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Author:

Joakim Nesheim

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(signature of author)

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Maintenance strategies and associated costs

By

Joakim Nesheim

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Abstract

Choosing the correct maintenance strategy can be challenging for the decision maker as there are many approaches to the same problem; equipment wear out and break down. In this thesis three simulations on maintenance strategies are done using Vensim. The first, second and third strategy focuses on preventive maintenance, corrective maintenance and condition-based maintenance respectively. The author has 3 years of offshore experience as a drilling and maintenance operator, therefore the selected system to be simulated are the mud pumps in the drilling facility. The thesis does not include the drilling operation and the results are not limited to the oil industry, the focus is on the maintenance strategies.

The main aim for the thesis is to estimate the cost of maintenance and operation in terms of downtime hours and maintenance hours used in the operational phase of the equipment over a 10-year period. Methods used in thesis are interviewing, literature review and simulations.

The simulation consists of a system divided into sub-systems, where each sub-system is built up by several components. Equipment wear down over time and has its condition restored by maintenance events. Each maintenance event is counted and assigned a duration which is then accumulated to get a total amount of maintenance hours used. The equipment has a chance of a random breakdown which causes downtime. The corrective maintenance scenario will let equipment run to failure, thus allowing for more downtime to occur. The total amount of downtime is also accumulated.

The preventive maintenance scenario came out as the best scenario in terms of lowest amount of downtime hours but at the cost of the highest amount of maintenance hours used. The condition-based maintenance scenario has 11% less hours used in maintenance than the preventive maintenance scenario but has 10% more downtime. The corrective maintenance scenario has 30% less hours used in maintenance than the preventive maintenance scenario but has 160% more downtime.

Parts that are critical to either the operation, safety or environment should have condition monitoring implemented and follow a condition-based maintenance program. Parts that are not critical and inexpensive should follow a corrective maintenance approach, whereas the rest should be maintained on a scheduled basis, following a preventive maintenance program.

Achnowledgement

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I would also like to thank Jarle Toft for providing valuable information regarding maintenance data used to create the simulation files.

Stavanger, July 10th, 2018

Joakim Nesheim

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Abbreviations

The following abbreviations are used in this document:

CBM	Condition based maintenance
CM	Condition monitoring
DNV	Det Norske Veritas
ETTF	Estimated time to failure
FFT	Fast fourier transform
FMECA	Failure mode, effects & criticality analysis
HSQE	Health, safety, quality & environment
ID	Inner diameter
ISO	International Organization for Standardization
MTBF	Mean time between failures
MTTR	Mean time to repair
NDT	Non-destructive testing
OD	Outer diameter
O&G	Oil and gas
PDS	Power drive system
PM	Preventive maintenance
RPM	Revolutions per minute
RPN	Risk priority number
USD	United States dollar
WOT	Wear over time

Terms and definitions

Ageing failure

Failure whose probability of occurrence increases with the passage of calendar time.

Note 1: This time is independent of the operating time of the item.

Note 2: Ageing is a physical phenomenon which involves modification of the physical and/or chemical characteristics of the material.

(Norsk Standard NS-EN 13306:2010).

Degraded state

State in which the ability to provide the required function is reduced, but within defined limits of acceptability.

Note: A degraded state may be the result of faults at lower indenture levels.

(Norsk Standard NS-EN 13306:2010)

Down state

State of an item characterized either by a fault, or by a possible inability to perform a required function during preventive maintenance.

Note 1: This state is related to availability performance.

Note 2: A down state is sometimes referred to as an internal disabled state.

(Norsk Standard NS-EN 13306:2010)

EX rating

Explosive atmosphere rating. A classification of hazardous areas (zoning) and selected equipment.

(UK Government HSE, n.d.)

Failure

Termination of the ability of an item to perform a required function.

(Norsk Standard NS-EN 13306:2010)

Maintenance

Combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function.

(Norsk Standard NS-EN 13306:2010)

Maintenance plan

Structured and documented set of tasks that include the activities, procedures, resources and the time scale required to carry out maintenance.

(Norsk Standard NS-EN 13306:2010)

Up-state

State of an item characterized by the fact that it can perform a required function, assuming that the external resources, if required, are provided.

(Norsk Standard NS-EN 13306:2010)

Wear-out-failure

Failure whose probability of occurrence increases with the operating time or the number of operations of the item and the associated applied stresses. Note: Wear-out is a physical phenomenon which results in a loss, deformation or change of material.

(Norsk Standard NS-EN 13306:2010)

1 Introduction

This chapter aims to introduce how maintenance affects the industry related to performance, reliability, redundant maintenance, breakdowns, and implementation of condition-based maintenance. The chapter also describes the main objective, scope, limitations and delimitations of the thesis.

1.1 Background

Prior to the Second World War machines were run to failure as the philosophy was “If it works, don’t fix it.” (Brown and Sondalini, n.d.). During the second generation of maintenance, which lasted from the second world war until the 1970s, the focus was on scheduled maintenance and overhauls, thus extending equipment’s lifetime, whereas the third generation extended the focus on the cost effectiveness and health, quality, safety & environment (HSQE)(Dunn, 2018). The importance of training personnel has become extra important as the equipment and systems become more advanced (Taylor and Patankar, 2001). The market today has a rapid flow of information and technology, thus increasing competition and demand for reliability and efficiency. The fourth generation of maintenance started in 2010 (Hide, 2013), and this modern age of maintenance is where computers and sensors monitor and predict equipment’s condition and remaining lifetime.

Many companies had to reduce costs when the oil price dropped in 2014 to avoid bankruptcy. A common tactic is to lower the maintenance budget, which is an unsafe strategy as undone maintenance work piles up and future expenses increases. Maintenance ineffectiveness has a big financial impact and the maintenance policy and strategy must be revised by the decision makers (Aoudia et al., 2008). Reducing preventive maintenance will give short term gains but will in the long run acquire more corrective maintenance, thus giving long term losses (Woodhouse, 1999). Reduction in preventive maintenance has hidden costs such as increased equipment lifetime losses, unplanned maintenance service required, wrong staff size and more (ALD, n.d.; Wienker et al., 2016). Machine breakdowns are due to maintenance strategies failing its basic function; to keep the equipment in an up-state. There is also the danger of overdoing maintenance as from a certain point the amount of maintenance done gives diminishing returns, consequently not maximizing the return of investment made on maintenance. Condition based maintenance (CBM) is a modern approach to prevent redundant maintenance and breakdowns by using condition monitoring (CM) to survey the health of the equipment (Hide, 2013).

1.2 Problem description

A wrong maintenance strategy is a cause for concern as the impact is hard to determine. The effects can be extended, and consequences spread in a chain reaction, thus hiding the root of the problem and provide hidden costs of maintenance such as (Efficient Plant, n.d.; Wienker et al., 2016):

Poor documentation

Increased breakdown risk since the state of the equipment may be either unknown or misinterpreted. Wrong planning on maintenance will either cause overdoing or underdoing, depending on the interval of maintenance work. Higher unexpected breakdown associated costs will occur, as linked problems may stay unidentified.

Downtime losses

Downtime provides losses due to lost production which leads to late deliveries and lost sales. Personnel must work overtime to get equipment back to a working state and poor performance may cause customers to switch to a competitor.

Health loss

Equipment in poor condition will experience a more rapid health loss and may produces goods of a lower quality. An increase in lifetime losses on the equipment and an increase in risk of environmental impacts must be expected as well.

Only the tip of the iceberg on maintenance costs can be seen. Planning for maintenance is a difficult task, as unexpected breakdowns or failures are hard to predict. The size of the workforce may not be properly scaled to the workload and as Fitch (2006) says: "*Knowing when a piece of equipment is going to fail is much more difficult than making it last long*".

There are several standards which contributes to the process of designing and implementing a maintenance program such as ISO, DNV and NORSOK to mention a few. Today, digitalisation is a hot topic in the industry, and companies look into how computers and sensors can make better decisions and spot anomalies or inconsistencies which are otherwise undetectable by a human.

1.3 Thesis main goal

The aim of this master's thesis is to establish a foundation of information regarding how the maintenance strategy will affect the amount of maintenance hours needed to keep equipment in a working condition, and how many hours of downtime that strategy provides. Downtime and maintenance hours are highly correlated with costs and provides insight on expenses and lost production. Information and results from this thesis shall make the decision maker aware of the economic potential the maintenance strategy has. The thesis has the following goals to maintenance and operation:

1. Reduce downtime.
2. Reduce redundant maintenance.
3. Keep equipment in a working condition.
4. Prevent wear-out-failure.
5. Enlighten the decision maker in an economical view of the situation regarding each maintenance strategy.

1.4 Research question

The main research question is "*How can maintenance expenses be kept to a minimum without compromising productivity*?" The main method this thesis solves this question is by setting up three maintenance strategies and look into their long-term costs.

1.5 Methodology

To be able to address the problem posted in the abstract and in chapter 1.3 & 1.4, the information and data used in this thesis are collected from either online databases, books, journals, academic papers, interviews and the authors own experience as a drilling and maintenance operator. Dynamic modelling in Vensim PLE 7.2a is used where the simulation uses one-week time steps for a total of 520 weeks. Data and graphs are then extracted from Vensim to draw a conclusion on costs.

1.6 Delimitations, limitations and assumptions

Delimitations:

1. Only three maintenance strategies are simulated due to the amount of time required to build the strategies and simulate them. The simulations are simplified versions of reality, but the selected system is well known to the author and will thus provide the best possible outcome of the simulation.

2. Parts and subsystems that are not critical to the operation are not included in the simulation.
3. The simulation does not include cost of storage associated with the chosen strategy.
4. The research is based on Norwegian rules and standards used on the Norwegian continental shelf.

Limitations:

1. Available literature is limited by the university library and the amount of free literature found online.
2. There are many ways to combine maintenance types and create maintenance strategies, plans and programs. Other types of maintenance than PM, CBM and corrective maintenance will not be applied to the case study.
3. Costs will not be given as a currency but as in maintenance hours and downtime hours due to two factors:
    a. Prices varies greatly depending on location, industry and the workers skill and education.
    b. Prices regarding operation and maintenance is either confidential or unknown.

Assumptions:

1. Information received from literature and interviews is assumed to be correct.

1.7 Thesis outline

The report consists of six chapters. The first chapter presents the project and the background of maintenance policies. The second chapter presents theory related to the types of maintenance which is later used in the simulation. The third chapter describes the simulation and presents the expected results. Chapter four describes the selected system and analyses this system to identify critical components. Chapter five provides information and snapshots of the simulations and presents the simulation results. Lastly, chapter six discusses the realism of the simulation, what could be done in the future and provides a conclusion based on research and simulation results.

2 Theoretical Background

This chapter aims to describe existing theories on how the process of performing maintenance is done in order to keep equipment in a working condition, including technical, administrative and managerial actions. A description of a pump and its critical parts is given in addition to how the author is using Vensim to simulate different maintenance plans.

2.1 Maintenance

Different types of maintenance strategies are used for different scenarios. Due to this it is necessary to understand the differences between these types, as they will impact equipment condition and productivity. Figure 2.1 provides an overview of the main maintenance types (Murthy and Nat, 2014) and when the timing of the maintenance event shall occur. The primary function of PM is to keep equipment in a working condition, and corrective maintenance is a necessity when PM fails.

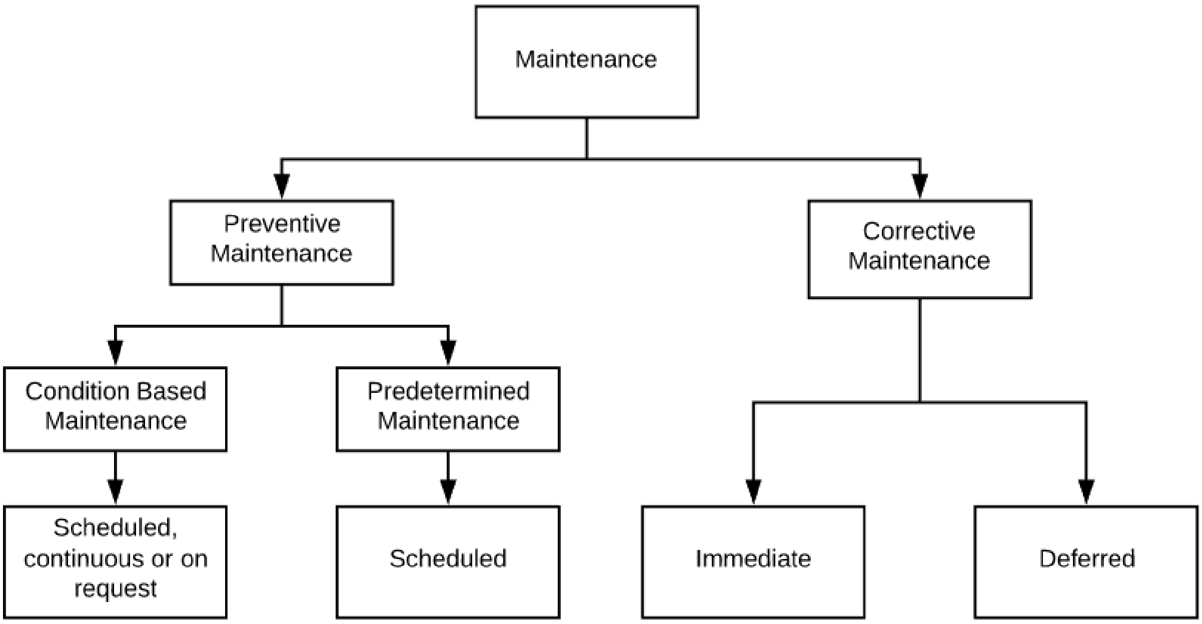


Figure 2.1 A model of the maintenance types and when they are conducted. (Murthy and Nat, 2014).

A maintenance plan is to be able to handle the workload and logistics for reserve equipment, spare parts and available personnel. For this, a maintenance program is a useful tool when selecting a maintenance plan, however, plans become obsolete, whereas programs evolve. Figure 2.2 gives an example on how to create a maintenance program. By actively using statistics and available data the quality of both plans and programs increase over time.

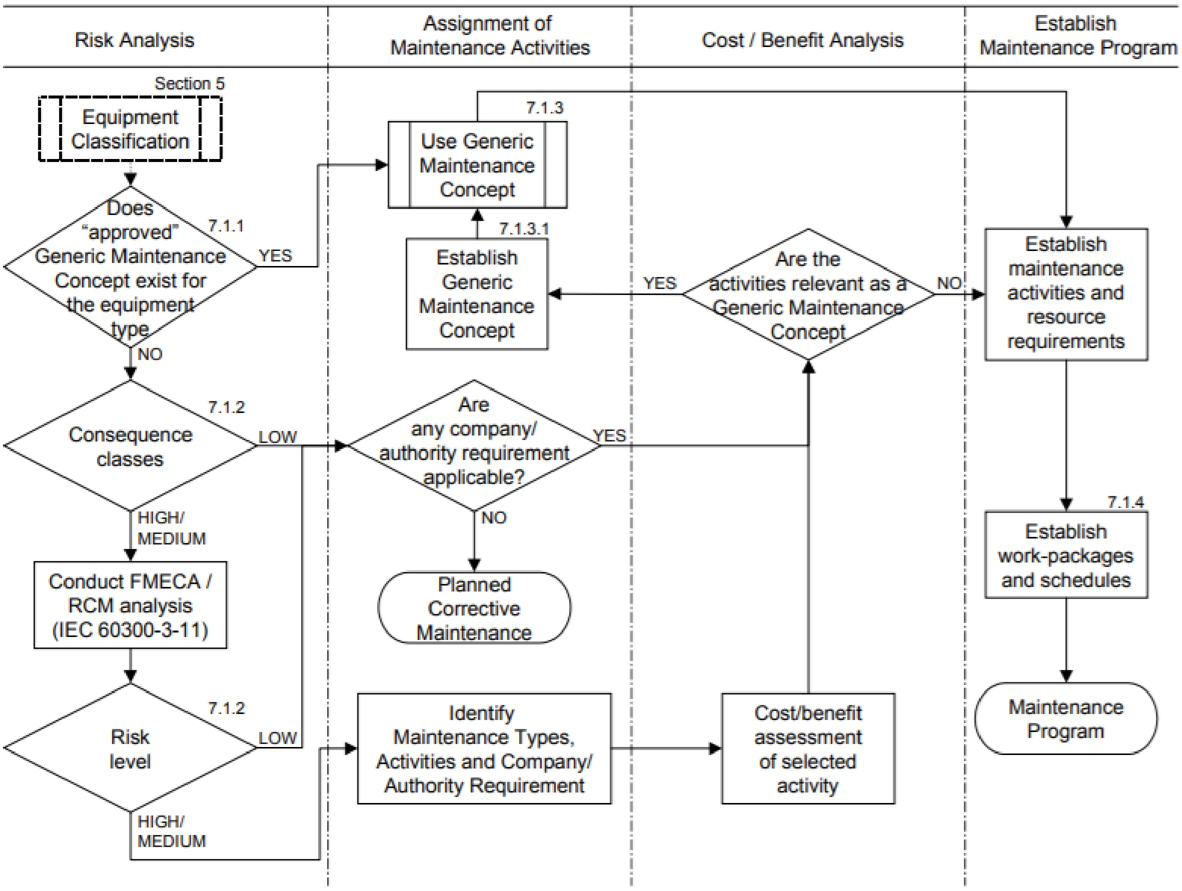


Figure 2.2 A process diagram for establishing a maintenance program (Norsok Z-008).

An updated maintenance plan is achieved by continuously updating the maintenance program. The maintenance program sets goals and requirements such as availability, maintainability, reliability, condition, wear-out rate and standardisation for the equipment. A maintenance strategy combines the different types of maintenance for a system such that non-critical parts gets less surveillance and maintenance than parts that are critical for the operation. The performance of a system depends on the performance of each individual part (Murthy and Nat, 2014), and each of these individual parts needs to be maintained to prevent breakdown during operation. The system as a whole is a complex entity which is as strong as its weakest part. An improvement in maintenance strategies will make the system more reliable as Figure 2.3 illustrates; how the failure rate declines with improved maintenance strategies (Sethiya, 2005).

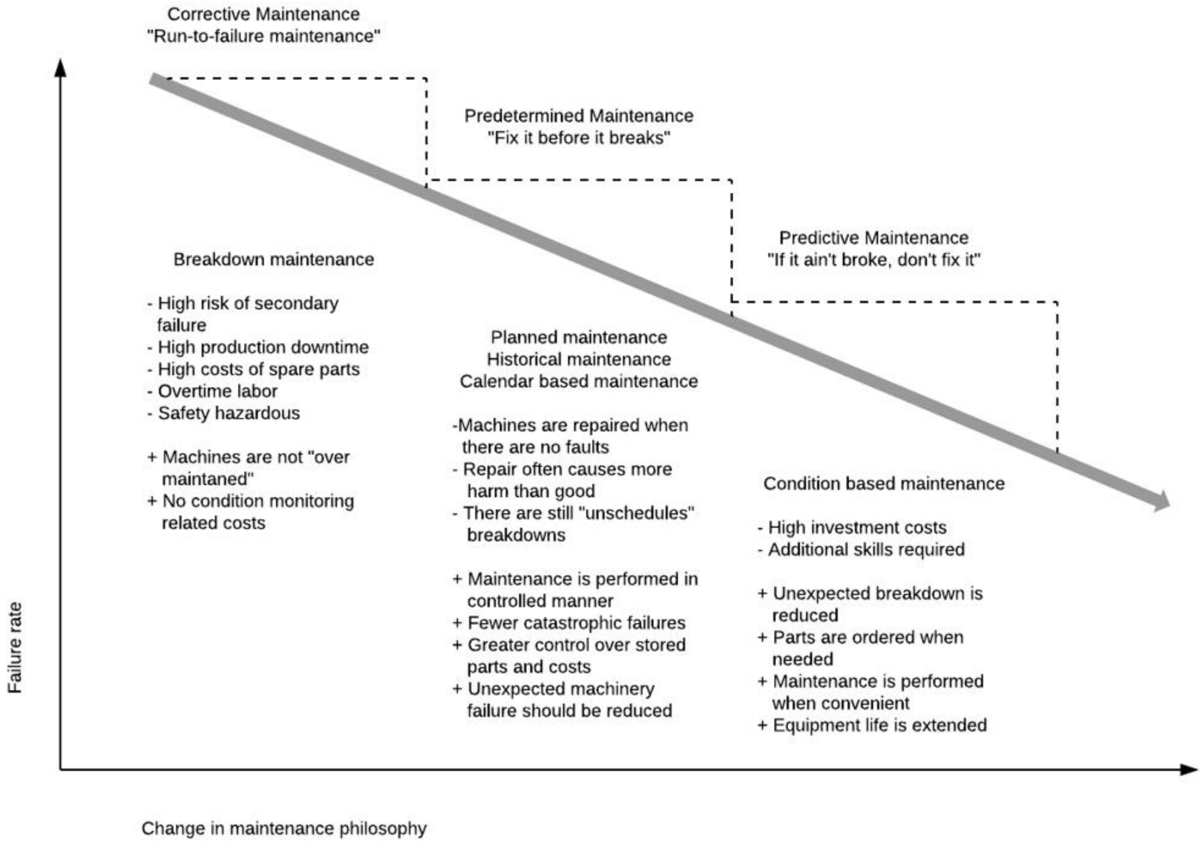


Figure 2.3 A declining trend in rate of failure and its corresponding maintenance philosophy, and listing each strategy's pros and cons (Sethiya, 2005).

2.2 Preventive maintenance

There are two categories of PM; predetermined maintenance and CBM (Murthy and Nat, 2014). Both aims to prevent the equipment from breakdown and failure but cannot prevent random breakdowns. Investing more in PM gives diminishing returns, meaning that the increased effectiveness, efficiency and productivity the equipment achieves is only reasonable up to a certain point, from beyond this point it will costs more than what it saves in expenses (World Economic Forum, n.d.).

2.2.1 Predetermined maintenance

Predetermined maintenance is either based on calendar time, use-based, total operating time, mileage or number of operations conducted, thus not considering the current condition of the equipment. The maintenance work is then performed as scheduled even though equipment may have a remaining lifetime to endure operation for an extended period of time. Predetermined maintenance makes it easy to schedule work and thus adjust the workforce according to the workload.

2.2.2 Condition based maintenance

A condition-based maintenance system considers the condition of the equipment before action is taken to prevent downtime or redundant maintenance by using a CM system. In CM, sensors are measuring temperature, pressure, wear debris and/or vibration (Machinery Lubrication, n.d.). Non-destructive testing (NDT) equipment is an alternative way to test the equipment for damage by using methods such as acoustic measurements, thermal imaging and x-ray scans (Cawley, 2001). The data is then analysed to determine the condition of the equipment, allowing for the probability of failure to be estimated, making it possible for decision makers to choose whether maintenance should be delayed or not. The goal is to time the maintenance event to the optimum operating range as illustrated in Figure 2.4 (World Economic Forum, n.d.).

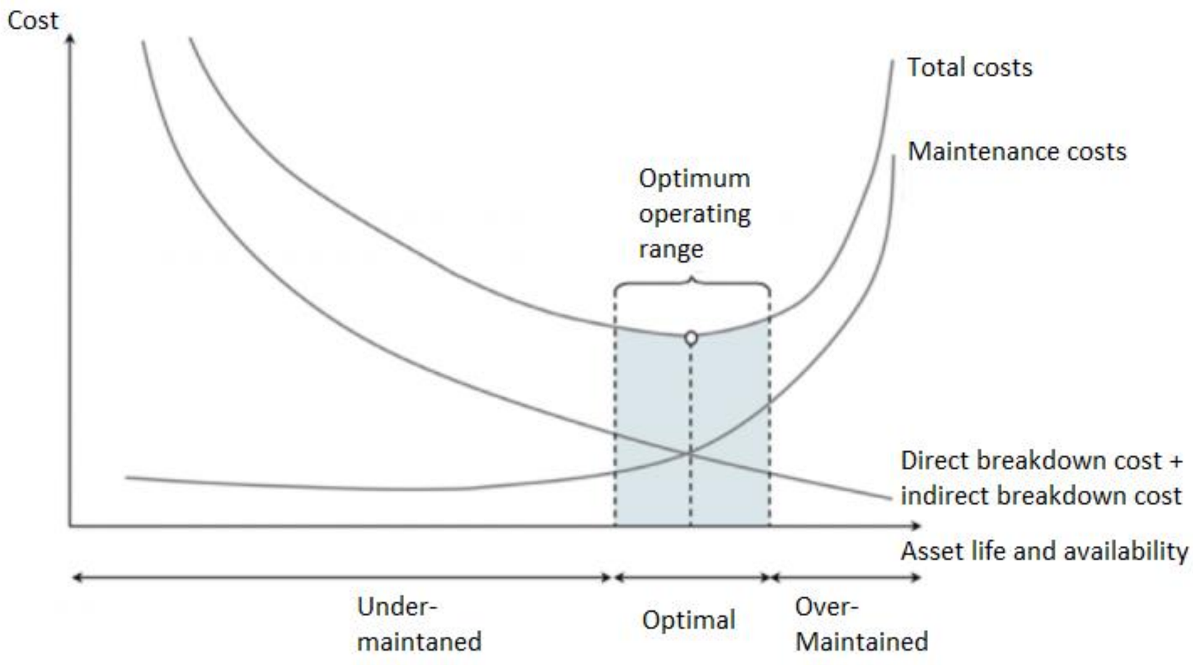


Figure 2.4 Condition-based maintenance aims to perform maintenance at the optimal timing to prevent both under-maintenance and over-maintenance (World Economic Forum, n.d.).

CM allows the user to perform maintenance based on the actual condition of the equipment, with evidence supporting its condition. The condition is monitored in real-time or near real-time as this improves the systems reliability and availability. One can, with a much lower effort, see if the equipment can last through another period of production without further maintenance, and if not, repair it so that it will not cause downtime during production or any critical operation. For CBM to be implemented one must consider the cost of installing such equipment versus the benefit it gives.

2.3 Condition monitoring

CM is a process which collects data and analyses this to determine the equipment's health. There are several ways CM is used to detect precautionary failure (Sethiya, 2005):

Trend analysis

Analysing data over time provides a trendline on equipment behaviour which provides easy insight for the operator to interpret. Changes in equipment's state is detected by looking at changes over time by documenting data on e.g. noise levels, vibration and/or temperature. If a change is detected, then equipment may need further inspection to find the cause of change. Increase in temperature may be the result of worn out parts not running smoothly, thus increasing friction. Debris in oil or other lack of lubrication may also be the source. Overall, the trend analysis estimates the remaining lifetime by using current age, past conditions and statistical data.

Pattern recognition

Performing a fast fourier transformation (FFT) on, for instance vibration samples, will convert the original signal to a representation in the frequency domain, showing the combination of frequencies that would make up the original signal. By knowing the frequency of vibration on a normal working condition, one can spot abnormalities indicating a fault in the equipment.

Tests against limits and ranges

If the equipment can work above or below its limits on working condition, or move out of its allowed range of motion, then there will most likely be either a sensor fault or a more severe fault to the equipment. Work out of allowed range of motion or limits indicates a peculiar behaviour and may need further inspection.

2.3.1 Vibration monitoring

Vibration monitoring is an efficient type of CM for rotating equipment (Sundberg, 2003). Rotation generates a vibration frequency which depends on the rotation speed, alignment, balance and rotation around center of mass. Isolating the vibration reduces wear on equipment, and detection of abnormal vibration gives cause for investigation. The vibration characteristics amplitude helps in detecting the severity of the fault, the frequency helps in indicating the cause of the defect, and phase helps in determining the cause of the defect (Dynapar, n.d.). When analysing vibration data, the peak-to-peak value reveals the maximum excursion of the wave (Goutam and Sathish, 2018). It is key to know the frequency of vibration and its amplitude for equipment in a healthy state which is working under normal load and revolutions per minute (RPM). This is used as a reference point to FFT data to detect possible faults.

2.3.2 Fast fourier transformation

Performing an FFT on raw vibration time waveform data provides a frequency domain of the combined vibrations and their associated amplitudes that makes up a raw data image. Beats on synchronous peaks in vibration data on the rotational frequency of an axel provides insight on issues related to the rotation of that shaft (Dynapar, n.d.). FFT is a useful tool to vibration monitoring in order to spot vibration which should not be present on rotating equipment such as ball bearings, shafts and/or axels.

2.4 Corrective maintenance

Corrective maintenance is carried out either when a failure is detected, or equipment breaks down and needs fixing. Parts are then either replaced or repaired. Corrective maintenance is an effective approach to equipment where costs are relatively low, and where the equipment is not critical to either safety, production or the environment (Arts, 2013). The workload from corrective maintenance is hard to predict as most breakdowns cannot be predicted thus making it difficult to size the staff according to the workload. A staff which is to small cannot keep up with the workload on ordinary hours, triggering overtime in order to get the equipment to working condition. On the contrary, increasing staff size will result in unused ordinary hours.

2.5 Data collection and documentation

Data gathering on e.g. condition versus performance, faults & breakdowns, maintenance events, CM data etc. is useful for future operations and is a long-term investment and provides statistics. Documentation allows for efficient experience transfer and works as a safety measure in case a company were to lose competence, thus solving issues which were solved in the past without the need of re-investigate an earlier solved problem (Arinze and Banerjee, 1992).

2.6 Failure

Equipment is prone to failure due to factors such as water, sludge, heat, aeration and particles which has been introduced to the system. These factors increase the wear rate, reducing equipment condition and reliability, consequently lowering its lifespan. There are many reasons why equipment fails, where the most common causes are wear-out, ageing, or malfunctions due to human error. The mean time between failure (MTBF) is used to refer to the statistical probability for the amount of time it takes for a failure to occur. Torell and Avelar (n.d.) defines failure as either *"The termination of the ability of the product as a whole to perform its required function."* or *"The termination of the ability of any individual component to perform its required function but not the termination of the ability of the product as a whole to perform"*.

The failure rate of equipment has a bathtub shaped model as shown in Figure 2.5. The early failure period has a higher rate of failure than the normal operating period which is due to run-in issues such as installation, lack of knowledge and/or experience/expertise to operate. At the end of an equipment's lifetime the rate of failure increases due to parts wearing out due to fatigue, oxidation etc. This is illustrated in Figure 2.5 (Torell and Avelar, n.d.).

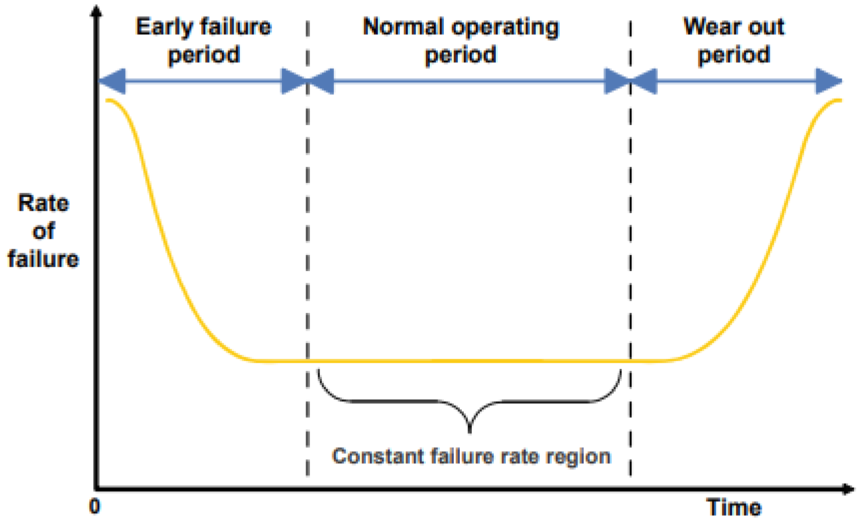


Figure 2.5. The bathtub model illustrating the rate of failures (Torell and Avelar, n.d.).

2.6.1 Bearings failure

Major causes of premature bearing failure in the machinery are dirt, misassemble, misalignment, insufficient lubrication, overloading, corrosion and manufacturing error (Shah and Patel, 2014) Vibration and friction is bad for the bearings and may be the result of foreign particles and/or water entering the system. Damages to the ball bearings will then cause a non-smooth rolling of the balls, thus inducing vibration (Machinery Lubrication, n.d.). The lifetime of a bearing is expressed in total revolutions or hours with a 90% reliability and is calculated using Equation 2.1 and Equation 2.2 respectively. The basic rating of lifetime in a ball bearing is defined as the lifetime associated with 90% reliability and the calculation is based on JIS B 1518 (nmbtc, n.d.). In the Vensim simulation the bearings are lubricated using recirculating oil as this allows for reuse and cooling, thus making the simulation realistic to what the author has experienced in maintenance work offshore. Reuse of oil results in accumulation of debris which increases wear on the parts (Schaeffler, n.d.).

Equation 2.1

$$L_{10} = ({}^{C_r}/_{P_r})^3$$

L_{10}	Basic rating life (10^6 revolutions)
C_r	Basic dynamic radial loading [N]
P_r	Dynamic equivalent radial loading [N]

Equation 2.2

$$L_{10} = \left({}^{10^6}/_{60n}\right) * ({}^{C_r}/_{P_r})^3$$

L_{10}	Hours [h]
n	Speed [rpm]

2.7 Dynamic modelling

A dynamic model replicates the behaviour of a system over time. The dynamic model used in Vensim in this thesis is a non-casual model, meaning that it is based on statistics, correlations and experience, and not theory based like a casual model (Yaman and Stanley, 1990). Non-casual models express observed associations among variables of a real system. Dynamic models may be used to predict the cost and benefit of maintenance strategies, thus alerting decision makers and stakeholders of potential economic pitfalls.

3 Research methodology and model development

This chapter aims to describe the simulation and its goal. Information provided here is key to understanding the simulation and thus the conclusion in the thesis. The expected outcome of the simulation is similar to Figure 3.1 which illustrates a performance measure against a maintenance strategy.

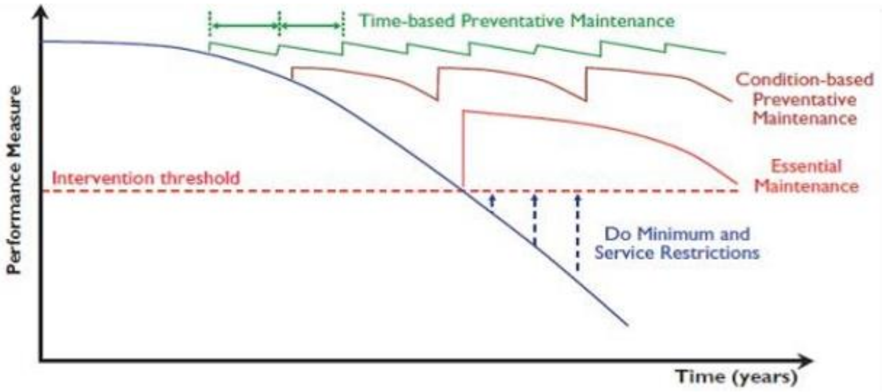


Figure 3.1 Performance measured over time is affected by the type of maintenance done to equipment (Lifetime Reliability Solutions, n.d.).

3.1 Description of the simulation

The simulation takes place during the normal operating period where one time-step in the simulation is equal to one week and simulation is run for 10 years. The system consists of parts that make up a sub-system, where each part has been assigned a wear rate. The level of a part represents its condition. Equipment that has been excluded from the circulation system is: fluid storage, degasser unit, mixing station, pipes, and all valves. The condition of a part has an initial value of 10 and wears down over time. Maintenance restores values to prevent it from reaching zero, where zero means a breakdown. Each part has an assigned chance of a random breakdown which will take the condition to zero thus creating a need for corrective maintenance to return the part or equipment to an up-state. Breakdowns cause downtime, where the total downtime and total amount of maintenance hours used are accumulated to be used for the end result.

3.1.1 Expected result: Preventive Maintenance

The PM strategy scenario is expected to have low downtime, but a high amount of total maintenance hours used due to maintenance being overdone has shown by the green graph in Figure 3.1.

3.1.2 Expected result: Corrective Maintenance

The corrective maintenance strategy scenario is expected to have the highest amount of downtime since the equipment will run to failure. This scenario is expected to have the lowest amount of maintenance hours done as there will be no redundant maintenance performed.

3.1.3 Expected result: Condition Based Maintenance

The CBM strategy scenario is expected to have a lower amount of maintenance done than the PM scenario as the goal here is to remove the amount of maintenance work which is redundant. The amount of downtime is expected to be approximately the same as the preventive maintenance scenario as they share the same probability of a random breakdown.

3.2 Vensim

A level box in Vensim can be illustrated as a tank that can either be filled or drained with fluid. This volume represents whatever unit is defined in that level, and its volume is an integral or a function from all other levels, variables, functions, equations and/or rates connected to it, where an arrow indicates a connection. A rate connected to a level will give a flow equal to the value or function entered in that rate and can be either positive or negative, respectively filling or draining that level. Variables are inserted and given a value or a function, and connected to other rates, variables or levels. The direction of the arrow tells Vensim which other component shall be affected by starting location of that arrow. A simple example of the components used in Vensim is shown in Figure 3.2.

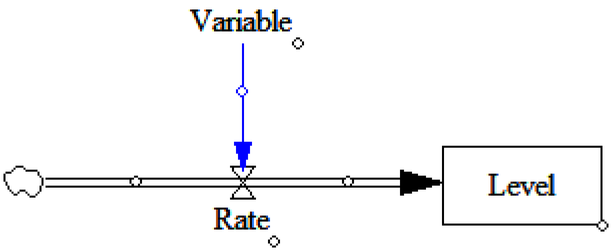
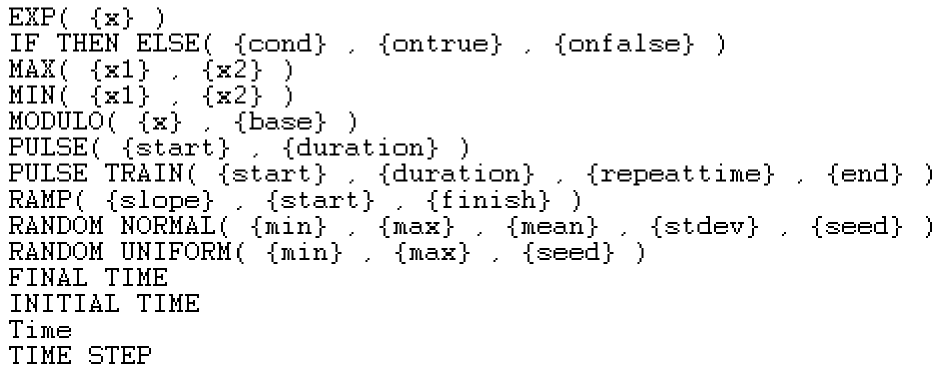


Figure 3.2 A model where a rate is filling a level, and the rate is affected by a variable.

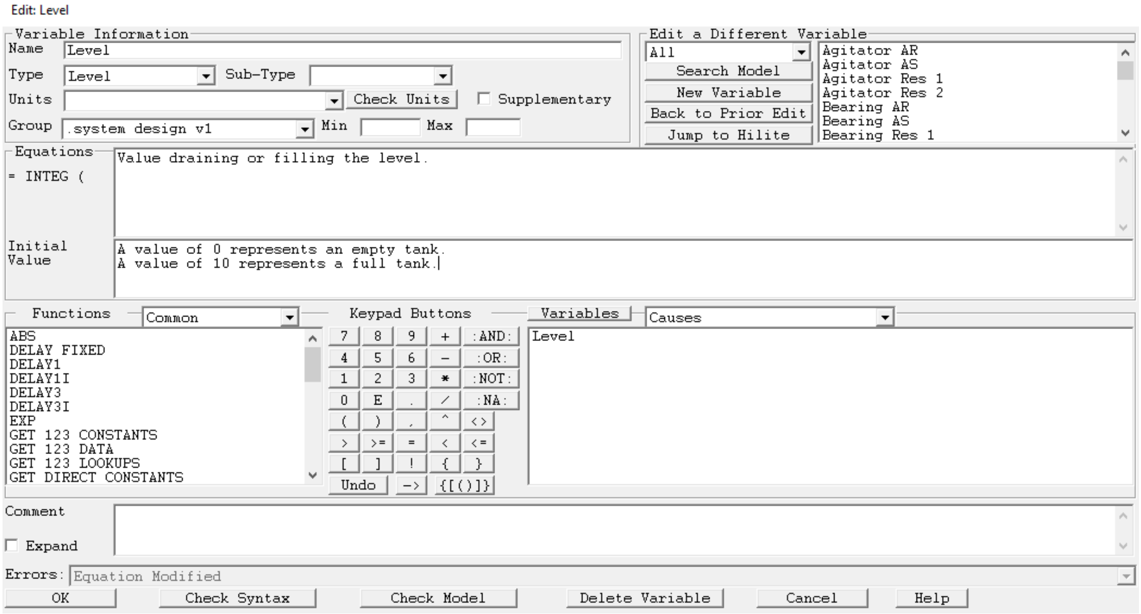
The functions used in Vensim are listed in Figure 3.3. Note that functions can be inserted as values or arguments inside other functions. For instance, the function Random Normal can be inserted for the value {duration} in the Pulse Train function.



```
EXP( {x} )
IF THEN ELSE( {cond} , {ontrue} , {onfalse} )
MAX( {x1} , {x2} )
MIN( {x1} , {x2} )
MODULO( {x} , {base} )
PULSE( {start} , {duration} )
PULSE TRAIN( {start} , {duration} , {repeattime} , {end} )
RAMP( {slope} , {start} , {finish} )
RANDOM NORMAL( {min} , {max} , {mean} , {stdev} , {seed} )
RANDOM UNIFORM( {min} , {max} , {seed} )
FINAL TIME
INITIAL TIME
Time
TIME STEP
```

Figure 3.3 Functions used in Vensim.

The level in Figure 3.3 can be opened and edited in Vensim and the editor is shown in Figure 3.4. Note that explanatory information to the reader is inserted in the input cells instead of values, equations or functions in Figure 3.4.



Edit: Level

Name: Level
Type: Level
Group: .system design v1
Equations: = INTEG (Value draining or filling the level.
Initial Value: A value of 0 represents an empty tank. A value of 10 represents a full tank.
Errors: Equation Modified
Variables: Causes: Level

Figure 3.4 Editing a level in Vensim.

4 Case study

This chapter aims to describe the system and equipment. Information in this chapter comes from several interviews with an operations and maintenance operator with 20 years of experience.

4.1 The selected system for simulation

The selected system for simulation is the mud pumps responsible for circulating the drilling fluid in a drilling operation. An example of the circulation system can be seen in Figure 4.1. The selected system has three mud pumps, and only maintenance regarding the mud pumps will be simulated. The mud pumps use pistons to circulate drilling fluids.

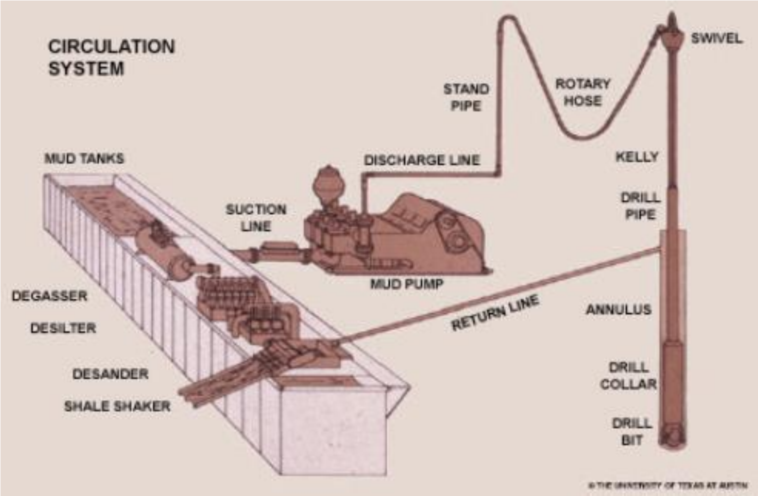


Figure 4.1 The circulation system in a drilling operation (Oil & Gas Portal, n.d.).

The system consists of four sub-systems as shown in Figure 4.2. This means that the electric motor, power drive system, feeder pump and pump action make up the mud pump system which are to be simulated.

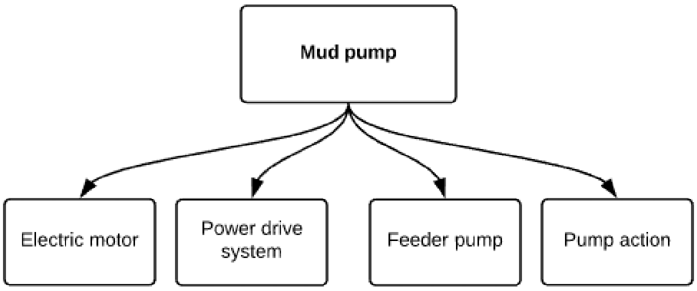


Figure 4.2 The selected system and its associated sub-systems.

4.2 Pump

A pump is a device which can move, raise, compress, drive, and exhaust fluids or gases by using a mechanical action such as either a piston, plunger or a set of rotating parts. Pumps have a low-pressure side, called the suctions side, and a high-pressure side, called the discharge side. Some pumps may require a super-charge pump to feed the main pump with fluid or gas in case the suction side does not deliver the volume the main pump requires. A super-charge pump, also called a feeder pump, is included in all the mud pumps in the Vensim simulation. A pump is driven by either an electric engine or combustion engine and they have a big area of application, thus several factors and requirements must be considered before choosing a pump. Typical factors and requirements for choosing a pump is:

- Volume per time unit,
- Operating pressure,
- Operating temperature,
- Noise level,
- Power rating,
- EX rating,
- Dimensions,
- Weight,
- State of matter,
- Accessibility.

4.2.1 Piston pump

Piston pumps benefit from being able to change piston and liner to meet requirements in flowrate and pressure. Replacing the piston and liner to a set of a different size allows the pump to operate at different pressures and flow-rates. A smaller diameter on the piston results in a higher pumping pressure, but at a lower flow-rate. The liner is a cylinder inserted in the pumps cylinder to seal the gap that would emerge between the outer diameter of the piston and the inner diameter of the pumps cylinder, as a smaller diameter piston is installed. Figure 4.3 shows a cross section of a pump with and without a liner installed. It is convenient to inspect parts when the pump is open, thus removing the need for a disassembly for inspection. Some piston pumps however can work through their entire required range in terms of pressure and flow-rate and do therefore not benefit from this convenience.

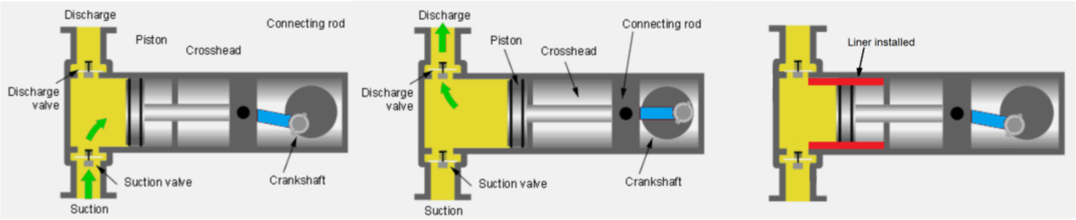


Figure 4.3 A cross section of a piston pump (Global pumps, 2016). Right figure illustrates a liner installed.

4.2.2 Centrifugal pump

A centrifugal pump has the inflow at the centre of the pump and uses a rotating chamber which slings fluid outwards. The pressure from the pump comes from the centrifugal force acted upon the fluid by the rotating chamber as shown in Figure 4.4 (Centrifugal Pump n.d.; Dairy Processing Handbook, n.d.). This type of pump is used in the Vensim simulation as a feeder pump to the mud pump.

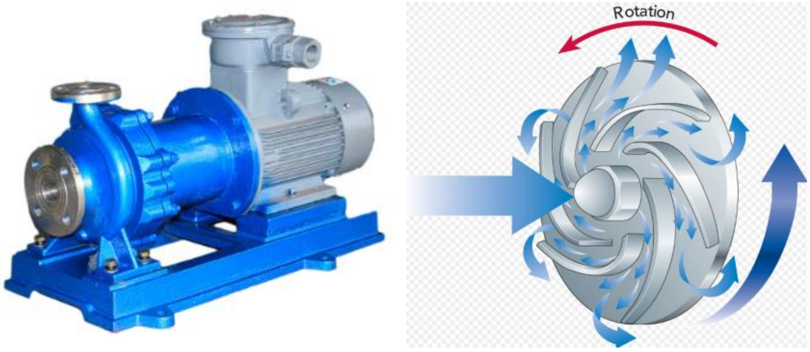


Figure 4.4 An electric motor attached to a centrifugal pump. The inflow is on the centre of the chamber where centrifugal forces force the fluid to the outflow (Centrifugal Pump n.d.; Dairy Processing Handbook, n.d.)

4.3 System analysis

Failure Mode Effect and Criticality Analysis (FMECA) and fault trees are good tools to analyse and identify a systems critical parts and bottlenecks. This information is useful when designing maintenance plans and to identify hazards and potential faults. Norsok Z-008 contains information and recommendations for a general consequence on a criticality analysis.

4.3.1 FMECA

Aven et al. (2007) defines FMECA as: "*an analysis method used to reveal potential errors and predict the effect of failures in components in a system*". The FMECA focuses on one part at a time, identifying its potential failure modes and that failure modes effect on the system. The criticality of this is then analysed, and the frequency of the failures are compiled in a score. The end result of this score will show what is most critical to the system. A FMECA has been conducted in Table 4.1 for the selected system.

Table 4.1 FMECA for a piston pump.

Name / Function	Potential failure mode	Potential effect(s) of failure	Severity	Potential cause(s) of failure	Occurr.	Current process controls (prevention)	Current process controls (detection)	Detection	RPN	Recommended actions	Score
Seat	Leakage	Washout	5	Wot. Chunks in fluid. Valve malfunction. Mechanical clearance.	4	PM. Item replaced the manufacturers recommended working hours intervals. Visual inspections.	Pressure drops. Spillage.	2	4	Do not exceed manufacturers guaranteed working hours. Inspection whenever convenient. Make sure pop-off valves are set to the correct pressure.	15
		Fluid flow in wrong direction	7	Wot. Chunks in fluid. Valve malfunction	2		Pressure drops. Spillage. Pop-off valve breaking.				15
	Fracture	Washout	5	To high pressure. Fatigue	2		Pressure surveillance. Do not exceed maximum working pressure.	5	7		19
Valve	Failure to close	Fluid flow in wrong direction	7	Wot. Chunks in fluid. Valve malfunction. Misalignment. Spring fault.	2	PM. Item replaced the manufacturers recommended working hours intervals. Visual inspections.	Pressure drops. Spillage. Pop-off valve breaking.	6	7		22
	Leakage	Washout	5	Steel or other hard objects scraping surface. Wear.	4			2	4		15
Bearings	Failure to rotate/ carry load.	PDS failure to transfer power.	8	Wot. Fatigue. Foreign particles introduced to the system.	2	PM. Item replaced the manufacturers recommended working hours intervals. Visual inspections. CM, vibration and sound, NDT.	Vibrations and sound detectable by the human ear. Otherwise changed on PM intervals.	4	8	Implement CM for early fault detection.	22
	Fire		9	Overheat. Lack of lubrication.	1	Frequent oil level inspections.	Increased friction. RPM drops.	1	10	Implement CM for oil level.	21
Piston Liner	Pump fails to compress	Pump does not deliver required pressure	3	Spacing between piston and liner. Either due to OD of piston has decreased or ID of liner has increased.	7	PM. Item replaced the manufacturers recommended working hours intervals.	Visual inspection. Pressure drops.	2	3	Do not exceed manufacturers guaranteed working hours. Inspection whenever convenient.	15
Power drive system	Vibration.	Increased wear on other parts.	6	Misalignment. Damaged bearings	2	PM. Item replaced the manufacturers recommended working hours intervals. Maintenance shall only be performed by qualified personnel.	Vibration and sound detectable by the human ear.	4	2	Maintenance shall only be performed by qualified personnel. Oil lubricant shall be topped up at certain intervals. Oil debris analysis will indicate need for replacement.	14
	Shaft bend / break	Pump breaks down	8	Fatigue. Overload.	1			5	9		23
	Overheat	Shaft breaking	9	Debris in oil. Oil level to low.	2		Coolant and lubrication temperature surveillance.	7	8		26
Water cooling	Insufficient cooling	Piston overheat	4	Hose rupture.	5	Inexpensive part, replace it before critical operation.	Regularly visual inspections. Surveillance.	1	4	Install video surveillance to detect rupture.	14
Electric motor	Not delivering full power	Pump rate decrease. RPM decrease	5	Voltage to low. PLS issues. Software bugs.	5	Routine inspection. Software updates.	Low RPM. Lower flowrate.	4	2	Ensure grid supplies enough power. Electrician shall control PLS.	16
	Overheat	Breakdown	7	Insignificant cooling. El motor overloaded.	2	Do not exceed maximum power.	Temperature monitoring	2	3	If overheat is a frequent issue, consider replacing motor.	14
Belt	Lose	Heat generation. Failure to transmit power from el. motor to PDS	4	Not properly installed. Poor quality.	6	After belt replacement, tighten belt after run-in.	Smoke alarm. Odor detectable by human.	2	5	Install according to manufacturer’s recommendation by qualified personnel.	17

The result of the FMECA shows that parts have different levels of importance for the operation. It is recommended that the bearings, oil level and oil debris have CM implemented to prevent the potential failure modes from occurring and to increase detection. Scheduled preventive maintenance is recommended for the crankshaft, electric motor, valve seat, valve, piston and liner to keep occurrence at a low score. Corrective maintenance or replacement before critical operations can be used for both the belt and the water cooling hoses in order to prevent a potential breakdown as these are quick to replace and are easily accessible. In no situation should the mud pump run over the recommended working condition.

4.3.2 Fault tree

Fault trees is a useful tool for detailing the path of events. The fault tree provides a top to bottom approach to a system including the parts and components that make up the system (Torell and Avelar, n.d.).

5 Simulation and data collection

This chapter illustrates how the collected data is analysed. Each variable, rate and level are explained in detail in the tables in the appendix.

The total amount of breakdowns in the scenarios varies although all three scenarios have the same chance of a random breakdown. The selected system to be simulated consists of three mud-pumps, these are however identical therefore only one mud-pump is created in Vensim and the values given are multiplied by three.

The input information used in Vensim, such as lifetime, wear rates and maintenance intervals have either been found in manufacturer manuals, articles and/or most importantly, from interviews with an operations and maintenance operator with over 20 years of experience.

All the simulations accumulate each sub-system's use of maintenance hours and downtime hours. This is then combined to make up the overall usage of labour and downtime for the mud pump, which is then to be used in the conclusion in this thesis.

5.1 The preventive maintenance scenario

The setup of the preventive maintenance scenario is shown in Table 5.1. This scenario focuses on performing maintenance on a scheduled basis to prevent equipment from breaking down.

Table 5.1 Vensim system for the PM scenario.

Sub-system	Figure	Table
Electric motor	Figure 5.1	Appendix A
Power drive system	Figure 5.2	Appendix B
Feeder pump	Figure 5.3	Appendix C
Pump action	Figure 5.4	Appendix D

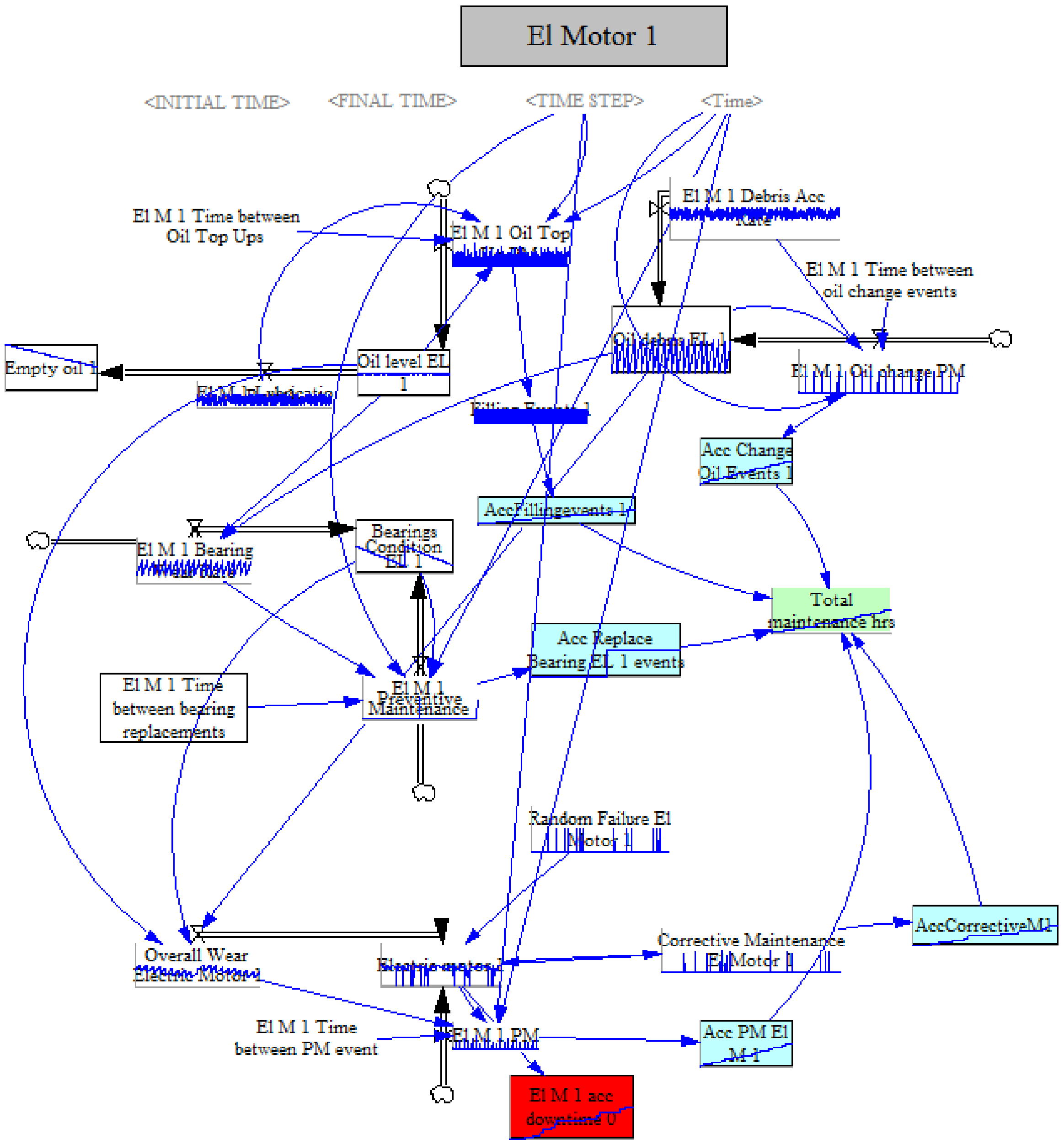


Figure 5.1 A snapshot of the electric motor in Vensim. Each variable, rate and level are explained in appendix A.

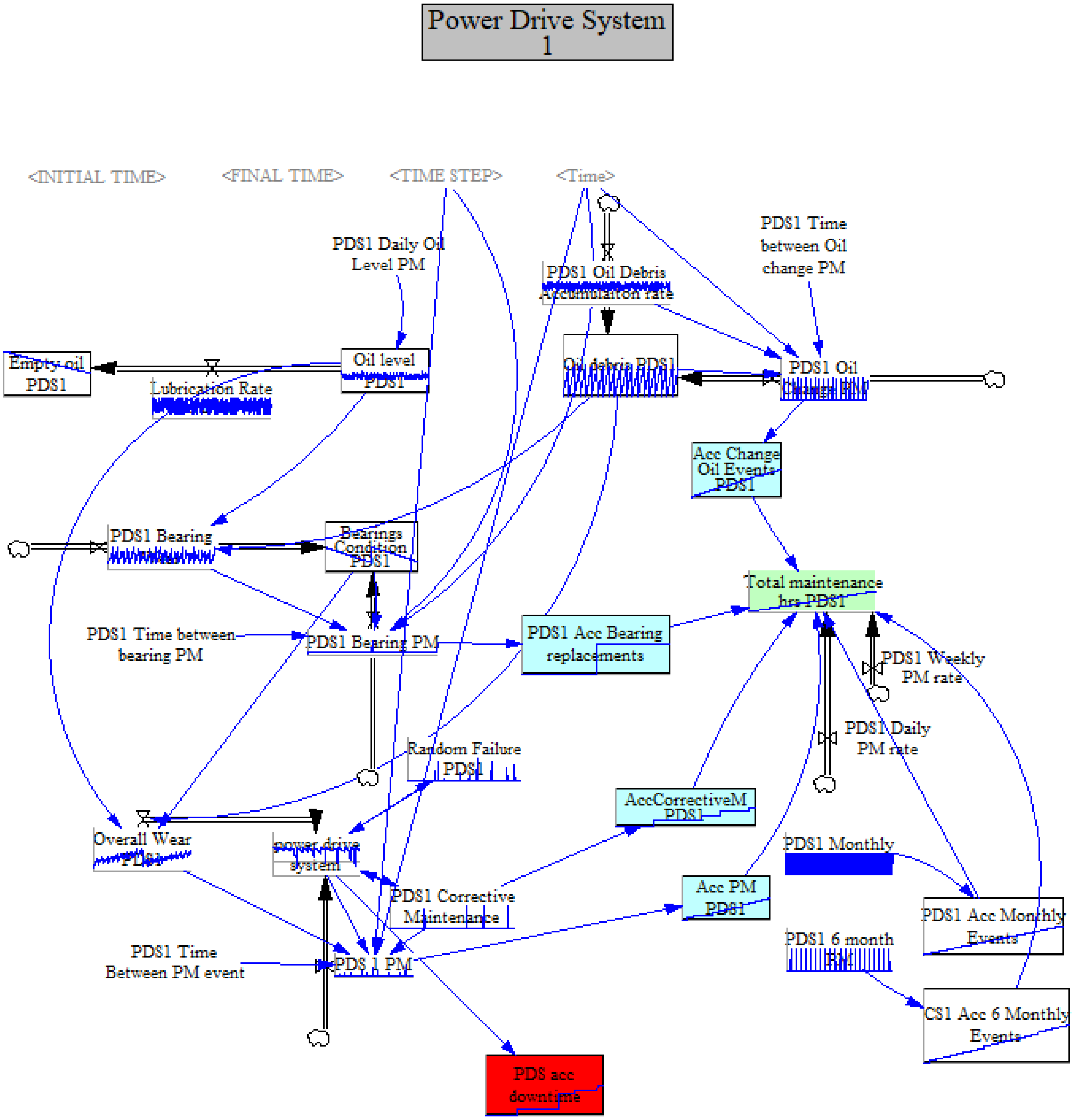


Figure 5.2 A snapshot of the power drive system in Vensim. Each variable, rate and level are explained in appendix B.

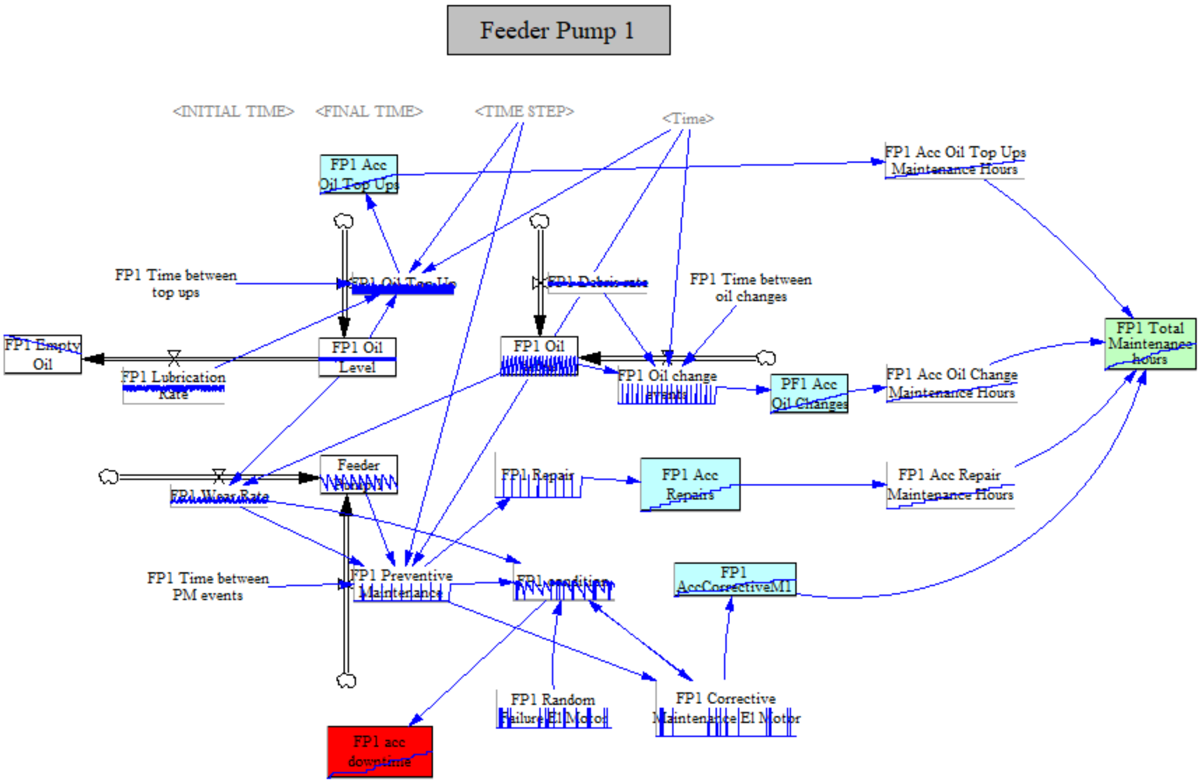


Figure 5.3 A snapshot of the feeder pump in Vensim. Each variable, rate and level is explained in appendix C.

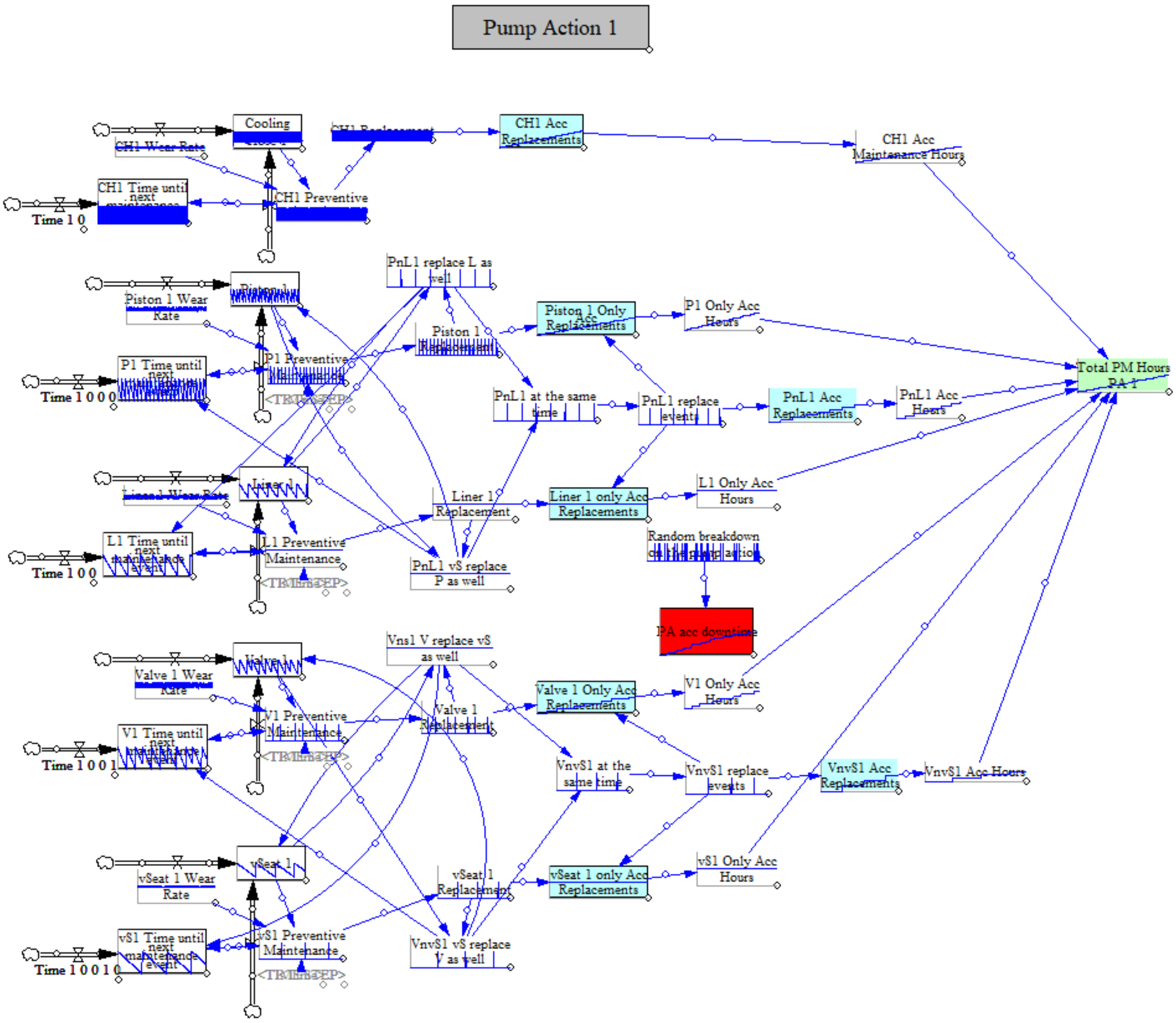


Figure 5.4 A snapshot of the pump action in Vensim. Each variable, rate and level is explained in appendix D.

5.2 The corrective maintenance scenario

The setup of the corrective maintenance scenario is shown in Table 5.2. This scenario focuses on minimizing maintenance hours used by allowing equipment to run to failure. Lubrication is done on a scheduled basis.

Table 5.2 Vensim system for the corrective maintenance scenario.

Sub-system	**Figure**	**Table**
Electric motor	Figure 5.5	Appendix E
Power drive system	Figure 5.6	Appendix F
Feeder pump	Figure 5.7	Appendix G
Pump action	Figure 5.8	Appendix H

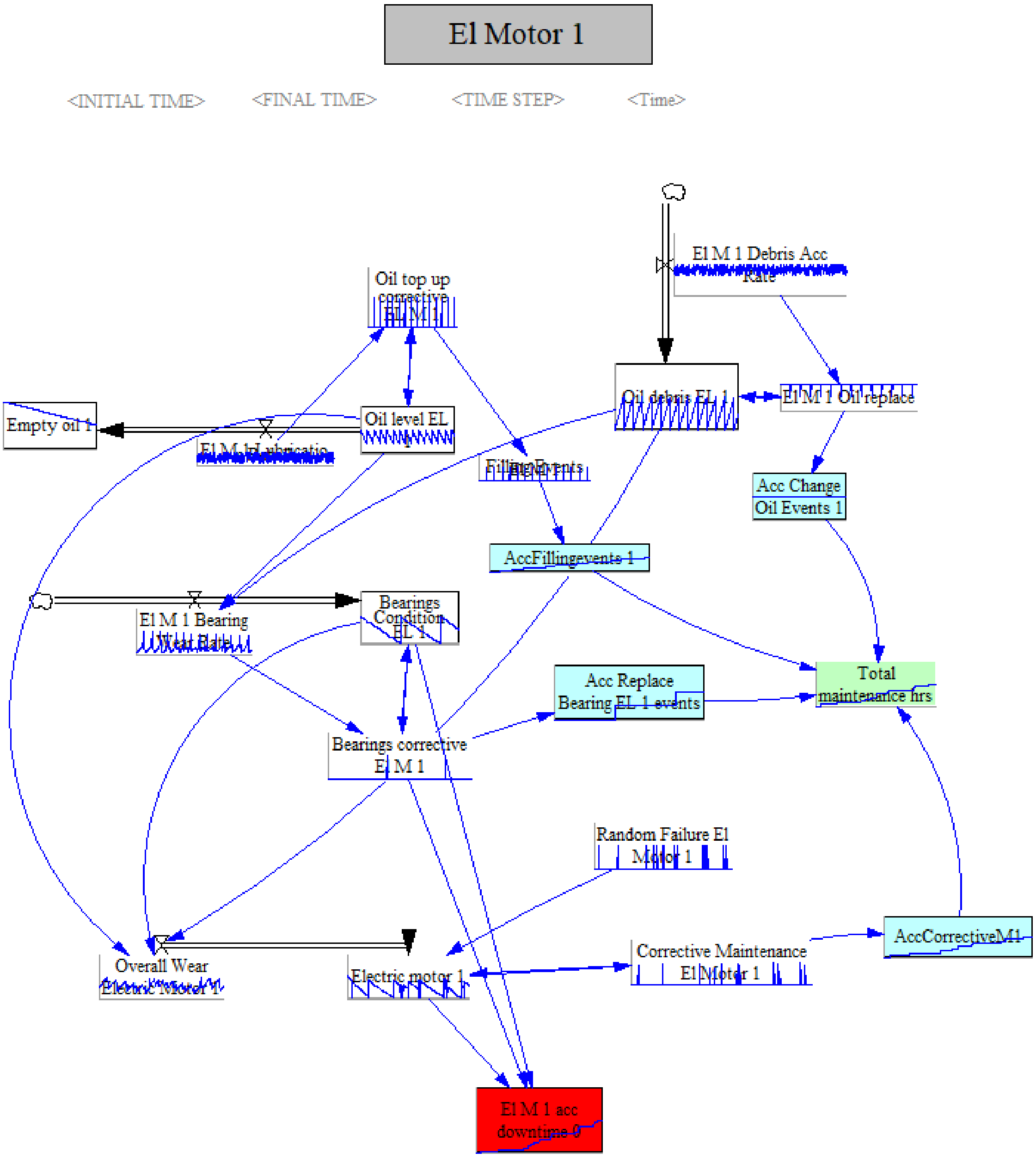


Figure 5.5 A snapshot of the electric motor in Vensim. Each variable, rate and level are explained in appendix E.

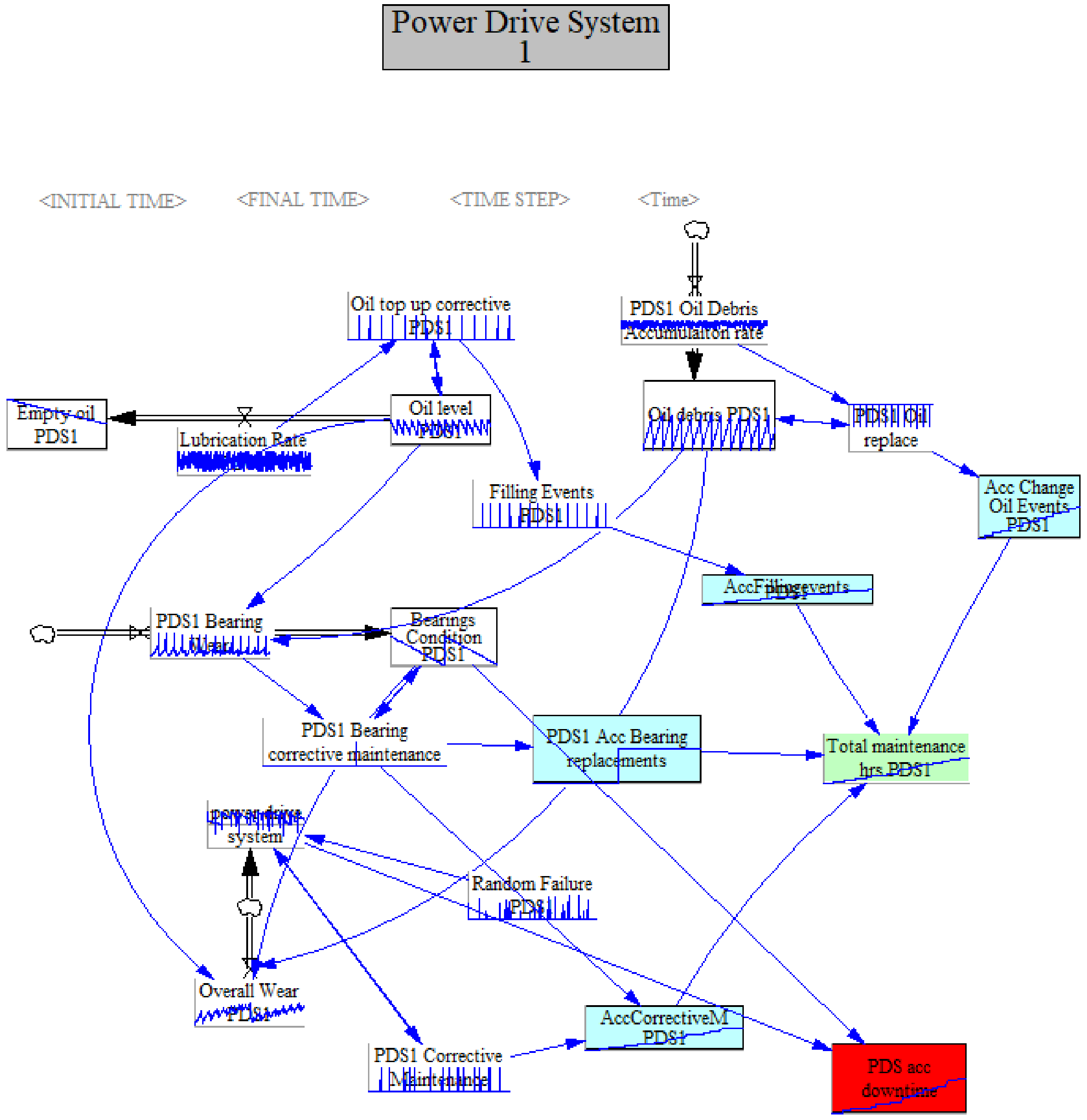


Figure 5.6 A snapshot of the power drive system in Vensim. Each variable, rate and level are explained in appendix F.

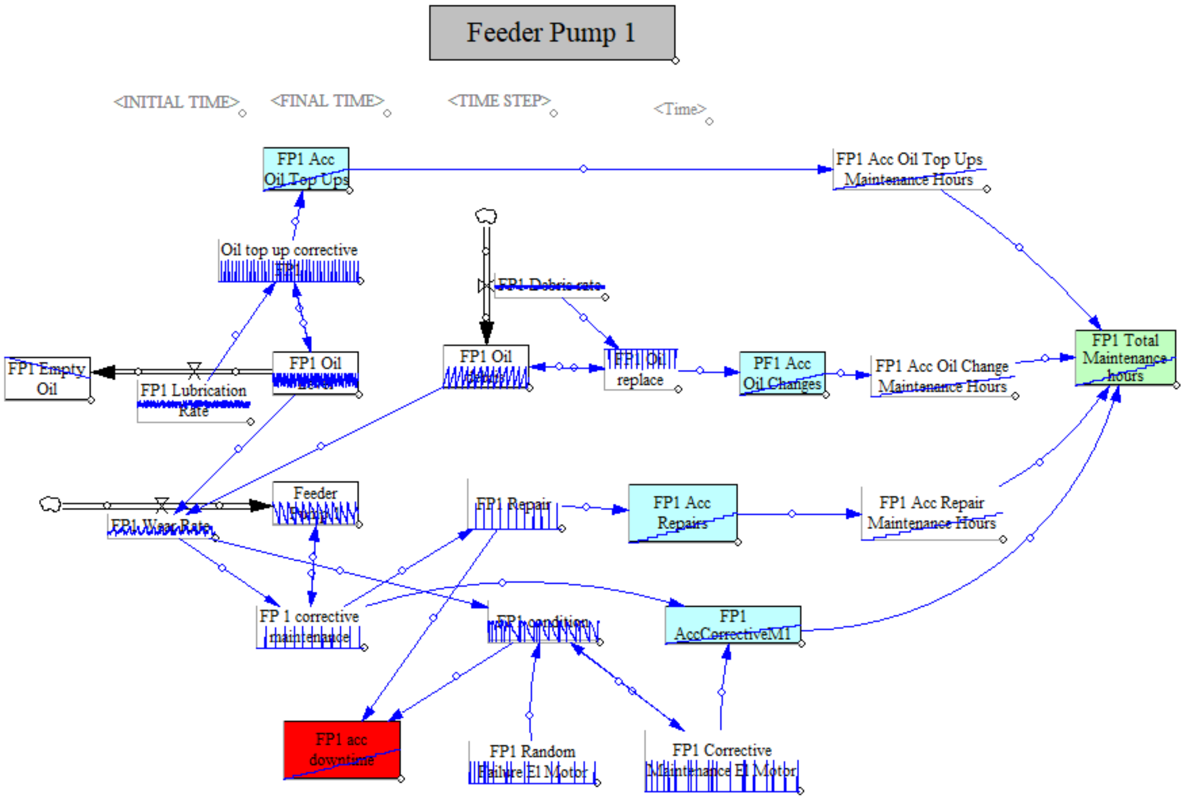


Figure 5.7 A snapshot of the feeder pump in Vensim. Each variable, rate and level are explained in appendix G.

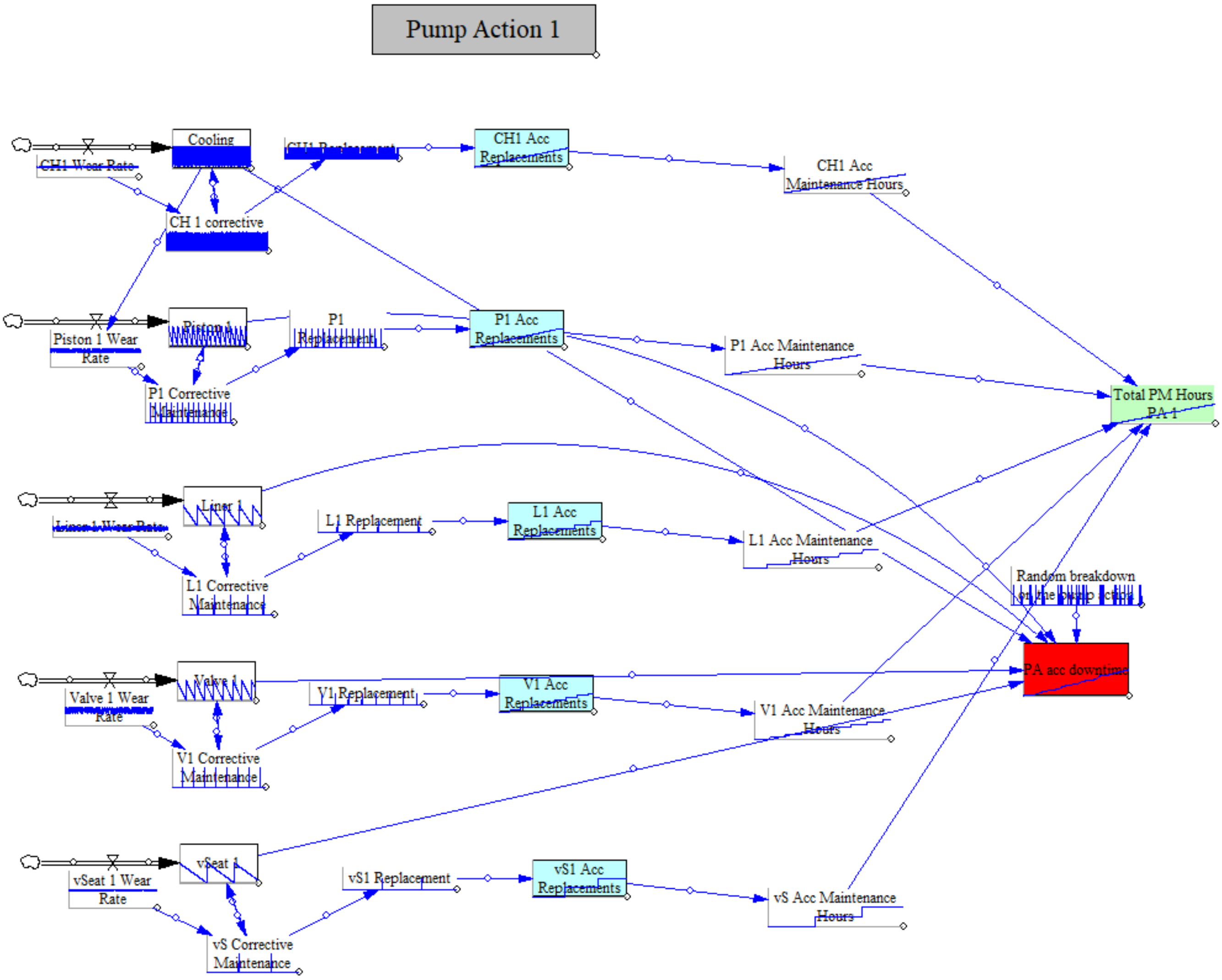


Figure 5.8 A snapshot of the pump action in Vensim. Each variable, rate and level are explained in appendix H.

5.3 The condition-based maintenance scenario

The setup of the CBM scenario is shown in Table 5.3. This scenario uses monitoring to determine the condition of the parts and components and maintenance is then performed as needed. The key element in the CBM scenario is to use information regarding other parts when performing maintenance. For instance, if the condition of any other parts in the pump action is low when maintenance is performed on a given part, then maintenance will be done to other parts as well. This reduced the total amount of maintenance hours done in order to keep the equipment in a functional condition.

Table 5.3 Vensim system for the CBM scenario.

Sub-system	**Figure**	**Table**
Electric motor	Figure 5.9	Appendix I
Power drive system	Figure 5.10	Appendix J
Feeder pump	Figure 5.11	Appendix K
Pump action	Figure 5.12	Appendix L

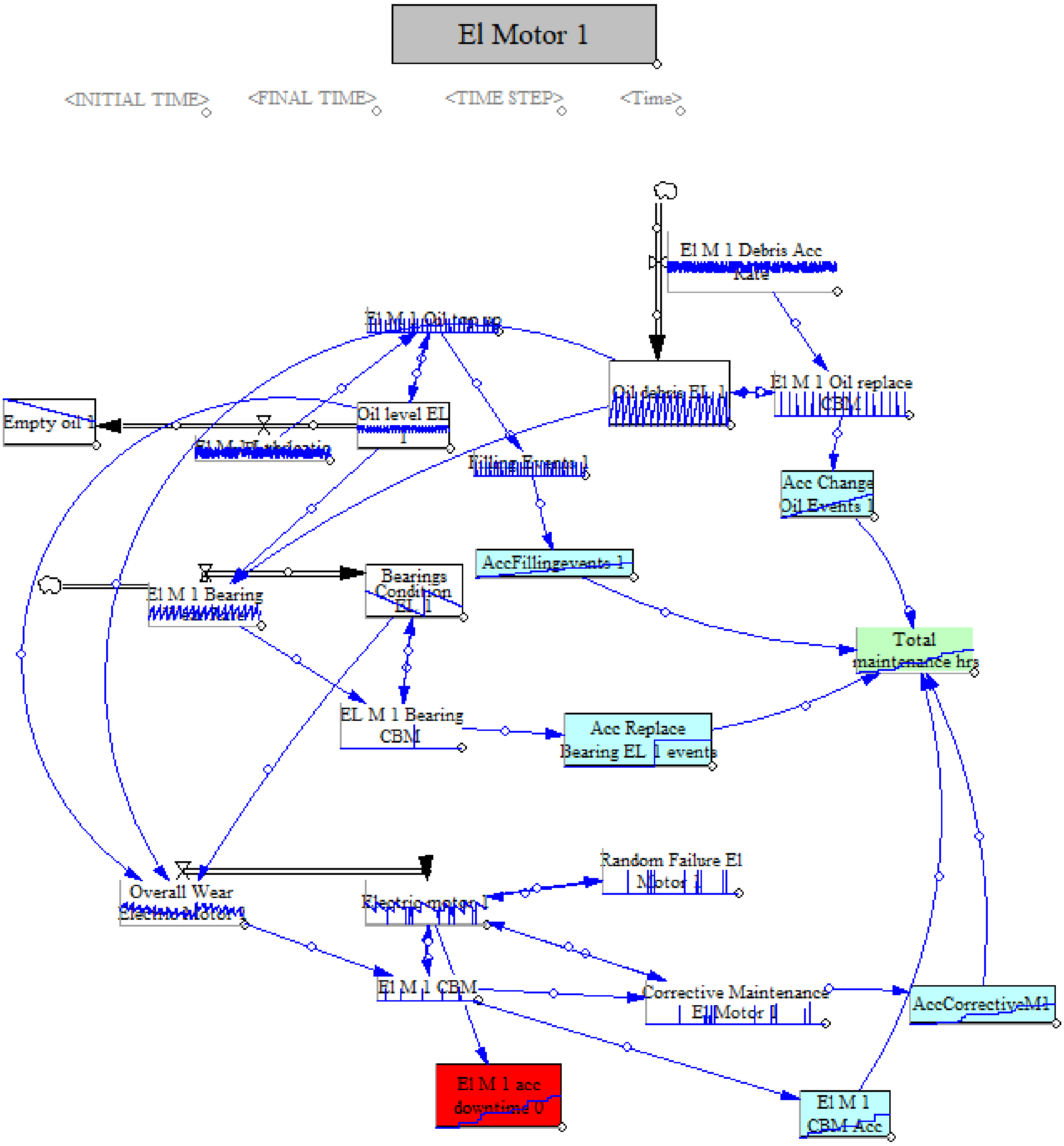


Figure 5.9 A snapshot of the electric motor in Vensim. Each variable, rate and level are explained in appendix I.

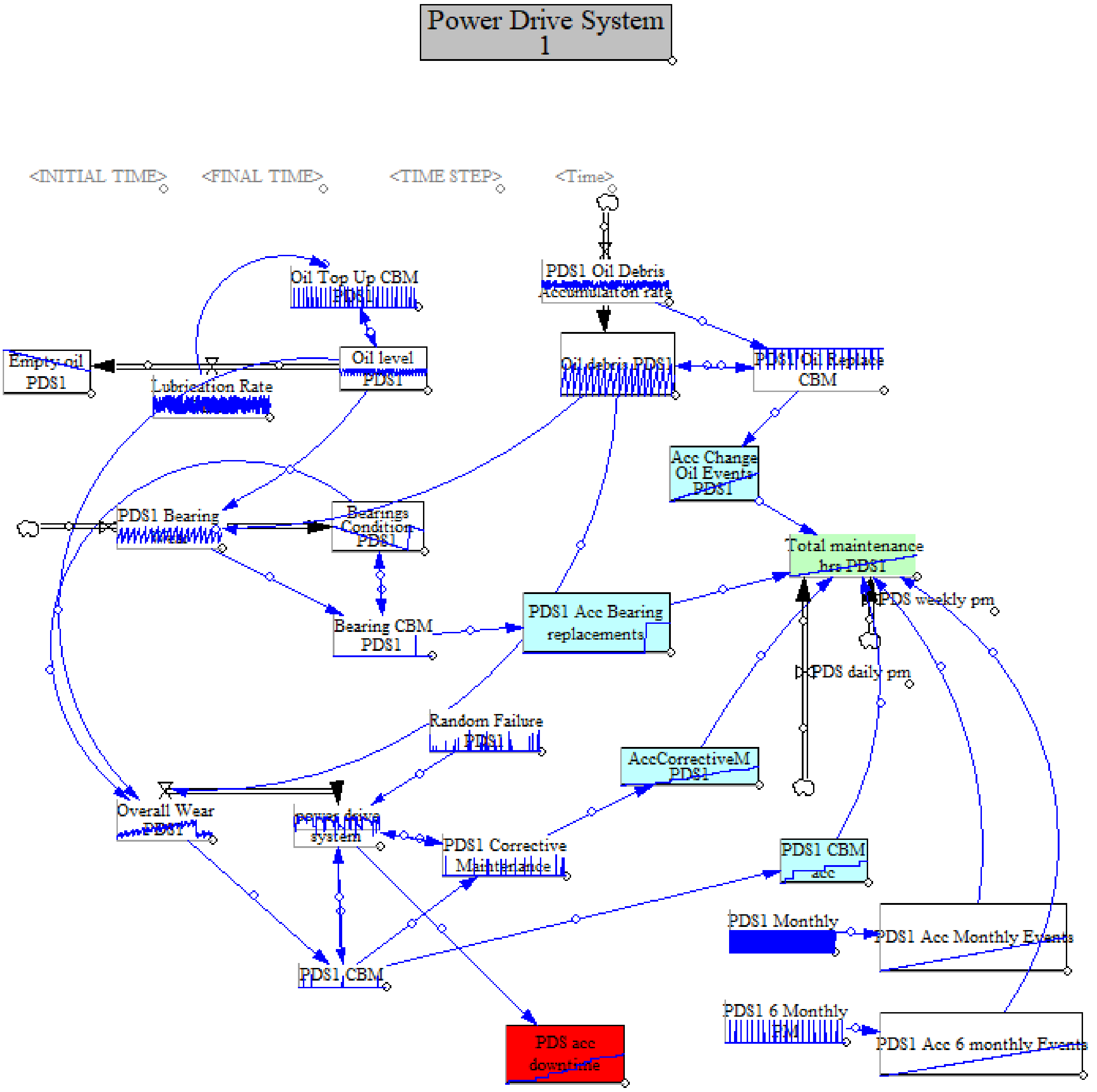


Figure 5.10 A snapshot of the power drive system in Vensim. Each variable, rate and level are explained in appendix J.

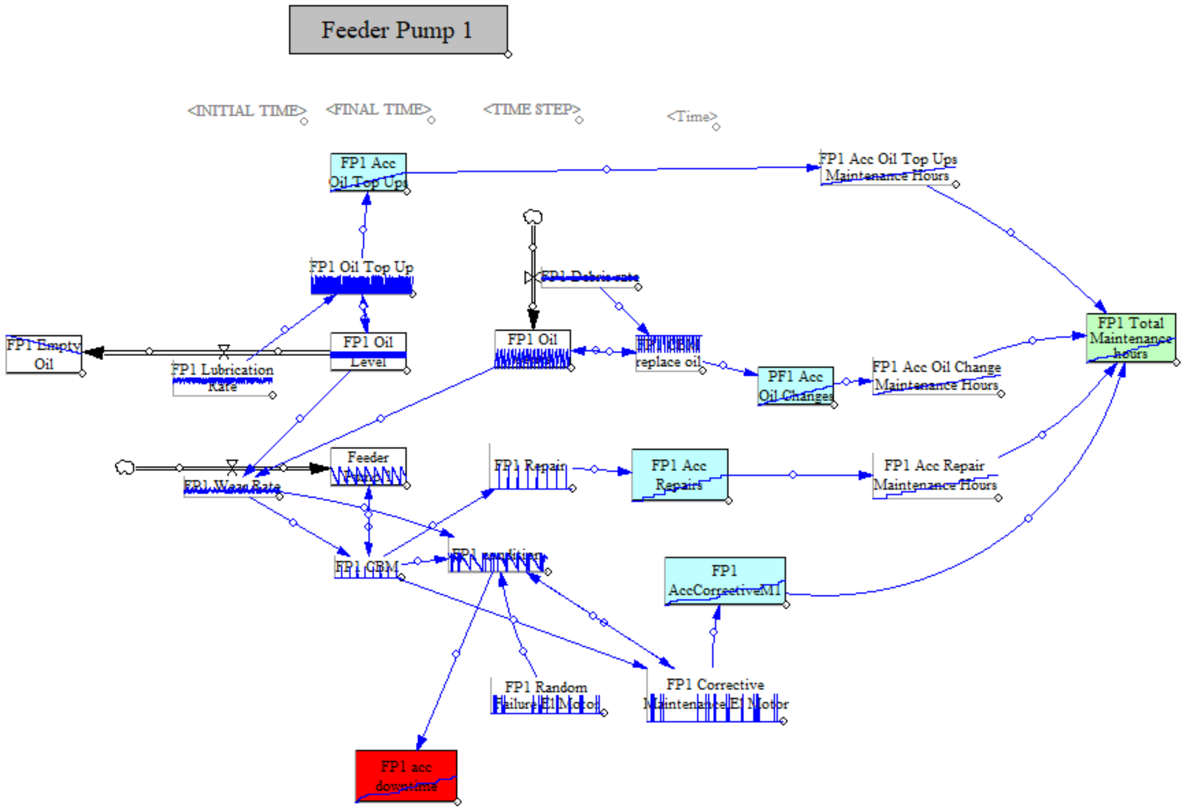


Figure 5.11 A snapshot of the feeder pump in Vensim. Each variable, rate and level are explained in appendix K.

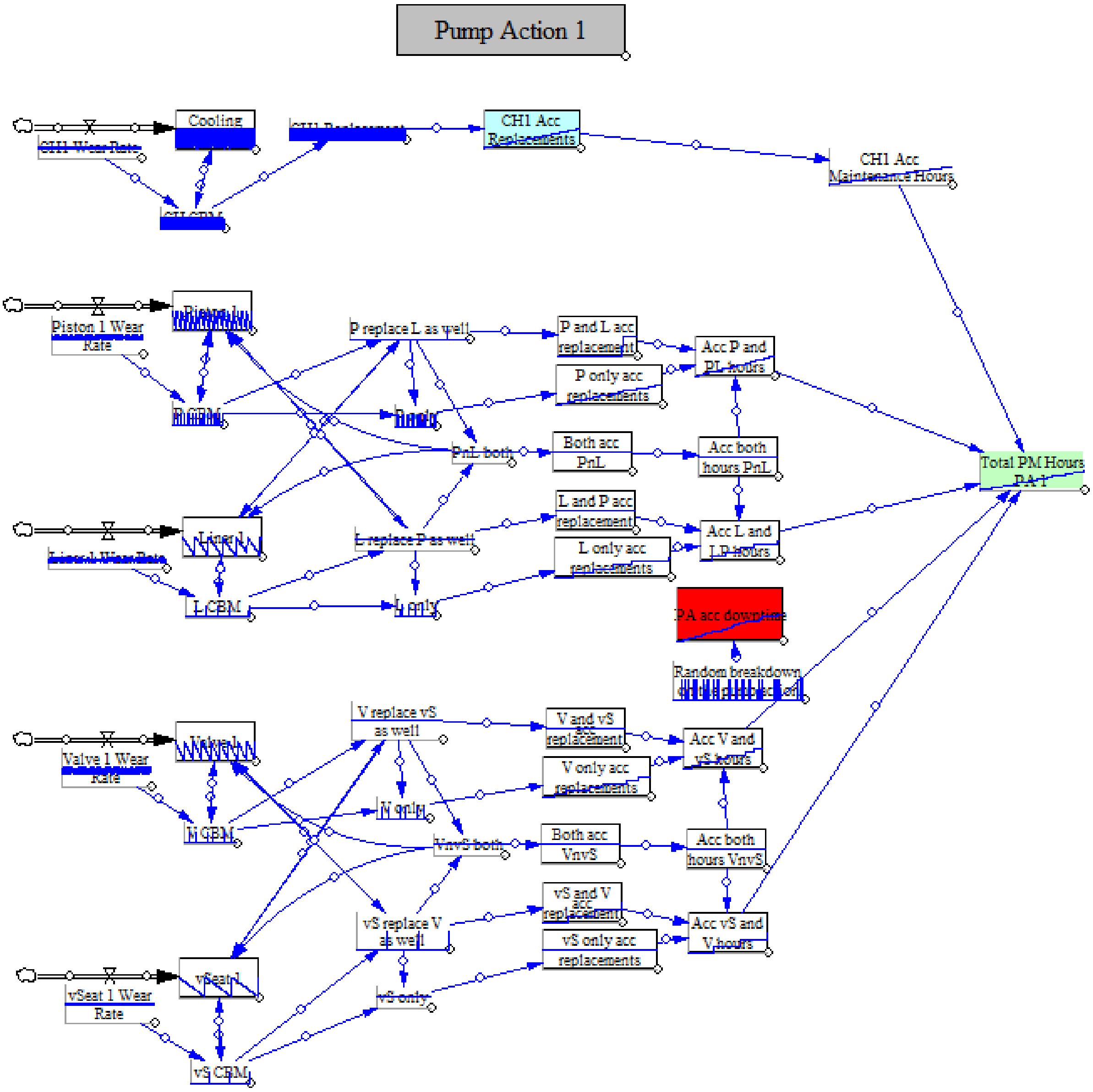


Figure 5.12 A snapshot of the pump action in Vensim. Each variable, rate and level are explained in appendix L.

5.4 PM strategy scenario results.

The total downtime hours are 524 hours and the total amount of maintenance hours used is 7016 hours. This is shown in Figure 5.13 and Figure 5.14 respectively. The numbers come from combining the data from the electric motor, power drive system, feeder pump and the pump action in the PM strategy scenario.

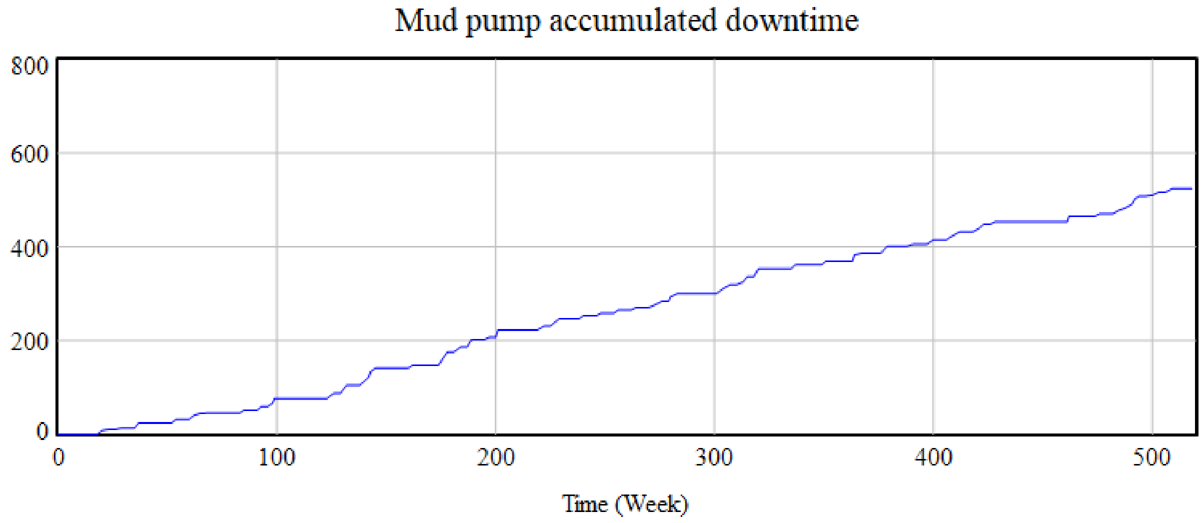


Figure 5.13 The accumulated amount of downtime hours (y-axis) on the mud pump for the PM strategy scenario.

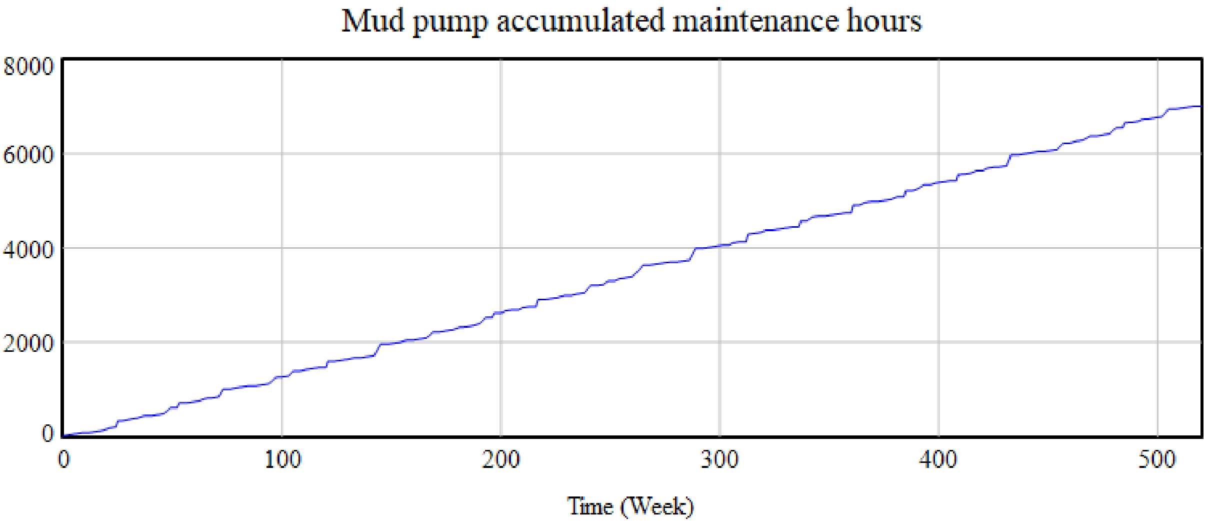


Figure 5.14 The accumulated amount of maintenance hours (y-axis) on the mud pump for the PM strategy scenario.

5.5 Corrective maintenance strategy scenario results.

The total downtime hours are 1363 hours and the total amount of maintenance hours used is 4887 hours. This is shown in Figure 5.15 and Figure 5.16 respectively. The numbers come from combining the data from the electric motor, power drive system, feeder pump and the pump action in the corrective maintenance strategy scenario.

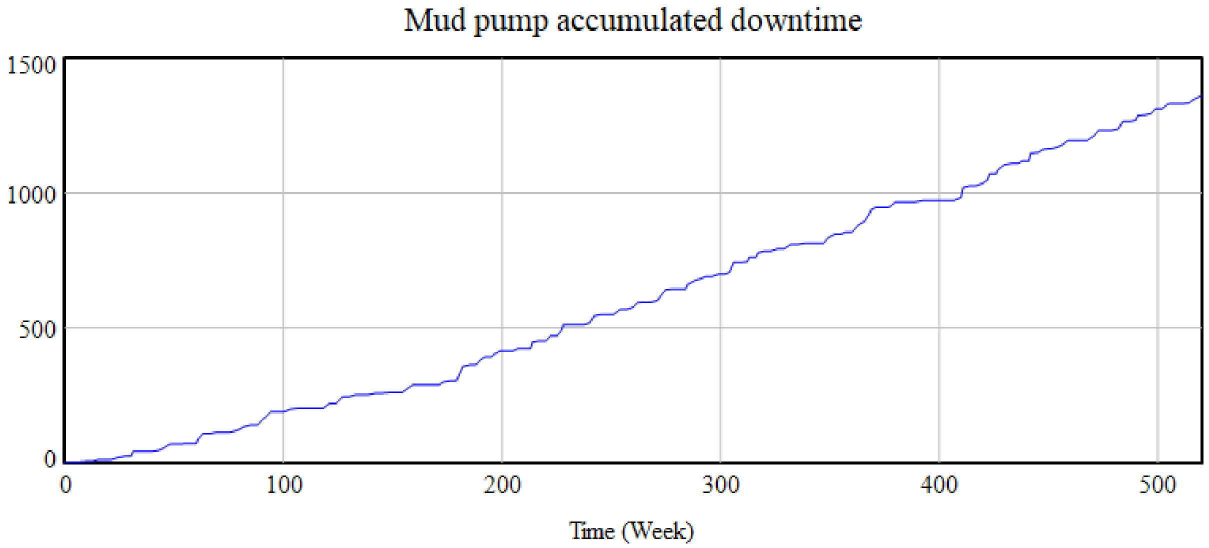


Figure 5.15 The accumulated amount of downtime hours (y-axis) on the mud pump for the corrective maintenance strategy scenario.

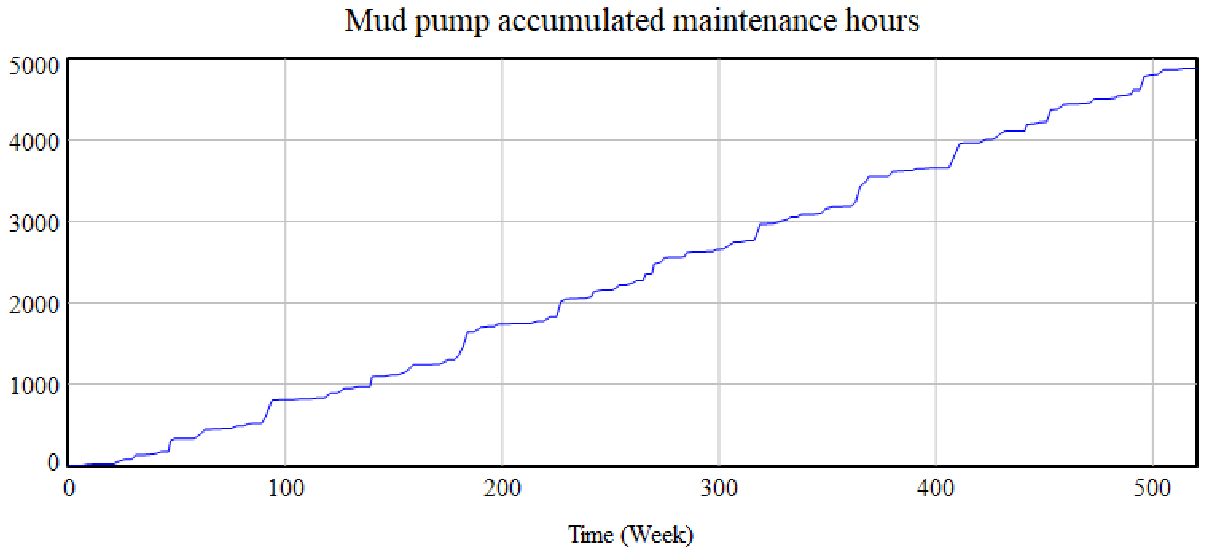


Figure 5.16 The accumulated amount of maintenance hours (y-axis) on the mud pump for the corrective maintenance strategy scenario.

5.6 Condition based maintenance strategy scenario results.

The total downtime hours are 577 hours and the total amount of maintenance hours used is 6247 hours. This is shown in Figure 5.17 and Figure 5.18 respectively. The numbers come from combining the data from the electric motor, power drive system, feeder pump and the pump action in CBM strategy scenario.

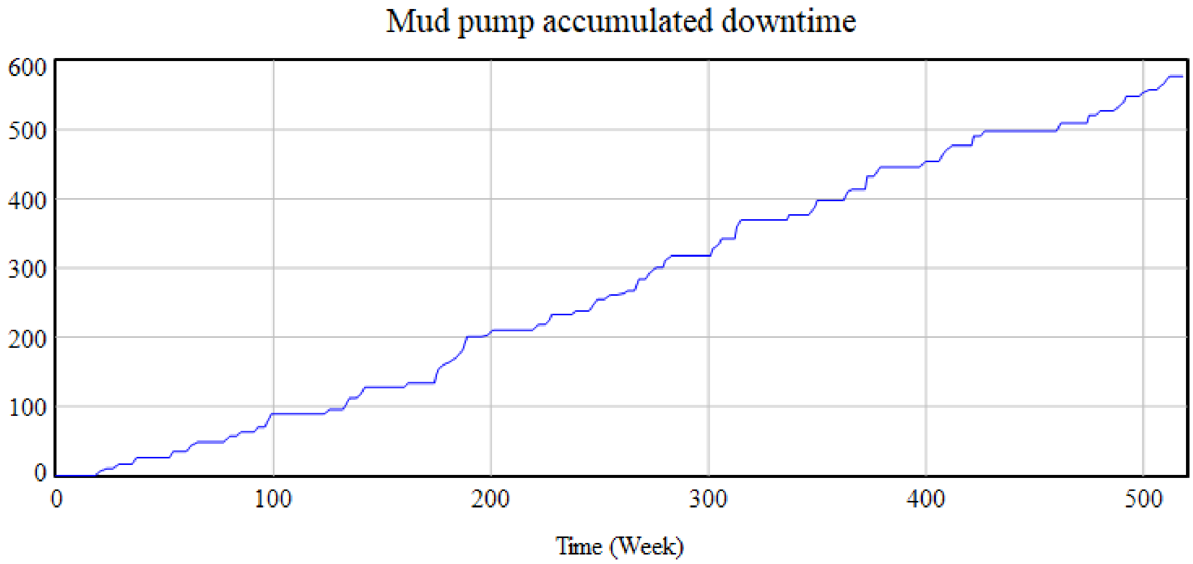


Figure 5.17 The accumulated amount of downtime hours (y-axis) on the mud pump for the CBM strategy scenario.

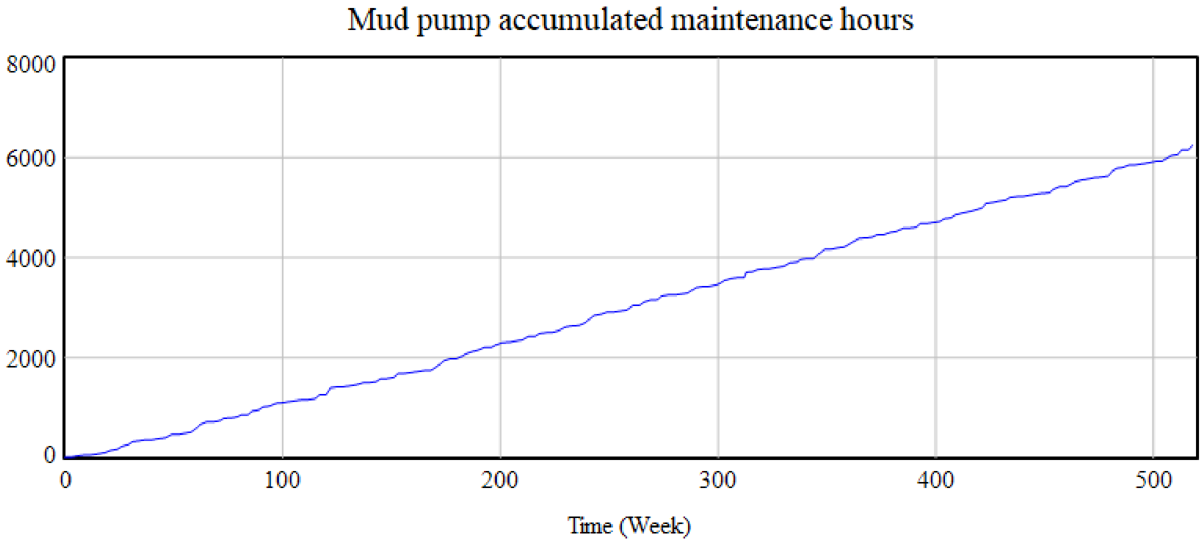


Figure 5.18 The accumulated amount of maintenance hours (y-axis) on the mud pump for the CBM strategy scenario.

6 Discussion and conclusion

Chapter six contains a discussion and the conclusion of the results of the simulations and how realistic the dynamic model is. Future work describes how the model can be enhanced, consequently increasing the value of the simulations. Further, the usefulness of the results is discussed in light of the decision maker and how these results are applicable for other fields than the selected system.

6.1 Discussion

The three strategies simulated in this thesis provides reference points useful for a decision maker when compiling a maintenance strategy. A simulation will never give 100% realistic results, and the results should therefore be used with caution.

Choosing the optimal maintenance strategy depends on the market situation. The decision maker must weigh the price of downtime against cost of maintenance carefully before choosing a strategy. The price for downtime in the drilling facility varies as drilling rig rates varies from 100k to 600k USD per day depending on the supply and demand of drilling rigs (Oljedirektoratet, 2014). The price of helicopter tickets, accommodation and salary to the maintenance operator is the counterweight to downtime costs. Downtime in the oil industry may be more costly than in other industries, therefore the decision maker must consider the current situation in his industry when creating a maintenance plan and/or program.

The dynamic model simulated in Vensim is a non-casual model and should only be used for a prediction purpose, as it only works within a certain range of values for the variables (Barlas and Carpenter, 1990). Barlas and Carpenter (1990) states that: "*If the theory T is true, then the conclusion C follows... ...But the verifying argument "C is observed, therefore T is true" is logically incorrect, since in reality C may occur as a result of a process different from the one hypothesized in T."* More variables could be added to the system, however, it is plausible that more variables would make the model more unrealistic as many variables may correlate in an unknown way.

The use of fault trees, FMECA and process diagrams for establishing a maintenance program should be implemented and used by any company seeking long-term gains. Calculating expected lifetimes and wear-rates for a system and simulating it using dynamic modelling will provide useful data for the decision maker regarding cost-effective solutions for the operation.

This thesis has focused on the maintenance strategies and not the system which has been simulated. The data provided is thus useful for other systems as well. Correct use of maintenance programs on parts will drive costs down and lifetime up by utilizing ordinary hours and minimizing downtime and overtime hours used. The use of a rented workforce to aid in short term maintenance programs to avoid overtime hours and minimizing downtime has not been included in this thesis but should be included for any decision maker when considering maintenance programs or major maintenance events.

Storage facilities and strategies are not included in the thesis and is therefore not linked to the maintenance strategies. The demand for stored reserve equipment and spare parts depends on the chosen maintenance strategy. This is key for future work on the model.

Only one set of parts have been considered in the simulation, whereas there are thousands of different qualities on the components that make up the system. One example of this is as the operation and maintenance operator stated in the interview, that the wrong type of piston for an operation can last only 50 hours, whereas a correct type with high quality lasts up to 6000 hours. The model would be improved by running several simulations using parts with different qualities to map cost of equipment versus quality and lifetime. This is potential for future work.

An increase in types of strategies simulated will yield more results which will increase the quality of the data. This thesis has only used three maintenance scenarios where each scenario has focused on one main strategy, being either corrective maintenance, PM or CBM. The author would like to run more simulations on maintenance strategies, but this would however require the need for a longer duration for the project. Creating maintenance strategies which combines the three main maintenance types will show a broader spectrum of results, thus increasing the overall efficiency of the best outcome from the maintenance programs.

6.2 Future work

The dynamic model created for this thesis does only consider the critical parts used in circulation in a drilling operation. A complete model involving all machinery, parts and components will without doubt create a better model. In depth details on each part would pinpoint bottlenecks in machinery reliability. For instance, expanding the PDS to all the parts that makes up the PDS provides more components to work with. Each of these parts will then have an associated wear-rate and follow recommended maintenance plans in order to create an enhanced model. Simulating a dynamic model involving the entire drilling system where each part has more in-depth details and simulating a larger variety of strategies with a combination of corrective maintenance, CBM, PM and include reliability centered maintenance will provide more accurate outcomes. In addition to this, the storage facility could be linked to each of these strategies for a greater extent in depth of cost investigation.

6.3 Conclusion

The outcome of the different scenarios is listed in Table 6.1. The corrective maintenance scenario has the lowest amount of maintenance hours used, however, it also has the highest amount of downtime hours. The CBM scenario requires 11% less maintenance hours than the PM scenario, but has 10% more downtime hours. The reason for CBM having more downtime hours has to do with a higher frequency of random breakdowns. The corrective maintenance scenario has 30% less maintenance hours used but has 160% more downtime compared to the PM scenario.

Table 6.1 Simulation results.

Scenario	Downtime hours	Maintenance hours used
PM	524	7016
Corrective maintenance	1363	4887
CBM	577	6247

The research question was *"How can maintenance expenses be kept to a minimum without compromising productivity?"* This is achieved by implementing CBM, continuously documenting equipment states, failure rates, lifetime, maintenance work done and by updating the maintenance plans and programs. Documentation allows for data to be used in statistics to further enhance the maintenance plans and programs. Improved simulations provide more accurate results, and a larger variety of simulations creates a broader spectrum of possible outcomes, allowing for best case and worst-case scenarios to be mapped. This will result in achieving the thesis's main goals, which were to (1) reduce downtime, (2) reduce redundant maintenance, (3) keep equipment in an up-state, (4) prevent wear-out-failure and (5) enlighten the decision maker in an economical view of the situation regarding maintenance strategy.

The value of the thesis is highly dependable on the reader. Information is useful for decision maker and leaders when compiling a maintenance program. It is not very useful for the personnel which operates and maintains the equipment as they merely follow a weekly maintenance plan provided by the maintenance supervisor. This thesis should make the reader question the quality of the parts used in their own system as for the lifetime, availability and reliability that comes with the associated parts. By researching and using equipment with a proven track of record which has a documented lifetime under similar working conditions is fundamental when it comes to choosing the correct equipment for the job. Cheap equipment is usually only inexpensive in a short-term perspective and becomes costly when it starts to fail as low-quality products tend to reach the wear-out phase on the bathtub model in a shorter period of time. Each system and sub-system should have a maintenance program which reflects its criticality on either the environment, operation or safety. Therefore, the maintenance strategy should be a mix of corrective maintenance, PM and CBM as the decision maker sees fit.

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Appendix A

In depth information of each variable, rate and level in the electric motor shown in Figure 5.1.

Electric Motor			
Name	**Type**	**Equation**	**Initial Value** (Levels only)
El M 1 Time between Oil Top Ups	Constant	4	
El M 1 Oil Top Up PM	Rate	IF THEN ELSE (modulo (Time , El M 1 Time between Oil Top Ups) = 0 , ((RANDOM UNIFORM(9.5, 10, 0))-Oil level EL 1)+El M 1 Lubrication Rate 1 , 0) / TIME STEP	
Oil level EL 1	Level	-El M 1 Lubrication Rate 1+El M 1 Oil Top Up PM	10
El M 1 Lubrication Rate 1	Rate	RANDOM UNIFORM(0.05, 0.3, 0)	
Empty oil 1	Level	-El M 1 Lubrication Rate 1	0
Filling Events 1	Variable	IF THEN ELSE(El M 1 Oil Top Up PM>0, 1, 0)	
AccFillingevents 1	Level	IF THEN ELSE(Filling Events 1>0, 1, 0)	0
El M 1 Time between oil change events	Constant	26	
El M 1 Oil change PM	Rate	IF THEN ELSE(modulo(Time, El M 1 Time between oil change events)=0, Oil debris EL 1+El M 1 Debris Acc Rate, 0)	
Oil debris EL 1	Level	El M 1 Debris Acc Rate-El M 1 Oil change PM	0
El M 1 Debris Acc Rate	Rate	0.2143+RANDOM UNIFORM(-0.05, 0.05, 0)	
Acc Change Oil Events 1	Level	IF THEN ELSE(El M 1 Oil change PM>0, 1, 0)	0

El M 1 Time between bearing replacements	Constant	260	
El M 1 Preventive Maintenance	Rate	IF THEN ELSE (modulo (Time , El M 1 Time between bearing replacements) = 0 , ((RANDOM UNIFORM(9.5, 10, 0))-Bearings Condition EL 1)+El M 1 Bearing Wear Rate , 0) / TIME STEP	
Bearings Condition EL 1	Level	El M 1 Preventive Maintenance-El M 1 Bearing Wear Rate	0
El M 1 Bearing Wear Rate	Rate	0.015+Oil debris EL 1*0.005+IF THEN ELSE(Oil level EL 1<4, 0.1, 0)+IF THEN ELSE(Oil level EL 1< 5, 0.02, 0)+IF THEN ELSE(Oil level EL 1<6, 0.012, 0)+IF THEN ELSE(Oil level EL 1<7, 0.005, 0)	
Acc Replace Bearing EL 1 events	Level	IF THEN ELSE(El M 1 Preventive Maintenance>0, 1, 0)	0
El M 1 Time between PM event	Constant	24	
El M 1 PM	Rate	IF THEN ELSE (modulo (Time , El M 1 Time between PM event) = 0 , ((RANDOM UNIFORM(9.5, 10, 0))-Electric motor 1)+Overall Wear Electric Motor 1 , 0) / TIME STEP	
Electric motor 1	Level	(-Overall Wear Electric Motor 1-Electric motor 1*0.001)-(IF THEN ELSE(Random Failure El Motor 1>0, Electric motor 1 , 0))+Corrective Maintenance El Motor 1+El M 1 PM	10
Overall Wear Electric Motor 1	Rate	0.0173+Oil debris EL 1*0.005+Bearings Condition EL 1*0.005+(10-Oil level EL 1)*0.005	
Random Failure El Motor 1	Variable	PULSE TRAIN(0, (1/7), RANDOM NORMAL(0, 10 , 5 , 1, 520), 520)	
Corrective Maintenance El Motor 1	Variable	IF THEN ELSE(Electric motor 1<=0, RANDOM NORMAL(5, 10, 8, 1, 1), 0)	
AccCorrectiveM1	Variable	IF THEN ELSE(Corrective Maintenance El Motor 1>0, 1, 0)*RANDOM UNIFORM(0.5, 12, 1)	
Acc PM El M 1	Level	IF THEN ELSE(El M 1 PM>0, 1, 0)*RANDOM UNIFORM(4, 8, 0)	0
El M 1 acc downtime 0	Level	IF THEN ELSE(Electric motor 1<=0, 1, 0)*RANDOM NORMAL(1, 48, 12, 5, 0)	0
Total maintenance hrs	Variable	0.5*Acc Change Oil Events 1+6*Acc Replace Bearing EL 1 events+0.25*AccFillingevents 1+AccCorrectiveM1+Acc PM El M 1	

Appendix B

In depth information of each variable, rate and level in the power drive system shown in Figure 5.2.

Power Drive System

Name	**Type**	**Equation**	**Initial Value** (Levels only)
PDS1 Daily Oil Level PM	Constant	1	
Oil level PDS1	Level	IF THEN ELSE(Oil level PDS1<6, RANDOM NORMAL(1.5, 4, 2.5, 1, 0)*PDS1 Daily Oil Level PM, 0)-Lubrication Rate PDS1	10
Lubrication Rate PDS1	Rate	RANDOM NORMAL(0.05, 0.3, 0.125, 1, 520)	
Empty oil PDS1	Level	-Lubrication Rate PDS1	0
PDS1 Time between bearing PM	Constant	260	
PDS1 Bearing PM	Rate	IF THEN ELSE (modulo (Time , PDS1 Time between bearing PM) = 0 , ((RANDOM UNIFORM(9.5, 10, 0))-Bearings Condition PDS1)+PDS1 Bearing Wear , 0) / TIME STEP	
Bearings Condition PDS1	Level	PDS1 Bearing PM-PDS1 Bearing Wear	10
PDS1 Bearing Wear	Rate	0.01+Oil debris PDS1*0.004+IF THEN ELSE(Oil level PDS1<4, 0.08, 0)+IF THEN ELSE(Oil level PDS1<5, 0.015, 0)+IF THEN ELSE(Oil level PDS1<6, 0.01, 0)+IF THEN ELSE(Oil level PDS1<7, 0.0035, 0)	
PDS1 Acc Bearing replacements	Level	IF THEN ELSE(PDS1 Bearing PM>0, 1, 0)	0
PDS1 Time Between PM event	Constant	36	
PDS 1 PM	Rate	(IF THEN ELSE (modulo (Time , PDS1 Time Between PM event) = 0 , ((RANDOM UNIFORM(9.5, 10, 0))-power drive system)+Overall Wear PDS1 , 0) / TIME STEP)*IF THEN ELSE(PDS1 Corrective Maintenance>0, 0, 1)	
power drive system	Level	-Overall Wear PDS1-power drive system*0.0005+IF THEN ELSE(PDS1 Corrective Maintenance>0, 10-power drive system+Overall Wear PDS1, 0)-Random Failure PDS1+PDS 1 PM	10

Overall Wear PDS1	Rate	0.00865+Oil debris PDS1*0.005+(10-Bearings Condition PDS1)*0.01+(10-Oil level PDS1)*0.005	
Random Failure PDS1	Variable	(PULSE TRAIN(0, 1, RANDOM NORMAL(0, 50, 25, 10, 0) , 520)*RANDOM UNIFORM(0, 10, 0))*IF THEN ELSE(power drive system>8.5, 0, 1)	
PDS1 Corrective Maintenance	Variable	IF THEN ELSE(power drive system<=0, RANDOM NORMAL(5, 10, 8, 1, 1), 0)	
PDS acc downtime	Level	IF THEN ELSE(power drive system<=0, 1, 0)*RANDOM NORMAL(0.15, 72, 10, 5, 0)	0
AccCorrectiveM PDS1	Level	IF THEN ELSE(PDS1 Corrective Maintenance>0, RANDOM NORMAL(5, 10, 8, 1, 1), 0)	0
Acc PM PDS1	Level	IF THEN ELSE(PDS 1 PM>0, 1, 0)*RANDOM UNIFORM(3, 12, 0)	0
PDS1 6 month PM	Variable	6*PULSE TRAIN(24, 1, 24, 520)	
PDS1 Monthly PM	Variable	6*PULSE TRAIN(4, 1, 4, 520)	
CS1 Acc 6 Monthly Events	Level	IF THEN ELSE(PDS1 6 month PM>0, 1, 0)	0
PDS1 Acc Monthly Events	Level	IF THEN ELSE(PDS1 Monthly PM>0, 1, 0)	0
PDS1 Daily PM rate	Rate	3.5	
PDS1 Weekly PM rate	Rate	1	
PDS1 Time between Oil change PM	Constant	26	
PDS1 Oil Change PM	Rate	IF THEN ELSE(modulo(Time, PDS1 Time between Oil change PM)=0, Oil debris PDS1+PDS1 Oil Debris Accumulaiton rate, 0)	
Oil debris PDS1	Level	PDS1 Oil Debris Accumulaiton rate-PDS1 Oil Change PM	0
PDS1 Oil Debris Accumulaiton rate	Rate	0.2143+RANDOM UNIFORM(-0.05, 0.05, 0)	
Acc Change Oil Events PDS1	Level	IF THEN ELSE(PDS1 Oil Change PM>0, 1, 0)	0
Total maintenance hrs PDS1	Variable	2*Acc Change Oil Events PDS1+12*CS1 Acc 6 Monthly Events+6*PDS1 Acc Monthly Events+PDS1 Daily PM rate+PDS1 Weekly PM rate +AccCorrectiveM PDS1+PDS1 Acc Bearing replacements*6+Acc PM PDS1	

Appendix C

In depth information of each variable, rate and level in the feeder pump shown in Figure 5.3.

Feeder pump

Name	**Type**	**Equation**	**Initial Value** (Levels only)
FP1 Time between top ups	Constant	4	
FP1 Oil Top Up	Rate	IF THEN ELSE (modulo (Time , FP1 Time between top ups) = 0 , ((RANDOM UNIFORM(9.5, 10, 0))-FP1 Oil Level)+FP1 Lubrication Rate , 0) / TIME STEP	
FP1 Oil Level	Level	-FP1 Lubrication Rate+FP1 Oil Top Up	10
FP1 Lubrication Rate	Rate	RANDOM UNIFORM(0.4, 0.6 , 0)	
FP1 Empty Oil	Level	-FP1 Lubrication Rate	0
FP1 Acc Oil Top Ups	Level	IF THEN ELSE(FP1 Oil Top Up>0, 1, 0)	0
FP1 Acc Oil Top Ups Maintenance Hours	Variable	FP1 Acc Oil Top Ups*0.25	
FP1 Time between PM events	Constant	52	
FP1 Preventive Maintenance	Rate	IF THEN ELSE (modulo (Time , FP1 Time between PM events) = 0 , ((RANDOM UNIFORM(9.5, 10, 0))-Feeder Pump 1)+FP1 Wear Rate , 0) / TIME STEP	
Feeder Pump 1	Level	-FP1 Wear Rate+FP1 Preventive Maintenance	10
FP1 Wear Rate	Rate	RANDOM UNIFORM(0.081, 0.141, 0)+IF THEN ELSE(FP1 Oil Level<9, 0.02, 0)+IF THEN ELSE(FP1 Oil Level<8, 0.03, 0)+IF THEN ELSE(FP1 Oil debris>1, 0.005, 0)+IF THEN ELSE(FP1 Oil debris>2, 0.01, 0)+IF THEN ELSE(FP1 Oil debris>3, 0.02, 0)+IF THEN ELSE(FP1 Oil debris>4, 0.03, 0)+IF THEN ELSE(FP1 Oil debris>5, 0.05, 0)+IF THEN	

		ELSE(FP1 Oil debris>6, 0.08, 0)+IF THEN ELSE(FP1 Oil debris>7, 0.01, 0)+IF THEN ELSE(FP1 Oil debris>8, 0.015, 0)+IF THEN ELSE(FP1 Oil debris>9, 0.025, 0)	
FP1 condition	Level	-(FP1 Wear Rate+(10-FP1 condition)*0.001)+IF THEN ELSE(FP1 Preventive Maintenance>0, 10-FP1 condition, 0)+FP1 Corrective Maintenance El Motor-IF THEN ELSE(FP1 Random Failure El Motor>0, FP1 condition, 0)	10
FP1 acc downtime	Level	IF THEN ELSE(FP1 condition<=0, 1, 0)*RANDOM NORMAL(0.15, 24, 4, 2, 0)	0
FP1 Random Failure El Motor	Variable	PULSE TRAIN(0, (1/7), RANDOM NORMAL(0, 10 , 5 , 1, 520), 520)	
FP1 Corrective Maintenance El Motor	Variable	IF THEN ELSE(FP1 condition<=0, 10-FP1 condition, 0)*IF THEN ELSE(FP1 Preventive Maintenance>0, 0, 1)	
FP1 AccCorrectiveM1	Level	IF THEN ELSE(FP1 Corrective Maintenance El Motor>0, 1, 0)*RANDOM UNIFORM(0.5, 12, 1)	0
FP1 Repair	Variable	IF THEN ELSE(FP1 Preventive Maintenance>0, 1, 0)	
FP1 Acc Repairs	Level	FP1 Repair	0
FP1 Acc Repair Maintenance Hours	Variable	FP1 Acc Repairs*6	
FP1 Time between oil changes	Constant	26	
FP1 Oil change events	Rate	IF THEN ELSE(modulo(Time, FP1 Time between oil changes)=0, FP1 Oil debris+FP1 Debris rate, 0)	
FP1 Oil debris	Level	FP1 Debris rate-FP1 Oil change events	0
FP1 Debris rate	Rate	RANDOM UNIFORM(0.18, 0.25, 0)	
PF1 Acc Oil Changes	Level	IF THEN ELSE(FP1 Oil change events>0, 1, 0)	0
FP1 Acc Oil Change Maintenance Hours	Variable	PF1 Acc Oil Changes*0.5	
FP1 Total Maintenance hours	Variable	FP1 Acc Oil Change Maintenance Hours+FP1 Acc Oil Top Ups Maintenance Hours+FP1 Acc Repair Maintenance Hours+FP1 AccCorrectiveM1	

Appendix D

In depth information of each variable, rate and level in the pump action shown in Figure 5.4.

Pump action			
Name	**Type**	**Equation**	**Initial Value** (Levels only)
Time 1 0	Rate	1	
CH1 Time until next maintenance event	Level	-Time 1 0+IF THEN ELSE(CH1 Preventive Maintenance>0, 4-CH1 Time until next maintenance event, 0)	4
CH1 Preventive Maintenance	Rate	IF THEN ELSE(CH1 Time until next maintenance event=0, (10-Cooling Hose 1)+CH1 Wear Rate , 0)	
Cooling Hose 1	Level	-CH1 Wear Rate+CH1 Preventive Maintenance	10
CH1 Wear Rate	Rate	RANDOM UNIFORM(1.75, 2.25, 0)	
CH1 Replacement	Variable	IF THEN ELSE(CH1 Preventive Maintenance>0, 1, 0)	
CH1 Acc Replacements	Level	IF THEN ELSE(CH1 Replacement>0, 1, 0)	0
CH1 Acc Maintenance Hours	Variable	CH1 Acc Replacements*0.25	
Time 1 0 0 0	Rate	1	
P1 Time until next maintenance event	Level	-Time 1 0 0 0+IF THEN ELSE(P1 Preventive Maintenance>0, 24- 0, 0)+IF THEN ELSE(PnL1 vS replace P as well>0, 24-P1 Time until next maintenance event , 0)	24
P1 Preventive Maintenance	Rate	IF THEN ELSE(P1 Time until next maintenance event=0, (10-Piston 1)+Piston 1 Wear Rate , 0)	
Piston 1	Level	-Piston 1 Wear Rate+P1 Preventive Maintenance+IF THEN ELSE(PnL1 vS replace P as well>0, (10-Piston 1)+Piston 1 Wear Rate, 0)	10
Piston 1 Wear Rate	Rate	RANDOM UNIFORM(0.283, 0.383, 0)	

Piston 1 Replacement	Variable	IF THEN ELSE(P1 Preventive Maintenance>0, 1, 0)	
PnL1 replace L as well	Variable	IF THEN ELSE(Piston 1 Replacement>0, 1, 0)*IF THEN ELSE(Liner 1<3, 1, 0)	
Piston 1 Only Acc Replacements	Level	IF THEN ELSE(Piston 1 Replacement>0, 1, 0)-IF THEN ELSE(PnL1 replace events>0, 1, 0)	0
P1 Only Acc Hours	Variable	6*Piston 1 Only Acc Replacements	
PnL1 at the same time	Variable	PnL1 replace L as well+PnL1 vS replace P as well	
PnL1 replace events	Variable	IF THEN ELSE(PnL1 at the same time>0, 1, 0)	
PnL1 Acc Replacements	Level	IF THEN ELSE(PnL1 replace events>0, 1, 0)	0
PnL1 Acc Hours	Variable	PnL1 Acc Replacements*7	
Time 1 0 0	Rate	1	
L1 Time until next maintenance event	Level	-Time 1 0 0+IF THEN ELSE(L1 Preventive Maintenance>0, 74-L1 Time until next maintenance event, 0)+IF THEN ELSE(PnL1 replace L as well>0, 74-L1 Time until next maintenance event, 0)	74
L1 Preventive Maintenance	Rate	IF THEN ELSE(L1 Time until next maintenance event=0, (10-Liner 1)+Liner 1 Wear Rate , 0)	
Liner 1	Level	-Liner 1 Wear Rate+L1 Preventive Maintenance+IF THEN ELSE(PnL1 replace L as well>0, (10-Liner 1)+Liner 1 Wear Rate, 0)	10
Liner 1 Wear Rate	Variable	RANDOM UNIFORM(0.081, 0.141, 0)	
Liner 1 Replacement	Variable	IF THEN ELSE(L1 Preventive Maintenance>0, 1, 0)	
PnL1 vS replace P as well	Variable	IF THEN ELSE(Liner 1 Replacement>0, 1, 0)*IF THEN ELSE(Piston 1>5, 0, 1)	
Liner 1 only Acc Replacements	Level	(IF THEN ELSE(Liner 1 Replacement>0, 1, 0)-IF THEN ELSE(PnL1 replace events>0, 1, 0))*MIN(Liner 1 Replacement, PnL1 replace events)	0
L1 Only Acc Hours	Variable	Liner 1 only Acc Replacements*6	

Time 1 0 0 1	Rate	1	
V1 Time until next maintenance event	Level	-Time 1 0 0 1+IF THEN ELSE(V1 Preventive Maintenance>0, 52-V1 Time until next maintenance event, 0)+IF THEN ELSE(VnvS1 vS replace V as well >0, 52-V1 Time until next maintenance event, 0)	52
V1 Preventive Maintenance	Rate	IF THEN ELSE(V1 Time until next maintenance event=0, (10-Valve 1)+Valve 1 Wear Rate , 0)+Time*TIME STEP*0	
Valve 1	Level	-Valve 1 Wear Rate+V1 Preventive Maintenance+IF THEN ELSE(VnvS1 vS replace V as well>0, (10-Valve 1)+Valve 1 Wear Rate, 0)	10
Valve 1 Wear Rate	Rate	RANDOM UNIFORM(0.127, 0.207, 0)	
Valve 1 Replacement	Variable	IF THEN ELSE(V1 Preventive Maintenance>0, 1, 0)	
Vns1 V replace vS as well	Variable	IF THEN ELSE(Valve 1 Replacement>0, 1, 0)*IF THEN ELSE(vSeat 1<3, 1, 0)	
Valve 1 Only Acc Replacements	Level	IF THEN ELSE(Valve 1 Replacement>0, 1, 0)-IF THEN ELSE(VnvS1 replace events>0, 1, 0)*MIN(Valve 1 Replacement, VnvS1 replace events)	0
V1 Only Acc Hours	Variable	6*Valve 1 Only Acc Replacements	
VnvS1 at the same time	Variable	Vns1 V replace vS as well+VnvS1 vS replace V as well	
VnvS1 replace events	Variable	IF THEN ELSE(VnvS1 at the same time>0, 1, 0)	
VnvS1 Acc Replacements	Level	IF THEN ELSE(VnvS1 replace events>0, 1, 0)	0
VnvS1 Acc Hours	Variable	VnvS1 Acc Replacements*7	
Time 1 0 0 1 0	Rate	1	
vS1 Time until next maintenance event	Level	-Time 1 0 0 1 0+IF THEN ELSE(vS1 Preventive Maintenance>0, 144-vS1 Time until next maintenance event, 0)+IF THEN ELSE(Vns1 V replace vS as well >0, 144-vS1 Time until next maintenance event, 0)	144
vS1 Preventive Maintenance	Rate	IF THEN ELSE(vS1 Time until next maintenance event=0, (10-vSeat 1)+vSeat 1 Wear Rate , 0)+Time*TIME STEP*0	

vSeat 1 Wear Rate	Rate	RANDOM UNIFORM(0.0526, 0.0586, 0)	
vSeat 1	Level	vS1 Preventive Maintenance-vSeat 1 Wear Rate+IF THEN ELSE(Vns1 V replace vS as well>0, (10-vSeat 1)+vSeat 1 Wear Rate, 0)	10
VnvS1 vS replace V as well	Variable	IF THEN ELSE(vSeat 1 Replacement>0, 1, 0)*IF THEN ELSE(Valve 1>5, 0, 1)	
vSeat 1 Replacement	Variable	IF THEN ELSE(vS1 Preventive Maintenance>0, 1, 0)	
vSeat 1 only Acc Replacements	Level	IF THEN ELSE(vSeat 1 Replacement>0, 1, 0)-IF THEN ELSE(VnvS1 replace events>0, 1, 0)*MIN(VnvS1 replace events, vSeat 1 Replacement)	0
vS1 Only Acc Hours	Variable	vSeat 1 only Acc Replacements*6	
Total PM Hours PA 1	Variable	(CH1 Acc Maintenance Hours+L1 Only Acc Hours+P1 Only Acc Hours+PnL1 Acc Hours+V1 Only Acc Hours+VnvS1 Acc Hours+vS1 Only Acc Hours)*3	
PA acc downtime	Level	IF THEN ELSE(Random breakdown on the pump action>0, RANDOM NORMAL(1, 24, 8, 2, 0), 0)	0
Random breakdown on the pump action	Variable	PULSE TRAIN(0, (1/7), RANDOM NORMAL(0, 15 , 5 , 3, 520), 520)	

Appendix E

In depth information of each variable, rate and level in the electric motor shown in Figure 5.5.

Electric Motor			
Name	**Type**	**Equation**	**Initial Value** (Levels only)
Oil top up corrective EL M 1	Rate	IF THEN ELSE(Oil level EL 1<=4, 10-Oil level EL 1+El M 1 Lubrication Rate 1, 0)	
Oil level EL 1	Level	-El M 1 Lubrication Rate 1+Oil top up corrective EL M 1	10
El M 1 Lubrication Rate 1	Variable	RANDOM UNIFORM(0.05, 0.3, 0)	
Empty oil 1	Level	-El M 1 Lubrication Rate 1	0
Filling Events El M 1	Variable	IF THEN ELSE(Oil top up corrective EL M 1>0, 1, 0)	
AccFillingevents 1	Level	IF THEN ELSE(Filling Events El M 1>0, 1, 0)	0
Bearings corrective El M 1	Variable	IF THEN ELSE(Bearings Condition EL 1<=0, 10-Bearings Condition EL 1+El M 1 Bearing Wear Rate, 0)	
Bearings Condition EL 1	Level	-El M 1 Bearing Wear Rate+Bearings corrective El M 1	10
El M 1 Bearing Wear Rate	Rate	0.015+Oil debris EL 1*0.005+IF THEN ELSE(Oil level EL 1<4, 0.1, 0)+IF THEN ELSE(Oil level EL 1< 5, 0.02, 0)+IF THEN ELSE(Oil level EL 1<6, 0.012, 0)+IF THEN ELSE(Oil level EL 1<7, 0.005, 0)	
Acc Replace Bearing EL 1 events	Level	IF THEN ELSE(Bearings corrective El M 1>0, 1, 0)	0
Electric motor 1	Level	(-Overall Wear Electric Motor 1-Electric motor 1*0.001)-(IF THEN ELSE(Random Failure El Motor 1>0, Electric motor 1, 0))+Corrective Maintenance El Motor 1	10
Overall Wear Electric Motor 1	Variable	0.0173+Oil debris EL 1*0.005+Bearings Condition EL 1*0.005+(10-Oil level EL 1)*0.005	

Random Failure El Motor 1	Variable	PULSE TRAIN(0, (1/7), RANDOM NORMAL(0, 10 , 5 , 1, 520), 520)	
Corrective Maintenance El Motor 1	Variable	IF THEN ELSE(Electric motor 1<=0, RANDOM NORMAL(5, 10, 8, 1, 1), 0)	
AccCorrectiveM1	Level	IF THEN ELSE(Corrective Maintenance El Motor 1>0, 1, 0)*RANDOM UNIFORM(0.5, 12, 1)	0
El M 1 Oil replace	Variable	IF THEN ELSE(Oil debris EL 1>8, 0-Oil debris EL 1-El M 1 Debris Acc Rate, 0)	
Oil debris EL 1	Level	El M 1 Debris Acc Rate+El M 1 Oil replace	0
El M 1 Debris Acc Rate	Variable	0.2143+RANDOM UNIFORM(-0.05, 0.05, 0)	
Acc Change Oil Events 1	Level	IF THEN ELSE(El M 1 Oil replace>0, 1, 0)	0
Total maintenance hrs	Variable	0.5*Acc Change Oil Events 1+6*Acc Replace Bearing EL 1 events+0.25*AccFillingevents 1+AccCorrectiveM1	

Appendix F

In depth information of each variable, rate and level in the power drive system shown in Figure 5.6.

Power Drive System			
Name	**Type**	**Equation**	**Initial Value** (Levels only)
Oil top up corrective PDS1	Variable	IF THEN ELSE(Oil level PDS1<=4, 10-Oil level PDS1+Lubrication Rate PDS1, 0)	
Oil level PDS1	Level	-Lubrication Rate PDS1+Oil top up corrective PDS1	10
Lubrication Rate PDS1	Rate	RANDOM NORMAL(0.05, 0.3, 0.125, 1, 520)	
Empty oil PDS1	Level	-Lubrication Rate PDS1	0
Filling Events PDS1	Variable	IF THEN ELSE(Oil top up corrective PDS1>0, 1, 0)	
AccFillingevents PDS1	Level	IF THEN ELSE(Filling Events PDS1>0, 1, 0)	0
PDS1 Bearing Wear	Variable	0.012+Oil debris PDS1*0.004+IF THEN ELSE(Oil level PDS1<4, 0.08, 0)+IF THEN ELSE(Oil level PDS1< 5, 0.015, 0)+IF THEN ELSE(Oil level PDS1<6, 0.01, 0)+IF THEN ELSE(Oil level PDS1<7, 0.0035, 0)	
Bearings Condition PDS1	Level	-PDS1 Bearing Wear+PDS1 Bearing corrective maintenance	10
PDS1 Bearing corrective maintenance	Variable	IF THEN ELSE(Bearings Condition PDS1<=0, 10-Bearings Condition PDS1+PDS1 Bearing Wear, 0)	
PDS1 Acc Bearing replacements	Level	IF THEN ELSE(PDS1 Bearing corrective maintenance>0, 1, 0)	0
power drive system	Level	-Overall Wear PDS1-power drive system*0.0005+IF THEN ELSE(PDS1 Corrective Maintenance>0, 10-power drive system+Overall Wear PDS1, 0)-Random Failure PDS1	10
Overall Wear PDS1	Variable	0.00865+Oil debris PDS1*0.006+(10-Bearings Condition PDS1)*0.01+(10-Oil level PDS1)*0.006	

Random Failure PDS1	Variable	PULSE TRAIN(0, 1, RANDOM NORMAL(0, 50, 25, 10, 0) , 520)*RANDOM UNIFORM(0, 10, 0)	
PDS1 Corrective Maintenance	Variable	IF THEN ELSE(power drive system<=0, 1, 0)	
AccCorrectiveM PDS1	Level	IF THEN ELSE(PDS1 Bearing corrective maintenance>0, 1, 0)*12+IF THEN ELSE(PDS1 Corrective Maintenance>0, RANDOM NORMAL(5, 10, 8, 1, 1), 0)	0
PDS acc downtime	Level	IF THEN ELSE(power drive system<=0, 1, 0)*RANDOM NORMAL(0.15, 72, 10, 5, 0)+IF THEN ELSE(Bearings Condition PDS1=0, 24, 0)	0
Oil debris PDS1	Level	PDS1 Oil Debris Accumulaiton rate+PDS1 Oil replace	0
PDS1 Oil Debris Accumulaiton rate	Rate	0.2143+RANDOM UNIFORM(-0.05, 0.05, 0)	
PDS1 Oil replace	Variable	IF THEN ELSE(Oil debris PDS1>8, 0-Oil debris PDS1-PDS1 Oil Debris Accumulaiton rate, 0)	
Acc Change Oil Events PDS1	Level	IF THEN ELSE(PDS1 Oil replace<0, 1, 0)	0
Total maintenance hrs PDS1	Variable	2*Acc Change Oil Events PDS1+AccCorrectiveM PDS1+AccFillingevents PDS1*1+PDS1 Acc Bearing replacements*12	

Appendix G

In depth information of each variable, rate and level in the feeder pump shown in Figure 5.7.

Feeder pump			
Name	**Type**	**Equation**	**Initial Value** (Levels only)
FP1 Acc Oil Top Ups	Level	IF THEN ELSE(Oil top up corrective FP1>0, 1, 0)	0
Oil top up corrective FP1	Variable	IF THEN ELSE(FP1 Oil Level<=4, 10-FP1 Oil Level+FP1 Lubrication Rate, 0)	
FP1 Oil Level	Level	-FP1 Lubrication Rate+Oil top up corrective FP1	10
FP1 Lubrication Rate	Rate	RANDOM UNIFORM(0.4, 0.6 , 0)	
FP1 Empty Oil	Level	-FP1 Lubrication Rate	0
Feeder Pump 1	Level	-FP1 Wear Rate+FP 1 corrective maintenance	10
FP1 Wear Rate	Variable	RANDOM UNIFORM(0.081, 0.141, 0)+IF THEN ELSE(FP1 Oil Level<9, 0.02, 0)+IF THEN ELSE(FP1 Oil Level<8, 0.03, 0)+IF THEN ELSE(FP1 Oil debris>1, 0.005, 0)+IF THEN ELSE(FP1 Oil debris>2, 0.01, 0)+IF THEN ELSE(FP1 Oil debris>3, 0.02, 0)+IF THEN ELSE(FP1 Oil debris>4, 0.03, 0)+IF THEN ELSE(FP1 Oil debris>5, 0.05, 0)+IF THEN ELSE(FP1 Oil debris>6, 0.08, 0)+IF THEN ELSE(FP1 Oil debris>7, 0.01, 0)+IF THEN ELSE(FP1 Oil debris>8, 0.015, 0)+IF THEN ELSE(FP1 Oil debris>9, 0.025, 0)	
FP 1 corrective maintenance	Variable	IF THEN ELSE(Feeder Pump 1<=0, 10-Feeder Pump 1+FP1 Wear Rate, 0)	
FP1 Repair	Variable	IF THEN ELSE(FP 1 corrective maintenance>0, 1, 0)	
FP1 Acc Repairs	Level	FP1 Repair	0
FP1 Acc Repair Maintenance Hours	Variable	FP1 Acc Repairs*6	

FP1 condition	Level	-(FP1 Wear Rate+(10-FP1 condition)*0.001)+FP1 Corrective Maintenance El Motor-IF THEN ELSE(FP1 Random Failure El Motor>0, FP1 condition, 0)	10
FP1 acc downtime	Level	IF THEN ELSE(FP1 condition<=0, 1, 0)*RANDOM NORMAL(0.15, 24, 4, 2, 0)+IF THEN ELSE(FP1 Repair>0, 1, 0)*6	0
FP1 Random Failure El Motor	Variable	PULSE TRAIN(0, (1/7), RANDOM NORMAL(0, 10 , 5 , 1, 520), 520)	
FP1 Corrective Maintenance El Motor	Variable	IF THEN ELSE(FP1 condition<=0, 10-FP1 condition, 0)	
FP1 AccCorrectiveM1	Level	IF THEN ELSE(FP1 Corrective Maintenance El Motor>0, 1, 0)*RANDOM UNIFORM(0.5, 12, 1)+FP 1 corrective maintenance*RANDOM UNIFORM(3, 6, 0)	0
FP1 Debris rate	Rate	RANDOM UNIFORM(0.18, 0.25, 0)	
FP1 Oil debris	Level	FP1 Debris rate+FP1 Oil replace	0
FP1 Oil replace	Variable	IF THEN ELSE(FP1 Oil debris>8, 0-FP1 Oil debris-FP1 Debris rate, 0)	
PF1 Acc Oil Changes	Level	IF THEN ELSE(FP1 Oil replace<0, 1, 0)	0
FP1 Acc Oil Change Maintenance Hours	Variable	PF1 Acc Oil Changes*0.5	
FP1 Total Maintenance hours	Variable	FP1 Acc Oil Change Maintenance Hours+FP1 Acc Oil Top Ups Maintenance Hours+FP1 Acc Repair Maintenance Hours+FP1 AccCorrectiveM1	

Appendix H

In depth information of each variable, rate and level in the pump action shown in Figure 5.8.

Pump Action			
Name	**Type**	**Equation**	**Initial Value** (Levels only)
CH1 Wear Rate	Rate	RANDOM UNIFORM(1.75, 2.25, 0)	
Cooling Hose 1	Level	-CH1 Wear Rate+CH 1 corrective maintenance	10
CH 1 corrective maintenance	Variable	IF THEN ELSE(Cooling Hose 1<=1, 10-Cooling Hose 1+CH1 Wear Rate, 0)	
CH1 Replacement	Variable	IF THEN ELSE(CH 1 corrective maintenance>0, 1, 0)	
CH1 Acc Maintenance Hours	Variable	CH1 Acc Replacements*0.25	
Piston 1	Level	-Piston 1 Wear Rate+P1 Corrective Maintenance	10
Piston 1 Wear Rate	Variable	RANDOM UNIFORM(0.283, 0.383, 0)*IF THEN ELSE(Cooling Hose 1=0, 0, 1)	
P1 Corrective Maintenance	Variable	IF THEN ELSE(Piston 1<=0, 10-Piston 1+Piston 1 Wear Rate, 0)	
P1 Replacement	Variable	IF THEN ELSE(P1 Corrective Maintenance>0, 1, 0)	
P1 Acc Replacements	Level	IF THEN ELSE(P1 Replacement>0, 1, 0)	0
P1 Acc Maintenance Hours	Variable	P1 Acc Replacements*6	
Liner 1 Wear Rate	Variable	RANDOM UNIFORM(0.081, 0.141, 0)	
Liner 1	Level	-Liner 1 Wear Rate+L1 Corrective Maintenance	10
L1 Corrective Maintenance	Variable	IF THEN ELSE(Liner 1<=0, 10-Liner 1+Liner 1 Wear Rate, 0)	

L1 Replacement	Variable	IF THEN ELSE(L1 Corrective Maintenance>0, 1, 0)	
L1 Acc Replacements	Level	IF THEN ELSE(L1 Replacement>0, 1, 0)	0
L1 Acc Maintenance Hours	Variable	L1 Acc Replacements*6	
Valve 1 Wear Rate	Variable	RANDOM UNIFORM(0.127, 0.207, 0)	
Valve 1	Level	-Valve 1 Wear Rate+V1 Corrective Maintenance	10
V1 Corrective Maintenance	Variable	IF THEN ELSE(Valve 1<=0, 10-Valve 1+Valve 1 Wear Rate, 0)	
V1 Replacement	Variable	IF THEN ELSE(V1 Corrective Maintenance>0, 1, 0)	
V1 Acc Replacements	Level	IF THEN ELSE(V1 Replacement>0, 1, 0)	0
V1 Acc Maintenance Hours	Variable	V1 Acc Replacements*6	
vSeat 1 Wear Rate	Variable	RANDOM UNIFORM(0.0526, 0.0586, 0)	
vS Corrective Maintenance	Variable	IF THEN ELSE(vSeat 1<=0, 10-vSeat 1+vSeat 1 Wear Rate, 0)	
vSeat 1	Level	-vSeat 1 Wear Rate+vS Corrective Maintenance	10
vS1 Replacement	Variable	IF THEN ELSE(vS Corrective Maintenance>0, 1, 0)	
vS1 Acc Replacements	Level	IF THEN ELSE(vS1 Replacement>0, 1, 0)	0
vS Acc Maintenance Hours	Variable	vS1 Acc Replacements*6	
Random breakdown on the pump action	Variable	PULSE TRAIN(0, (1/7), RANDOM NORMAL(0, 15 , 5 , 3, 520), 520)	
PA acc downtime	Level	(IF THEN ELSE(Random breakdown on the pump action>0, RANDOM NORMAL(1, 24, 8, 2, 0), 0))+3*(IF THEN ELSE(Liner 1<=0, 1, 0)*6+IF THEN ELSE(Piston 1<=0, 1, 0)*6+IF THEN ELSE(Valve 1<=0, 1, 0)*6+IF THEN ELSE(vSeat 1<=0, 1, 0)*6+IF THEN ELSE(Cooling Hose 1<=0, 1, 0)*0.25)	0
Total PM Hours PA 1	Varialbe	(CH1 Acc Maintenance Hours+L1 Acc Maintenance Hours+P1 Acc Maintenance Hours+V1 Acc Maintenance Hours+vS Acc Maintenance Hours)*3	

Appendix I

In depth information of each variable, rate and level in the electric motor shown in Figure 5.9.

Electric Motor

Name	**Type**	**Equation**	**Initial Value** (Levels only)
El M 1 Oil top up	Variable	IF THEN ELSE(Oil level EL 1<7, 10-Oil level EL 1+El M 1 Lubrication Rate 1, 0)	
Oil level EL 1	Level	-El M 1 Lubrication Rate 1+El M 1 Oil top up	10
El M 1 Lubrication Rate 1	Rate	RANDOM UNIFORM(0.05, 0.3, 0)	
Empty oil 1	Level	-El M 1 Lubrication Rate 1	0
Filling Events 1	Variable	IF THEN ELSE(El M 1 Oil top up>0, 1, 0)	
AccFillingevents 1	Level	IF THEN ELSE(Filling Events 1>0, 1, 0)	0
Bearings Condition EL 1	Level	-El M 1 Bearing Wear Rate+EL M 1 Bearing CBM	10
El M 1 Bearing Wear Rate	Rate	0.015+Oil debris EL 1*0.005+IF THEN ELSE(Oil level EL 1<4, 0.1, 0)+IF THEN ELSE(Oil level EL 1< 5, 0.02, 0)+IF THEN ELSE(Oil level EL 1<6, 0.012, 0)+IF THEN ELSE(Oil level EL 1<7, 0.005, 0)	
EL M 1 Bearing CBM	Variable	IF THEN ELSE(Bearings Condition EL 1<0.5, 10-Bearings Condition EL 1+El M 1 Bearing Wear Rate, 0)	
Acc Replace Bearing EL 1 events	Level	IF THEN ELSE(EL M 1 Bearing CBM>0, 1, 0)	0
Electric motor 1	Level	(-Overall Wear Electric Motor 1-Electric motor 1*0.001)-(IF THEN ELSE(Random Failure El Motor 1>0, Electric motor 1, 0))+Corrective Maintenance El Motor 1+El M 1 CBM	10
Overall Wear Electric Motor 1	Rate	0.0173+Oil debris EL 1*0.005+Bearings Condition EL 1*0.005+(10-Oil level EL 1)*0.005	
El M 1 CBM	Variable	((IF THEN ELSE(Electric motor 1<RANDOM UNIFORM(4, 6, 0), 10-Electric motor 1+Overall Wear Electric Motor 1, 0)))*IF THEN ELSE(Electric motor 1<4, 0, 1)	
Random Failure El Motor 1	Variable	PULSE TRAIN(0, (1/7), RANDOM NORMAL(0, 10 , 5 , 1, 520), 520)*IF THEN ELSE(Electric motor 1>=8, 0, 1)	

Corrective Maintenance El Motor 1	Variable	(IF THEN ELSE(Electric motor 1<=0, RANDOM NORMAL(5, 10, 8, 1, 1), 0))*IF THEN ELSE(El M 1 CBM>0.5, 0, 1)	
AccCorrectiveM1	Level	IF THEN ELSE(Corrective Maintenance El Motor 1>0, 1, 0)*RANDOM UNIFORM(0.5, 12, 1)	0
El M 1 CBM Acc	Level	IF THEN ELSE(El M 1 CBM>0, 1, 0)*RANDOM UNIFORM(2, 6, 0)	0
El M 1 acc downtime 0	Level	IF THEN ELSE(Electric motor 1<=0, 1, 0)*RANDOM NORMAL(1, 48, 12, 5, 0)	0
El M 1 Oil replace CBM	Variable	-IF THEN ELSE(Oil debris EL 1>6, 0-Oil debris EL 1-El M 1 Debris Acc Rate, 0)	
El M 1 Debris Acc Rate	Rate	0.2143+RANDOM UNIFORM(-0.05, 0.05, 0)	
Oil debris EL 1	Level	El M 1 Debris Acc Rate-El M 1 Oil replace CBM	0
Acc Change Oil Events 1	Level	IF THEN ELSE(El M 1 Oil replace CBM>0, 1, 0)	0
Total maintenance hrs	Variable	0.5*Acc Change Oil Events 1+6*Acc Replace Bearing EL 1 events+0.25*AccFillingevents 1+AccCorrectiveM1+El M 1 CBM Acc	

Appendix J

In depth information of each variable, rate and level in the PDS shown in Figure 5.10.

Power Drive System			
Name	**Type**	**Equation**	**Initial Value** (Levels only)
Oil Top Up CBM PDS1	Variable	IF THEN ELSE(Oil level PDS1<7, 10-Oil level PDS1+Lubrication Rate PDS1, 0)	
Oil level PDS1	Level	-Lubrication Rate PDS1+Oil Top Up CBM PDS1	10
Lubrication Rate PDS1	Rate	RANDOM NORMAL(0.05, 0.3, 0.125, 1, 520)	
Empty oil PDS1	Level	-Lubrication Rate PDS1	0
Bearing CBM PDS1	Variable	IF THEN ELSE(Bearings Condition PDS1<0.5, 10-Bearings Condition PDS1+PDS1 Bearing Wear, 0)	
Bearings Condition PDS1	Level	-PDS1 Bearing Wear+Bearing CBM PDS1	10
PDS1 Bearing Wear	Variable	0.01+Oil debris PDS1*0.004+IF THEN ELSE(Oil level PDS1<4, 0.08, 0)+IF THEN ELSE(Oil level PDS1< 5, 0.015, 0)+IF THEN ELSE(Oil level PDS1<6, 0.01, 0)+IF THEN ELSE(Oil level PDS1<7, 0.0035, 0)	
PDS1 Acc Bearing replacements	Level	IF THEN ELSE(Bearing CBM PDS1>0, 1, 0)	0
PDS1 CBM	Variable	((IF THEN ELSE(power drive system<RANDOM UNIFORM(4, 6, 0), 10-power drive system+Overall Wear PDS1, 0)))*IF THEN ELSE(power drive system<4, 0, 1)	
power drive system	Level	-Overall Wear PDS1-power drive system*0.0005+IF THEN ELSE(PDS1 Corrective Maintenance>0, 10-power drive system+Overall Wear PDS1, 0)-Random Failure PDS1+PDS1 CBM	10
Overall Wear PDS1	Variable	0.00865+Oil debris PDS1*0.005+(10-Bearings Condition PDS1)*0.01+(10-Oil level PDS1)*0.005	
Random Failure PDS1	Variable	(PULSE TRAIN(0, 1, RANDOM NORMAL(0, 50, 25, 10, 0) , 520)*RANDOM UNIFORM(0, 10, 0))*IF THEN ELSE(power drive system>8.5, 0, 1)	
PDS1 Corrective Maintenance	Variable	(IF THEN ELSE(power drive system<=0, RANDOM NORMAL(5, 10, 8, 1, 1), 0))*IF THEN ELSE(PDS1 CBM>0.5, 0, 1)	

AccCorrectiveM PDS1	Level	IF THEN ELSE(PDS1 Corrective Maintenance>0, PDS1 Corrective Maintenance, 0)	0
PDS1 CBM acc	Level	IF THEN ELSE(PDS1 CBM>0, 1, 0)*RANDOM UNIFORM(2, 6, 0)	0
PDS acc downtime	Level	IF THEN ELSE(power drive system<=0, 1, 0)*RANDOM NORMAL(0.15, 72, 10, 5, 0)	0
PDS1 Acc Monthly Events	Level	IF THEN ELSE(PDS1 Monthly PM>0, 1, 0)	0
PDS1 Monthly PM	Rate	6*PULSE TRAIN(4, 1, 4, 520)	
PDS1 Acc 6 monthly Events	Level	IF THEN ELSE(PDS1 6 Monthly PM>0, 1, 0)	0
PDS1 6 Monthly PM	Variable	6*PULSE TRAIN(24, 1, 24, 520)	
PDS daily pm	Rate	3.5	
PDS weekly pm	Rate	1	
Oil debris PDS1	Level	PDS1 Oil Debris Accumulaiton rate+PDS1 Oil Replace CBM	0
PDS1 Oil Debris Accumulaiton rate	Rate	0.2143+RANDOM UNIFORM(-0.05, 0.05, 0)	
PDS1 Oil Replace CBM	Variable	IF THEN ELSE(Oil debris PDS1>6, 0-Oil debris PDS1-PDS1 Oil Debris Accumulaiton rate, 0)	
Acc Change Oil Events PDS1	Level	IF THEN ELSE(PDS1 Oil Replace CBM<0, 1, 0)	0
Total maintenance hrs PDS1	Variable	2*Acc Change Oil Events PDS1+AccCorrectiveM PDS1+PDS1 Acc Bearing replacements*6+PDS weekly pm+PDS daily pm+6*PDS1 Acc Monthly Events+12*PDS1 Acc 6 monthly Events+PDS1 CBM acc	

Appendix K

In depth information of each variable, rate and level in the feeder pump shown in Figure 5.11.

Feeder Pump

Name	**Type**	**Equation**	**Initial Value** (Levels only)
FP1 Oil Level	Level	-FP1 Lubrication Rate+FP1 Oil Top Up CBM	10
FP1 Lubrication Rate	Variable	RANDOM UNIFORM(0.4, 0.6 , 0)	
FP1 Empty Oil	Level	-FP1 Lubrication Rate	0
FP1 Oil Top Up CBM	Variable	IF THEN ELSE(FP1 Oil Level<7, 10-FP1 Oil Level+FP1 Lubrication Rate, 0)	
FP1 Acc Oil Top Ups	Level	IF THEN ELSE(FP1 Oil Top Up CBM>0, 1, 0)	0
FP1 Acc Oil Top Ups Maintenance Hours	Variable	FP1 Acc Oil Top Ups*0.25	
Feeder Pump 1	Level	-FP1 Wear Rate+FP1 CBM	10
FP1 Wear Rate	Variable	RANDOM UNIFORM(0.081, 0.141, 0)+IF THEN ELSE(FP1 Oil Level<9, 0.02, 0)+IF THEN ELSE(FP1 Oil Level<8, 0.03, 0)+IF THEN ELSE(FP1 Oil debris>1, 0.005, 0)+IF THEN ELSE(FP1 Oil debris>2, 0.01, 0)+IF THEN ELSE(FP1 Oil debris>3, 0.02, 0)+IF THEN ELSE(FP1 Oil debris>4, 0.03, 0)+IF THEN ELSE(FP1 Oil debris>5, 0.05, 0)+IF THEN ELSE(FP1 Oil debris>6, 0.08, 0)+IF THEN ELSE(FP1 Oil debris>7, 0.01, 0)+IF THEN ELSE(FP1 Oil debris>8, 0.015, 0)+IF THEN ELSE(FP1 Oil debris>9, 0.025, 0)	
FP1 CBM	Variable	IF THEN ELSE(Feeder Pump 1<=0.5, 10-Feeder Pump 1+FP1 Wear Rate, 0)	
FP1 Repair	Variable	IF THEN ELSE(FP1 CBM>0, 1, 0)	
FP1 Acc Repairs	Level	FP1 Repair	0
FP1 Acc Repair Maintenance Hours	Variable	FP1 Acc Repairs*6	

FP1 condition	Level	-(FP1 Wear Rate+(10-FP1 condition)*0.001)+IF THEN ELSE(FP1 CBM>0, 10-FP1 condition, 0)+FP1 Corrective Maintenance El Motor-IF THEN ELSE(FP1 Random Failure El Motor>0, FP1 condition, 0)	10
FP1 acc downtime	Level	IF THEN ELSE(FP1 condition<=0, 1, 0)*RANDOM NORMAL(0.15, 24, 4, 2, 0)	0
FP1 Random Failure El Motor	Variable	PULSE TRAIN(0, (1/7), RANDOM NORMAL(0, 10 , 5 , 1, 520), 520)	
FP1 Corrective Maintenance El Motor	Variable	IF THEN ELSE(FP1 condition<=0, 10-FP1 condition, 0)*IF THEN ELSE(FP1 CBM>0, 0, 1)	
FP1 AccCorrectiveM1	Level	IF THEN ELSE(FP1 Corrective Maintenance El Motor>0, 1, 0)*RANDOM UNIFORM(0.5, 12, 1)	0
FP1 Debris rate	Variable	RANDOM UNIFORM(0.18, 0.25, 0)	
FP1 Oil debris	Level	FP1 Debris rate+FP1 CBM replace oil	0
FP1 CBM replace oil	Variable	IF THEN ELSE(FP1 Oil debris>5, 0-FP1 Oil debris-FP1 Debris rate, 0)	
PF1 Acc Oil Changes	Level	IF THEN ELSE(FP1 CBM replace oil<0, 1, 0)	0
FP1 Acc Oil Change Maintenance Hours	Variable	PF1 Acc Oil Changes*0.5	
FP1 Total Maintenance hours	Variable	FP1 Acc Oil Change Maintenance Hours+FP1 Acc Oil Top Ups Maintenance Hours+FP1 Acc Repair Maintenance Hours+FP1 AccCorrectiveM1	

Appendix L

In depth information of each variable, rate and level in the pump action shown in Figure 5.12.

Pump Action

Name	**Type**	**Equation**	**Initial Value** (Levels only)
Cooling Hose 1	Level	-CH1 Wear Rate+CH CBM	10
CH1 Wear Rate	Variable	RANDOM UNIFORM(1.75, 2.25, 0)	
CH CBM	Variable	IF THEN ELSE(Cooling Hose 1<=1, 10-Cooling Hose 1+CH1 Wear Rate, 0)	
CH1 Replacement	Variable	IF THEN ELSE(CH CBM>0, 1, 0)	
CH1 Acc Replacements	Level	IF THEN ELSE(CH1 Replacement>0, 1, 0)	0
CH1 Acc Maintenance Hours	Variable	CH1 Acc Replacements*0.25	
Piston 1	Level	-Piston 1 Wear Rate+P CBM+IF THEN ELSE(L replace P as well>0, 10-Piston 1+Piston 1 Wear Rate, 0)*IF THEN ELSE(PnL both>0, 0, 1)	10
Piston 1 Wear Rate	Variable	RANDOM UNIFORM(0.283, 0.383, 0)	
P CBM	Variable	IF THEN ELSE(Piston 1<=0.5, 10-Piston 1+Piston 1 Wear Rate, 0)	
P replace L as well	Variable	IF THEN ELSE(P CBM>0, 1, 0)*IF THEN ELSE(Liner 1<2, 1, 0)	
P only	Variable	IF THEN ELSE(P CBM>0, 1, 0)-IF THEN ELSE(P replace L as well>0, 1, 0)	
P and L acc replacement	Level	P replace L as well	0
P only acc replacements	Level	P only	0
Acc P and PL hours	Variable	6*P only acc replacements+P and L acc replacement*7-Acc both hours PnL	

PnL both	Variable	IF THEN ELSE(P replace L as well>0, 1, 0)*IF THEN ELSE(L replace P as well>0, 1, 0)	
Both acc PnL	Level	PnL both	0
Acc both hours PnL	Variable	Both acc PnL*7	
Liner 1	Level	-Liner 1 Wear Rate+IF THEN ELSE(P replace L as well>0, 10-Liner 1+Liner 1 Wear Rate, 0)*IF THEN ELSE(PnL both>0, 0, 1)+L CBM	10
Liner 1 Wear Rate	Variable	RANDOM UNIFORM(0.081, 0.141, 0)	
L CBM	Variable	IF THEN ELSE(Liner 1<=0.5, 10-Liner 1+Liner 1 Wear Rate, 0)	
L replace P as well	Variable	IF THEN ELSE(L CBM>0, 1, 0)*IF THEN ELSE(Piston 1<2, 1, 0)	
L only	Variable	IF THEN ELSE(L CBM>0, 1, 0)-IF THEN ELSE(L replace P as well>0, 1, 0)	
L and P acc replacement	Level	L replace P as well	0
L only acc replacements	Level	L only	0
Acc L and LP hours	Variable	L and P acc replacement*7+L only acc replacements*6-Acc both hours PnL	
PA acc downtime	Level	IF THEN ELSE(Random breakdown on the pump action>0, RANDOM NORMAL(1, 24, 8, 2, 0), 0)	0
Random breakdown on the pump action	Variable	PULSE TRAIN(0, (1/7), RANDOM NORMAL(0, 15 , 5 , 3, 520), 520)	
Valve 1	Level	-Valve 1 Wear Rate+IF THEN ELSE(vS replace V as well>0, 10-Valve 1+Valve 1 Wear Rate, 0)*IF THEN ELSE(VnvS both>0, 0, 1)+V CBM	10
Valve 1 Wear Rate	Variable	RANDOM UNIFORM(0.127, 0.207, 0)	
V CBM	Variable	IF THEN ELSE(Valve 1<=0.5, 10-Valve 1+Valve 1 Wear Rate, 0)	
V replace vS as well	Variable	IF THEN ELSE(V CBM>0, 1, 0)*IF THEN ELSE(vSeat 1<2, 1, 0)	
V only	Variable	IF THEN ELSE(V CBM>0, 1, 0)-IF THEN ELSE(V replace vS as well>0, 1, 0)	

V only acc replacements	Level	V only	0
V and vS acc replacement	Level	V replace vS as well	0
Acc V and vS hours	Variable	6*V only acc replacements+V and vS acc replacement*7-Acc both hours VnvS	
VnvS both	Variable	IF THEN ELSE(V replace vS as well>0, 1, 0)*IF THEN ELSE(vS replace V as well>0, 1, 0)	
Both acc VnvS	Level	VnvS both	0
Acc both hours VnvS	Variable	Both acc VnvS*7	
vSeat 1	Level	-vSeat 1 Wear Rate+IF THEN ELSE(V replace vS as well>0, 10-vSeat 1+vSeat 1 Wear Rate, 0)*IF THEN ELSE(VnvS both>0, 0, 1)+vS CBM	10
vSeat 1 Wear Rate	Variable	RANDOM UNIFORM(0.0526, 0.0586, 0)	
vS CBM	Variable	IF THEN ELSE(vSeat 1<=0.5, 10-vSeat 1+vSeat 1 Wear Rate, 0)	
vS replace V as well	Variable	IF THEN ELSE(vS CBM>0, 1, 0)*IF THEN ELSE(Valve 1<2, 1, 0)	
vS only	Variable	IF THEN ELSE(vS CBM>0, 1, 0)-IF THEN ELSE(vS replace V as well>0, 1, 0)	
vS and V acc replacement	Level	vS replace V as well	0
vS only acc replacements	Level	vS only	0
Acc vS and V hours	Variable	vS and V acc replacement*7+vS only acc replacements*6-Acc both hours VnvS	
Total PM Hours PA 1	Variable	(Acc L and LP hours+Acc P and PL hours+Acc V and vS hours+Acc vS and V hours+CH1 Acc Maintenance Hours)*3	