Using a discrete-event simulation model to identify bottlenecks and determine the efficiency in a maintenance workshop

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Acronyms

AMP	Anglo American Platinum
EMV	Earth Moving Vehicle
OEE	Overall Equipment Effectiveness
BMP	Best Maintenance Practices
PM	Preventative Maintenance
CBM	Condition Based Maintenance
TOC	Theory of Constraints
FFS	Five Focusing Steps
ABS	Agent Based Simulation
DES	Discrete Event Simulation
IMIS	Inventory Management Information System
RI	Resonant Industrial

Chapter 1

Introduction

An investigative study of a maintenance workshop at the Anglo American Platinum (AMP) mine in Mogalakwena was done to identify possible bottlenecks in the maintenance process that influence the downtime of Earth Moving Vehicle (EMV). The workshop is currently under investigation to determine areas for improvement and management requires a tool that can be used to observe the efficiency of maintenance practices through reducing the overall downtime of EMV's.

1.1 Company background

Anglo American Platinum is the primary producer of platinum group metals around the world. One of the company's biggest open-pit platinum mines are based in the Mogalakwena district, Limpopo, South Africa. AMP strives to enable sustainable, safe and profitable business for South Africa. The company has always been a top tier organisation when it comes to mining operations. In order for Anglo Platinum Mogalakwena to perform to their high standards there are various external companies that performs specific mining activities at the mine. One of these companies are Komatsu. Komatsu is a world leading provider of mining, earthmoving and construction equipment. The company's vision is to be a leading equipment provider in South Africa from mining to construction sectors.

Currently Anglo Platinum is outsourcing the maintenance EMV's to Komatsu in order to maintain and service the earthmoving vehicles that are used for the mine. Included in the maintanance servicing are the following EMV's: 21 electric drive haul trucks, 3 wheel dozers, 3 track dozers, 2 dump trucks and 1 water truck.

Resonant Industrial (RI) is a leading engineering service provider which aims to provide comprehensive engineering and project management services to industry. The company's basic philosophy is to optimise engineering assets over the complete lifecycle. The well-known reputation of this company has been acknowledged by various leading engineering organisations around the world and as a result is currently working on engineering projects in cooperation with AMP (Resonant, 2017).

AMP and RI are working on various projects in and around the mine. Resonant Industrial was instructed by AMP to pursue this project in accordance with Komatsu to identify and resolve problem areas in the maintenance workshop.

1.1.1 Problem background

The project at hand is based on the Komatsu Truck Maintenance Workshop (from here on Komatsu workshop) at Anglo Platinum Mogalakwena. The Komatsu workshop aims to maintain and service EMV's in a time efficient way to ensure minimum downtime. The workshop is currently using a Preventative Maintenance (PM) approach. This approach requires the workshop to perform maintenance on EMV's based on the total amount of operating hours. Table 1.1 consists of the maximum amount of operating hours an EMV can acquire before preventative maintenance must be done. The policy is used to prevent machines from major breakdowns and ultimately extensive downtime.

Table 1.1: Preventative maintenance per EMV type.

EMV type	Service type/ Interval	Duration [Hours]
Haul truck	250-hr	1
Haul truck	500-hr	4
Haul truck	750-hr	8
Haul truck	6000-hr	48
Cable reeler	500-hr	7
Cable reeler	2000-hr	7
Track dozer	500-hr	48
Track dozer	2000-hr	48
Water/Dump truck	500-hr	7
Water/ Dump truck	2000-hr	7

There are a number of activities and unplanned occurrences that contribute to the increase in maintenance procedures. The main problems contributing to an increase in time in maintenance practices were identified by analysing two years of historical workshop data as well as meeting with supervisors and maintenance staff. Data was collected on unplanned downtime, planned downtime, planned PM service and rebuild schedules specifically for electric drive haul trucks. The data was specifically analysed to point out any problems that might affect the time spent on maintenance practices.
Figure 1.1 indicates the duration in hours of unplanned downtime.

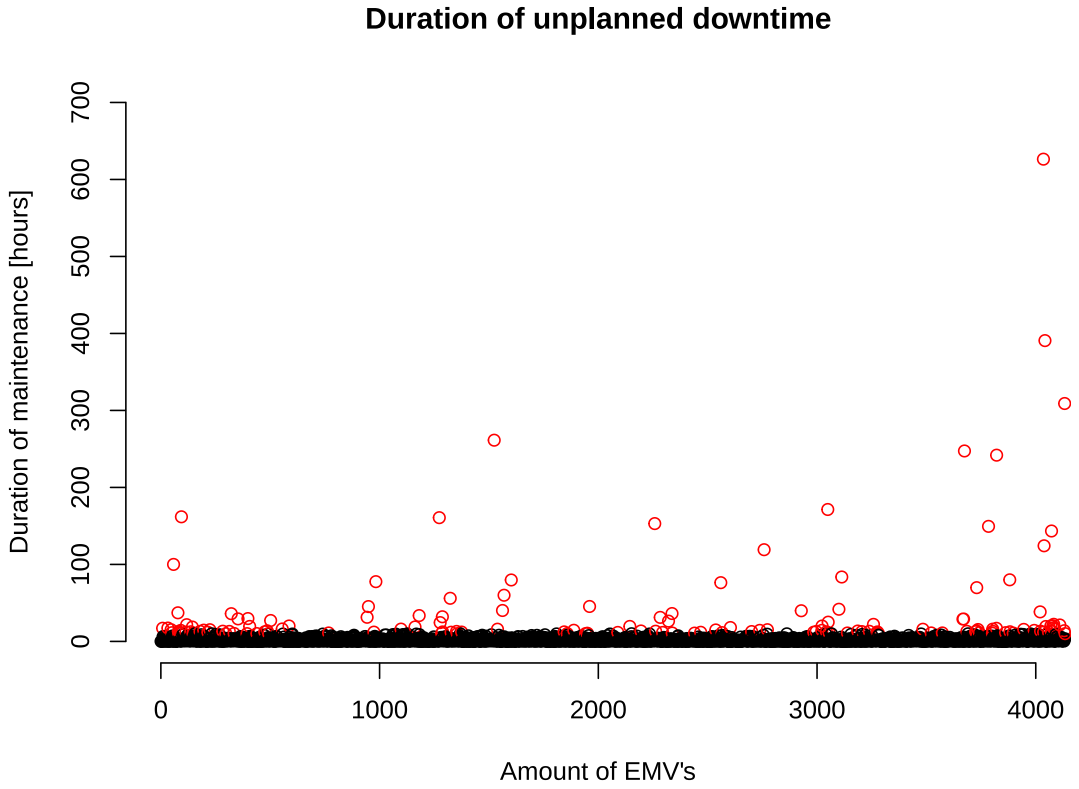


Figure 1.1: Duration of unplanned downtime

Statistical analyses of Figure 1.1 showed that over the period of two years a standard like average of 3 hours per EMV for unplanned downtime was obtained.This was verified by the supervisor and maintenance staff which agreed that 3 hours is the normal rate at which an unplanned occurrence usually takes before it is resolved. Thus by using this benchmark all points on Figure 1.1 that is above 3 hours was illustrated as a red circle. The points representing the outliers were investigated to determine the cause which produced the increase in unplanned downtime.

The number of points above the recommended 3 hours for unplanned downtime was 18.7% of the total points in the two year period. This indicated that 18.7% of the time it takes more than three hours to get maintenance done on an EMV with the maximum time being 626 hours or 26 days. This extreme occurrence was caused by the waiting time to receive the required part in which in this case was a new engine.

Planned downtime was analysed according to the PM policy on the total allowed operating hours per EMV before maintenance is required (see Table 1.1). This means that the downtime was planned according to the type of service needed. Figure 1.2 indicates the duration of planned downtime per EMV. The outliers were investigated to determine the cause of such a significant increase in downtime. Table 1.1 indicates that the maximum amount of time an EMV should spend in the maintenance workshop undergoing PM maintenance is 48 hours. However the outliers indicated that there are some points exceeding the 48 hour limit. The data indicated that of the total planned downtime, 2.23% exceeds the 48 hour limit with the maximum downtime being 713 hours or 30 days. This significant duration of downtime was caused by unavailability of parts. Also due to an increase in maintenance activities the working bays were occupied and the EMV had to wait outside the workshop contributing to the significant increase in downtime.

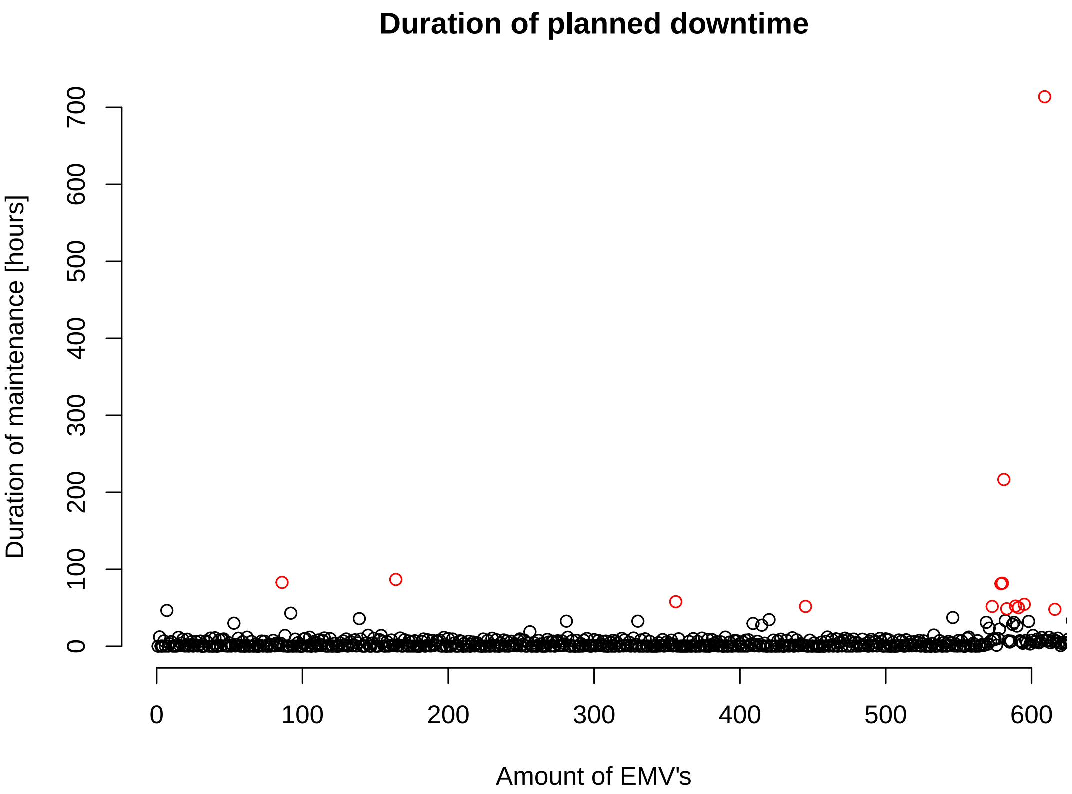


Figure 1.2: Duration of planned downtime

All of the outliers indicated with red circles in both Figures 1.1 and 1.2 were analysed more in depth to determine the causes of these occurences. Table 1.2 represents the percentage of parts, maintenance equipment and workspace not available that affected both planned and unplanned downtime. The percentages for unplanned downtime is based on the 18.7% of the time it takes more than 3 hours to get maintenance done and for planned maintenance the percentages are based on the 2.23% of time that exceeds 48 hours.

Table 1.2: Percentage of identified occurrences increasing the duration of planned and unplanned downtime.

Identified occurence	% of unplanned downtime	% of planned downtime
Parts not available	71.87	42.73
Maintenance equipment not available	28.12	31.64
Unavailable workspace	0	25.63

Table 1.2 indicates for example that 71.87% of the amount of unplanned downtime that is above 3 hours is caused by the unavailability of required parts and 31.64% of the time that maintenance takes 48 hours or longer for planned maintenance downtime is due to the fact that equipment is unavailable. However, after consulting with the supervisors

and maintenance staff from the Komatsu workshop it was pointed out that an increase in downtime is not only caused by the reasons listed in Table 1.2 but due to work overload and waiting time for EMV operators which can not be statistically analysed.

1.1.2 Problem statement

Currently the workshop is under a lot of pressure to try and increase the overall efficiency of the maintenance process by minimising the downtime per EMV. After consulting with the Komatsu supervisors and maintenance staff and analysing the data above, a list of problems contributing to the increase in downtime and inefficient practices were constructed. The major problems currently active in the workshop are:

1. lack of workspace;
2. spare parts are not constantly available;
3. critical equipment is not constantly available;
4. maintenance procedures can be inefficient; and
5. maintenance staff is unavailable.

All of these problems contribute to the downtime of EMV's which in effect reduces the efficiency of the overall workshop. Thus an opportunity exist to determine the efficiency of the workshop practices and to identify potential bottlenecks that causes the increase in downtime of the EMV's. In order to analyse these problems a simulation model will be developed to incorporate the maintenance process. The simulation model will provide performance measures that can be analysed to determine what specific maintenance practices contribute to downtime and in effect inefficiency of the overall workshop.

1.1.3 Document structure

In Chapter 2 a literature review describes and compares various different maintenance and simulation approaches and techniques that will be used to build a conceptual simulation model. The literature in Chapter 2 also contains previous work done by various different authors on simulation techniques used to model maintenance approaches as well as using these simulation models to identify bottlenecks in a process.

Chapter 3 of this report contains the conceptual simulation model that will be used to construct the actual model. This chapter explains the different elements that will be used in the simulation model as well as the different inputs and parameters that will be analysed throughout the simulation process. Chapter 4 refers to the data analyses and data interpretation. The data is explained and analysed on different aspects of the maintenance process. Chapter 5 refers to the actual computer based simulation model which interprets the current maintenance workshop. Chapter 6 refers to the results and recommendations obtained explaining the model outputs. Chapter 7 is the conclusion of the report.

Chapter 2

Literature review

Maintenance practices have always been an important area for improvement in mining industries, especially for cost saving strategies and availability of operational equipment. By examining maintenance practices and understanding the internal and external forces influencing the maintenance process a platform can be created to determine the efficiency and identify areas of improvement in maintenance workshops. Maintenance can thus be examined as an efficient way to improve the overall productivity and output of a production process.

According to Alabdulkarim et al. (2015), maintenance operations can be complex to monitor. Therefore Lightfoot et al. (2011) suggests using applicable monitoring technology that can incorporate the complexities of a maintenance process. Decision making tools such as simulation models provide a playground where different scenarios in the maintenance workshop can be created and ultimately be examined and analysed effectively without affecting the real system.

2.1 Significance of maintenance practices

Maintenance can be described as the preserving and continuing of an entity in good operating condition (Smith, 2004). Maintenance is becoming a crucial factor worth investigating for companies which aims to increase profitability, labour productivity and product quality (Noemi and Leigh, 1993). As the complexity of operating equipment increases, the required level of maintenance expertise increases.

Noemi and Leigh (1993) states that along with the increase in maintenance complexity, the maintenance and production cost increases and companies are forced to develop maintenance practices which can operate at the most cost effective way. According to Abdulnour et al. (1995) maintenance management is responsible for reducing equipment downtime and cost associated with unplanned disruptions. Unplanned downtime of a process indicates that activities responsible for the operation and flow of the process is currently at standstill due to unforseen ciscumstances. If a company is not prepared for a downtime to take place then ultimately profit is lost due to the increase in production and maintenance costs. However, Alabdulkarim et al. (2015) states that if maintenance management focuses on reducing unplanned downtime, maintenance cost and consequently production cost will be reduced.

2.1.1 Maintenance approaches

Maintenance can add substantial value to a company's reliability and can preserve it's assets if it is developed and managed properly. Over the years different maintenance approaches emerged to help companies manage maintenance operations effectively. According to Keith and Smith (2008) there are two main approaches. Reactive and proactive maintenance. The reactive approach responds immediately to an identified need or request in a production process. As can be seen in Figure 2.1 there are four main activities that takes place primarily with the focus to perform maintenance operations. These primary activities include notification, planning, scheduling and fix. The other five activities are secondary activities which only reacts to an order from a primary activity. For example, if maintenance is required a notification is sent out to a mechanic which then assesses the problem and determines the tools and parts required to perform the maintenance. Planning and scheduling of the maintenance procedure takes place after the assessment. The mechanic then executes the maintenance activity using the necessary parts and tools. The goal of this approach is to minimise response time and reduce equipment downtime. The reactive approach also incorporates preventative maintenance and is used by most companies today (Keith and Smith, 2008).

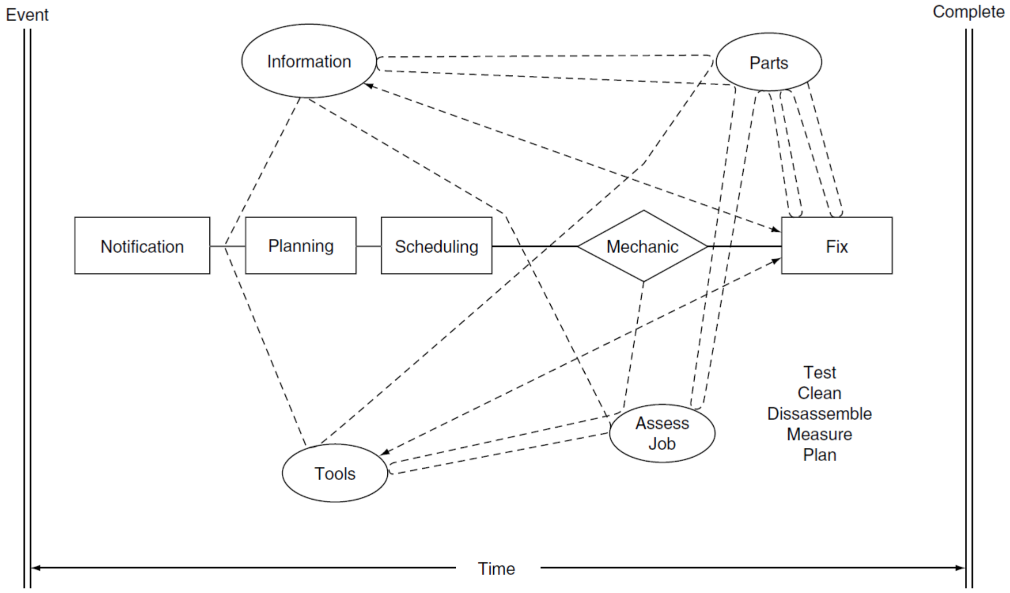


Figure 2.1: Reactive maintenance model(Keith and Smith, 2008)

The proactive approach contains more predictive measures and primarily reacts to equipment assessment. Figure 2.2 indicates the proactive maintenance model. The model begins the process with predictive procedures which includes daily and weekly inspections. The inspections include performance evaluation and as a result it can be monitored whether there is a need to perform maintenance to ensure prevention of future breakdowns. Also the model incorporates data on work performance that is gathered over the years to predict whether maintenance is necessary. After the evaluation, planning takes place. The planning phase is used to determine the type of work order/maintenance procedure that will be executed. When a work order is established a problem solving team is dispatched to perform the necessary maintenance required. After the maintenance is completed the process starts again with predictive procedures such as inspections with the help of historically work performance. The goal of this approach is to maintain continuous improvement in a production process by focusing on equipment performance, specifications and maintenance of productive capacity.

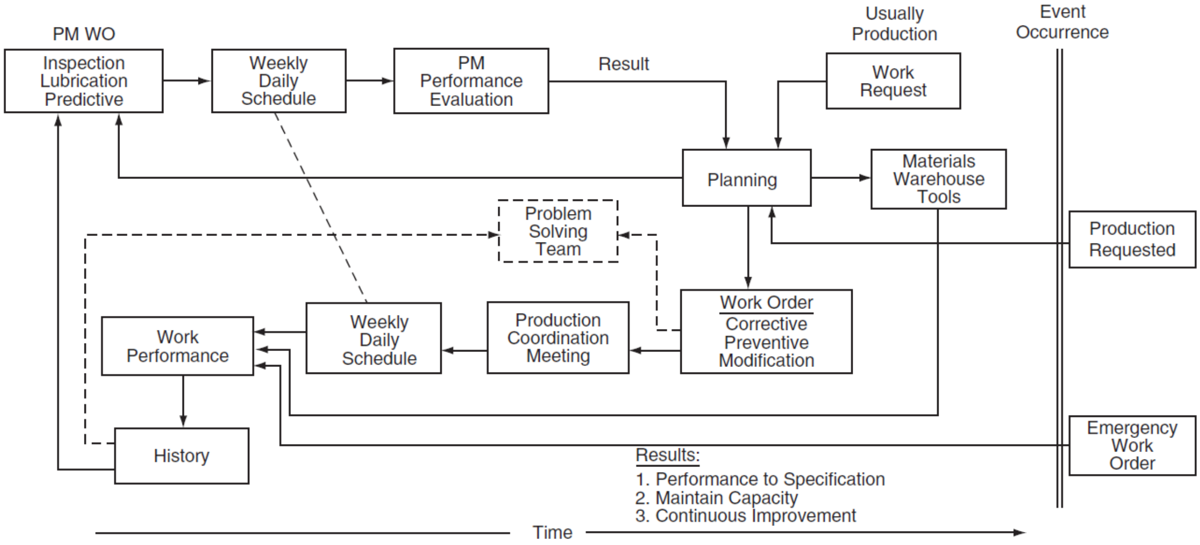


Figure 2.2: Proactive maintenance model (Keith and Smith, 2008)

These two approaches identified by (Keith and Smith, 2008) lay the foundation of more specific and developed maintenance approaches which can be implemented by companies to fit their needs and requirements.
One of these approaches are Best Maintenance Practices (BMP), developed by Smith (2004). According to Smith (2004) " it represents benchmarking standards that are real, specific and achievable for maintenance management". The following points are the benchmarking standards formulated by Smith (2004):

- work orders must always cover 100% of the maintenance personnel's time;
- preventative maintenance inspections must generate 90% of work orders;
- at least 30% of total labour hours are from preventative maintenance;
- planned or scheduled work must be executed 90% the time;
- total reliability is reached 100% of the time;
- overall equipment effectiveness (OEE) is greater than 85%; and
- only 2% of total maintenance time must be overtime.

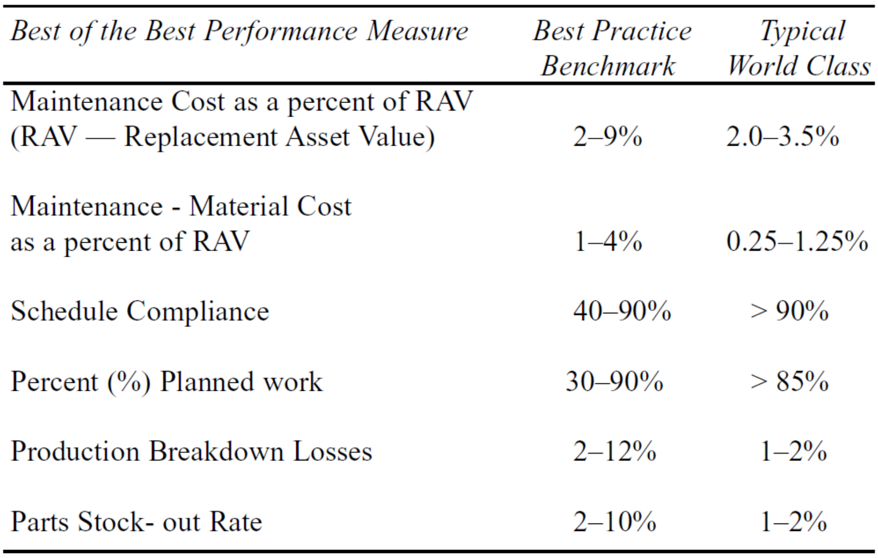
Smith (2004) identified the opportunity to effectively establish standards to which maintenance practices can be compared. The aim of BMP is to achieve more efficient maintenance areas, reduce maintenance costs and improve reliability and increased confidence of maintenance staff. Smith (2004) goes on to say that it is important to identify the reasons for a maintenance workshop not achieving BMP. The two most common reasons that a facility does not follow BMP are that current maintenance is sensitive to failure and in turn fails to safeguard maintenance practices as well as workforce in the maintenance department lacks the ability and discipline to follow BMP as well as management failing to define rules of conduct for BMP.

Smith (2004) states that management should actively pursue a proactive thinking when it comes to maintenance ineffectiveness. By combining a proactive approach with BMP, maintenance effectiveness will improve rapidly.

In the work of (Smith, 2004) it is stated that a leading global management consulting firm implemented a BMP proactive thinking approach to the maintenance operations of the company and within a period of three years the following results were obtained:

- increase in productivity of 28.2%;
- maintenance cost decrease of 19.4%;
- equipment availability and reliability increase of 20.1%; and
- reduction in inventory carrying cost of 17.8%.

Thus the BMP approach along with a proactive maintenance mindset will ultimately ensure cost savings, increase in reliability and efficient maintenance operations in any process. According to Gulati and Smith (2009) best practices in the maintenance and reliability areas have been implemented by organisations who are leaders in the industry. These companies are setting high standards with competitive low costs and world class benchmarks which makes it difficult for other companies to compete. Gulati and Smith (2009) states that a company can only achieve world class performance on various levels if best practices are implemented first. The following figure, Figure 2.3 indicates the increase in various performance measures by implementing best practice benchmarks. The values for best practice benchmark indicates the range of which performance measure must comply to in order for a company to achieve world class standards.



Best of the Best Performance Measure	*Best Practice Benchmark*	*Typical World Class*
Maintenance Cost as a percent of RAV (RAV — Replacement Asset Value)	2–9%	2.0–3.5%
Maintenance - Material Cost as a percent of RAV	1–4%	0.25–1.25%
Schedule Compliance	40–90%	> 90%
Percent (%) Planned work	30–90%	> 85%
Production Breakdown Losses	2–12%	1–2%
Parts Stock- out Rate	2–10%	1–2%

Figure 2.3: Comparing best practices benchmark
(Gulati and Smith, 2009)

According to Gulati and Smith (2009) a typical company's maintenance cost is 2% of the total replacement value of current assets whereas a company which implemented best practices can reduce maintenance cost to 0.5% of replacement value of current assets.

Thus increasing the replacement value for assets in a company and increasing overall net income. Also, Gulati and Smith (2009) states that the percentage of planned work can increase from 30% for a typical company to 90% for a best practice company. This increase is due to the fact that the company is proactively planning three times more work and will ultimately have higher up time and high utilization rates.

Preventative maintenance (PM) approach is described by Andriulo et al. (2015) as scheduled activities according to predetermined time intervals. The aim of PM is to conduct maintenance activities on a scheduled basis in order to prevent as much as possible failures. However, Alabdulkarim et al. (2015) argues that PM has a shortfall. This approach performs maintenance on a periodic basis regardless whether the asset is in need of maintenance or not. Thus by performing unnecessary maintenance activities the cost of maintenance becomes very high.

Grall et al. (2002) reckons that Condition-Based Maintenance (CBM) is a more efficient approach than preventative maintenance. CBM takes into account the health status of the asset. This is done through inspection and sensing technologies. CBM consists of two monitoring levels namely diagnostics and prognostics. The diagnostic level is when the component/machine diagnoses itself when a failure occur and gives feedback to a maintenance centre. Prognostics is when the component/machine consists of monitoring and sensing technology and predicts a failure based on the health of the component/machine (Alabdulkarim et al., 2015).

Ultimately there are numerous maintenance approaches that have been developed and implemented across various different systems and processes. The greatest effect a maintenance approach will have on any kind of system or process is when an approach is thoroughly investigated to address the specific needs and requirements of a company. Thus by using previous literature and research on maintenance approaches one can identify the best option which will satisfy all needs in a company.

2.2 Simulation of maintenance practices

Simulation as described by Tiwari and Alrabghi (2016) is a decision making tool that can be used to build different types of models to incorporate complex systems. A simulation model in effect can be developed to mimic a process to such an extent that by changing parameters and inputs in the model one can see what effect it will have on a real world process without affecting the system.

Tiwari and Alrabghi (2016) reckons that although maintenance systems are complex, with the use of simulation modeling these systems can be understood and improved effectively.

2.2.1 Importance of simulation in maintenance practices

According to Duffuaa et al. (2001) it is important to understand the complexity of maintenance systems. Maintenance systems interact with other complex subsystems like procurement processes for required parts. Also it is difficult to measure the output of maintenance in a quantifiable way and many uncertain elements exists in maintenance systems such as job arrival rates and time needed to perform maintenance (Duffuaa et al., 2001). All of these points contribute to the complexity of maintenance systems.

According to Alabdulkarim et al. (2015) the use of simulation has been widely used in healthcare, defence and public services. The different techniques in simulation can be used to analyse the performance of any operating system without affecting the real system. Alabdulkarim et al. (2015) states that because simulation is appropriate to monitor detailed operation systems it is relevant to maintenance systems as well.

Pannirselvam et al. (1999) argues that simulation is voted as the second most widely used monitoring technique in operations management and has the ability to represent the complexity of maintenance systems.

In the work done by Savsar (1990) the relationship between simulation and maintenance systems were studied to investigate the effect of different maintenance policies on production. It was concluded that simulation can also be used to find the optimal number of maintenance staff as well as optimal inventory in production systems.

In the work done by Joo et al. (1997) a simulation model was specifically developed to analyse a preventative maintenance approach with the main goal to improve efficiency. The average equipment utilization and average waiting time were used as measures of performance.

Mosley et al. (1998) developed a maintenance scheduling simulation model with the main objective to minimise downtime by scheduling only the necessary maintenance equipment and staff for the required job.

2.2.2 Simulation approaches

Nowadays there are various different simulation techniques that can be used as tools to represent complex processes and systems. It is critical to know the merits and shortfalls of a simulation technique. By knowing the capability of these techniques the modeler can avoid any limits or complexity in the quest to build an effective, accurate model.

The research conducted in this section of the literature review only includes two approaches to simulation modeling. Discrete Event Simulation (DES) and Agent Based Simulation (ABS).

Discrete-event simulation vs. Agent-based simulation

According to Baldwin et al. (2015) most model types have different perspectives on systems. One perspective is looking down on a system and the other is looking up from the system. DES follows a looking down perspective by modeling different events and ABS follows a looking up perspective that takes into account the functionality of the system.

Baldwin et al. (2015) states that ABS creates a model based on a collection of agents (autonomous decision making entities). The agents individually assess the situation from which it can make a decision based on a set of rules (Bonabeau, 2002). Baldwin et al. (2015) states that agents can be people, social factors, organizations or any individual system, the only requirement is that these agents must work independently of their environment. ABS can also be used for hypotheses testing to reveal whether an expected outcome will occur.

Discrete event simulation according to Baldwin et al. (2015) focuses on externally observable events that occur in different stages in a system. In other words, DES represent a collection of events that influence the system. Tiwari and Alrabghi (2016) states that the events in a DES are modeled as a queue and executed one by one as the simulation moves through the model.

Table 2.1 consists comparisons of discrete event simulation and agent based simulation.

As (Baldwin et al., 2015) states that one cannot predict whether DES or ABS will work better for modeling based on evaluating the merits and shortfalls of these two techniques. However, a decision must be made on whether the technique can address the specific purposes and needs of an organisation.

Table 2.1: Discrete-event simulation vs. agent-based simulation.

Discrete-event simulation	Agent-based simulation
Model creation is simple and easy understandable.	Model logic is complicated by the flexibility of agents.
Observes external events.	Observes decision making agents (entities).
Respond to discrete events.	Respond to functionality of agents.
State of system changes in response to events.	Agents are flexible and independent.
Events can impact the entire simulation.	Agents function as distinct parts.
Easy to validate.	Difficult to test.

2.2.3 Suitability of discrete event simulation in maintenance operations

According to Alabdulkarim et al. (2015) discrete event simulation has the potential to assess various maintenance approaches by taking into account all the maintenance characteristics like labour availability, spare part availability, asset location and travel time between assets. In the automotive industry a study conducted by Ali et al. (2008) used discrete event simulation to identify bottlenecks and optimise maintenance strategies. Ali et al. (2008) discovered that the overall availability in the production system has decreased as a result of excessive downtime due to machine/equipment failures.

Greasley (2000) developed a DES model for a maintenance project involving trains. The company benefited from the operational impacts by developing a variety of plans and ways to meet demand.

The Finnish Air Force also developed a DES model to monitor the effects of policies, maintenance resources and availability of aircrafts in different environments (Mattila et al., 2008).

Although DES is one of the few simulating techniques that can combine all the complex subsystems of a maintenance system (Tiwari and Alrabghi, 2016), studies in this area is limited (Alabdulkarim et al., 2015).

2.2.4 Using discrete event simulation modeling to identify bottlenecks

According to Lavoie et al. (2009) a discrete event simulation (DES) model is the preferred approach to evaluate the impact of dynamic aspects of processing plants. Lavoie et al. (2009) also states that it is a tool that can be used to identify bottlenecks in a plant, evaluate the response on implementing new technology in the plant, evaluate the impact on the plant if the workspace increases and optimize maintenance and operating practices without disrupting the operation.

The challenges faced in the iron ore plants were that production systems are very complex. This complexity made it a very difficult task to estimate the benefits of projects in existing operations. Adding to the effect was equipment reliability and maintenance schedules of which a shift in bottlenecks occurred frequently. To deal with this problem a dynamic simulation model was created based on specific system characteristics to exploit bottlenecks by creating different production scenarios.

Lavoie et al. (2009) states that DES is the most effective and comprehensive simulation approach to date to evaluate the production performance of complex systems. The model can interpret basic operations that mimic the behavior of a system. A key attribute of the DES is that it can reproduce elements of the system using representative statistical distributions. Other simulation approaches were also investigated by (Lavoie et al., 2009) like analytical models and Monte Carlo simulations but ruled out. Analytical models require real-world problems to be simplified to a point where they are not useful anymore and Monte Carlo simulations becomes less user-friendly over time when scheduled events such as maintenance must be incorporated.

The main and most important part of the project was the validation and sensitivity analysis of the simulation model. Lavoie et al. (2009) describes the aspects of validating a DES model as well as performing a sensitivity analyses. According to Lavoie et al. (2009) verification and validation is done in two steps:

1. Verify model calculations against an existing steady state model, for example like throughputs, yields, mass balances etc. The first step is done to indicate whether the results of the model would give similar outputs when events like scheduled and unscheduled downtime were ignored (when scheduled and unscheduled downtime is ignored the plant is in a steady state).

2. Validate the dynamics of the model - Lavoie et al. (2009) used historical plant performance data to compare the model results.
   According to Lavoie et al. (2009) the sensitivity analyses helped to validate the model by examining the effect it had to changes made in different input variables. By changing the inputs of the model an increase of ten per cent in filter and balling capacity were observed. This increase indicated a bottleneck in the process.

These two steps indicate the functionality of using discrete event simulation in order to identify potential bottlenecks in a process.

2.3 Techniques to help identify bottlenecks in a process

In any process or system it is often found that a constraint occur. A constraint in a process is a restriction that can limit the functionality and availability of resources needed in a process. According to Petersen et al. (2014) the negative impact a constraint can have in any process includes work overload, decrease in overall efficiency, delays and requirements become obsolete and creates stress in the organization.

The most effective and fastest way to improve efficiency and profitability in a process is by identifying and eliminating constraints. Theory of Constraints (TOC) is a method designed by Dr. Eliyahu Goldratt to help identify constraints. In manufacturing processes a constraint is usually referred to as a bottleneck. The TOC provides a set of tools to enable companies to identify potential bottlenecks. The tools include:

1. The Five Focusing Steps;

   This tool provides a method for identifying and eliminating bottlenecks in a process.

2. The Thinking Process

   This tool enables companies to analyse and resolve any problems that occur in a process.

3. Throughput Accounting

   This tool provides a method that measures performance as well as assist in management decisions.

Companies that implement TOC not only improve profitability and efficiency but also obtain various other benefits like system and processes improve at a fast rate, production capacity increases which means that more products can be manufactured, reduction in lead times, increase in product flow and reduction in inventory ensures less work-in-process. The TOC contains a specific method for identifying bottlenecks. The Five Focusing Steps (FFS) described above is used to identify bottlenecks. Figure 2.4 illustrates a diagram of these five steps.

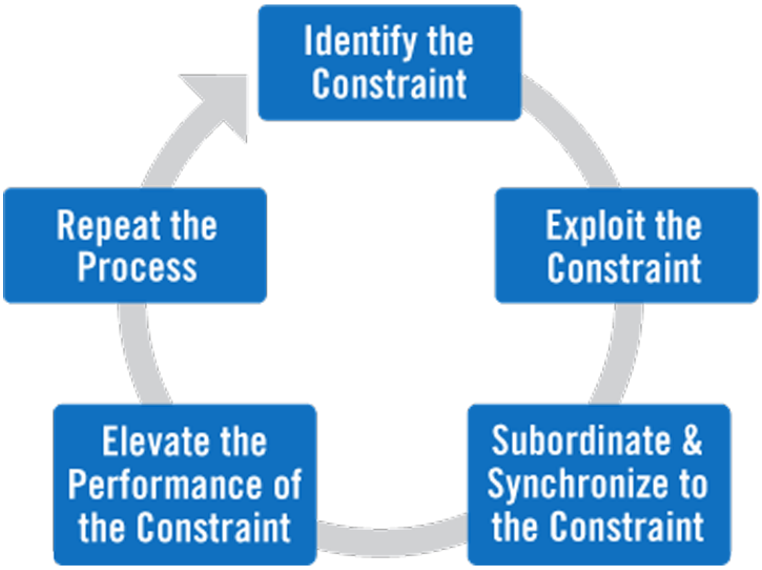


Figure 2.4: The five focusing steps

The implementation of these five steps will ultimately enable the exploitation of bottlenecks in a process.

Chapter 3

Conceptual model

The development of a conceptual model is subjected to the various specifications and elements in a maintenance process. The conceptual model will lead to a better understanding of the maintanance processes by exploiting their complexities. The specifications of the conceptual model lays the foundation for developing a simulation model (Duffuaa et al., 2001).

The specifications and elements of the conceptual model was based on the realistic characteristics of the Komatsu maintenance workshop. The conceptual model consists of seven elements each interpreting the specifications in the Komatsu workshop.

3.1 Elements of the conceptual model

The seven elements below contributed to the understanding of the complexity in the Komatsu workshop as well as the construction of the simulation model. The seven elements begin with the input element which contains all the data that were required for the simulation model. The maintenance load element represents the process of which the maintenance load is generated in the Komatsu workshop. The maintenance load is the input of the planning and scheduling element. This element schedules a job for execution by matching each job with a required resource. The planning and scheduling element initiates the materials and spares element in order to check whether there are materials and parts available for each job before the job is scheduled. The tools and equipment element is also initiated by the planning and scheduling element in order to check whether the required tools and equipment is available for each job. The quality inspection element determines the quality of the executed maintenance jobs. The final element is the measurement of performance indicators. This element were used to collect statistics on various performance measures.

3.1.1 Input element

The Komatsu workshop consists of many units (any type of machine or set of machines or department). The input element provides a configuration of the workshop in terms of the number of units considered. Thus by analysing the units any input can be obtained as desired. The following points are inputs that will be used in the simulation model:

- standard times;
- planned maintenance schedule;

- unplanned maintenance schedule (Breakdowns);
- plant configuration (number of units);
- staff job cards;
- spare parts requirements;
- critical equipment requirements;
- downtime of overall workshop practices; and
- historical maintenance data from the SAP system.

3.1.2 Maintenance load element

There are two main maintenance load elements in the workshop.

1. Planned maintenance load

   In the workshop this load is known in advance and provides job schedules, availability of spare parts and tools and equipment requirements. This is all planned according to when an EMV is scheduled for maintenance based on the amount of operating hours it completed.

2. Unplanned maintenance load

   The unplanned maintenance load is an instant occurrence that can happen at any given time. For the workshop this load is mostly dominated by breakdowns. Although it can not be predicted, historical data can show the pattern of occurrence and what elements are effected by it.

The flow chart in Figure 3.1 below indicates how the maintenance load is formed by planned and unplanned maintenance.

3.1.3 Planning and scheduling element

The planning and scheduling element is the core of the simulation model. The maintenance load consisting of planned and unplanned maintenance will be the input into this element. When the EMV arrives at the workshop the following steps are carried out in the simulation model:
The planning and scheduling element can be seen in Figure A.1 Appendix A.

1. Check priority level

   The model determines the maintenance priority for each EMV that arrives at the workshop.

2. Check parts availability and staff availability.

   The model will determine whether there are maintenance staff available to execute a job with the required parts needed.

3. Check tools and equipment availability.

   This element will determine whether key equipment, tools are available for maintenance procedures.

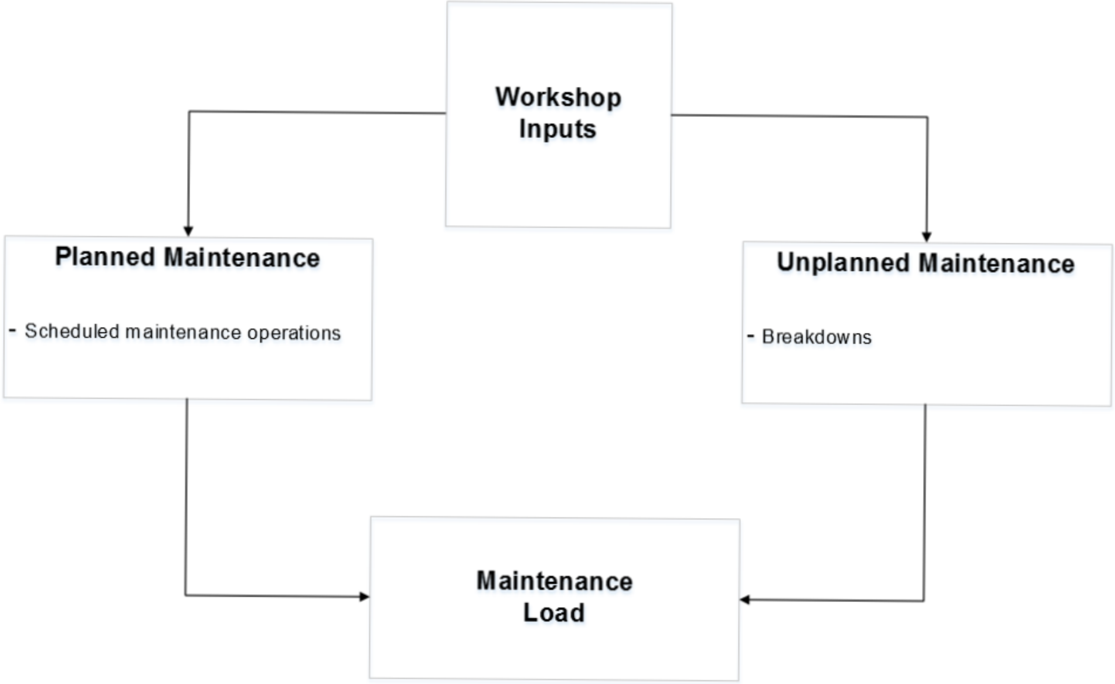


Figure 3.1: Maintenance load element

4. Schedule maintenance order.

   Based on the availability of the above mentioned resources the maintenance job will be scheduled according to its priority and arrival time.

5. The execution of the maintenance order.

   If the maintenance staff, spare parts, tools and equipment are available then the order is executed.

6. Quality inspection

   After the execution of the maintenance order a quality inspection will take place to ensure that the maintenance was done correctly.

3.1.4 Materials and spare parts element

The availability of spare parts and materials are crucial for maintenance operations. Information of the availability of spare parts and materials are gathered by an inventory management information system (IMIS). This information system will be incorporated in the simulation model in order to generate probabilities on the availability of materials and spare parts for a maintenance job. Using these probabilities, spare parts and materials will be classified into certain slots. When a maintenance job is scheduled these slots will be used to assign the required materials and spare parts to the maintenance job. The following diagram depicted in Figure 3.2 describes the process of when spare parts and materials are required or not.

3.1.5 Tools and equipment element

This element will be used in the simulation model to check equipment availability prior to job allocation. In the Komatsu workshop there are certain maintenance activities which

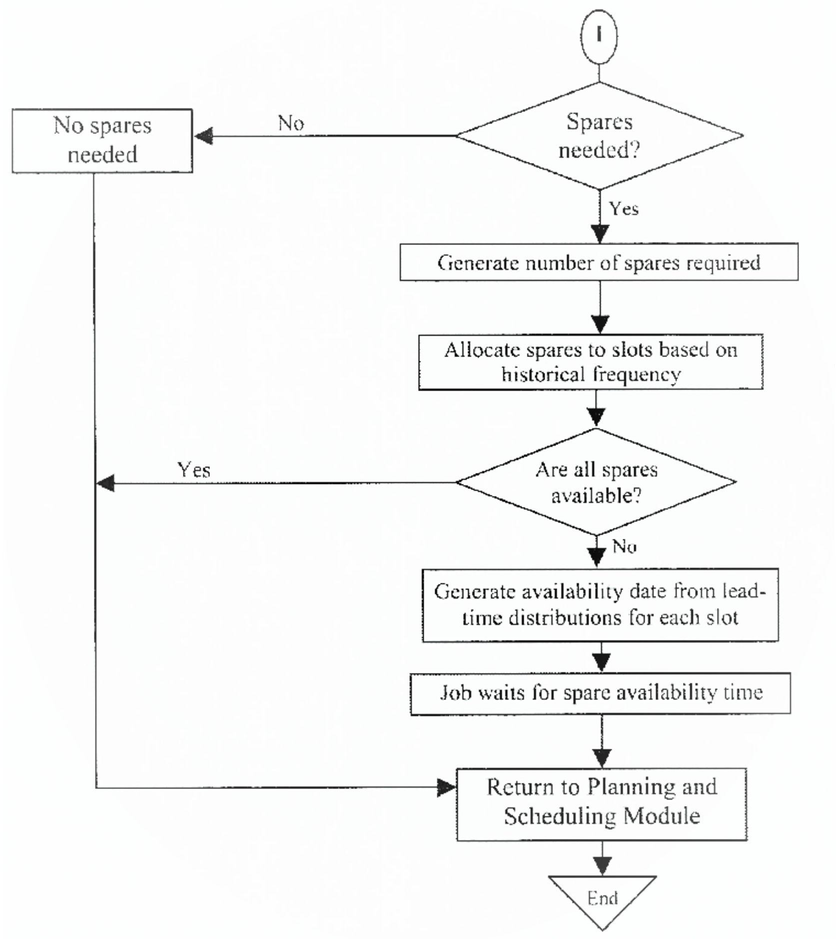


Figure 3.2: Materials and spare parts element

requires specific tools and equipment like an overhead crane or forklift. However, because of the limited space in the working area the availability of these critical tools are limited. Only the critical tools and equipment is considered in this element. Probabilities will be assigned to these tools to determine their availability for a maintenance job and can thus be modeled in the simulation. The following diagram in Figure 3.3 describes the logic the simulation model will follow when determining and assigning the critical tools to maintenance jobs.

3.1.6 Quality inspection and washing element

After a maintenance job is completed, the quality of the work done is checked to ensure that required quality standards have been met. After the inspection the EMV will be cleaned/washed. Although this activity seems unnecessary because of the fact that the EMV will always be working in an rough and dirty environment it is very important. Dust and dirt causes major problems like component failure for EMV's and so the Komatsu workshop has a strict policy to wash and clean components on the EMV's. The time it takes to wash a specific type of EMV will also be incorporated in the simulation model because it also contributes to the downtime of the machines.

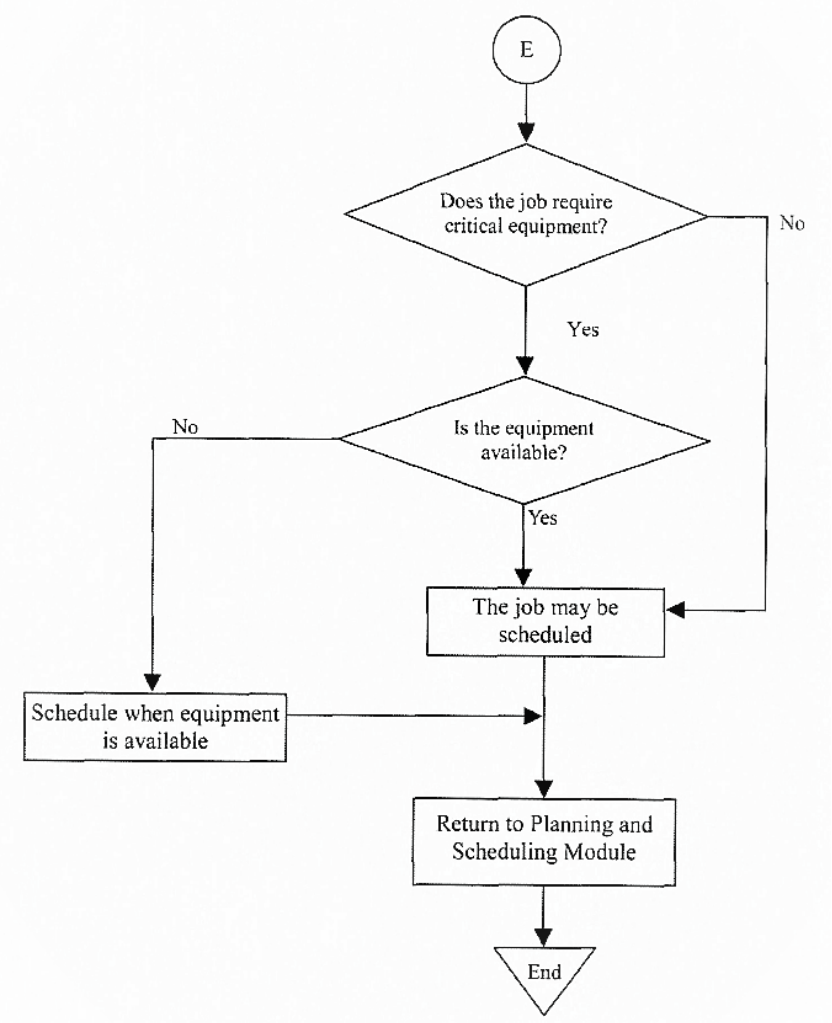


Figure 3.3: Tools and equipment element

3.1.7 Performance measure element

The purpose of this element is to generate the relevant performance measures of the maintenance process. The simulation model will be used to run different scenarios that can be expected in the maintenance process. Efficiency, unplanned and planned downtime and breakdowns will be measured in each scenario to determine the best practices that can be used by the workshop to maximise efficiency and minimise downtime.

This chapter explains the generic conceptual model for the Komatsu maintenance workshop. The conceptual model is structured according to various elements that represents key characteristics in the maintenance system. The conceptual model will be used to develop a discrete event simulation model using the simulation software AnyLogic.

Chapter 4

Data interpretation

The simulation model requires specific data parameters in order to accurately depict the current maintenance process. The different parameters that were obtained from the workshop can be seen in Section 3.1.1 of this report.
Parameters such as historical maintenance data from the SAP system, planned and unplanned maintenance schedules, standard times and rebuilds were investigated. The data was collected by visiting the mine and observing the maintenance process first hand. The investigation as well as the recommendations from the Komatsu maintenance staff resulted in obtaining the relevant data that would be used in the simulation model.

4.1 Data analysis

The data used to develop the required parameters for the simulation model were investigated and analysed. The work done by Tiwari and Alrabghi (2016) implies that it is important to analyse the crucial or high value parameters thoroughly before developing a simulation model. Thus parameters such as the amount of EMV's arriving at the workshop for planned maintenance as well as the amount of EMV's arriving at the workshop for unplanned maintenance per day were investigated. This is a high level parameter as it will be used in the simulation model to start the process. The different amount of time spent performing the various types of maintenance procedures, as stated in Table 1.1 are seen as high value parameters.

4.1.1 Planned maintenance analysis

The amount of EMV's arriving at the workshop per day for planned maintenance were analysed to statistically determine a distribution that will be used as a parameter in the simulation model. Figure 4.1 shows the data that was collected on the planned maintenance element.

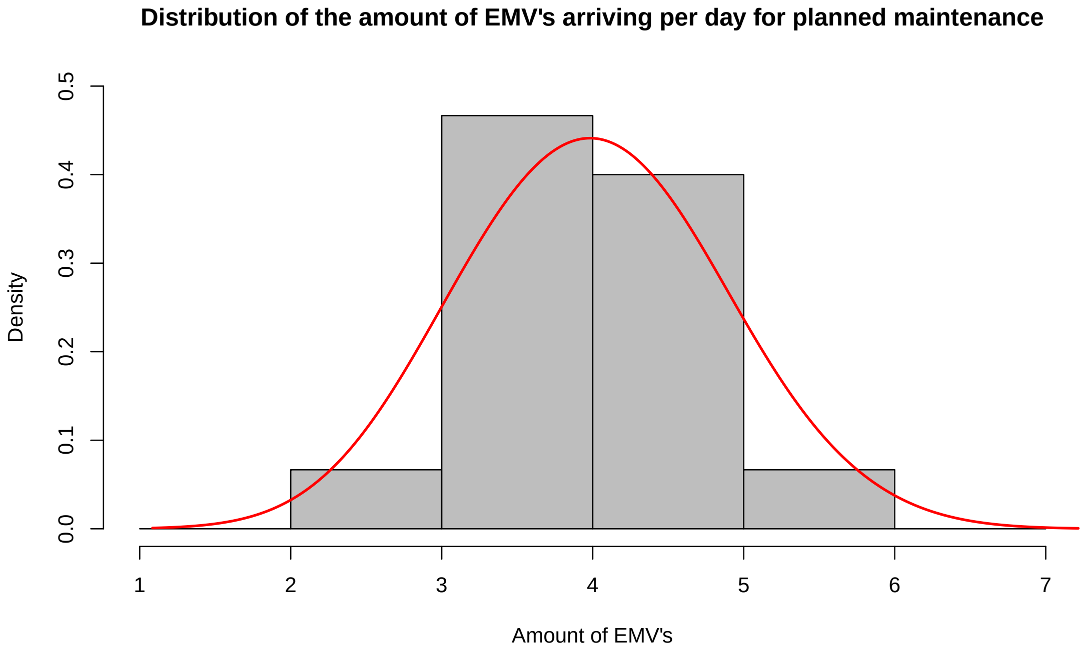


Figure 4.1: Distribution of the amount of EMV's arriving per day for planned maintenance.

The data is seen to be following a normal distribution with a mean value of 4 EMV's and with a standard deviation of 1. This suggests that over the two years of data analysed an average amount of 4 EMV's arrive at the workshop per day. However, the amount of EMV's arriving per day can vary from 1 to 6. The figure also indicates the density or probability that a certain amount of EMV's will arrive each day for planned maintenance. For example, there is approximately a 50% chance that between 3 and 4 EMV's will arrive at the workshop at any given time during the day for planned maintenance.

The planned maintenance element consists of various maintenance procedures as can be seen in Table 1.1. The focus will only be directed on the electric drive haul trucks as these vehicles are the only machines that are used for the direct mining process. The different maintenance procedures consists of a 250-hr, 500-hr, 750-hr and a 6000-hr maintenance schedule. After each of the machines reach the respective operating hours it is scheduled for a preventative maintenance procedure. The maintenance procedures were all analysed individually as this is a high level parameter that will be used in the simulation model.

Analysis of the 250-hour maintenance procedure

The 250-hr maintenance procedure consists of replacing an EMV's oil sample bottles. The Komatsu staff indicated that the ideal time for a 250-hr maintenance procedure is 1 hour.

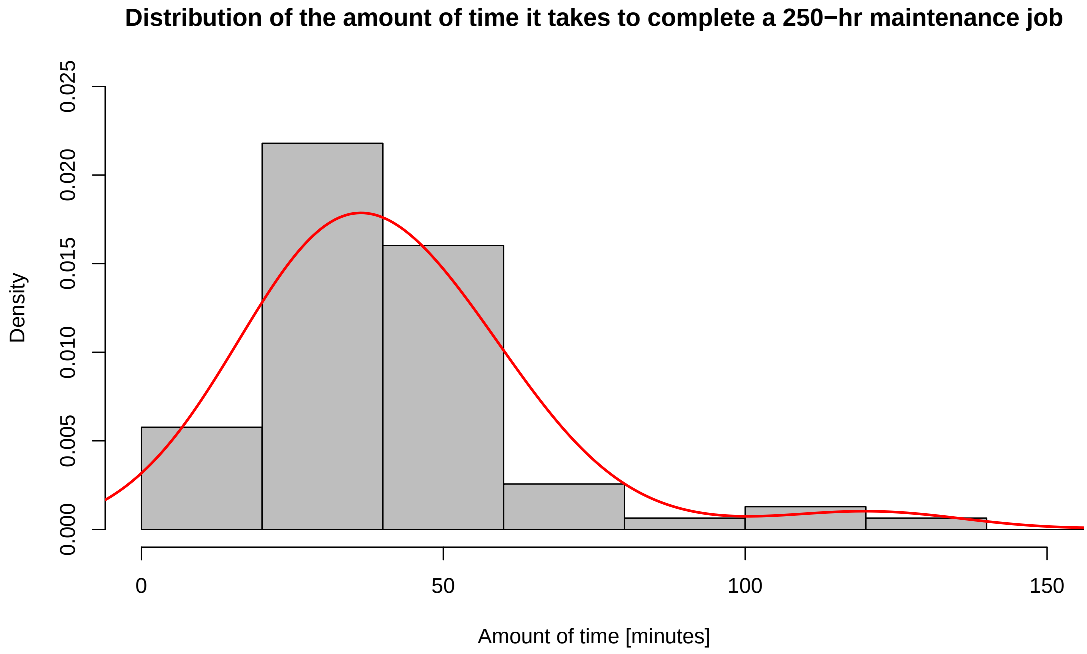


Figure 4.2: Distribution of the amount of time it takes to complete a 250hr maintenance job.

Figure 4.2 indicates the distribution of the amount of time it takes to complete a 250-hr maintenance procedure. The data is following a normal distribution which indicates that the average amount of time an EMV spends in the workshop undergoing a 250-hr maintenance procedure is 46 minutes. Although this seems as a good maintenance time, one must still consider the high standard deviation which is 35 minutes. The mean is greater that the median of 33 minutes which alternatively shows that the data is skew to the right. This is due to the fact that quite a number of data points fall above the 100 minute mark. Further investigation showed that random periodic inspections are done on a 250-hr maintenance procedure which usually takes longer than the standard time of 1 hour. It was concluded that this occurrence does not affect the flow of the maintenance workshop as it is only an inspection and not a maintenance procedure. Thus the mean and standard deviation with a normally distributed function are to be used as parameters in the simulation model.

Analysis of the 500-hr maintenance procedure

The 500-hr maintenance procedure also consists of replacing the oil sample bottles of the EMV's. However this maintenance process takes a standard time of 4 hours according to the Komatsu maintenance staff and historical data. Figure 4.3 shows the boxplot diagram of the data gathered on the 500-hr maintenance procedure.

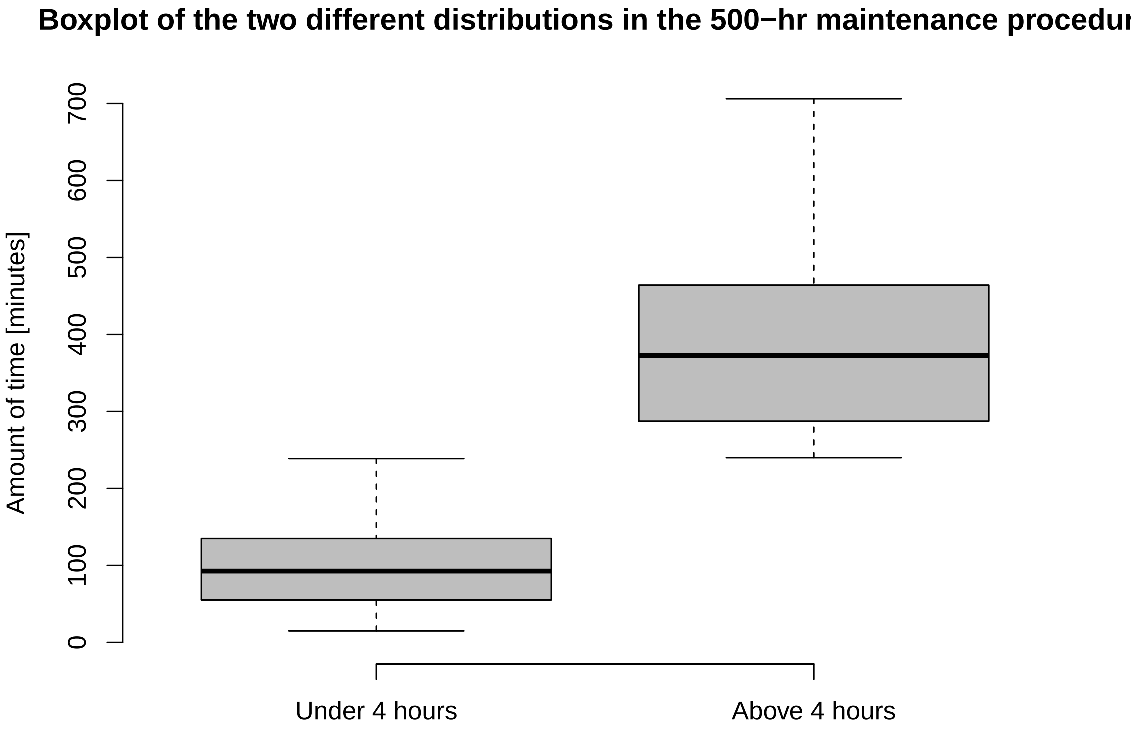


Figure 4.3: Boxplot of the two different distributions in the 500hr maintenance procedure.

The boxplot in Figure 4.3 indicates that there are two different distributions of the amount of time spent on a 500-hr maintenance procedure. The first distribution represents all of the values that are under the recommended 4 hours with a mean of 100 minutes, standard deviation of 62 minutes and median of 93 minutes. The fact that the mean and median is so close together indicates a normal distribution. The second distribution consists of all the values above the recommended 4 hours with a mean of 422 minutes, standard deviation of 280 minutes and median of 370 minutes. The fact that the mean is greater that the median indicates that the data is skew to the right.

The under 4 hours boxplot represents 66% of the analysed data which in effect means that for 66% of the time the maintenance procedure will take 4 hours or less. The blue box distribution represents only the remaining 34% of the data which means that only 34% of the time it will take more than 4 hours to complete a 500-hr maintenance procedure. The reason for the two distributions being so separate is because of the influence of the unplanned occurrences. The first boxplot has minimal to zero influence from unplanned occurrences which means that when an EMV arrives it can go directly to an open bay and begin the maintenance process. However, with the second boxplot unplanned maintenance on EMV's are being executed and thus contributing to the increase in downtime for a planned 500-hr maintenance job. Although there are two different distributions within the data of the 500-hr maintenance procedure time it is very important to interpret this difference in the simulation model. The probabilities (66% and 34%) as well as the mean and standard deviations of the respective distributions were used to determine the procedure time parameter in the model.

Analysis of the 750-hr maintenance procedure

The 750-hr maintenance procedure consists of a few maintenance activities that must be performed. These activities include replacing the hoist filter, steering filter, make-up tank breather, fuel filter, spin filter, air filter, v-belt set, outer element and inner element. Compared to the 250-hr and 500-hr maintenance procedures this procedure consists of a lot more maintenance activities and thus the standard time spent to perform all of these activities are estimated to be 8 hours.

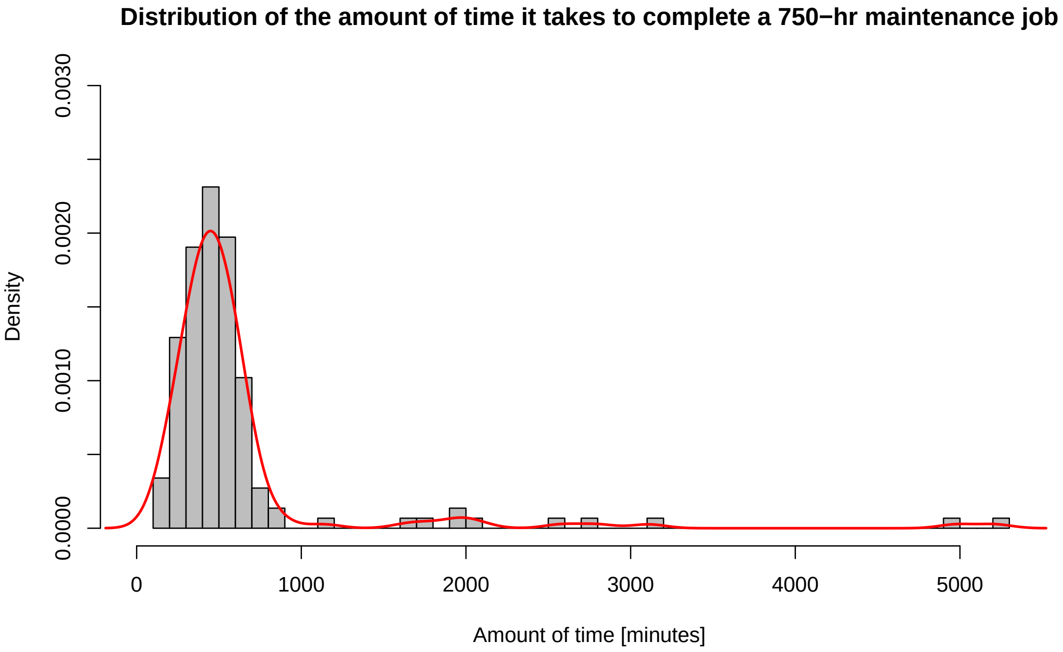


Figure 4.4: Distribution of the amount of time it takes to complete a 750hr maintenance job.

Figure 4.4 indicates the distribution of the time it takes to complete a 750-hr maintenance procedure. From 0 to 800 minutes the data is following a normal distribution. However, as seen in the figure there are a number of points falling above 800 minutes. The values that fall above the 800 minute mark contributes to only 7.5% of the data. This means that 7.5% of the time it will take more than 800 minutes (13 hours) to complete a 750-hr maintenance procedure.

There are various different reasons that can contribute to these outliers. Some of the reasons are that there are up to 10 activities that must be completed and that more maintenance staff is required to perform all of these activities and in effect contributes to the big difference in maintenance time. The outliers have a big impact on the mean and standard deviation values. If the outliers are included in the calculations then a mean of 613 minutes (11 hours) and standard deviation of 693 minutes (12 hours) are obtained. However, when analysing the data from 0 to 800 minutes the mean is 448 minutes (7.5 hours) and standard deviation is 147 minutes (2.45 hours). This can be used in the simulation model as a parameter to represent the maintenance time of the 750-hr maintenance procedure. The data points falling in the 0 to 800 minute category is 92.5%. This indicates that 92.5% of the time it will take 800 minutes or less to complete a 750-hr maintenance procedure.

Although it seems like the ideal strategy to exclude the oultiers, in this case they were included. The probability that the an EMV undergoes a 750-hr maintenance procedure that is above 800 minutes is 7.5%. This probability will be used in the parameters of the simulation model in order to get the time of the 750-hr maintenance procedure as accurate as possible.

Analysis of 6000-hr maintenance procedure

The 6000-hr maintenance procedure consists also of the same maintenance activities as in the 750-hr maintenance procedure except an oil change is added to the activities. The standard time to perform these maintenance activities for a 6000-hr procedure is 48 hours. Figure 4.5 is a boxplot of the amount of time it takes to perform a 6000-hr maintenance procedure.

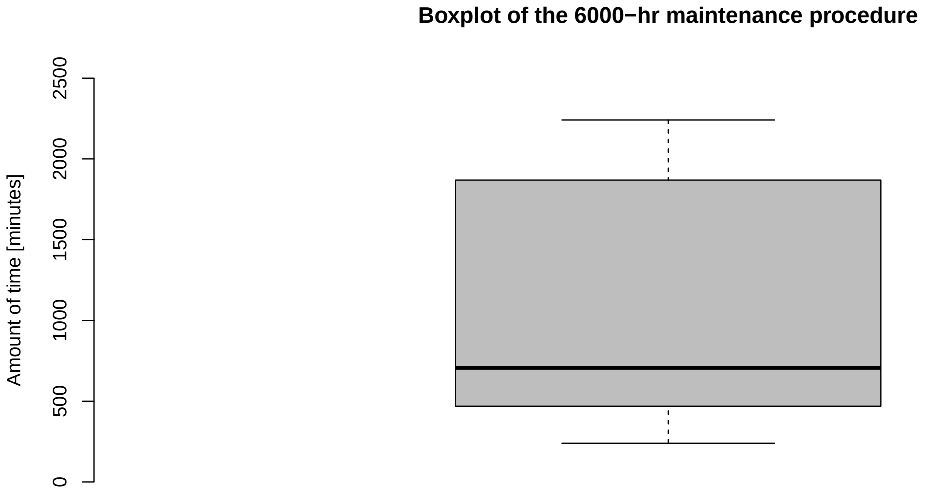


Figure 4.5: Boxplot of the 6000hr maintenance procedure

The boxplot splits the data set into quartiles. The grey area represents the box which is a range from the first quartile (Q1) to the third quartile (Q3). The black horizontal line is the median of the data which represents the middle of the data set. The median is 706 minutes (12 hours). The data is not distributed evenly on both sides of the median this is because the mean is greater than the median. The data indicated that 56% of the time the amount spent on a 6000-hr maintenance procedure will be normally distributed with a mean of 1172 minutes (20 hours) and a standard deviation of 614 minutes (10 hours).

The other 44% of the time the data will follow a normal distribution with a mean value of 408 minutes (7 hours) and standard deviation of 164 minutes (3 hours). Both of these distributions, each with their respective different probabilities will be used as parameters in the simulation model.

Probability of occurrence for all planned maintenance procedures

The data analysis done on each of the respective maintenance procedures represents the different individual time distributions. These values will serve as input parameters in the simulation model. However there is still one very important aspect that must be considered. The probability that either one of the maintenance procedures can take place at any given time during the day must be taken into account. Table 4.1 consists of the different probabilities that exist for the different maintenance procedures.

Table 4.1: Probabilities of occurrence for the different maintenance procedures.

Maintenance procedure	**Probability of occurrence**
250-hr	48.80%
500-hr	23.45%
750-hr	26.32%
6000-hr	1.44%

This table suggests for example that in any given day the probability that a planned maintenance procedure will be a 250-hr maintenance procedure is 48.80%. In other words, in a day 48.80% of the time for the planned maintenance schedule it will be a 250-hr maintenance procedure. The same goes for every single maintenance procedure with their respective probabilities.

4.1.2 Unplanned maintenance analysis

The amount of EMV's arriving at the workshop per day for unplanned maintenance were analysed to statistically determine a distribution that will be used as a parameter in the simulation model. Figure 4.6 shows the data that was collected on the unplanned maintenance element.

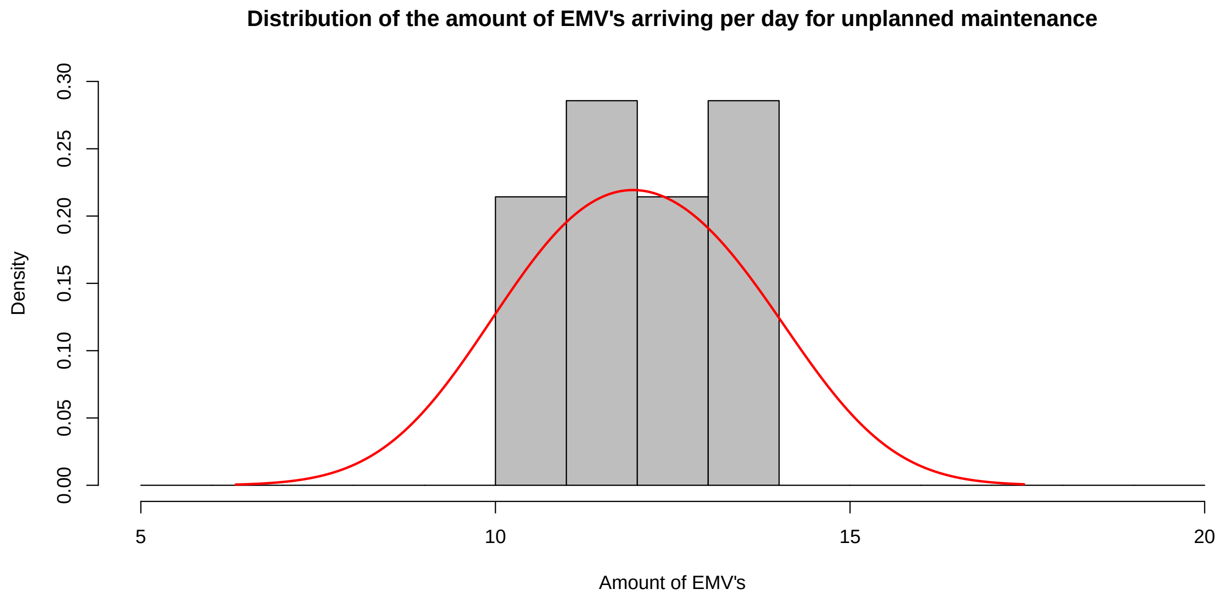


Figure 4.6: Distribution of the amount of EMV's arriving per day for unplanned maintenance.

Figure 4.6 indicates that the data is following a normal distribution with a mean value of 12 EMV's and standard deviation of 1 EMV. The density or probability readings suggests that 30% of the time the amount of EMV's that will arrive at the workshop for unplanned maintenance is between 12 and 13 EMV's. This is a good indication of the normal distribution as these values contains the mean value as well as one standard deviation from the mean. The normal distribution function will be used in the simulation model as an input parameter to initiate the process of unplanned maintenance arrivals at the workshop.

4.1.3 Inspection time analysis

Another crucial element that were analysed is the pre-inspection time of the maintenance process. Although the inspection time commence before the actual maintenance procedures it is still a vital activity that must be performed. The pre-inspection activity enables the maintenance staff to determine exactly what is wrong with the EMV. The inspection determines what parts, how many staff members and what critical equipment should be used for the specific maintenance procedure. Figure 4.7 reveals the distribution of the duration of the pre-inspection activity.

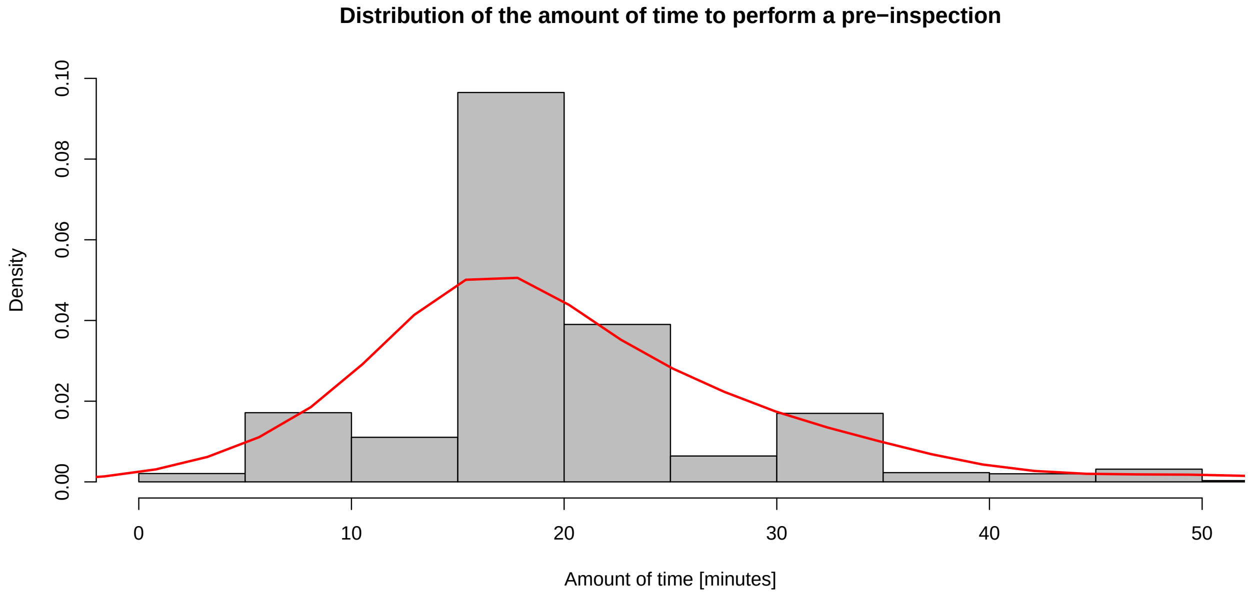


Figure 4.7: Distribution of the amount time to perform a pre-inspection

The distribution that Figure 4.7 follows is a normal distribution. However, it can be seen that the distribution is very wide or spread out between the mean value. This is because of the high standard deviation which is 26 minutes. The mean value is 20 minutes. The data is spread so wide from the mean because the standard deviation is greater that the mean. This indicates that for the pre-inspection activity, the duration can vary with 26 minutes. However, the figure also indicates the probability that a value will fall between 15 and 20 minutes is 10% which is the highest probability of any time category. Thus the probability that a pre-inspection will take between 15 and 20 minutes is 60% higher than the nearest time category which is 20 to 25 minutes. It is still important to interpret this high standard deviation as well as each probability of the different time categories in the simulation model. Thus the mean, standard deviation and probabilities will be used as input parameters to represent the distribution function for the pre-inspection activity in the simulation model.

4.1.4 Rebuild procedure analysis

A rebuild is a very important activity in the maintenance workshop. It consists of various different types of specific maintenance activities/ rebuild events such as engine assemblies, alternator replacements, wheel motor assemblies, rear and front suspension repair and many more. A rebuild does not occur very often but can be planned or unplanned but instead is a very timely activity. The reason for including this procedure in the simulation model is to incorporate as much elements that affects the downtime of EMV's as well as the maintenance process.

The rebuild is done by subcontracting seven Kulula artisans. This means that no additional maintenance staff from Komatsu is needed. However, the space required to perform a rebuild becomes a problem as a lot of large components such as engine blocks and suspensions sets have to be placed on the workshop floor and in effect takes up the space of the working bays where other maintenance activities are suppose to take place.

There are different rebuild events that can take place. The different rebuild events along with the average amount of time it takes to complete can be seen in Table 4.2.

Table 4.2: Different rebuild events.

Event description	Average event duration [hours]	Number of components	Planned
LH and RH wheelmotor	100.25	2	Yes
Major rebuild - 25000	534.98	18	Yes
Engine change out	452.8	6	Yes
Major rebuild	321.5	13	Yes
Truck rebuild	782.37	17	Yes
Major rebuild and engine midlife - 25000	413.41	20	Yes

Rebuilds are typically planned with only 2.5% being unplanned. Table 4.2 indicates the average amount of time it will take to complete a specific rebuild event. For example, the major rebuild occuring at 25000 operating hours for an EMV will usually take 535 hours with 18 components to repair and the event was planned. This example can be used to interpret the rest of the different events. In the simulation model these duration's of the different rebuild events will be incorporated to make the model as accurate as possible.

Chapter 5

Simulation model

A discrete-event simulation model was developed based on the statistical parameters and characteristics of the Komatsu maintenance workshop. The conceptual model described by Duffuaa et al. (2001) in Chapter 3.1 was used as a guideline in developing the simulation model. Alterations were made to the conceptual model in order to incorporate the workshop process as accurate as possible. The actual computer based simulation model can be seen in Appendix A. The objective of this simulation model is to imitate the current workshop process as accurate to the real system as possible in order to determine key areas that contribute in excessive downtime (bottlenecks) and potential inefficiency of maintenance procedures.

Different scenarios were created in the simulation. Scenarios such as increasing the standard times to perform certain maintenance activities, adding one more operating bay for increased work space and analysing the efficiency of the maintenance procedures were investigated. The change in downtimes and efficiency were measured per scenario to obtain information as to where an opportunity of improvement exists in the workshop.

The model validation was done by comparing the model outputs to the real maintenance process outputs. The validation of the model is a crucial step that must be performed in order to determine the accuracy to which the model simulates the current workshop process and evidently generate useful results.

5.1 Maintenance process flow

The simulation model was designed according to the current process flow of the maintenance workshop. It is important to first understand the basic activities that makes up the process flow. A simple schematic sketch can be seen in Figure 5.1 of the current process flow within the workshop.

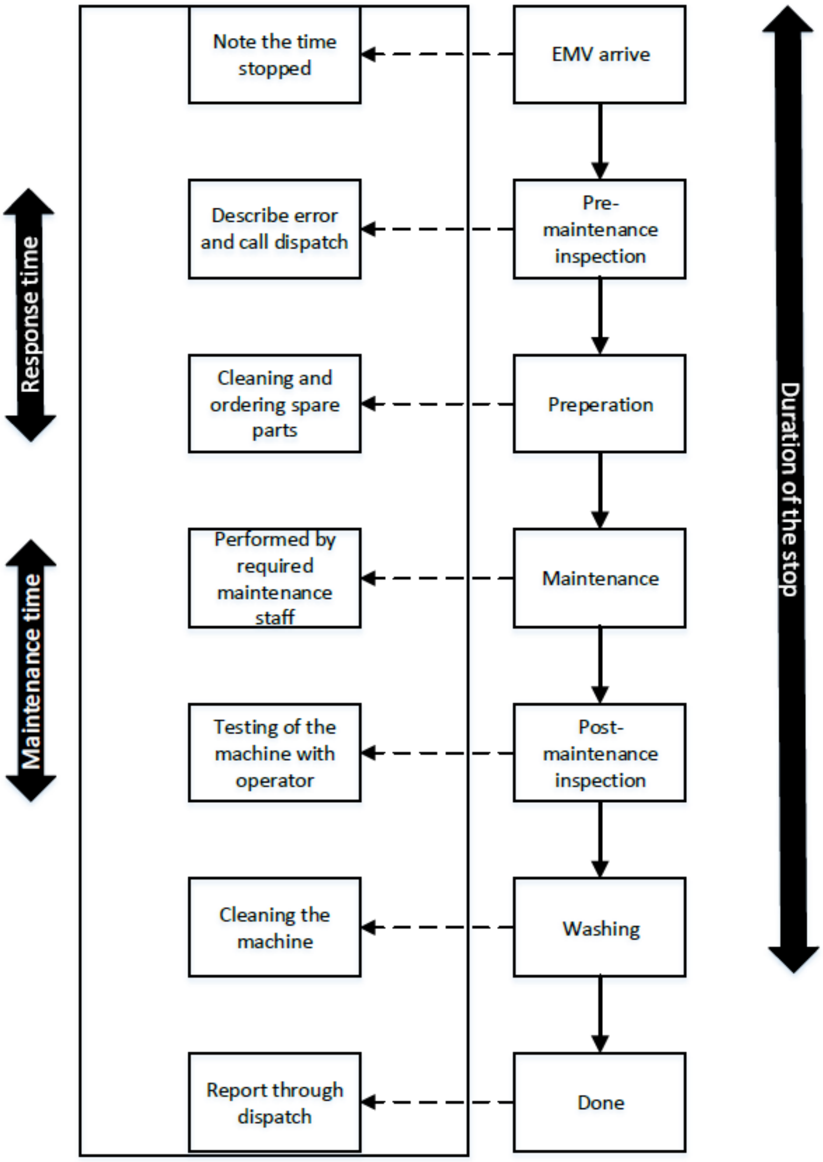


Figure 5.1: Current process flow of the workshop

The current process flow in the workshop works as follow. An EMV can arrive during the day at any given time for planned or unplanned maintenance. The EMV operator then does a pre-maintenance inspection with specialized staff members in order to determine what parts must be ordered and specifies what errors occur in the machine. After the inspection the physical maintenance starts on the EMV which is performed by the required artisans. When the maintenance is finished a post-maintenance inspection takes place along with the EMV operator to test if the machine is operational. After the inspection the EMV is washed and is ready to go about it's normal duties.
The duration of the stop or downtime of the EMV includes the time of arrival, pre-inspection, preparation, maintenance, post inspection and washing. These elements are the main activities that were used in constructing the simulation model as it directly influences the downtime of the EMV's. Other time measurements include the response time which

includes only the pre-maintenance inspection and preparation. The maintenance time measurement includes only the maintenance and post-inspection of the EMV's.
The current process flow of the workshop were also used to identify the areas where the data gathering was done described in Chapter 4.

5.2 Model interpretation

The simulation model was constructed using Figure 5.1 as a basic guideline for the construction of the simulation model as well as the conceptual model design. The first part of the simulation model consists of the arrival rate and inspection time which can be grouped as the arrival module. The second part consists of the maintenance time and post-maintenance inspection time which can be grouped as the maintenance module. The last part of the simulation model consists of the washing and cleaning time which can be grouped as the washing module. These different processes were divided into the specific modules in order to help develop the simulation model and understand the complexity of the workshop.

5.2.1 Simulation of arrival module

The arrival module consists of a number of elements. These elements include the planned and unplanned arrival rates and inspection times of the EMV's. The simulation model executes the arrival module in discrete time events. The model starts with a source which represents the planned and unplanned arrival rates for the EMV's. The data from Section 4.1.1 and Section 4.1.2 were used as the arrival rates in the simulation model. Once the EMV has arrived at the workshop either as a planned or unplanned entity it is then inspected to determine what type of maintenance must be done. The model uses a delay to represent the inspection element and incorporates the inspection time obtained from the data analysis in Section 4.1.3 as an input parameter. After the execution of each event in the arrival module the simulation model moves on to the maintenance module.

5.2.2 Simulation of the maintenance module

The maintenance model consists of a number of elements. These elements include the different maintenance procedures and the post-maintenance inspection time. The various maintenance procedures are incorporated in the simulation model by using the respected probabilities and distribution functions as described in Chapter 4.1. In order to incorporate these different maintenance procedures with their respective statistics the model uses an object that routes the planned EMV to a port given the probability it occurs and for how long it endures the specific maintenance procedure. This mechanism incorporates the crucial elements in the workshop and is very useful in the simulation model. After the completion of the specific maintenance procedure the model moves towards the post-maintenance inspection object. This object simulates the amount of time any given EMV spends in the post-maintenance inspection phase. The simulation model uses a delay object to simulate this event and in effect delay/ pause the process in order to incorporate the time an EMV will spend in post-maintenance inspection. The maintenance module can be considered as the most important focus point in the simulation model as it represents the different kinds of maintenance procedures which contributes the most to downtime in EMV's. After the model has executed the events of the maintenance module, it moves on to the washing module.

5.2.3 Simulation of the washing module

The washing module consists of washing and cleaning of the EMV after all the above mentioned modules have been executed in the simulation model. This module is also very important as it contributes to the overall downtime of the EMV's. The model interprets this event by using a delay object. After the washing is complete the EMV exits the maintenance workshop area and thus complete the maintenance process. This is also where the simulation model stops.

5.3 Model validation

The model validation was done by comparing certain outputs from the model to the current real-time data of the maintenance workshop. The validation was done by analysing the different maintenance procedure times as well as the number of EMV's that arrive and exit the workshop per day. The simulation model was executed a thousand times in order to get the most possible outputs that can be analysed. Table 5.1 indicates the different validation criteria that was used to validate and verify the accuracy of the model.

Table 5.1: Validation criteria of the simulation model.

Validation criteria:	**Maintenance duration: Real time/units**	**Maintenance duration: Simulation time/units**	**Model accuracy**
250-hour maintenance procedure	60 min	49 min	**82%**
500-hour maintenance procedure	240 min	266 min	**90%**
750-hour maintenance procedure	480 min	459 min	**96%**
6000-hour maintenance procedure	2880 min	2323 min	**81%**
EMV washing	120 min	100 min	**83%**
Inspection	30 min	22 min	**74%**
Amount of planned EMV's arriving per day	4	4	**100%**
Amount of unplanned EMV's arriving per day	12	8	**67%**

The validation criteria is based on certain parts or sections in the simulation model. This was done because there are various different aspects and variables that must be taken into consideration. The different maintenance procedures were each executed separately in the simulation model in order to effectively obtain the model time of the duration of each maintenance procedure. Time observations for the washing and inspection events where also monitored to obtain the model outputs of the durations of each event respectively. The amount of planned and unplanned arrivals where also monitored in the simulation model to indicated whether the model can give outputs that are similar to real time data of the workshop.

The real time data that were used to compare the model outputs were analysed in Chapter 4.1 and also obtained from the SAP system and the historical maintenance data schedules. The validation shows that the maintenance procedure times are in the range of 82% to 96% accuracy. This means for example that the model interprets or simulate the 250-hour maintenance procedure with an accuracy of 82%. It can be observed that the accuracy of the simulation model simulating the amount of unplanned EMV's arriving per day at the workshop is 67%. This is due to the fact that these events can happen at any time during the simulation model. However, the value is not fixed it can still deviate by a certain amount and in effect increase the accuracy of the simulation model output.

The validation of the model verifies the fact that by simulating the maintenance workshop and obtaining end results it can be analysed in order to recommend accurate possible solutions.

Chapter 6

Results and recommendations

The simulation model was executed for different scenarios, changing some parameters in the model in order to determine areas which contributes to excessive downtime of the EMV's as well as inefficient activities. The different scenarios were formulated according to the current data analysis as well as information gathered from the Komatsu supervisors as to where they think possible problems occur that contribute to inefficient practices and unnecessary downtime of the EMV's. The different scenarios include the following.

1. Increasing the amount of operating bays.
2. Changing the amount of workers per maintenance procedure.
3. Measuring the time efficiency of maintenance procedures.

6.0.1 Increasing the amount of operating bays

The workshop is currently using four of the five operating bays for pure maintenance procedures. The other operating bay is used for temporary storage of the big components when and EMV undergoes maintenance. This results in the workshop having one less operating bay to perform possible maintenance procedures. In the simulation model the effect of changing the number of operating bays from 1 through to 10 were observed. The model indicated that if the operating bay were to be changed to either one, two or three, a 0% time reduction will occur. By increasing the amount of operating bays from four to five, a 20% reduction in downtime was observed from the simulation model. Although 20% seems small it is in fact a very large proportion of downtime reduction in the overall maintenance process. Table 6.1 indicates the percentage time reductions of the different amount of operating bays.

Table 6.1: Percentage of time reductions and duration of downtime for different amounts of operating bays.

Number of operating bays	% time reduction	Duration of downtime [minutes]
1	0%	1071
2	0%	903
3	0%	831
4	Current amount of bays	819
5	20%	814
6	22%	805
7	24%	790
8	24%	780
9	25%	770
10	25.30%	760

The increase in operating bays results in the reduction of downtime per EMV in the maintenance workshop. However, Figure 6.1 indicates the distribution of the different number of bays vs the time reduction.

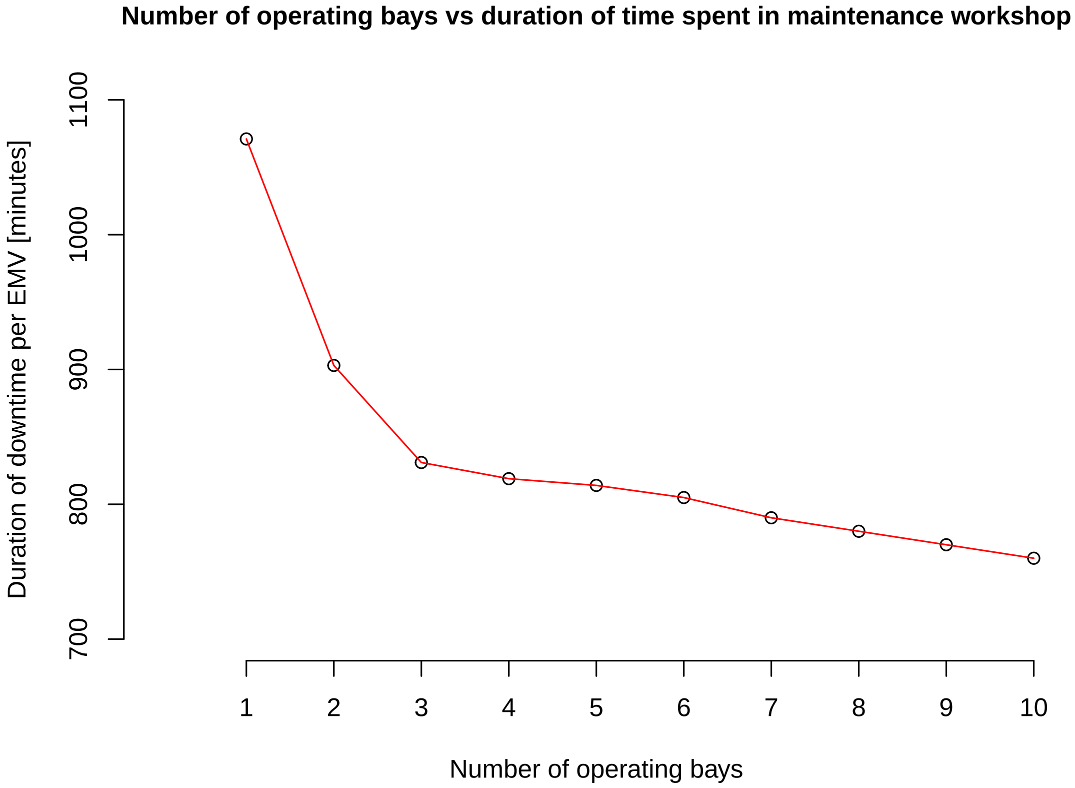


Figure 6.1: Number of operating bays vs time reduction

Figure 6.1 is seen to follow an exponential distribution for the number of operating bays against the time spent in the workshop. The more operating bays that are added only decreases the downtime of the EMV's by a smaller margin every time causing the data to follow and exponential distribution. The reason for this small margin decrease in downtime is because of the utilisation of workers. When there are more bays more work has to be done and in effect increases the utilisation of workers to such an extent that they struggle to keep up with maintenance schedules.

6.0.2 Changing the amount of workers per maintenance procedure

The different maintenance procedures described in Section 4.1.1 each have a unique number of artisans assigned to a different maintenance procedure. The simulation model was used to gather the current information regarding the worker utilisation per maintenance procedure as well as changing the amount of workers and observing the effect of the worker utilisation. The current worker utilisation were analysed first in order to determine which maintenance processes are over utilised. After analysing the utilisation of the workforce per maintenance procedure it was observed that some of the procedures were performed effectively in terms of worker utilisation and some procedures over utilised the workforce. Table 6.2 indicates the utilisation of workers of the different maintenance procedures.

Table 6.2: Utilisation of workers at different maintenance procedures.

Maintenance procedures	**Amount of workers required**	**Worker utilisation**
250-hour	1	57%
500-hour	1	84%
750-hour	5	95%
6000-hour	5	95%

The 250-hour maintenance procedure indicates that only 57% of the workforce is being utilised for this procedure. This is understandable as the 250-hour procedure only requires one artisan to execute the maintenance procedure. The 500-hour maintenance procedure is at a respected 84% utilisation which is acceptable for this kind of maintenance procedure as it also only requires one artisan. The use of the simulation model for these two maintenance procedures were to only determine the worker utilisation. These two procedures are already utilised effectively so it was not necessary to change the amount of workers and analysed the effect from the simulation model.

The 750-hour and 6000-hour maintenance procedures indicated that 95% of the workforce is being utilised. This utilisation of the workforce is unnecessarily high and must be reduced. The maintenance time and number of activities that must be performed on each of these procedures are very high which causes the high workforce utilisation. Both of these procedures require atleast five skilled artisans to perform the maintenance. The simulation model were used to change the amount of workers for each respective maintenance procedure. Table 6.3 indicates the change in worker utilisation for the 750-hr and 6000-hr maintenance procedures for different amount of workers.

Table 6.3: Change in worker utilisation for the 750-hr and 6000-hr maintenance procedures for different amount of workers.

Maintenance procedures	**Amount of workers**	**Worker utilisation**
750-hour	5	95%
	6	76%
	7	59%
6000-hour	5	95%
	6	70%
	7	59%

The increase of one worker (to six) for the 750-hr maintenance procedure decreased the worker utilisation from 95% to 76%. This increase of one more worker indicated that the worker utilisation for the 750-hr maintenance procedure can be reduced to a reasonable and effective worker utilisation. However, by increasing the number of workers to seven it was observed that the worker utilisation only decreased by a marginal amount. Thus it was concluded that for the 750-hr maintenance procedure a optimal amount of 6 workers must be available to perform the maintenance activities.

The 6000-hr maintenance procedure also indicated a change in worker utilisation after changing the amount of workers in the simulation model. The simulation model results indicated that by increasing the amount of workers to six a decrease (from 95% to 70%) of 25% in worker utilisation was observed. The change in worker utilisation to 70% is a respectable worker utilisation for the maintenance procedure and it is recommended that the workshop hire one more worker for the 6000-hr maintenance procedure as well.

For both of these procedures it is recommended that if the management of the workshop wishes to implement more than five workers per maintenance procedure, they must take into account the cost associated to hire more workers.

These two maintenance procedures are seen as areas of improvement and it is recommended that the workshop investigate this matter in order to appoint more artisans that can execute these maintenance procedures.

6.0.3 Efficiency of maintenance procedures

The efficiency of the different maintenance procedures were gathered from the simulation model in order to determine areas for improvement.The maintenance procedure efficiencies as well as the workforce utilisation, as seen in Table 6.2, were analysed. It was important to observe the efficiency along with the workforce utilisation as both of these outputs interrelate with one another. The efficiency of the maintenance procedures were calculated using formula 6.1.

$$Efficiency = \frac{SLH}{ATW} \times 100 \tag{6.1}$$

Where SLH = standard labour hours and ATW = actual time worked.
The standard labour hours were obtained from previous data from the workshop and the actual time worked relates to the different outputs gathered from the simulation model. Table 6.4 indicates the efficiency measurements on the different maintenance procedures along with the worker utilisation results gathered in Table 6.2.

Table 6.4: Efficiency measurements of the different maintenance procedures

Maintenance procedure	Standard time	Actual time	Efficiency	Worker utilisation
250-hour	60 min	46 min	130%	57%
500-hour	240 min	190 min	126%	84%
750-hour	480 min	613 min	78%	95%
6000-hour	2880 min	1172 min	246%	95%

At first it was observed that the 250-hour, 500-hour and 6000-hour maintenance procedures had efficiencies greater than 100%. This indicated that the actual time observed from the simulation model for each of these procedures were less than the standard time proposed by the historical maintenance data. Although this seams as a good indication of efficient maintenance procedures it is also important to look at the worker utilisation along with the efficiency. The efficiency of the 250-hour maintenance procedure indicated that it is 130% efficient with a worker utilisation of 57%. This procedure is being executed efficiently and no opportunity for improvement exist.

The efficiency of the 750-hour maintenance procedure indicated that it is 78% efficient with a worker utilisation of 95%. The high worker utilisation suggested that all of the required workforce needed for this maintenance procedure is being used to only achieve a 78% efficiency. This meant that the actual time to perform the maintenance activity took longer than the standard time. This resulted in an increase in downtime for EMV's and in effect established an area for improvement. Increasing the workforce for this maintenance procedure by one artisan decreased the worker utilisation to 76% and increased the efficiency to 87%. This recommended solution seems promising, although the cost analysis of hiring one more worker does not fall within the scope of this project it must be taken into consideration as cost always plays an important role in any organisation.

Chapter 7

Conclusion

This report describes and outlines the current problems that exists in the maintenance workshop as well as the need to measure efficiencies to establish potential bottlenecks. Through investigating the workshop first hand and by implementing industrial techniques such as statistical data analysis, simulation modeling, system analysis as well as systems engineering, a problem background, literature study and conceptual model were formulated. Using the information and literature gathered in these chapters a computer base simulation model was developed in order to accurately identify areas of improvement in the maintenance workshop.

The respected parameters that were obtained from the statistical analysis in Chapter 4 enabled the user to accurately incorporate the main activities that are executed in the workshop. After validating each section of the model different scenarios were analysed to identify key improvement areas.

It was found that by increasing the number of operating bays in the maintenance workshop a reduction in downtime of EMV's were observed from the model outputs. This area clearly indicated an opportunity for improvement.

Analysing the worker utilisation and changing the amount of workers per maintenance procedure indicated another area for improvement. Both the 750-hr and 6000-hr maintenance procedures decreased their worker utilisation by increasing the number of workers to six. The 750-hour maintenance procedure was established to be less efficient with an abnormal high workforce utilisation. Increasing the work force for this maintenance procedure resulted in an increase in efficiency of the maintenance procedure as well.

These three areas were identified in being areas that contribute to the excessive downtime and in-efficient workshop practices. By implementing the recommendations and investigating these areas more in depth it can be assured that the Komatsu maintenance workshop will increase the efficiency of maintenance practices and in effect decrease the amount of downtime for EMV's.

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Appendices

Appendix A

Planning scheduling element

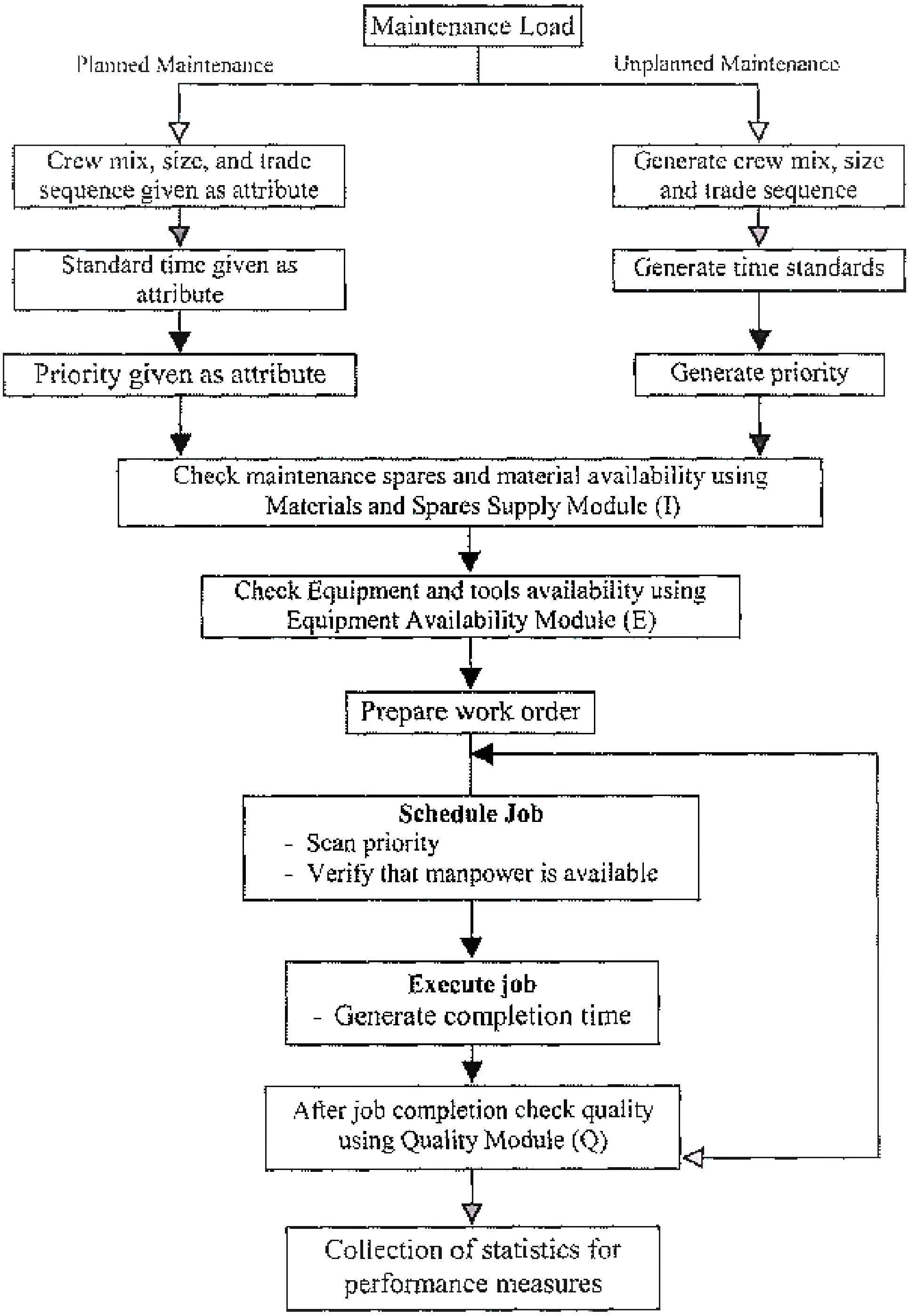

Figure A.1: Planning and scheduling element

Appendix B

Computer-based simulation model

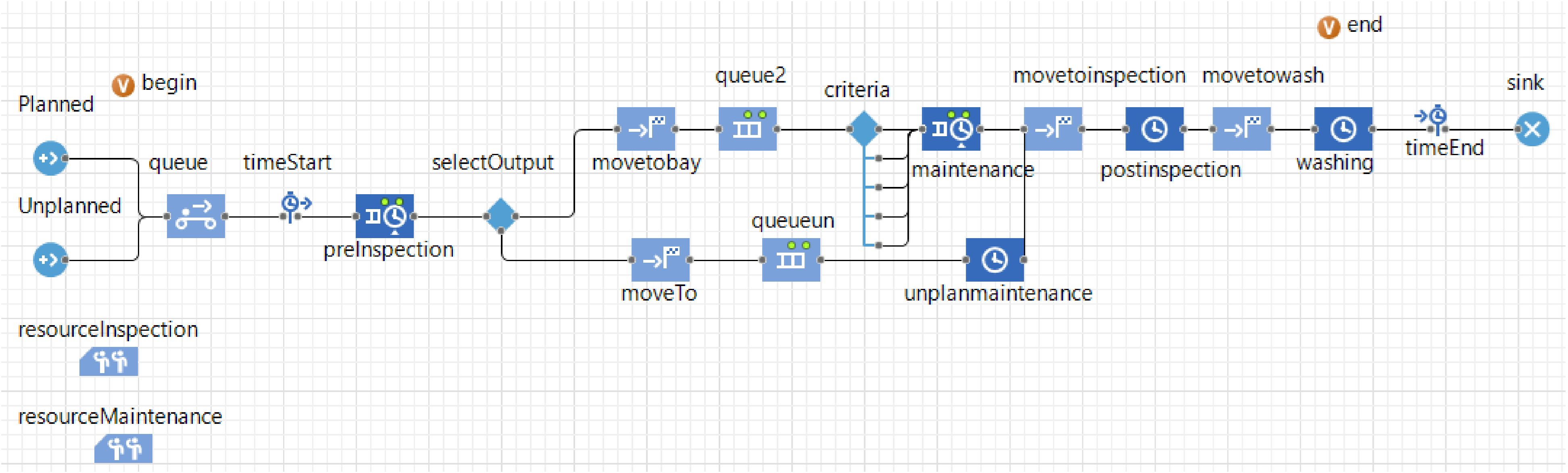

Figure B.1: Actual simulation model

Appendix C

Sponsorship form

Department of Industrial & Systems Engineering
Final Year Projects
Identification and Responsibility of Project Sponsors

All Final Year Projects are published by the University of Pretoria on *UPSpace* and thus freely available on the Internet. These publications portray the quality of education at the University and have the potential of exposing sensitive company information. It is important that both students and company representatives or sponsors are aware of such implications.

Key responsibilities of Project Sponsors:

A project sponsor is the key contact person within the company. This person should thus be able to provide the best guidance to the student on the project. The sponsor is also very likely to gain from the success of the project. The project sponsor has the following important responsibilities:

1. Confirm his/her role as project sponsor, duly authorised by the company. Multiple sponsors can be appointed, but this is not advised. The duly completed form will considered as acceptance of sponsor role.
2. Review and approve the Project Proposal, ensuring that it clearly defines the problem to be investigated by the student and that the project aim, scope, deliverables and approach is acceptable from the company's perspective.
3. Review the Final Project Report (delivered during the second semester), ensuring that information is accurate and that the solution addresses the problems and/or design requirements of the defined project.
4. Acknowledges the intended publication of the Project Report on UP Space.
5. Ensures that any sensitive, confidential information or intellectual property of the company is not disclosed in the Final Project Report.

Project Sponsor Details:

Company:	**Resonant Industrial (Pty) Ltd (in co-operation with Anglo Platinum Mines)**
Project Description:	**Simulation and measurement of the activities in a maintenance workshop at Anglo Platinum Mines for mining trucks, to identify potential bottlenecks.**
Student Name:	**Francois MF Venter**
Student number:	**14118735**
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