one another.



Appendix C (Master evaluation sheet)

A Conditioned Based Maintenance Approach for a Rotary Drum Crop Shear
Experimental Component 2
Master Questionnaire Evaluation Sheet

Questionnaire Identification

Question Number	Available options	1 of 30	2 of 30	3 of 30	4 of 30	5 of 30	6 of 30	7 of 30	8 of 30	9 of 30	10 of 30	11 of 30	12 of 30	13 of 30	14 of 30	15 of 30	16 of 30	17 of 30	18 of 30	19 of 30	20 of 30	21 of 30	22 of 30	23 of 30
1	Yes	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1
	No																							
18	Yes	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1
	No									1	1													
20	Yes																							
	No	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1
25	Yes																							
	No																							
2	You have **only** heard of and seen the crop shear in operation				1					1				0	1			1						
	You have physically conducted maintenance on the crop shear before	1	1	1		1	1	1	1			1	1						1	1	1	1	1	
	You have operated the crop shear before		1				1	1	1			1	1	0		1				1	1	1	1	1
	You have been involved in trying to improve the reliability of the crop shear	1				1		1	1		1	1	1				1		1	1	1	1	1	1
3	Your knowledge from a **systems** point of view (Very good)	1						1	1											1				
	Your knowledge from a **systems** point of view (Fair)			1	1	1	1			1		1	1	0		1	1							1
	Your knowledge from a **systems** point of view (Not good)		1								1				1			1	1		1	1	1	
	Your knowledge from a **mechanical** point of view (Very good)	1				1				1		1	1						1	1	1	1	1	1
	Your knowledge from a **mechanical** point of view (Fair)		1	1	1		1	1	1		1				1	1	1							
	Your knowledge from a **mechanical** point of view (Not good)													0				1						
	You knowledge from an **operating** point of view (Very good)	1						1	1	1	1	1	1			1			1	1	1	1	1	1
	You knowledge from an **operating** point of view (Fair)		1	1	1	1	1							0	1		1							
	You knowledge from an **operating** point of view (Not good)																	1						
	Your knowledge from a **reliability** point of view (Very good)	1							1			1	1				1		1	1	1	1	1	1
	Your knowledge from a **reliability** point of view (Fair)		1		1	1	1	1		1	1					1								
	Your knowledge from a **reliability** point of view (Not good)			1										0	1			1						

Questionnaire Evaluation

Evaluation Description	Value
No. of questionnaires received	23
No. of questionnaires approved from validation	22
No. of answer "Yes"	22
No. of answer "No"	0
Percentage of answer "Yes"	100
Percentage of answer "No"	
No. of questionnaires approved from validation	22
Percentage of questionnaires approved from validation	96
No. of "X" for 2.1	4
No. of "X" for 2.2	14
No. of "X" for 2.3	12
No. of "X" for 2.4	14
Percentage of "X" for 2.1	18
Percentage of "X" for 2.2	64
Percentage of "X" for 2.3	55
Percentage of "X" for 2.4	64
No. of "X" for 3.1	4
No. of "X" for 3.2	10
No. of "X" for 3.3	8
No. of "X" for 3.4	11
No. of "X" for 3.5	10
No. of "X" for 3.6	1
No. of "X" for 3.7	14
No. of "X" for 3.8	7
No. of "X" for 3.9	1
No. of "X" for 3.10	11
No. of "X" for 3.11	8
No. of "X" for 3.12	3
Percentage of "X" for 3.1	18
Percentage of "X" for 3.2	46
Percentage of "X" for 3.3	36
Percentage of "X" for 3.4	50
Percentage of "X" for 3.5	45
Percentage of "X" for 3.6	5
Percentage of "X" for 3.7	63.6
Percentage of "X" for 3.8	31.8
Percentage of "X" for 3.9	4.5
Percentage of "X" for 3.10	50
Percentage of "X" for 3.11	36
Percentage of "X" for 3.12	14

4	Yes			1	1			1	1			1	1			1			1	1	1	1	1	1	No. of answer "Yes"	13
	No	1	1			1	1			1	1			0	1		1	1							No. of answer "No"	9
																									Percentage of answer "Yes"	59
																									Percentage of answer "No"	41
5	Yes	1		1			1	1	1		1	1	1	0	1	1			1	1	1	1	1	1	No. of answer "Yes"	16
	No		1		1	1				1							1	1							No. of answer "No"	6
																									Percentage of answer "Yes"	73
																									Percentage of answer "No"	27
6	Yes	1										1	1	0				1							No. of answer "Yes"	4
	No		1	1	1	1	1	1	1	1	1			0	1	1	1		1	1	1	1	1	1	No. of answer "No"	18
																									Percentage of answer "Yes"	18
																									Percentage of answer "No"	82
7	Insufficient detail related to process introduction		1	1	1	1	1		1		1			0	1	1	1		1	1	1	1	1	1	No. of "X" for 7.1	16
	Insufficient detail related to process parameters		1	1	1	1	1	1	1	1	1			0	1	1			1	1	1	1	1	1	No. of "X" for 7.2	17
	Insufficient detail related to preferred maintenance strategies		1	1	1	1			1	1	1			0	1	1	1		1	1	1	1	1	1	No. of "X" for 7.3	16
	Insufficient detail related to maintenance execution		1	1	1	1			1	1	1			0	1	1	1		1	1	1	1	1	1	No. of "X" for 7.4	16
	Insufficient detail related to trouble shooting manual		1	1	1	1		1	1	1	1			0	1	1	1		1	1	1	1	1	1	No. of "X" for 7.5	17
																									Percentage of "X" for 7.1	73
																									Percentage of "X" for 7.2	77
																									Percentage of "X" for 7.3	73
																									Percentage of "X" for 7.4	73
																									Percentage of "X" for 7.5	77
8	Yes	1	1	1	1	1		1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	No. of answer "Yes"	21
	No						1																		No. of answer "No"	1
																									Percentage of answer "Yes"	95
																									Percentage of answer "No"	5
9	Number of cuts conducted per cartridge	1	1	1	1	1	0	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	No. of "X" for 9.1	21
	Number of days the crop shear cartridge is in operation	1			1		0	1	1	1	1	1	1	0	1		1			1					No. of "X" for 9.2	11
	UDT (Unplanned Down Time)		1		1	1	0	1	1	1	1	1	1	0		1	1	1	1	1	1	1	1	1	No. of "X" for 9.3	18
	Mechanical yield	1	1	1	1	1	0	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	No. of "X" for 9.4	21
																									Percentage of "X" for 9.1	100
																									Percentage of "X" for 9.2	52
																									Percentage of "X" for 9.3	86
																									Percentage of "X" for 9.4	100
10	Yes	1	1		1		0		1	1	1		1			1	1							1	No. of answer "Yes"	10
	No			1		1		1				1		0	1			1	1	1	1	1	1		No. of answer "No"	11
																									Percentage of answer "Yes"	48
																									Percentage of answer "No"	52
11	Yes	0	0	1		1	0	1				1	0	0			0	1	1	1	1	1	1	0	No. of answer "Yes"	10
	No														1										No. of answer "No"	1
																									Percentage of answer "Yes"	91
																									Percentage of answer "No"	9
12	The performance/utilisation has improved	1	1	1	1	1	1	1	1	1		1	1	0		1		1	1	1	1	1	1	1	No. of "X" for 12.1	19
	The performance/utilisation has remained more or less the same													0			1								No. of "X" for 12.2	1
	The performance/utilisation has become worse										1			0	1										No. of "X" for 12.3	2
																									Percentage of "X" for 12.1	86
																									Percentage of "X" for 12.2	5
																									Percentage of "X" for 12.3	9
13	Yes	1	1		1		1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	No. of answer "Yes"	20
	No			1		1																			No. of answer "No"	2

																									Percentage of answer "Yes"	91
																									Percentage of answer "No"	9
14	Maintenance execution team (Artisans) - (Strongly agree)		1			1	1			1		1	1	0			1	1	1	1	1	1	1	1	No. of "X" for 14.1	14
	Maintenance execution team (Artisans) - (Agree)	1		1	1			1	1						1	1									No. of "X" for 14.2	7
	Maintenance execution team (Artisans) - (Strongly Disagree)										1														No. of "X" for 14.3	1
	Maintenance execution team (Artisans) - (Strongly disagree)																								No. of "X" for 14.4	0
	Mechanical reliability team (Supt. and engineer) - (Strongly agree)	1	1	1	1	1	1	1		1	1	1	1	0	1		1	1	1	1	1	1	1	1	No. of "X" for 14.5	20
	Mechanical reliability team (Supt. and engineer) - (Agree)								1							1									No. of "X" for 14.6	2
	Mechanical reliability team (Supt. and engineer) - (Disagree)																								No. of "X" for 14.7	0
	Mechanical reliability team (Supt. and engineer) - (Strongly disagree)																								No. of "X" for 14.8	0
	Systems reliability team (Technicians and technologists) - (Strongly agree)									1		1	1	0			1								No. of "X" for 14.9	4
	Systems reliability team (Technicians and technologists) - (Agree)	1	1	1	1	1	1	1	1		1				1	1					1				No. of "X" for 14.10	12
	Systems reliability team (Technicians and technologists) - (Disagree)																	1	1	1			1	1	No. of "X" for 14.11	5
	Systems reliability team (Technicians and technologists) - (Strongly disagree)																					1			No. of "X" for 14.12	1
	Production team (Operators and production specialists) - (Strongly agree)											1	1	0											No. of "X" for 14.13	2
	Production team (Operators and production specialists) - (Agree)	1	1		1				1	1	1					1	1								No. of "X" for 14.14	8
	Production team (Operators and production specialists) - (Disagree)			1		1	1	1							1			1	1	1	1	1	1	1	No. of "X" for 14.15	12
	Production team (Operators and production specialists) - (Strongly disagree)																								No. of "X" for 14.16	0
																									Percentage of "X" for 14.1	64
																									Percentage of "X" for 14.2	32
																									Percentage of "X" for 14.3	5
																									Percentage of "X" for 14.4	0
																									Percentage of "X" for 14.5	91
																									Percentage of "X" for 14.6	9
																									Percentage of "X" for 14.7	0
																									Percentage of "X" for 14.8	0
																									Percentage of "X" for 14.9	18.2
																									Percentage of "X" for 14.10	54.5
																									Percentage of "X" for 14.11	22.7
																									Percentage of "X" for 14.12	4.5
																									Percentage of "X" for 14.13	9
																									Percentage of "X" for 14.14	36
																									Percentage of "X" for 14.15	55
																									Percentage of "X" for 14.16	0
15	Maintenance execution team (Artisans) - (Strongly agree)		1	1	1		1		1		1	1	1	0			1	1	1	1	1	1	1	1	No. of "X" for 15.1	16
	Maintenance execution team (Artisans) - (Agree)	1				1		1		1					1	1									No. of "X" for 15.2	6
	Maintenance execution team (Artisans) - (Strongly Disagree)																								No. of "X" for 15.3	0
	Maintenance execution team (Artisans) - (Strongly disagree)																								No. of "X" for 15.4	0
	Mechanical reliability team (Supt. and engineer) - (Strongly agree)	1	1	1	1	1	1		1	1	1	1	1	0	1		1	1	1	1	1	1	1	1	No. of "X" for 15.5	20
	Mechanical reliability team (Supt. and engineer) - (Agree)							1								1									No. of "X" for 15.6	2
	Mechanical reliability team (Supt. and engineer) - (Disagree)																								No. of "X" for 15.7	0
	Mechanical reliability team (Supt. and engineer) - (Strongly disagree)																								No. of "X" for 15.8	0
	Systems reliability team (Technicians and technologists) - (Strongly agree)	1	1				1		1	1	1	1	1	0			1		1						No. of "X" for 15.9	10
	Systems reliability team (Technicians and technologists) - (Agree)			1	1	1		1							1	1							1	1	No. of "X" for 15.10	8
	Systems reliability team (Technicians and technologists) - (Disagree)																	1		1	1	1			No. of "X" for 15.11	4
	Systems reliability team (Technicians and technologists) - (Strongly disagree)																								No. of "X" for 15.12	0
	Production team (Operators and production specialists) - (Strongly agree)		1				1		1		1	1	1	0											No. of "X" for 15.13	6
	Production team (Operators and production specialists) - (Agree)	1		1	1			1		1					1	1	1		1			1		1	No. of "X" for 15.14	11
	Production team (Operators and production specialists) - (Disagree)					1												1		1			1		No. of "X" for 15.15	4
	Production team (Operators and production specialists) - (Strongly disagree)																				1				No. of "X" for 15.16	1

																									Percentage of "X" for 15.1	73
																									Percentage of "X" for 15.2	27
																									Percentage of "X" for 15.3	0
																									Percentage of "X" for 15.4	0
																									Percentage of "X" for 15.5	91
																									Percentage of "X" for 15.6	9
																									Percentage of "X" for 15.7	0
																									Percentage of "X" for 15.8	0
																									Percentage of "X" for 15.9	45.5
																									Percentage of "X" for 15.10	36.4
																									Percentage of "X" for 15.11	18.2
																									Percentage of "X" for 15.12	0
																									Percentage of "X" for 15.13	27
																									Percentage of "X" for 15.14	50
																									Percentage of "X" for 15.15	18
																									Percentage of "X" for 15.16	5
16	Yes	1	1		1	1	1	1	1	1	1			0	1	1	1	1	1	1	1	1	1	1	No. of answer "Yes"	19
	No			1								1	1												No. of answer "No"	3
																									Percentage of answer "Yes"	86
																									Percentage of answer "No"	14
17	Condition-based maintenance		1	0				0	0	1	0			0	0									0	No. of "X" for 17.1	2
	Run-to-failure maintenance													0											No. of "X" for 17.2	0
	Predictive maintenance							0	1					0			1					1		1	No. of "X" for 17.3	4
	Preventative maintenance	1			1	1	1	1			1			0	1	1		1	1	1	1		1		No. of "X" for 17.4	13
																									Percentage of "X" for 17.1	11
																									Percentage of "X" for 17.2	0
																									Percentage of "X" for 17.3	21
																									Percentage of "X" for 17.4	68
19	Yes	1	1		1	1	1	1	1		1	1	1	0	1	1	1	1	1	1	1	1	1	1	No. of answer "Yes"	20
	No			1						1															No. of answer "No"	2
																									Percentage of answer "Yes"	91
																									Percentage of answer "No"	9
21	Yes			1		1	1	1	1	1				0				1	1	1					No. of answer "Yes"	9
	No	1	1		1						1	1	1		1	1	1				1	1	1	1	No. of answer "No"	13
																									Percentage of answer "Yes"	41
																									Percentage of answer "No"	59
23	Yes		1	1	1				1		1	1	1	0	1	1	1		1	1	1	1	1	1	No. of answer "Yes"	16
	No	1				1		1																	No. of answer "No"	3
																									Percentage of answer "Yes"	84
																									Percentage of answer "No"	16
26	Yes	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	No. of answer "Yes"	22
	No																								No. of answer "No"	0
																									Percentage of answer "Yes"	100
																									Percentage of answer "No"	0
27	Yes	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	No. of answer "Yes"	22
	No																								No. of answer "No"	0
																									Percentage of answer "Yes"	100
																									Percentage of answer "No"	0
28	Yes	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	No. of answer "Yes"	22
	No																								No. of answer "No"	0
																									Percentage of answer "Yes"	100
																									Percentage of answer "No"	0

Appendix D (Measurement report)

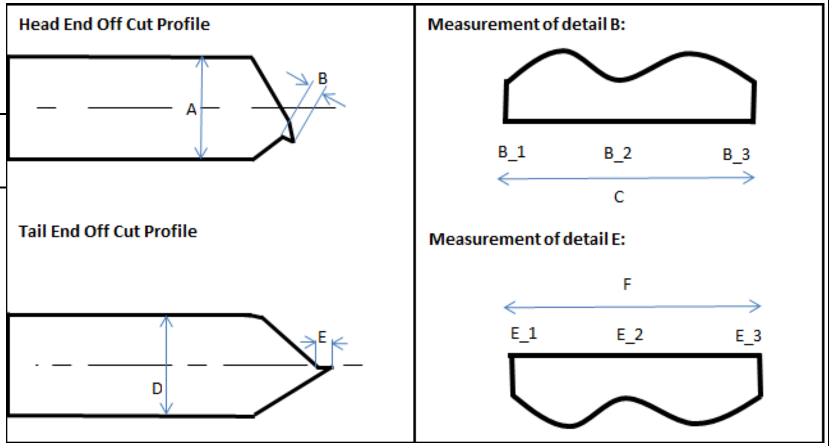
Experiment: Experimental Component 3 - Burr Length Measurment Experiment

Cartridge Specific Data Sheet

Date cartridge inserted: ______________________

Date Cartridge replaced: ______________________

Measurement Information:



Measurement Number	**Date**	**Sample Number**	**Dimensional Characteristics**									
			A	**B_1**	**B_2**	**B_3**	**C**	**D**	**E_1**	**E_2**	**E_3**	**F**
1		1										
		2										
		3										
		Average										
	Comments:											
2		1										
		2										
		3										
		Average										
	Comments:											

Measurement Number	Date	Sample Number	Dimensional Characteristics									
			A	B	C	D	E	F	G	H	I	J
3		1										
		2										
		3										
		Average										
	Comments:											
4		1										
		2										
		3										
		Average										
	Comments:											
5		1										
		2										
		3										
		Average										
	Comments:											
6		1										
		2										
		3										
		Average										
	Comments:											
7		1										
		2										
		3										
		Average										
	Comments:											

Appendix E (Master result sheet for burr length measurement experiment)

Cartridge Description		Cartridge Measurement No.	Date of Measurement	Sample Number	Dimensional Characteristics									
Cartridge No.	Circulation No.				A	B_1	B_2	B_3	C	D	E_1	E_2	E_3	F
1	1	1	06/02/2014	1	36	0.3	0.3	0.3	1210	36	1.4	1.3	1.2	1210
1	1	1	06/02/2014	2	34	0.2	0.3	0.3	1132	36	1.6	1.1	1.7	1210
1	1	1	06/02/2014	3	34	0.3	0.3	0.4	1257	38	1.5	1.5	1.3	1210
1	1	2	10/02/2014	1	34	0.5	0.4	0.5	1240	34	1.6	1.5	1.3	1235
1	1	2	10/02/2014	2	38	0.5	0.3	0.5	910	36	1.6	1.9	1.6	1235
1	1	2	10/02/2014	3	36	0.5	0.4	0.5	1080	36	1.5	1.6	2	1240
1	1	3	20/02/2014	1	35	1	1.1	1	1940	34	2.3	1.8	3.5	1510
1	1	3	20/02/2014	2	36	1	1	1	1500	36	2.5	3.5	4.0	1510
1	1	3	20/02/2014	3	36	1	0.9	1	1240	35	3	3.5	3.2	1235
1	1	4	28/02/2014	1	35	0.8	0.8	1.2	1100	34	5	5.5	5.5	1600
1	1	4	28/02/2014	2	35	0.8	0.7	1.2	1100	36	6	6	7	1080
1	1	4	28/02/2014	3	36	0.9	1	1.3	1240	36	6	5.7	6	1600
1	2	1	11/04/2014	1	40	0.4	0.5	0.5	992	40	1	1.2	1.1	992
1	2	1	11/04/2014	2	40	0.35	0.4	0.5	992	40	0.95	1.2	1.05	992
1	2	1	11/04/2014	3	40	0.35	0.5	0.45	992	40	1	1.1	1	992
1	2	2	16/04/2014	1	34	0.5	0.7	0.6	1259	35	1.2	1	1.4	1259
1	2	2	16/04/2014	2	40	0.5	0.7	0.6	959	40	1.1	1.8	1	1080
1	2	2	16/04/2014	3	40	0.6	0.6	0.7	956	36	2.2	2.3	2.3	1080
1	2	3	24/04/2014	1	32	1	1	1	1310	32	1.8	1.2	1.3	1600
1	2	3	24/04/2014	2	32	0.9	1	1	1310	32	1.7	1.1	1.8	1600
1	2	3	24/04/2014	3	32	1	1.1	1.1	1634	32	2.3	1.7	2	1600
1	2	4	02/05/2014	1	36	1	1.2	1	1510	36	2.2	2.4	2.5	1510
1	2	4	02/05/2014	2	36	1	1.3	1.1	1510	36	2.2	2	2.4	1510
1	2	4	02/05/2014	3	36	1.1	1.4	1.2	1510	36	2.2	2.2	2.4	1510
1	2	5	13/05/2014	1	32	1.4	1.4	1.3	1335	32	2	1.9	2.3	1600
1	2	5	13/05/2014	2	34	1.3	1.5	1.2	1335	32	2.7	2.5	2.2	1335
1	2	5	13/05/2014	3	36	1.4	1.5	1.3	1335	32	2.4	2.6	2	1335
1	2	6	20/05/2014	1	36	1	1.2	1	992	36	2.1	1.7	2.5	992
1	2	6	20/05/2014	2	36	1.3	1.5	1.3	992	36	2.6	2.4	2.4	992

1	2	6	20/05/2014	3	36	1.2	1.4	1.3	1082	36	2.7	2.5	2.9	1082
1	2	7	26/05/2014	1	35	1.6	1.7	1.4	1235	35	3.5	3.4	3.2	1235
1	2	7	26/05/2014	2	35	1.5	1.5	1.5	1235	35	3.9	3.7	3.4	1235
1	2	7	26/05/2014	3	35	1.6	1.7	1.2	1235	35	3.4	3.2	3.4	1235
2	2	1	27/05/2014	1	34	0.5	0.5	0.5	1082	34	1	1	1	1235
2	2	1	27/05/2014	2	34	0.5	0.5	0.4	1235	34	1	1	1.1	1235
2	2	1	27/05/2014	3	34	0.5	0.5	0.5	1235	34	1	1	1	1235
2	2	2	02/06/2014	1	34	0.7	0.7	0.7	1082	34	1.5	1.5	1.7	1080
2	2	2	02/06/2014	2	34	0.5	0.7	0.7	956	34	1.2	1.4	1.6	1080
2	2	2	02/06/2014	3	34	0.7	0.8	0.8	1097	34	1.5	1.6	1.6	1100
2	2	3	11/06/2014	1	34	0.7	0.9	0.7	1235	34	2.2	2.2	2.3	956
2	2	3	11/06/2014	2	34	0.8	0.9	0.7	1259	34	2	2.2	2.3	959
2	2	3	11/06/2014	3	34	0.8	0.8	0.8	1132	34	2	2.2	2	1235
2	2	4	18/06/2014	1	34	1	1	1	1259	34	2.7	2.9	3	1132
2	2	4	18/06/2014	2	34	0.8	1.1	1	1235	34	2.9	3	3.6	957
2	2	4	18/06/2014	3	34	0.8	1	0.9	1082	34	2.9	3.3	3.9	957
2	2	5	26/06/2014	1	36	1	1	1	992	34	3.4	4	3.1	992
2	2	5	26/06/2014	2	36	1	1	1.3	1082	36	3.3	3.4	3.2	992
2	2	5	26/06/2014	3	36	1	1.2	1.3	959	36	3.4	3.3	3.1	1080
2	2	6	02/07/2014	1	35	1.3	1.4	1.5	1132	34	3.9	4.1	3.9	1335
2	2	6	02/07/2014	2	35	1.1	1.4	1.4	197	34	3.9	3.8	3.9	1334
2	2	6	02/07/2014	3	35	1.4	1.3	1.2	1310	35	3.9	3.9	3.9	1235
2	2	7	09/07/2014	1	34	1.8	1.6	1.5	948	36	4.6	4.8	4.8	959
2	2	7	09/07/2014	2	34	1.7	1.6	1.6	948	36	4.8	4.7	4.8	948
2	2	7	09/07/2014	3	34	1.8	1.7	1.6	948	36	4.5	4.4	4.7	959
1	3	1	13/07/2014	1	36	0.5	0.5	0.5	1257	36	1.6	2	1.6	1235
1	3	1	13/07/2014	2	36	0.5	0.5	0.4	1257	36	1.6	1.8	1.8	1235
1	3	1	13/07/2014	3	36	0.3	0.4	0.5	1259	36	2	2.2	2	1235
1	3	2	17/07/2014	1	34	0.5	0.5	0.5	800	32	2.3	2.5	2.5	800
1	3	2	17/07/2014	2	34	0.6	0.5	0.5	800	32	2.2	2.6	2.4	800
1	3	2	17/07/2014	3	36	0.5	0.6	0.6	800	32	2.1	2.3	2.4	800
1	3	3	22/07/2014	1	36	0.5	0.5	0.5	1082	36	2.2	2.3	1.8	959
1	3	3	22/07/2014	2	36	0.5	0.5	0.5	1082	36	2.4	3.8	2.7	1257

1	3	3	22/07/2014	3	36	0.5	0.5	0.5	1082	36	2.3	2.9	2.95	1257
1	3	4	25/07/2014	1	34	0.7	0.7	0.7	1335	34	2.5	2.7	2.8	1200
1	3	4	25/07/2014	2	34	0.7	0.5	0.4	1235	34	2.9	3.8	2.2	1335
1	3	4	25/07/2014	3	34	0.7	0.5	0.5	1235	34	2.7	3.4	2.4	1335
1	3	5	11/08/2014	1	34	1	0.8	0.9	1082	36	2.95	3.6	2.9	1100
1	3	5	11/08/2014	2	34	0.9	1.1	0.9	1200	36	3	4.2	3.6	1100
1	3	5	11/08/2014	3	34	1.1	1	1	1100	36	2.9	3	2.95	1100
2	3	1	15/08/2014	1	36	0.5	0.5	0.6	907	42	2.5	3	2.9	907
2	3	1	15/08/2014	2	36	0.5	0.5	0.6	907	34	1.8	2	1.8	910
2	3	1	15/08/2014	3	36	0.6	0.6	0.5	842	42	2	3	2	907
2	3	2	21/08/2014	1	36	0.6	0.5	0.5	1256	36	5	7	6	959
2	3	2	21/08/2014	2	36	0.6	0.6	0.7	942	36	5	5.9	6.6	957
2	3	2	21/08/2014	3	36	0.6	0.6	0.7	942	36	7	7	6	1080
2	3	3	26/08/2014	1	36	0.7	0.6	0.6	942	36	6.2	7	6.8	1259
2	3	3	26/08/2014	2	36	0.7	0.7	0.7	957	36	5.8	6.5	6	1083
2	3	3	26/08/2014	3	36	0.4	0.8	0.5	957	36	6.5	7	6	1082
1	4	1	01/09/2014	1	35	0.5	1	0.7	1229	35	2	2.5	2	1310
1	4	1	01/09/2014	2	35	0.5	1	0.7	1080	36	2.3	2.2	2.6	1360
1	4	1	01/09/2014	3	35	0.8	0.9	0.9	1229	36	2.6	2.3	2.5	1335
1	4	2	05/09/2014	1	36	0.9	1.1	1.1	1300	35	3.1	3	3.3	1020
1	4	2	05/09/2014	2	36	0.7	1	0.9	1000	34	3.4	3.2	3.7	1150
1	4	2	05/09/2014	3	36	0.6	0.8	1	942	34	3.6	3.5	3.6	1335
1	4	3	07/09/2014	1	34	0.8	1.1	0.9	942	35	3.4	4.5	3.9	1335
1	4	3	07/09/2014	2	34	1	1	0.9	1000	35	3.9	4.2	3.7	1400
1	4	3	07/09/2014	3	34	0.7	1.1	0.8	1300	36	3.3	4.1	3.7	1400
2	4	1	15/09/2014	1	34	0.3	0.45	0.5	942	36	3	3.2	3	959
2	4	1	15/09/2014	2	35	0.5	0.5	0.4	942	36	3.1	3	2.2	959
2	4	1	15/09/2014	3	36	0.35	0.3	0.4	942	36	2.7	2.8	2.5	1082
2	4	2	18/09/2014	1	34	0.4	0.45	0.5	942	34	2.4	3	2	1020
2	4	2	18/09/2014	2	35	0.5	0.5	0.4	942	36		4.2	3.8	1020
2	4	2	18/09/2014	3	36	0.35	0.4	0.4	942	36	3.9	4.4	4.3	1020
2	4	3	21/09/2014	1	34	0.5	0.5	0.55	1210	32	3	5	4.1	1210
2	4	3	21/09/2014	2	34	0.5	0.4	0.3	1210	32	3.5	4.5	4.2	1210

2	4	3	21/09/2014	3	33	0.4	0.5	0.5	1080	34	3	4	4	1050
2	4	4	07/10/2014	1	36	0.6	0.6	0.5	1335	35	2.6	4	3.5	1080
2	4	4	07/10/2014	2	35	0.5	0.6	0.6	1275	34	3.7	4	4	920
2	4	4	07/10/2014	3	36	0.4	0.5	0.6	1275	33	4	3.7	4.2	1050
2	4	5	12/10/2014	1	33	0.6	0.7	1	1100	35	3	4	3.3	1235
2	4	5	12/10/2014	2	35	0.4	0.6	0.7	1100	35	3.3	3.8	3.2	1132
2	4	5	12/10/2014	3	35	0.7	0.8	0.5	1300	36	3.25	4.1	3.5	1050
2	4	6	14/10/2014	1	34	0.5	0.7	0.5	960	35	2.81	3.32	2.34	1335
2	4	6	14/10/2014	2	34	0.4	0.5	0.8	959	34	2.43	3.54	4	1260
2	4	6	14/10/2014	3	34	0.8	0.7	1.1	960	34	3.8	4.65	4.2	1255
2	4	7	16/10/2014	1	36	0.7	0.5	1	1235	34	3.6	4.2	3.6	960
2	4	7	16/10/2014	2	34	0.7	0.9	0.8	1259	36	4.2	4.3	3	1259
2	4	7	16/10/2014	3	35	0.5	0.8	0.6	1259	33	3.7	4.5	4	1400
2	4	8	19/10/2014	1	33	0.8	1.2	1	1200	33	4.8	5.1	3.5	1430
2	4	8	19/10/2014	2	35	1	0.9	0.7	1430	33	4.5	5.5	5	1200
2	4	8	19/10/2014	3	33	0.8	1.1	0.9	1430	35	4	5.2	6	920
1	5	1	21/10/2014	1	34	0.3	0.7	0.6	1255	35	0.95	2.05	1.9	1255
1	5	1	21/10/2014	2	34	0.45	0.4	0.35	1255	32	1	1	0.5	1235
1	5	1	21/10/2014	3	35	0.4	0.35	0.5	1280	36	1	2.7	1.5	1255
1	5	2	27/10/2014	1	34	0.3	0.5	0.45	1275	34	2.45	3	2.45	1275
1	5	2	27/10/2014	2	34	0.5	0.6	0.7	1275	35	2.3	3.55	2.35	1510
1	5	2	27/10/2014	3	34	0.35	0.4	0.5	1275	34	2.5	4.5	3	1295
1	5	3	31/10/2014	1	36	0.5	0.65	0.45	980	35	2.8	4.2	3.3	965
1	5	3	31/10/2014	2	35	0.7	0.5	0.65	980	36	0.9	2.2	1.7	970
1	5	3	31/10/2014	3	35	0.38	0.4	0.55	980	33	2.5	3.4	2.4	975
1	5	4	04/11/2014	1	34	0.5	1.2	0.65	980	36	2.3	2.9	2.6	980
1	5	4	04/11/2014	2	34	0.9	0.6	0.5	959	35	2	2.1	2	980
1	5	4	04/11/2014	3	34	0.45	0.5	0.7	980	36	2.1	2.6	2.4	1000
1	5	5	10/11/2014	1	34	0.2	0.4	0.68	950	41	2.6	2.7	2.5	950
1	5	5	10/11/2014	2	36	0.4	0.9	0.5	956	35	2.6	2.4	2.3	960
1	5	5	10/11/2014	3	36	0.5	0.65	1	980	40	2.6	2.45	2.4	950
1	5	6	13/11/2014	1	35	0.6	0.55	0.7	1100	32	1.9	2.65	2.7	1495
1	5	6	13/11/2014	2	34	0.6	0.7	0.6	1236	33	1.9	2.7	2.7	1265

1	5	6	13/11/2014	3	34	0.7	0.8	1.2	1330	35	1.9	2.7	2.7	1280
1	5	7	18/11/2014	1	34	0.65	0.9	1.1	1235	35	1.8	2.6	2.6	1280
1	5	7	18/11/2014	2	36	0.8	1	0.7	1430	33	2.2	3	1.9	1245
1	5	7	18/11/2014	3	36	1.1	0.55	1.3	1400	33	-	3.1	3.1	1235
1	5	8	25/11/2014	1	34	0.9	1.2	0.8	1500	34	3.1	3.5	3.2	1220
1	5	8	25/11/2014	2	34	1.3	1.4	0.7	1510	33	3.4	3.4	3.3	1385
1	5	8	25/11/2014	3	34	1	1	1.5	1330	34	3.1	3.8	3.4	1410
2	5	1	07/12/2014	1	34	0.5	0.4	0.8	959	35	1.3	2	1.1	980
2	5	1	07/12/2014	2	36	0.4	0.35	0.55	980	34	1.5	1.4	0.9	980
2	5	1	07/12/2014	3	34	0.55	0.5	0.7	980	34	1.4	1.1	0.7	980
2	5	2	10/12/2014	1	36	0.7	1.4	1.4	1600	35	2.2	3.3	4.1	1510
2	5	2	10/12/2014	2	40	1	0.9	1	1600	35	2.2	3.3	3.65	1585
2	5	2	10/12/2014	3	40	0.9	1.2	1.1	1600	36	2.2	3.3	4.1	1810
1	6	1	16/12/2014	1	35	0.2	0.5	0.3	1205	34	1.5	1.2	1	1235
1	6	1	16/12/2014	2	35	0.4	0.1	0.2	1210	34	1.1	0.9	1.3	1410
1	6	1	16/12/2014	3	35	0.16	0.2	0.25	1205	35	0.9	1.1	1.5	1205
1	6	2	21/12/2014	1	34	0.45	0.5	0.55	1259	34	0.6	1	0.9	1335
1	6	2	21/12/2014	2	34	0.3	0.35	0.6	1275	36	0.8	0.7	1.2	1600
1	6	2	21/12/2014	3	34	0.35	0.5	0.8	1205	35	0.9	1	1.1	1410
1	6	3	28/12/2014	1	34	0.5	0.5	0.6	1256	35	1.8	2.2	2	1800
1	6	3	28/12/2014	2	35	0.3	0.45	0.55	959	34	2	2.2	2.5	1235
1	6	3	28/12/2014	3	36	0.4	0.5	0.7	959	34	2.1	2.6	2.3	1205
1	6	4	05/01/2015	1	40	0.4	0.4	0.5	1150	32	2.8	3.5	4.1	1205
1	6	4	05/01/2015	2	40	0.8	1.3	1	959	32	3	3.5	4.5	1565
1	6	4	05/01/2015	3	34	0.9	1	1	1080	34	3.4	3.3	3.9	1600
1	6	5	06/01/2015	1	35	1.2	0.9	0.7	1235	34	2.1	2.7	2.5	1525
1	6	5	06/01/2015	2	40	1	1.2	1	942	36	1.8	2.5	2.7	1310
1	6	5	06/01/2015	3	36	1	1.3	1.1	1032	35	2	2.9	3.3	960
1	6	6	12/01/2015	1	40	0.7	1.4	1.2	1310	35	2.5	4	3.5	1032
1	6	6	12/01/2015	2	34	0.9	1.1	1.5	1229	35	2.2	3.2	2	1300
1	6	6	12/01/2015	3	34	1.6	1.5	1	959	36	2.8	3.5	3	957
1	6	7	20/01/2015	1	34	1	1.8	1.3	1259	36	1.9	3	2.8	980

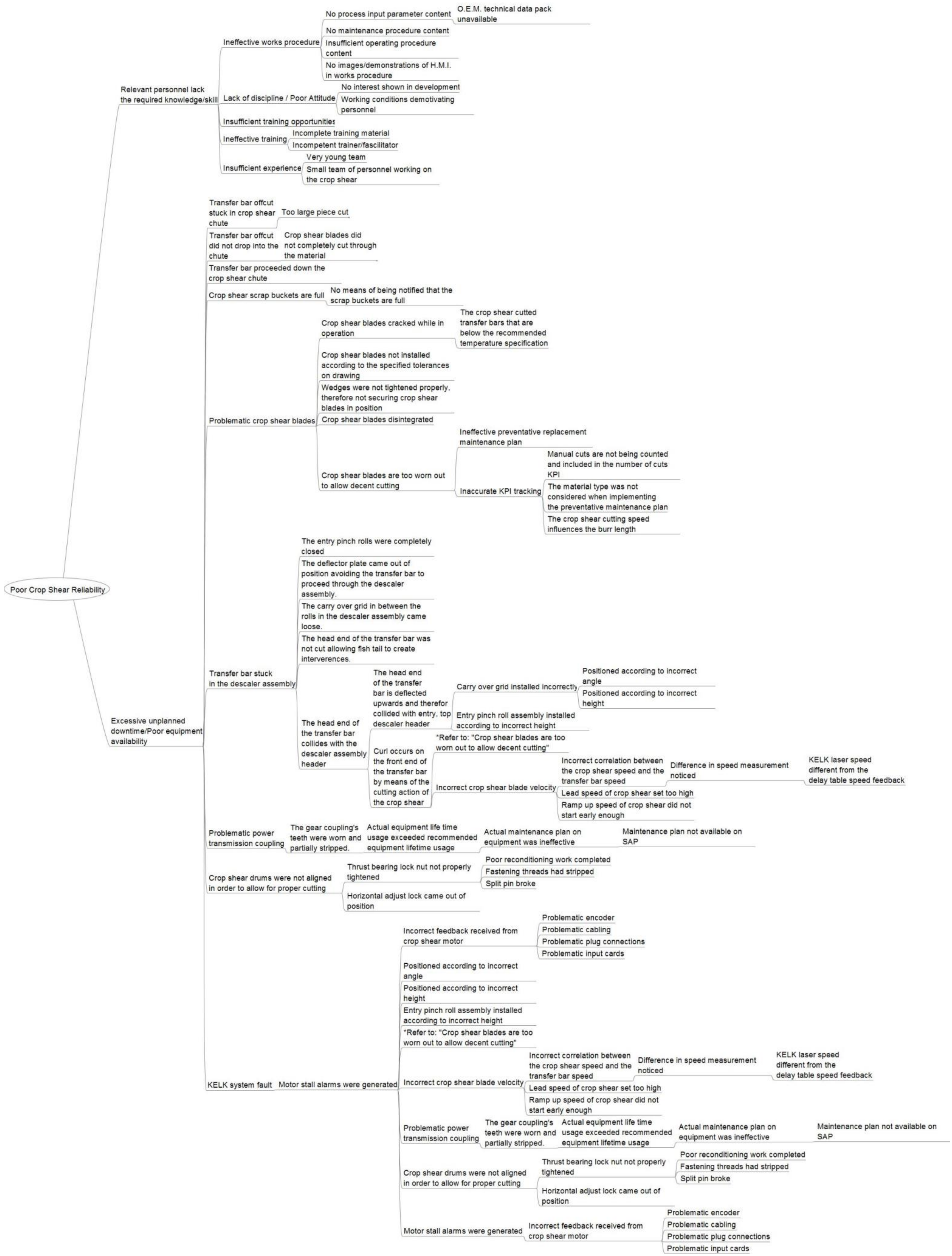
1	6	7	20/01/2015	2	34	1.2	1.4	1	1235	36	2.8	4.1	3.5	959
1	6	7	20/01/2015	3	36	1	1.5	1.7	1235	34	3.3	3.4	3.5	980
1	6	8	25/01/2015	1	36	1.1	1.3	1.6	1257	34	4.8	4.5	3.7	1235
1	6	8	25/01/2015	2	36	1.6	1.5	1.4	1034	36	5	4.8	3.3	1257
1	6	8	25/01/2015	3	40	1.1	1.5	1.5	1232	34	4.1	3.9	3.5	1082
2	6	1	01/02/2015	1	34	0.1	0.3	0.4	1232	35	2.2	3.3	4.1	1510
2	6	1	01/02/2015	2	36	0.3	0.3	0.5	1232	35	2.2	3.3	3.7	1510
2	6	1	01/02/2015	3	34	0.5	0.8	0.4	1235	37	2.2	3.3	4.1	1810
2	6	2	02/02/2015	1	36	0.4	0.45	0.7	957	35	1.8	2.0	2.1	1810
2	6	2	02/02/2015	2	35	0.5	0.8	0.6	948	36	1.1	1.1	2.3	1800
2	6	2	02/02/2015	3	33	0.35	0.6	0.4	1082	35	1.7	1.7	2.1	1525
2	6	3	11/02/2015	1	36	0.5	0.5	0.7	1510	34	1.3	1.3	0.4	1800
2	6	3	11/02/2015	2	36	0.7	0.5	0.4	1257	38	2.0	2.3	2.0	1257
2	6	3	11/02/2015	3	36	0.6	0.4	0.7	1257	36	1.8	2.6	1.4	1310
2	6	4	12/02/2015	1	35	0.5	0.5	0.7	1257	37	2.8	3.4	4.5	1232
2	6	4	12/02/2015	2	34	0.7	0.5	0.4	959	35	2.1	2.5	2.3	1235
2	6	4	12/02/2015	3	34	0.6	0.4	0.7	959	40	3.3	1.8	1.7	1800
2	6	5	17/02/2015	1	34	0.4	0.6	0.6	957	36	2.7	3.6	2.6	1257
2	6	5	17/02/2015	2	40	0.6	0.7	0.8	959	34	3.0	4.0	4.7	1257
2	6	5	17/02/2015	3	36	0.8	1.1	0.4	956	35	3.2	4.8	4.2	957
2	6	6	25/02/2015	1	36	0.6	0.7	0.6	1259	38	2.2	3.5	3.0	957
2	6	6	25/02/2015	2	36	0.7	0.8	1.2	1235	40	3.5	3.6	3.7	959
2	6	6	25/02/2015	3	40	0.65	0.9	1.1	1235	38	3.5	3.9	4.3	1235
2	6	7	27/02/2015	1	34	0.8	1	0.7	1210	36	3.2	3.6	2.6	1210
2	6	7	27/02/2015	2	34	1.1	0.55	1.3	1082	34	3.0	4.0	4.7	1080
2	6	7	27/02/2015	3	35	0.9	1.2	0.8	948	35	3.2	4.8	4.2	1081
2	6	8	04/03/2015	1	35	0.9	1.2	0.7	1235	35	4.6	4.2	4.4	1400
2	6	8	04/03/2015	2	35	1.1	0.7	1	907	36	3.5	3.9	4.7	1256
2	6	8	04/03/2015	3	35	0.9	1.1	1	907	35	3.4	4.5	3.5	1350
1	7	1	13/03/2015	1	40	0.3	0.2	0.5	1256	34	0.7	1.0	0.9	1235
1	7	1	13/03/2015	2	35	0.5	0.4	0.5	1256	35	1.0	1.4	1.6	1310
1	7	1	13/03/2015	3	36	0.2	0.5	0.4	1256	33	1.1	0.8	1.0	1132

1	7	2	16/03/2015	1	34	0.3	1	0.6	1210	34	0.9	1.5	-	1259
1	7	2	16/03/2015	2	34	0.3	0.5	0.5	1150	37	-	1.6	1.5	1510
1	7	2	16/03/2015	3	34	0.5	0.6	0.4	1150	41	1.2	1.8	1.9	1800
1	7	3	23/03/2015	1	36	0.4	0.6	0.5	1150	37	3.1	4.4	4.6	1235
1	7	3	23/03/2015	2	36	0.6	0.5	0.8	1150	36	2.4	3.9	4.0	1150
1	7	3	23/03/2015	3	35	0.6	0.8	1.1	1150	35	3.1	2.6	2.3	1235
1	7	4	30/03/2015	1	34	0.7	0.6	0.8	1275	36	3.7	4.3	4.6	1310
1	7	4	30/03/2015	2	34	0.7	0.9	1.2	1210	35	4.0	3.8	4.1	1262
1	7	4	30/03/2015	3	34	1	0.9	0.6	1400	33	4.0	4.6	3.8	1030
1	7	5	07/04/2015	1	35	1	1.1	0.8	1260	37	3.0	4.8	3.8	1800
1	7	5	07/04/2015	2	36	0.8	1	0.9	1430	36	3.7	5.5	5.0	1700
1	7	5	07/04/2015	3	36	0.8	1.3	1	1334	38	3.0	5.0	3.4	1800
2	7	1	14/04/2015	1	34	0.3	0.5	0.5	1235	36	0.9	1.5	2.9	1100
2	7	1	14/04/2015	2	34	0.5	0.4	0.4	1229	36	1.0	1.5	1.5	1000
2	7	1	14/04/2015	3	34	0.3	0.5	0.2	1235	35	1.5	1.5	2.5	1430
2	7	2	20/04/2015	1	40	0.3	0.6	0.4	1032	34	3.2	4.9	2.2	1335
2	7	2	20/04/2015	2	36	0.4	0.5	0.5	1032	33	2.4	3.3	4.4	1335
2	7	2	20/04/2015	3	36	0.2	0.4	0.3	1080	34	2.6	4.3	2.8	1335
2	7	3	28/04/2015	1	35	0.5	0.7	0.6	1260	34	3.0	3.7	3.4	1430
2	7	3	28/04/2015	2	35	0.9	0.6	0.5	1310	34	2.2	3.6	2.5	1285
2	7	3	28/04/2015	3	40	0.5	0.6	0.3	1235	35	2.7	3.3	2.1	1235
2	7	4	06/05/2015	1	36	0.8	1.5	1	1310	36	2.4	4.1	3.8	1229
2	7	4	06/05/2015	2	36	0.9	1	1.6	1310	35	4.2	4.3	3.7	775
2	7	4	06/05/2015	3	36	0.6	1.1	0.7	1310	35	3.5	4.1	3.6	956
2	7	5	12/05/2015	1	36	1.4	0.9	1.3	1235	35	3.9	4.5	3.8	957
2	7	5	12/05/2015	2	36	0.7	1.7	1	957	34	4.0	3.9	4.3	957
2	7	5	12/05/2015	3	36	1.1	1	1.2	942	33	3.6	4.9	5.5	1200
1	8	1	18/05/2015	1	35	0.2	0.1	0.2	1080	37	1.4	2.1	2.5	942
1	8	1	18/05/2015	2	35	0.3	0.3	0.3	1080	41	2.5	2.6	2.5	943
1	8	1	18/05/2015	3	40	0.5	0.2	0.2	1235	36	2.5	2.2	3.0	957
1	8	2	20/05/2015	1	34	0.2	0.5	0.3	1400	35	1.2	2.0	1.9	1280
1	8	2	20/05/2015	2	34	0.4	0.5	0.6	1505	36	1.8	1.7	1.9	1235

1	8	2	20/05/2015	3	34	0.4	0.6	0.4	1505	41	0.5	1.5	1.1	1310
1	8	3	05/06/2015	1	34	0.5	0.9	0.6	942	36	1.4	2.5	3.3	1235
1	8	3	05/06/2015	2	36	0.6	0.6	0.5	1235	36	2.3	3.0	2.2	1600
1	8	3	05/06/2015	3	40	0.5	0.4	0.5	1310	35	3.0	2.7	2.6	1830
1	8	4	12/06/2015	1	40	0.7	0.5	0.5	1235	36	4.1	3.8	3.4	1215
1	8	4	12/06/2015	2	34	0.9	0.7	0.6	942	40	2.9	3.8	4.3	940
1	8	4	12/06/2015	3	34	0.5	0.7	0.6	942	40	3.6	3.5	3.8	1080
1	8	5	22/06/2015	1	35	1.2	0.9	1	1510	34	3.5	4.1	4.0	1335
1	8	5	22/06/2015	2	35	1.3	1.3	0.9	1310	34	2.5	4.8	3.5	1285
1	8	5	22/06/2015	3	35	1.1	1.2	1	1510	35	2.9	4.5	4.4	775
2	8	1	01/07/2015	1	35	0.3	0.3	0.2	1215	35	0.6	0.9	0.7	1215
2	8	1	01/07/2015	2	35	0.2	0.2	0.1	1215	35	0.5	0.9	1	1220
2	8	1	01/07/2015	3	35	0.2	0.2	0.2	1215	35	0.5	1	1	1215
2	8	2	06/07/2015	1	34	0.3	0.5	0.6	1345	34	2	1.8	1.6	1135
2	8	2	06/07/2015	2	34	0.3	0.4	0.5	1345	33	2	2	1.9	970
2	8	2	06/07/2015	3	34	0.4	0.5	0.6	1345	34	2	1.8	2.2	1350
2	8	3	08/07/2015	1	38	0.3	0.9	0.7	1200	38	0.6	2	2.4	1215
2	8	3	08/07/2015	2	38	0.1	1.4	0.6	1200	36	1.5	1.9	1.3	1535
2	8	3	08/07/2015	3	39	0.7	1.3	0.7	1200	38	2.1	2.2	2.7	1255
2	8	4	16/07/2015	1	35	0.3	0.5	0.8	1250	34	2	1.6	2.4	1250
2	8	4	16/07/2015	2	34	0.4	0.6	0.9	1000	40	1.6	1.5	1.3	980
2	8	4	16/07/2015	3	34	0.2	0.6	0.8	1000	35	1.5	1.3	1.6	970
2	8	5	17/07/2015	1	35	0.3	0.3	0.7	1200	34	2	2.3	2.4	1240
2	8	5	17/07/2015	2	34	0.4	0.7	0.4	1200	35	2	2	2.3	1235
2	8	5	17/07/2015	3	35	0.3	0.5	0.6	1200	34	2.2	2.5	2.4	1225
2	8	6	21/07/2015	1	33	0.2	0.3	0.5	1400	34	2.2	2.9	2.8	1410
2	8	6	21/07/2015	2	33	0.5	0.5	0.4	1350	34	2	2.3	2.8	1500
2	8	6	21/07/2015	3	34	0.4	0.7	0.4	1500	34	2.1	2.5	2.8	1350
2	8	7	06/08/2015	1	35	0.9	1.1	1	1100	35	3.4	3.6	3.6	957
2	8	7	06/08/2015	2	35	0.7	0.8	1	1200	35	3.2	3.6	3.7	1200
2	8	7	06/08/2015	3	35	1	1	1.2	1200	36	3.3	3.4	3.4	1345
2	8	8	12/08/2015	1	35	1.4	1.4	1.1	980	34	3.3	4.1	3.4	1100

2	8	8	12/08/2015	2	35	1.3	1.3	1.4	980	35	3.9	4.5	4.5	1250
2	8	8	12/08/2015	3	35	1.2	1.4	1.4	1000	35	4	4.2	4.4	980

Appendix F (Why-Why diagram)


Poor Crop Shear Reliability
Relevant personnel lack the required knowledge/skill
Ineffective works procedure
No process input parameter content
O.E.M. technical data pack unavailable
No maintenance procedure content
Insufficient operating procedure content
No images/demonstrations of H.M.I. in works procedure
Lack of discipline / Poor Attitude
No interest shown in development
Working conditions demotivating personnel
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Ineffective training
Incomplete training material
Incompetent trainer/fascilitator
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Small team of personnel working on the crop shear
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Transfer bar offcut stuck in crop shear chute
Too large piece cut
Transfer bar offcut did not drop into the chute
Crop shear blades did not completely cut through the material
Transfer bar proceeded down the crop shear chute
Crop shear scrap buckets are full
No means of being notified that the scrap buckets are full
Problematic crop shear blades
Crop shear blades cracked while in operation
The crop shear cutted transfer bars that are below the recommended temperature specification
Crop shear blades not installed according to the specified tolerances on drawing
Wedges were not tightened properly, therefore not securing crop shear blades in position
Crop shear blades disintegrated
Crop shear blades are too worn out to allow decent cutting
Ineffective preventative replacement maintenance plan
Inaccurate KPI tracking
Manual cuts are not being counted and included in the number of cuts KPI
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The deflector plate came out of position avoiding the transfer bar to proceed through the descaler assembly.
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The head end of the transfer bar collides with the descaler assembly header
The head end of the transfer bar is deflected upwards and therefor collided with entry, top descaler header
Carry over grid installed incorrectly
Positioned according to incorrect angle
Positioned according to incorrect height
Entry pinch roll assembly installed according to incorrect height
Curl occurs on the front end of the transfer bar by means of the cutting action of the crop shear
*Refer to: "Crop shear blades are too worn out to allow decent cutting"
Incorrect crop shear blade velocity
Incorrect correlation between the crop shear speed and the transfer bar speed
Difference in speed measurement noticed
KELK laser speed different from the delay table speed feedback
Lead speed of crop shear set too high
Ramp up speed of crop shear did not start early enough
Problematic power transmission coupling
The gear coupling's teeth were worn and partially stripped.
Actual equipment life time usage exceeded recommended equipment lifetime usage
Actual maintenance plan on equipment was ineffective
Maintenance plan not available on SAP
Crop shear drums were not aligned in order to allow for proper cutting
Thrust bearing lock nut not properly tightened
Poor reconditioning work completed
Fastening threads had stripped
Split pin broke
Horizontal adjust lock came out of position
KELK system fault
Motor stall alarms were generated
Incorrect feedback received from crop shear motor
Problematic encoder
Problematic cabling
Problematic plug connections
Problematic input cards
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Incorrect feedback received from crop shear motor
Problematic encoder
Problematic cabling
Problematic plug connections
Problematic input cards

Appendix G (Interview agenda and questions)

Interview Agenda

Interviewee: Dominique Cosset

2015/09/09

12H00

1. **Opening session: 2 Minutes**

2. **Provide information to interviewee: 8 Minutes**
    a. Discuss crop shear unplanned downtime and ineffective SOP in assisting HSM personnel to effectively manage and operate the crop shear.
    b. Demonstrate the advantages we have seen on crop shear equipment reliability performance since the interviewee's earlier visit and implementation of the reliability improvement program.
    c. Discuss the approach implemented in generating the proposed CBM approach as to how the crop shear could be maintained and operated with noticeable improvement concerning the reliability of operation and blades.
    d. Elaborate on the advantages noticed in phase 2 of experimental component 3.

3. **Capture information from interviewee: 18 Minutes**

    The following questions seek answering:

    3.1. What replacement strategy does the interviewee suggest be used?

    3.2. Can the interviewee suggest a known specialist in the field one could contact?

    3.3. What blade replacement procedure would the interviewee suggest be used?

    3.4. Does the interviewee find the proposed CBM approach to be effective from results seen in experimental component 3? Feeling upon effective implementation of the proposed CBM approach.

    3.5. What approach would the interviewee consider other than the discussed experimental approach?

4. **Closing session: 2 Minutes**

Appendix H (Revised HSM crop shear SOP)

Centre	Vanderbijlpark Works	Document Type	KPR	Effective Date	30 September 2015
Document	WWNPWA0000043	Version	2	Revision Date	30 September 2016
Status	Released			Approved By	SAREL (SJ) NIEMANDT
Title	Use of the Crop Shear				

This document replaces	WWNPWA0000043/01
Reason for revision	Include new condition based maintenance approach and process parameters
Destination group	All FM and RM maintenance and production personnel

1. **Purpose**

The purpose of this works procedure is to communicate the correct maintenance and operating procedure for the crop shear.

2. **Definitions and terms**

Accu crop auto mode	- KELK system will cut the heads and tails automatically
Accu crop Ready	- Crop shear is in KELK /HMD mode. Green light: KELK mode
CBM	- Condition based maintenance
Crop shear parked	- The crop shear has parked in the head / tail position
Cut aborted	- Cut will be aborted most likely due to invalid speed.
Cut HMD	- The transfer bar has reached the KELK / HMD
Cut HMD healthy	- The KELK / HMD is operational
Cut initiate	- The crop shear has begun moving
Double tail cut	- The crop shear will rotate 2 times on the tail end
Drive healthy	- The crop shear drive is ready
HMD	- Hot metal detector
HMDCS	- Hot metal detector, crop shear
HMI	- Human-machine interface
Motor stalled	- The crop shear has not parked in a reasonable amount of time and may be stuck. The operator will have to un-stall the motor

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3. Process introduction

The crop shear is used to cut the front and tail ends of the transfer bar. The edging at the roughing mill causes fishtails on the strip ends, which causes problems during rolling, coiling and later processing of the material. The uneven edges have to be cut off to ensure a straight edge.

The crop shear is a rotary drum type. The shear consists of a frame with a removable cartridge (drums). The rotating drums are driven by a 281kw DC electrical motor with a gear mechanism to synchronise the top and bottom drum. The rotating drums are equipped with blades for cutting the strip. The cut should consist of a 40% cut portion and 60% break portion.

The position and strip speed is determined by 2 HMD’s in front of the crop shear along the delay table. If the position and speed are known, it is possible to make an accurate cut on the front and tail end.

The blade for the head end cutting is slightly curved to improve the biting action. The tail end blade is straight.

To ensure a proper cut, a few control parameters can be adjusted. The cutting speed manages the lead speed and the lag speed. The lead speed on the front end cut should be faster than the strip speed and the lag speed on the tail end should be slower than the strip speed. A tolerance of 10 either side of 0 is available to make adjustments.

4. Process parameters

The following parameters and instruction discussed in this section are important for the operator to understand and adhere to when operating the crop shear and KELK system.

Table 1: KELK system parameters

Head			Tail		
Head fixed length	mm	400	Tail fixed length	mm	400
Head body width	%	95	Tail body width	%	95 - 93
Head body width dogbone detect	%	105	Tail body width dogbone detect	%	105
Head body width dogbone cut	%	101	Tail body width dogbone cut	%	101
A symetric head cut	%	15	A symetric tail cut	%	15
Head cut offset	mm	85	Tail cut offset	mm	85
Maximum cut length head	mm	900	Maximum cut length tail	mm	900
Minimum cut length head	mm	150	Minimum cut length tail	mm	150 - 200
Rectangulat shape length	mm	100	Rectangulat shape length	mm	0
Head cut lead speed	%	5	Tail cut lead speed	%	-5

5. Process instructions

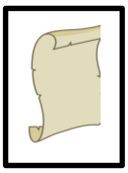
The following section elaborates on the instructions to be followed when operating the crop shear.

5.1. Buttons

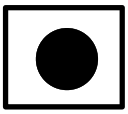
The buttons illustrated on the top left of KELK screen is explained below:

P

The button allows the user to set a wiggle angle to the tail end. It also allows the user to turn the extra revolution on the tail end ON or OFF.



ONLY use this option when width gauge 3 is out of operation and no images are available



This button must be pressed when the motor drive trips. Only press the button once and uninstall only if the drive has been reset.

5.2. General instructions

- If the crop shear is in the wrong position, press the "immediate cut" button ONCE.
- There should never be two sequential slabs in the tracking zone of the crop shear at the same time. The tracking zones consist of HMDCS2 and HMDCS3.
- When a transfer bar enters the tracking zone of the crop shear and the delay tables are stopped, the slab must first be pulled back out of the tracking zone of the crop shear. After the process interruption has been resolved, the tables can be started and the crop shear will cut normally.
- If a cobble has occurred or the transfer bar has to be removed after an image has been captured, the bar ID must be cleared from the KELK screen.

5.3. Zeroing the crop shear

Table 2: Zeroing the crop shear

Instruction	How	Why
1. Take the green light	Interrupt the production process by selecting the green / red production process light to the green selection and roll the extracted slabs finished.	The production process must be interrupted in order to zero the crop shear
2. Put the crop shear on manual	Go to screen 341 by pressing the "HOME" button and key in 341 and press the "ENT" button. Move the cursor into "CROP SHEAR MODE" field and press the "ACT" button. The "MANUAL" and "AUTO" buttons on the HMI keyboard will light up. Press the	The crop shear must be selected onto manual mode in order to jog into the correct position for zeroing.

	“MANUAL” button to put the crop shear on manual mode	
3. Jog the crop shear	Verbally ask the first roller to check position of the crop shear blades. The first roller will check at the back of the crop shear on the top crop shear drum and on the housing where two arrows are painted. The first roller will verbally inform over the two-way radio or with hand signal to jog the crop shear and instruct to stop as soon as these arrows are aligned.	The crop shear must be jogged in order to ensure that the tail blades are aligned.
4. Go to screen 311	Press the “HOME” button on the HMI keyboard and key in 311 and press the “ENT” button	Must go to screen 311 in order to zero the crop shear.
5. Zero the crop shear	Move the cursor to the “ZERO ENABLE” field and press the “ACT” button. The “IN” and “OUT” buttons on the HMI keyboard will light up. Press the “IN” button. The cursor will automatically jump to the “ZERO REQUEST” field and the “IN” and “OUT” buttons will be lit up again. Press the “IN” button to zero the crop shear. The “CROP SHEAR DEGREE” field will show a value of 0^0 if the crop shear is zeroed successfully. Move	The crop shear must be zeroed in order to ensure that the strip is cut correctly without damaging the crop shear blades or the crop shear itself.

	the cursor to the “ZERO ENABLE” field and press the “ACT” button. The “IN” and “OUT” buttons on the HMI keyboard will be lit up. Press the "OUT" button to disable the “ZERO ENABLE” field.	
6. Do a manual cut	Jog the crop shear away from the zero position. Press the “PARK RESET” button on the direct action keyboard. The crop shear will go to either the tail end cut or head end cut position. Test the crop shear cut by pressing either the head end cut or tail end cut button on the direct action keyboard, depending on which button is lit up. Keep cutting the crop shear until the crop shear is on the head end cut position.	The crop shear must be tested and you must ensure that it is at the correct position to cut the following slab.
7. Go to screen 341	Press the “HOME” button and key in 341 and press the “ENT” button. Move the cursor in to the “CROP SHEAR MODE” field and press the “ACT” button. The “MANUAL” and “AUTO” buttons on the HMI keyboard will light up. Press the “AUTO” button to put the crop shear on auto mode. Put off green production process light and commence	The crop shear must be selected onto auto mode before rolling can commence in order for the crop shear to automatically cut the head end and tail end of the transfer bar.

	rolling again.	

5.4. Calibration of the HMD system

Table 3: Calibration of the HMD system

Instruction	How	Why
1. Switch over to manual mode	Select the “SERVICE STATUS” button the HMI screen. Press the “CROP SHEAR” button and then the “MANUAL” button	Calibration of the HMD system is only possible in the manual mode.
2. Align drive side calibration arrows	Jog the crop shear using the direct action keyboard until the arrows on the drive side of the crop shear are aligned.	The straight blades responsible for cutting the tail end must be aligned.
3. Zeroing the HMD	Press the “SELECT ZERO” button on the HMI to “ON”. Then press the “ZERO REQUEST” button. Press “SELECT ZERO” to “OFF”.	To conduct the zeroing process

6. Maintenance strategy

This section elaborates on the latest maintenance strategy revision. The procedure discussed below ensures that personnel have an effective step-by-step guide when seeking guidance as to how the crop shear should be maintained.

Table 4: Maintenance strategy

Instruction	How	Why
1. Daily measure the crop shear offcut burr length	Using a vernier, measure the burr length of 3 different samples of the head end and tail end on a daily frequency.	Frequent measuring ensures for more effective condition monitoring of the blades.
2. Capture the measurement readings on the master data sheet	On the tab below on the excel spreadsheet, specify which crop shear cartridge is currently in use. Then refer to the latest circulation number table. Along with the data, insert the burr length data.	To capture all measurements on a mutual datasheet. More importantly, the burr length measurements are compared here, to monitor the burr length increase.
3. Replace cartridge in accordance with maximum allowable burr length specification	Whichever obtained first: Front end burr length: 1.5mm Tail end burr length: 4.5mm Then the cartridge should be considered to replace.	To ensure the cartridge is replaced preventatively before normal wear progresses to a point where cuts are no longer successful.

*Please refer to paragraph 9.1 to for the communication guideline related to the table content.

The crop shear cartridges should be reconditioned according to a 3 year frequency. In cases where only one cartridge will be available if a scheduled cartridge is supposed to be reconditioned the ruling is to be postponed until enough operational crop shear cartridges are available on site.

7. Maintenance execution

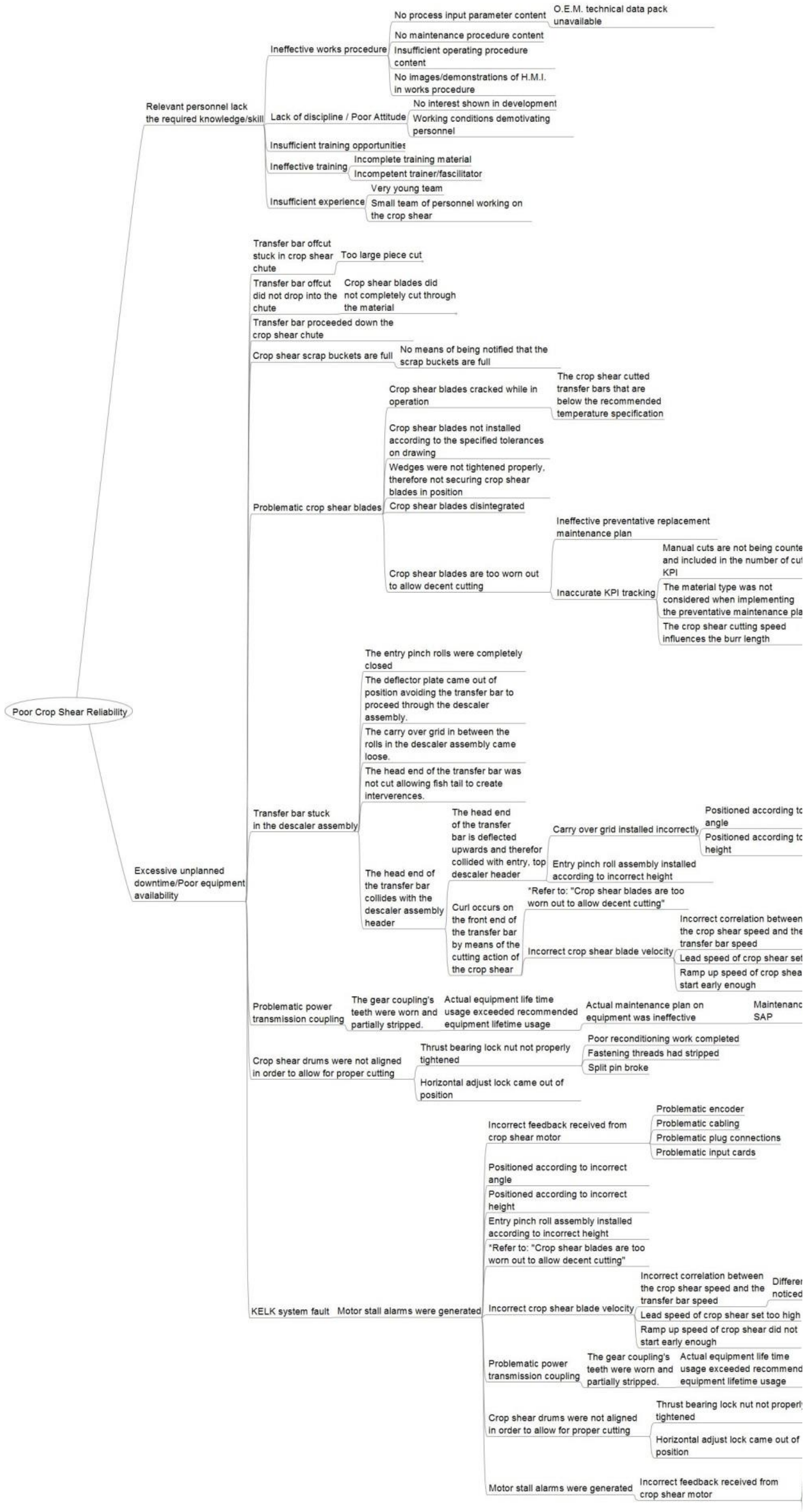
The finishing mill mechanical maintenance crew are responsible for the crop shear scheduled blade replacements. The blade positioning and assembly should be done in accordance with drawing no. V0901 – 0515 – 0005.001

Emphasis is placed on the following specifications:

1. The horizontal centre position of blades.
2. The 5mm overlapping specification of the top and bottom blade in “cut” position.
3. The fastening of the wedges to obtain initial blade position when in operation.

8. Trouble shooting

Please refer to the Why-Why diagram which elaborates on previously identified and known problems of the crop shear operation.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Insufficient experience
Very young team
Small team of personnel working on the crop shear
Excessive unplanned downtime/Poor equipment availability
Transfer bar offcut stuck in crop shear chute
Too large piece cut
Transfer bar offcut did not drop into the chute
Crop shear blades did not completely cut through the material
Transfer bar proceeded down the crop shear chute
Crop shear scrap buckets are full
No means of being notified that the scrap buckets are full
Problematic crop shear blades
Crop shear blades cracked while in operation
The crop shear cutted transfer bars that are below the recommended temperature specification
Crop shear blades not installed according to the specified tolerances on drawing
Wedges were not tightened properly, therefore not securing crop shear blades in position
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Crop shear blades are too worn out to allow decent cutting
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Inaccurate KPI tracking
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The material type was not considered when implementing the preventative maintenance pla
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The deflector plate came out of position avoiding the transfer bar to proceed through the descaler assembly.
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The head end of the transfer bar was not cut allowing fish tail to create interverences.
The head end of the transfer bar collides with the descaler assembly header
The head end of the transfer bar is deflected upwards and therefor collided with entry, top descaler header
Carry over grid installed incorrectly
Positioned according to angle
Positioned according to height
Entry pinch roll assembly installed according to incorrect height
Curl occurs on the front end of the transfer bar by means of the cutting action of the crop shear
*Refer to: "Crop shear blades are too worn out to allow decent cutting"
Incorrect crop shear blade velocity
Incorrect correlation between the crop shear speed and the transfer bar speed
Lead speed of crop shear set
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The gear coupling's teeth were worn and partially stripped.
Actual equipment life time usage exceeded recommended equipment lifetime usage
Actual maintenance plan on equipment was ineffective
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Crop shear drums were not aligned in order to allow for proper cutting
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Poor reconditioning work completed
Fastening threads had stripped
Split pin broke
Horizontal adjust lock came out of position
KELK system fault
Motor stall alarms were generated
Incorrect feedback received from crop shear motor
Problematic encoder
Problematic cabling
Problematic plug connections
Problematic input cards
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*Refer to: "Crop shear blades are too worn out to allow decent cutting"
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Incorrect correlation between the crop shear speed and the transfer bar speed
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Crop shear drums were not aligned in order to allow for proper cutting
Thrust bearing lock nut not properl tightened
Horizontal adjust lock came out of position
Motor stall alarms were generated
Incorrect feedback received from crop shear motor

9. Communication and enforcement

9.1. Communication related to maintenance strategy

The finishing mill mechanical superintendent is to be informed according to the following guideline mentioned below

1. Unexpected data that may be of a concern should be communicated via email and telephonic discussion to describe the data. The superintendent will take further action upon their assessment.
2. Once either of the actual head or tail end burr length targets is within 5% of the specified target the superintendent should be informed so that the necessary planning of replacement can be done to avoid breaching the limit.
3. Upon every replacement a thorough post-usage report should be compiled by the Mechanical Engineer and be handed over to the superintendent within a week after the replacement occurred.

Piet van Rensburg is the current finishing mill mechanical maintenance superintendent and can be contacted accordingly:

Tel: 016 889 5296 (2-5296 for internal calls)

Email: pietvanrensburg@arcelormittal.com

9.2. Communication related to production abnormalities

The production and millwright shift are to adhere to the following production guidelines:

- In the case of a too cold transfer bar received from roughing mill, the exposure thereof to the crop shear and finishing mill is to be denied, and therefor removed from the process. A plate shear feedback report is then to be submitted on the HSM daily production feedback report (Production personnel) and a notification to be created on SAP (Millwright).
- Crop shear operation abnormalities (i.e. cut too cold transfer bar and cutting double-front ends) are to be reported to the mechanical engineer by means of email and a feedback report on the HSM daily production feedback report.

Evo Ribeiro is the current finishing mill mechanical engineer and can be contacted accordingly:

Tel: 016 889 5059 (2-5059 for internal calls)

Email: evoribeiro@arcelormittal.com

9.3. Communication related to SOP management

The following instructions refer to the proposed means of managing this SOP:

1. If a fault or shortcoming is noticed after one has been referred to the SOP, the preferred amendment should please be brought to the attention of the finishing mill mechanical maintenance engineer. The proposed amendment shall then be considered.
2. A register shall be conveyed along with a new revision to ensure the relevant personnel are well informed of the amendments.

9.4. Management's responsibility to enforce the SOP

1. The SOP should be reviewed on an annual frequency.
2. It is the responsibility of management to ensure that all understand the content of the SOP and that the SOP is adhered to.
3. Not adhering to the SOP should result in disciplinary action if actual action displays an attitude of negligent behaviour.

10. Safety

Ensure that the task HIRA is completed. In the case of sub-contractors a permit to work is also required. The specifics thereof can be obtained from Piet van Rensburg, Finishing Mill Mechanical Maintenance Superintendent.

The following risks, by no means the only risks, should be considered:

- Possibility of falling when working on top of crop shear frame.
- Possibility of falling down the chute – wear harness.
- Crushing zones (i.e. when inserting the crop shear cartridge).