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Decision-making Framework for Maintenance Management

by

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Dedicated to my parents

Abstract

The objective of this study is to develop a decision-making framework for maintenance management targeting remotely operated assets. Using external data as an input, the developed framework can improve decision-making ability on maintenance from the field or remote office. This was achieved by presenting additional information from related departments in addition to data assessments, and identification and sorting of failures. The idea of accessing the information via digital devices which has internet access is also explored in this thesis.

This framework is developed using the Structured Analysis and Design Technique (SADT). The field data related to tire failures were used to gain the insight of the practical application of this framework. It is observed that this framework is more feasible in the field where operating conditions are similar over a long period. This framework can also help the decision-maker to make analytical decisions as compared to only relying on intuition.

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Chapter 1

1. Introduction

Effective maintenance management is essential for a manufacturing company to keep its production assets available for use [1]. This is achieved not only by reducing the downtime during which assets are unproductive, but also by improving the capacity of assets to operate effectively and safely.

To increase the availability of assets, organizations use different maintenance strategies, depending on the nature of the business and the criticality of the assets. With the development of new maintenance methods and advancements in technology, the maintenance environment has changed over the years [2]. Data collection has become an important part of the organizational processes, for financial, legal, standardization, safety, and reliability purposes. Wherever equipment is monitored for operational control or regulatory reasons, sensors are used with data acquisition, analysis and archiving system to give alerts and alarms depending on changes in sensor readings that relate to faults. The process of data acquisition, analysis, and decision-making is known as condition-based maintenance [3]. Data collection can be done manually, or with dedicated networks of monitoring systems. The data collection interval, the type of monitoring, and the distance over which monitoring is done all affect the choice of process- and condition-monitoring technologies [4]. Due to the availability of sensors at affordable prices, the data collection process has improved over the years [5]. Sensor values can be used to assess the deterioration trends of the assets, in addition to alerting impending failure. In cases where there is a relationship present between sensor values and the deterioration trends of assets, this relationship can help maintenance excel in analytical maintenance techniques and support logistical decisions necessary to order spare parts and conduct maintenance activities. Weibull analysis is considered a traditional technique, and is the most common technique used to perform data analysis [5].

Information plays an important role in decision-making, whether the information is a specific datum in context or an output of an analysis of a data set. Information is derived by defining data with some purpose and relevance [6]. Any information package for decision-making should have an appropriate format and correct data.

In many cases, the decision-maker is assessing the condition of assets from a distance. Due to the remote nature of assets in mining and oil and gas companies, information packages need to be displayed on a computer screen or on a portable device, such as a smartphone, depending on where the decision-maker is, the office or the field. Information presents needs to include sufficient context to and in an effective decision.

1.1.Background

Maintenance management has evolved from reactive maintenance in the past to a suite of maintenance methods. Different maintenance strategies have been developed to improve availability and reduce downtime. Maintenance management has seen a transition from interval-based maintenance to reliability-centered maintenance, and finally to expert systems [7]. Arunraj and Maiti [8] divided this transition into four generations, where first generation belongs to the time prior to the Second World War, and followed the strategy of routine, reactive, and corrective maintenance. The time period between the Second World War and the late 1970s is considered the second generation, and during this time, maintenance strategies were planned-preventive and time-based. Condition-based maintenance, reliability-centered maintenance, and computer-aided maintenance management were the strategies followed in the third generation, which comprises the time between 1980 and 2000. The latest generation includes risk-based inspection and maintenance in addition to the strategies found in the third generation. Along with the development of maintenance strategies, process improvement techniques have also been implemented in maintenance functions to streamline or sometimes align the maintenance with operations. Furthermore, mathematical and analytical models that consider different inputs and techniques have also been developed. Mathematical modeling is required in the case where optimization or numerical predictions are required for maintenance [9]. These models also show the importance of failure mode and effect analysis, system assessment technique options enumeration, and continuous improvement. Details of these models and process improvement techniques can be found in chapter 2.

Even with the development of these maintenance techniques, it seems that there is still some gap in maintenance decision-making in terms of exploring the area of information requirements, especially in the case of remote assets.

A maintenance management framework that can work on real-time basis needs to be developed to help decision makers. Therefore, the structured analysis and design technique (SADT) can be used to develop the framework, considering its capability to describe system qualities such as "*coordination, real-time interactions*, and *feedback*" [10].

1.2.Problem Setting and Definition

With the recent advancements in technology, increase in production demand, and increase in penalty clauses for not meeting production targets, companies not only pay attention to production and operations management but also pay attention to maintenance management. Prior to the 1980s, maintenance departments were not given sufficient attention; rather, a maintenance department was considered good if it could bring the equipment in running condition [11].

Maintenance management systems (MMS) are not something new; rather, their roots can be found in manufacturing companies from the late 1960s [11]. MMSs have basic requirements, situation-based strategies, measurement methodologies, and opportunities to achieve excellence.

Some of the attributes of a good management system can be user friendliness, stability over a long period of time, and independence from human skills. In order to obtain these attributes, the system needs to be standardized and integrated into other management systems. These standardized systems can take different shapes, depending upon the organizational requirement or business criticality. Likewise, a maintenance management system can take many shapes, such as computer-based and/or paper-based; however, it should still satisfy some key requirements.

With the availability of production plans, it is now much easier to plan maintenance and shutdowns. Modern planning techniques along with the standardization of production facilities have led to the development of maintenance planning and scheduling processes [12].

An MMS should be able to run the plant effectively with a minimal impact on its financial statements, and measure the results with the help of data [13]. An MMS could take some of the following requirements to satisfy its basic needs: a complete and accurate list of equipment that require maintenance; maintenance instructions for the maintainers, keeping their safety in mind; work orders; daily and weekly maintenance schedules; integration of a preventive maintenance plan with production plans; logical flow of maintenance for in-line production equipment; weekly reports; the capability to handle breakdowns; and the availability of data to measure maintenance [11] [13]. Since such systems are now computer-based, they are commonly referred to as computer-based maintenance management systems (CMMS).

This study involves modeling a decision-making framework for maintenance management. The framework was developed with the understanding that production plans, a complete list of equipment along with their failures, sensor data archives for finding correlation, maintenance logistics, and information from other departments will be easily available for decision-making purposes.

1.3. Objective of the Thesis

This work was carried out to investigate how to integrate analytics into a client's maintenance decision-making procedures. Deliverables will help companies balance maintenance time and reliability, and further, it will try to avoid unwanted run-to-failures. With the application of this project, clients will be able to adopt a proactive approach rather than reactive approach. Further clients can take the opportunity costs of lost production into account for decision-making.

The main focus of this study is to increase clients' confidence level in decision-making, while looking at the data related to operations, maintenance, and unnecessary run-to-failures. A decision-making framework is developed in this study, having the following qualities:

- **Sorting of data**: The framework should be able to identify the failures related to the equipment of interest, and sort these failures according a risk ranking incorporated within the framework.
- **System assessment**: The developed framework should have the capability to perform a system assessment for the already-collected data to determine any correlations that are present between the failure and sensor values.
- **Information flow**: The framework should be capable of accessing the required information for decision makers from other departments.

- **Information presentation**: The framework should have the capability to present the information related to remote assets or to send information to the decision maker who is at a distant location. This framework will also help with the integration of customer requirements for analytics of interest, i.e., what problems the customer needs to be informed of and how does the customer want the information package (IP) to be made available to them. The IP will include reports that are easily understood, and will provide a faster way to communicate with the customer/customer representatives.
- **Input analysis**: An analysis should be done to figure out the inputs required for the decision-making framework to work properly.

The importance of some of the traits, such as sorting for data and system assessment, can be found in the literature. However, this framework also includes the concept of sharing the information from different departments that could help in maintenance decision-making. Further, this framework explores the opportunities related to presenting the information on remotely-operated assets to decision-makers. This information-sharing can be made available at the decision-makers dashboard, which can be accessed through personal computers or with the use of mobile devices.

This framework will be evaluated through two case studies:

1. The first case study involves performing a basic statistical analysis on already-available data related to tire failures, structured workflow analysis and putting this information in a maintenance decision-making context.

2. The second case study involves collecting data from heavy oil production companies and analyzing how they perform on a daily basis related to different aspects of maintenance decision-making.

Chapter 2

2. Literature Review

This chapter will looks into the decision-making concepts required for this framework, explains the failure trends, maintenance strategies, process improvement techniques, and their application in maintenance, provides a review of maintenance models developed in the past, along with some definitions and highlights knowledge gaps relevant to the present work.

2.1.Decision-Making Concepts

2.1.1. Decision-Making

Decision analysis is used to compare competitive solutions based on their ratings in different criteria; however, these solutions may supersede each other in different selection criteria [14]. A difficult task is to rank these alternatives in the presence of several decision criteria. This prioritization of alternatives with respect to criteria and sub-criteria to obtain higher gains, coupled with dependencies within alternatives, has made decision-making a mathematical science [15]. Multi-criteria decision-making (MCDM) is considered to be an effective technique for solving the criteria-ranking problem [16]; this field of decision analysis covers the majority of maintenance problems [14]. Due to the importance of MCDM, a brief overview of this technique will be discussed in the next section.

An important aspect of decision-making is human judgment. Research shows that most of the time, people think that the decisions that they made in the past were “just fine” [17]. Some authors recommend that linear models should be used instead of human judges in every possible condition; however, greater accuracy can be achieved if an expert defines the criteria and then uses statistical methods to come up with a more effective decision according to some objective function or key criteria [17].

Considering the outcome of any decision, it has been found that in the case of gains people prefer to choose a firm option rather than a probable option of higher gain value. For example they would prefer a guaranteed win $3000 instead of taking risk for a 80% chance to win $4000, and in the case of loss, people select the option of losing more on a probable outcome compared to a certain loss of lower value. For example they would prefer to opt for 80% chance of losing $4000 as compare to a confirmed loss of $3000 [17].

Another important input of decision-making is information. Excessive information flow makes it difficult for managers to make effective decisions [18]. In order to make good decisions, managers should be provided with “recent, relevant, and reliable” information, where “recent” and “reliable” relate to the information itself, and “relevant” is dependent on the user requirements [18].

Some of the factors that are considered in selecting how much information is required are [19]:

- willingness to process the amount of information,
- the type of information required,
- external factors such as operating conditions,
- internal factors such as enthusiasm, and
- time and money constraints.

The importance of information presentation in decision-making has been well-recognized by research in information systems [17] [20]. Out of many available presentation methods, this literature review will only discuss graphs and tables. Graphs are used in the data analysis where finding relationships between data is important; on the other hand, tables are used when analysis requires specific data values [20].

Multi-Criteria Decision-Making

It has become more difficult for a decision-maker to identify the potential alternative that provides the most benefit in relation to other available alternatives, as the nature of decisions has become complex [21]. Decision problems related to competitive multiple options can be analyzed by following the MCDM framework [21]. The MCDM application can be found in many functional areas, such as planning, control, and industrial production [22].

A typical framework for MCDM works by [21]:

- defining the objectives,
- selecting the criteria for the purpose of calculating the objective,
- identifying alternatives,
- converting the criterion scales into proportional units,
- giving weightage to criteria according to their impact,
- using a selected mathematical algorithm to rank alternatives, and
- selecting an alternative.

Ananda and Herath [21] and Vassilev, Genova, and Vassileva [22] classify MCDM problems in two groups:

1. Continuous: the selection of a most effective decision set from a set of infinite possible solutions in the light of a finite number of constraints.
2. Discrete: the selection of an alternative from a finite set of alternatives that can be ranked with some criteria, and a set of objectives.

Some of the techniques that can be used to solve continuous problems are linear programming, goal programming, and aspiration-based models [21], whereas discrete problems can be solved by using multi-attribute utility (value) theory methods, and the analytical hierarchy process (AHP) [22]. Out of many available techniques, we will briefly discuss AHP to illustrate how MCDM is done.

Analytical Hierarchy Process:

AHP in a technique that uses a scale of 1–9 to compare activities amongst each other, where 1 means equally-important activities and 9 means that one activity, when compared to the others, is the most important in order to achieve objectives [15] [23].

Saaty [15] used a four-step framework to decompose the decision in order to generate priorities:

1. The problem needs to be defined, and the sort of knowledge needed must be determined.
2. A decision hierarchy needs to be developed, with goals on the top, followed by the objectives in a broad spectrum, followed by the criteria that can be used to determine dependencies, and the bottom level should be a set of alternatives.
3. A pairwise comparison matrix is then used to compare each element with respect to an element from an immediate lower level.
4. The resulting prioritization from the comparison can be used to weigh the immediately-lower-level priorities. This needs to be done for every element. Then, a global priority needs to be collected for every element in the lower level by adding its weighted values. This process needs to be done until all the alternatives in the bottommost level obtain their overall priorities.

2.1.1. Data Quality

Data is either consumed as an input or produced as an output in most organizational processes, whether they are operational or strategic [24]. Excessive use and storage of data has caused problems such as data quality and accessibility of data for information development [25] [26]. One of the problems related to data quality is "lost opportunities" [25]. Data quality is an important factor for any organization's decision-making [25].

The quality of data is dependent on its state of "completeness, validity, consistency, and timeliness" to make data fit for any decision-making, but it can also be defined as the ability to meet the stated requirements [26]. Most organizations characterize data into three groups: "master data, transactional data, and historical data" [24]. Maintenance of master data is considered to be one of the barriers in achieving data quality [24].

2.1.2. Analytics

Industries have been using analytics to look at past events, compare them with current measures, and predict what could happen in the future, in case a certain trend continues [27] [28]. Data mining and statistical analysis can be used to identify patterns of data, which can be used for process improvement [28].

Some of the advantages of being analytical are that it helps to manage and run the business in difficult times by predicting the market shifts; an advanced level of analytics can verify the results as expected from the inputs; and it can be used to reduce risk, cut costs, and eliminate waste [27].

Before applying analytics, organizations need to figure out the way in which they will be using the data to address their needs [27]:

- Information-based: forecasting the outcome by comparing the current data with the reported data
- Insight-based: predicting and optimizing the results by using modeling and experimental techniques

Depending upon the data collected, the organization can perform either a qualitative or quantitative analysis, or both. Data can be categorized as qualitative, such as those collected from opinion polls, or quantitative, which are numerical in nature [29].

Qualitative Data Analysis:

In qualitative data analysis, inductive reasoning is used to extract information from the data, i.e., to generate a hypothesis from the data [30]. Some of the strategies that can be used in qualitative data analysis are [30]:

- Constant comparative analysis: This strategy involves finding a relationship between different data sets by comparing various pieces of data with one master data set.
- Phenomenological approaches: This strategy focuses more on individual cases and performing in-depth analyses to identify the experiences particular to each study.

The qualitative data analysis approach involves four components [31]:

1. Data collection: Interviews, focus groups, and open-ended questionnaire techniques can be used to collect information.
2. Data display: Data can be presented in the form of charts, graphs, and matrices.
3. Data reduction: Raw data is converted to useful information by selecting and simplifying the raw data.
4. Conclusions: Initially, conclusions are drawn by looking at the pattern of the data and the related findings, and later, these conclusions are verified by checking the data.

Some of the properties of qualitative data analysis are that it is a continuous, iterative, and cyclical process that performs data collection along with data analysis [31].

Quantitative Data Analysis:

Quantitative data analysis can be performed with the help of statistics. Statistics can be characterized in two broad spectrums [29]:

1. Descriptive statistics: This part of statistics provides information related to averages and performance evaluations.
2. Inductive statistics: This part of statistics uses the population of measured data for evaluative and predictive purposes to make decisions.

Statistical modeling can be used in the field of reliability, where reliability modeling is used to estimate the reliability of a system based on lifetime distributions [32].

A reliability model works in six steps [32]:

1. Data collection: The lifetime of a component within a system of interest is calculated.
2. Estimating failure probability function: A histogram can be plotted by using time-to-failure data, and can be used to select a distribution.
3. Fitting the distribution: The cumulative distribution function is plotted for potential distributions, and a distribution with a straight line plot is selected as an option for the final distribution.
4. Estimating parameters: A statistical technique such as maximum likelihood estimation can be used to estimate the model's parameters.
5. Goodness-of-fit test: These tests are carried out to determine how well a distribution fits the data.
6. Final reliability function: The reliability function is drawn after the selected distribution passes the goodness-of-fit test.

There are many distributions and goodness-of-fit tests available in the literature; some of them are covered in the next sections.

Continuous Distribution Functions:

O'Connor [33] describes the following continuous distribution functions with respect to reliability; a brief overview is given below:

- Normal distribution: This is considered to be the most widely-used distribution, as the combination of variations from different sources tends to approach normal distribution. The probability distribution function of an s-normal distribution is given in equation 2-1.

$$f(x) = \frac{1}{\sigma(2\pi)^{1/2}} \exp\left[-\frac{1}{2}\left(\frac{x-\mu}{\sigma} \right)^2 \right] \qquad \textbf{2-1}$$

Where:

μ is the mean and location parameter, and

σ is the standard deviation and scale parameter.

Due to the symmetrical nature of the distribution, mode and median align with the mean. An important property of this distribution is that the population is evenly distributed about the mean. Normal distribution fits in the majority of quality control, and some of the reliability data, such as those related to wear-out failures.

- Lognormal distribution: This is considered more versatile than normal distribution. A lognormal distribution fits better to the reliability data population with wear-out features. Additionally, it does not go below zero, like normal distribution. The probability distribution function of a lognormal distribution is given in equation 2-2.

$$f(x) = \begin{cases} \frac{1}{\sigma x (2\pi)^{1/2}} \exp\left[-\frac{1}{2} \left(\frac{\ln x - \mu}{\sigma} \right)^2 \right] \end{cases} \quad \text{(for } x \geq 0\text{)} \qquad \textbf{2-2}$$

- Exponential distribution: This distribution is used in the case where the hazard rate is constant, which is denoted by λ. The mean time-to-failure is given by 1/λ, and the probability distribution function is given in equation 2-3.

$$f(t) = \lambda \exp(-\lambda t) \quad \text{(for } t \geq 0\text{)} \qquad \textbf{2-3}$$

The independent variable x is replaced with t, as the hazard function is mostly calculated as a function of time.

- Gamma distribution: From a reliability perspective, this distribution describes the possibility of partial failures. The probability distribution function is given in equation 2-4.

$$f(x) = \frac{\lambda}{\Gamma(a)} (\lambda x)^{a-1} \exp(-\lambda x) \quad \text{(for } x \geq 0\text{)} \qquad \textbf{2-4}$$

Where λ is the failure rate, a denotes the number of partial failures that lead to a failure, and Γ (a) is given in equation 2-5:

$$\Gamma(a) = \int_0^\infty x^{a-1} \exp(-x) dx \qquad \textbf{2-5}$$

- Weibull distribution: This distribution has a special property, which is considered an advantage for reliability work. Its distribution parameters can be changed to fit many life distributions. The probability distribution function is given in equation 2-6.

$$f(t) = \frac{\beta}{\eta^{\beta}} t^{\beta-1} \exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right] \qquad \text{(for t≥o)} \qquad \textbf{2-6}$$

Where β is shape parameter and η is scale parameter.

Goodness-of-fit tests:

As described earlier in the reliability modeling, goodness-of-fit tests need to be performed in order to evaluate how well a data set fits the distribution. Some of the tests described by O'Connor [33] are as follows:

- The chi-square goodness-of-fit test: In the presence of a large number of data points, this test is equally applicable to all distributions. Its accuracy increases if at least three data cells, each having at least five data points, are available. This test works on the assumption that a normal distribution is obtained within every cell about the expected value, when the sample is divided into n number of cells.
- The Kolmogorov-Smirnov test: This is another test that can be used in reliability modeling. It is used in the cases where fewer data are available. This test is based on the cumulative ranked data.

There are other statistical techniques that can be used in data analysis along with the techniques used by reliability modeling. A correlation analysis can be used to assess how well two measures are correlated within the same concept [34]. Variance analysis is a technique used in cases where two populations need to be analyzed at the same point [34].

2.2.Failure Modes and Effects Analysis

Failure modes and effects analysis (FMEA) is a technique that was initially developed by United States army in the 1949; however, this technique later found applicability in the field of aerospace and the automotive industry, due to its strength and validity [35]. FMEA aims to correct potential failure problems at the design and production stages [36].

FMEA works in two phases:

Phase 1: This phase is carried out to identify potential failure modes and their effects.

Phase 2: This phase is used to perform an analysis to determine and rank the severity of failure modes [36] [37].

In general, the FMEA process can be carried out by following these ten steps [36]:

1. Analyze the system under consideration and divide it into subsystems. Develop a list of all the components present in the subsystem.
2. Identify relationships amongst the components by developing block diagrams.

3. Identify every possible failure mode for every single component in the list, along with their causes and effects on the related components and the entire system.
4. Evaluate every failure mode on the basis of its worst possible consequences.
5. Identify mitigation strategies along with failure detection methods.
6. Use qualitative and quantitative techniques to estimate the probability of occurrence.
7. Calculate the risk priority number (RPN). The RPN is the product of occurrence, severity, and the probability that a failure cannot be detected.
8. Decide, on the basis of the RPN, whether a corrective action is required.
9. Recommend a procedure to improve the system performance.
10. Summarize the analysis in a table to finalize the FMEA report.

Some of the challenges that occur during the implementation stage of FMEA are forming a capable team, timing the process itself, co-ordination between the departments on the contents of the report, and agreement between the departments on the improvements suggested in the report [37].

2.3. Qualitative Risk Analysis:

Qualitative risk analysis is a technique that is used to sort identified risks according to their impact and occurrence values, in order for the project team to focus on the high-priority risks [38].

Some of the factors that contribute to a successful implementation of qualitative risk analysis are [39]:

- Using an agreed-upon approach: Some of the factors that play an important role in the prioritization of risks are probability of occurrence, effect on individual objectives, lead time required for the execution of risk response, treatment of risks in case they are not manageable, and whether a risk has an effect outside the project boundaries.
- Using agreed-upon definitions of risk terms: Important terms such as probability and impact of a risk should have consistent and agreed-upon definitions in order to have a realistic assessment, and to communicate the results to stakeholders.
- Collecting high-quality information about risks: Techniques such as interviews, workshops, and expert judgment should be used to collect information that is unbiased.
- Performing iterative qualitative risk analysis: To improve the success of qualitative risk analysis, the process should be performed periodically.

Some of the techniques that can be used in performing qualitative risk analysis are risk probability and impact assessment, probability and impact matrix, risk data quality assessment, risk categorization, risk urgency assessment, and expert judgment [38]. For this literature review, we will be discussing the probability and impact matrix.

Probability and Impact Matrix:

Due to the subjective nature of qualitative risk analysis, a standard risk rating system needs to be developed to overcome the natural attribute of someone rating the risk [40]. According to the agreed-upon definitions of probability and impact, a standard probability and impact matrix can take different shapes. One example of a probability and impact matrix is shown in figure 2-1.

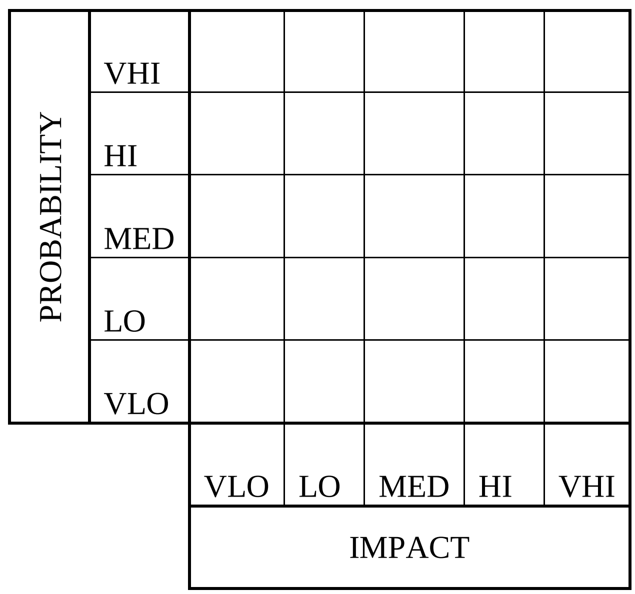

Figure 2-1 Probability impact matrix example [41]

2.4.Failure Trends

In order to decide a maintenance strategy, one of the most important inputs is to categorize equipment under expected failure trends. There are six failure trends with respect to operating age [1]:

1. **Worst old:** This applies to components, which wear out with the passage of time or through being in contact with abrasive components.

2. **Bathtub:** This trend is a combination of two different trends, one where equipment fails in the start of its life randomly, and one where the equipment fails due to wear. This is generally true for equipment that has a combination of mechanical and electronic parts, such as DVD players.
3. **Slow aging:** This trend is observed by simple components such as pipes or rubber tires, which follow a constant deterioration rate until the end of their lives.
4. **Best new:** This trend can be observed as a highly complex system developed by subject matter experts and handed over to users. Hydraulic systems are an example of such a system.
5. **Constant:** This trend is found in complex devices such as electronic systems, and does not show any relationship between failure and age.
6. **Worst new:** This trend is the most common of all the trends described. This applies to complex systems that observe failures in the start of their life cycles. It is also true for plants and systems when they are brought back to operation after their shutdown.

2.5.Maintenance Strategies

Strategy can be defined as a plan to achieve certain goals by utilising a number of inputs, available choices, and outputs [42]. Maintenance strategies are also dependant on many variables, such as type of equipment, nature of maintenance required, nature of business (manufacturing in comparison to processing), cost of equipment, criticality of equipment, and importance of equipment in different circumstances either internal operating conditions or external disturbances such as weather, supply chain disruption, or market conditions. Depending upon the decision criteria, a maintenance department can select one or more strategies from those described below.

2.5.1. Reactive Maintenance

Run-to-failure and breakdown maintenance are the names that fall under the reactive maintenance category. Reactive maintenance is only carried out when the equipment fails, and that result in replacement or a temporary fix for the equipment [43]. Reactive maintenance helps in minimizing the maintenance cost; however, production capacity may vary, quality may suffer, and capital investments may be required to repair or replace the broken assets [43]. This maintenance strategy is generally used for equipment that will not cause any safety or environmental issues or production loss, such as light bulbs [1] (although a light bulb in an alarm system may be critical).

2.5.2. Proactive Maintenance

Proactive maintenance is a strategy that requires maintenance operations to be carried out prior to any failure, which is done by monitoring the equipment health and doing routine maintenance [43]. Preventive and predictive maintenance are two types of strategies that fall under this category.

Preventive Maintenance

In this strategy, maintenance activities such as cleaning, lubrication, and parts replacement are done depending upon the time equipment is used [43]. Some of the advantages of this strategy are increased life and fewer chances of failure, whereas disturbing production on regular intervals is considered a disadvantage for this strategy [43].

Predictive Maintenance

Predictive maintenance comprises two activities:

- Condition monitoring: In this activity, physical conditions such as temperature, vibration, lubrication, and corrosion are used to identify faults and associated maintenance triggers.
- Condition-based maintenance: In this activity, maintenance work is carried out in order to bring the equipment back to normal operating conditions once the monitored physical condition reaches the trigger point [1] [43] [44].

Predictive maintenance is only done in cases where a condition leading to failure is detectable and has an attractive benefit/cost ratio compared to other approaches, and this is considered an additional benefit over preventive maintenance [43] [44].

2.5.3. Shutdown Maintenance

In shutdown maintenance, plants or facilities are shut down for an interval of time while maintenance activities like "inspection, repairs, overhauls, and replacement" are performed [45].

Shutdowns:

- can be planned or sometimes unforeseen and are performed on process plants;
- are carried out in five phases: "planning, initiating, executing, completion, and closeout"; and
- use a computerized maintenance management system (CMMS) as a tool to plan maintenance jobs and track status with the use of a work order system [45].

2.5.4. Contract Maintenance

In contract maintenance, part or all of the maintenance work is outsourced. Outsourcing helps companies to concentrate on their value-added activities, and reduce "operational cost and capital investments" [46] [47]. The decision to outsource maintenance may seem simple and attractive; however, it should be dealt with strategically as it may bring risk and failures along with it [46] [47]. This is a resourcing strategy. The maintenance strategies themselves are all applicable.

2.5.5. Risk-based Maintenance

The purpose of risk-based maintenance (RBM) is to lower the overall risk of an operating organization [48]. Arunraj and Maiti [8] acknowledge the risk-based maintenance (RBM) framework as qualitative, quantitative, and semi-quantitative in their literature review, and mention RBMs' use in industrial applications and transportation systems. However, in this study, we will only discuss a quantitative approach.

Khan and Haddara [7] present an RBM approach that works in three modules:

1. Risk estimation:
    i. All events or combination of events that may lead to a failure are identified.
    ii. Consequences that may occur once the failure event takes place are analyzed on the basis of system performance loss, financial loss, human health loss, and environment and/or ecological loss.
    iii. Probabilistic failure analysis is performed to determine the frequency of the occurrence of a failure with the help of fault tree analysis.
    iv. The output of consequences and probabilistic failure analysis is then used to calculate the value of risk that may occur in the case of a failure.
2. Risk evaluation:
    i. A risk acceptance criterion is defined specific to each risk.
    ii. All risks are compared against their acceptance criteria in order to identify risks that do not satisfy their acceptance criteria.

3. Maintenance planning:

   i. A maintenance plan is developed by performing a reverse fault analysis to determine the required value of failure probability.

   ii. Finally, the developed maintenance plan is verified against the total acceptable risk level of the system.

2.6.Measuring Maintenance Performance

Maintenance functions consume a substantial amount of funds allocated for operations, and should be measured to track their functional performance [49]. Maintenance performance can be measured by using one or a combination of the following parameters: availability, reliability, maintainability, process rate, quality rate, overall equipment effectiveness, cost index, performance index, labour performance index, planned vs. unplanned hours calculation, and inventory value analysis [1] [50].

2.7. Achieving Maintenance Excellence

Reliability-centered maintenance and total productive maintenance models fall under the “achieving maintenance excellence” category.

2.7.1. Reliability-Centered Maintenance

Reliability-centred maintenance (RCM) is a tool that is used to select a maintenance strategy against an asset in a given operating condition [1] [51]. It is used to find maintenance periods by finding equilibrium between risk and required maintenance [52]. RCM generates two outputs: (1) the ranking of an asset within a group of assets, and (2) an applicable strategy such as breakdown, planned, or condition monitoring [53]. RCM can employ elements of other maintenance strategies, as well as modifications of equipment design and operating practice.

2.7.2. Total Productive Maintenance

Total productive maintenance (TPM) aims to optimize overall equipment effectiveness (OEE) with the help of production and maintenance teams. OEE can be measured by using the equation 2-7 [54].

$$OEE = Av \times Pe \times Qr \qquad \textbf{2-7}$$

Where:

Av – Availability

Pe – Performance efficiency

Qr – Quality rate

Production, maintenance, and engineering teams not only improve the equipment’s effectiveness, but also work together to improve equipment design for easy operation and maintenance [55].

2.8. Process Improvement Techniques

Process improvement techniques are also applied in the maintenance function; or they are used to integrate the maintenance function with other departments; the details, along with the technique basics, are discussed below.

2.8.1. Process Mapping

Process mapping is a tool used to map all the processes carried out in a business in order to find the improvement opportunities [56]. Process mapping can be performed anywhere from the macro (organizational level) to the micro (individual activities) level; however, quality and cost of mapping increases with the increase in details [56]. Process mapping not only shows alignment of different business areas, but also shows the dependencies and the resources required to help achieve the future state [57]. Process mapping is carried out in three phases: mapping what you are doing now, which is called the "As-Is model"; the expected model with improvements, which is called the "To-Be model"; and how to get there, which is called "Bridging the chasm" [58].

2.8.2. Total Quality Management

Total quality management (TQM) is a process improvement technique that is based on the philosophy of continuous improvement by keeping the focus on the customer through employee involvement and management strategy [59]. TQM can be implemented using standard models such as the Malcolm Baldrige National Award, the European Foundation for Quality Management, and the Deming Application Prize [60]. Along with the selection of critical factors such as process management or training, success factors need to be properly defined in order to avoid implementation failures [60]. Involvement of the operator is one of the main and commonly-used tools in TQM and TPM [61].

2.8.3. Lean

The Lean philosophy is based on the identification of value-added, non-value–added, and wasteful activities on an individual product production process [62]. The value stream mapping (VSM) technique is used to map the activities related to the process in order to identify the value-added and non-value–added activities in the current process, which is called "current state" [62]. A current-state map is then used to develop a future-state map with the help of lean tools such as cell design [62]. One of the main advantages of using VSM is its capability to link product flow with information flow [62].

2.8.4. Six Sigma

Six Sigma is a process improvement technique that increases the performance of a process by reducing the defect rate to below 3.4 defects for every million opportunities [62].

This reduction in variation is achieved by following a strategy called DMAIC:

- Define: Definition of problem and its cause
- Measure: Data collection with respect to the problem
- Analyze: Data interpretation with the help of graphical and/or statistical tools
- Improve: Improvement strategy to reduce variation
- Control: Monitoring of indicators that may lead to process deviation [63].

Six Sigma is used in maintenance by controlling the processes related to unscheduled breakdowns, labour requirements for preventive maintenance, equipment effectiveness, and customer satisfaction [63].

2.9. Maintenance Models

Apart from maintenance strategies and process improvement techniques discussed earlier in the chapter, different maintenance models are also found in the literature. These models can be broadly categorized as mathematical models, analytical models, and decision support systems.

Murthy, Atrens, and Eccleston [64] developed a strategic management approach based on maintenance as an important area for business success, integrating maintenance with other functional areas with the help of quantitative models.

In their approach, Murthy et al. put emphasis on:

- measuring and assessing the state of equipment state through the use of reliability theory,
- continuously improving the maintenance function to increase availability and reduce maintenance or both,
- using information technology and statistical techniques for data collection and analysis purposes,
- identifying decision criteria for in-house in comparison to outsourcing maintenance, and

- using hierarchal levels for maintenance function along with the respective competencies.

Pun, Chin, Chow, and Lau [65], in their effectiveness-centred maintenance (ECM), used the concepts of quality management, total productive maintenance, and reliability-centred maintenance. In their management technique, Pun et al. used statistical analysis to prioritize the equipment failure modes; employee participation to reduce the frequency of the same failures; and used performance indices such as overall system effectiveness, and individual system effectiveness to measure ECM performance.

Márquez, León, Fernández, Márquez, and Campos [66] developed an eight-phase maintenance management framework. Important aspects of the framework are:

- the use of a balance scorecard to define key performance indicators,
- the use of a probability/risk number to prioritize assets,
- the design and optimization of a preventive maintenance plan,
- life cycle cost analysis, and
- continuous improvement.

Tam and Price [67] proposed a maintenance framework that prioritised the maintenance with respect to three dimensions:

- meeting production targets and satisfying regulatory requirements,
- financial and non-financial losses due to failures, and
- cost for maintenance logistics.

Tam and Price used a time index, maintenance investment index, and budget index as measures to prioritise maintenance and update the maintenance plan.

Cassady, Pohl, and Murdock Jr. [68] developed a mathematical programming framework for the optimization of maintenance activities considering the time and cost constraints. In their model, Cassady et al. assumed that cost and time are known constants for any repair work.

Nagarur and Kaewplang [69] introduced a decision support system (DSS) for maintenance management by using object-oriented approach. In their DSS, Nagarur and Kaewplang used databases to store information such as inventory and schedule, and used mathematical decision-making models based on performance index, statistics, and optimization.

Jardine, Makis, Banjevic, Braticevic, and Ennis [70] used a proportional-hazard model with the Weibull hazard function to estimate the component’s reliability in their decision optimization model for condition-based maintenance. Jardine et al. used the optimization function to minimize the total maintenance cost in their condition-based maintenance software.

Sharma and Sharma [71] built a qualitative framework that targeted reliability and maintainability problems. Sharma and Sharma proposed the use of:

- root cause analysis to identify failure causes,
- failure mode effect analysis to define failure effects on the system performance, and
- fuzzy methodology to rank failures.

Almeida and Bohoris [72] proposed a maintenance decision model in the light of decision theory. Almeida and Bohoris used optimization and sensitivity analysis to make a decision in the presence of information such as data and experts' estimates.

Zaim, Turkyılmaz, Acar, Al-Turki, and Demirel [73] compared corrective, periodic, and predictive maintenance strategies using the analytical hierarchical process and analytical network process models for a newspaper printing facility. Zaim et al. used added value, cost, safety, and implementation as the main four selection criteria.

2.10. Discussion

Maintenance approaches have changed from reactive to optimized maintenance during the twentieth century due to the demand of production, lack of human resources, and maintenance costs [52]. Some of these techniques, along with some process improvement techniques, are discussed earlier in this chapter. The availability of the equipment can be increased by using condition monitoring techniques and directing maintenance at essential levels [52].

These process improvement techniques can be used independently or in a combination to improve industrial processes. These techniques are applicable in a wide variety of industries, and they address various problems. However, VSM is also considered to leave gaps in mapping the process because of its pencil-and-paper approach; furthermore, its considered that the maximum benefit of lean philosophy can only be achieved by applying lean practices along with tools such as 5S and single-minute exchange of die (SMED) [62]. On the other hand, Six Sigma is considered to be a process control tool with lots of statistics being involved, and its implementation can be costly for some businesses [62]. It is also considered that RCM and TPM only deal in short- to medium-term operational issues, and do not take into consideration the operating conditions and their effects on the equipment [64].

By looking at models in the past, it is evident that statistical techniques have been used to perform analysis [64] [65]. Jardine et al. [70] also used the Weibull hazard function to estimate the reliability of components. Murthy et al. [64] further defined the competencies of people working in maintenance departments. Márquez et al. [66] and Sharma and Sharma [71] used the concepts of failure modes and effects analysis in their models. Márquez et al. also proposed the use of the balanced scorecard technique to define key performance indicators along with continuous improvement. Tam and Price [67] used production targets and regulatory requirements to prioritize maintenance in their framework. Nagarur and Kaewplang [69] used the concept of a database to store information related to faults. However, use of information that could affect maintenance decision-making from other departments apart from production is not found in the discussed models. Evaluation of the decisions made in the past is also not seen in the proposed models. Neither did these models discuss the decision-making options related to remote assets. Furthermore, new techniques can be incorporated to push the alarms/alerts to the decision-makers.

The basic requirements of maintenance operations, maintenance techniques, process improvement techniques, and information and data analytics are discussed in this chapter. A high level of importance of data assessment and failure ranking was found during the literature review. It can be seen that there is still a possibility available to include information flow and display techniques such as a dashboard to help a decision-maker obtain the maximum benefit. The use of information flow and display can help the decision-maker asses the various options available to him while looking at the current state of equipment. The current state of equipment in comparison with some statistical analysis can help with the prediction of potential failure modes in the near future. Access to the information such as spares and manpower availability, production target, production schedules, penalty clauses, maintenance schedules, and maintenance required for the equipment in the near future can help the decision-maker to fit the maintenance of specific equipment into the maintenance schedule, keeping in view the other available information. This possibility of adjusting the maintenance schedule in light of production targets and penalty clauses can lead to taking advantage of the opportunity cost of lost production. Another advantage that may be taken by pushing the alarms on mobile platforms is to get any required decision approval from a person who is not available on site.

Along with these advantages, there will be some added costs that may arise for the development of a graphical user interface in light of a dashboard, and for the mobile application to be used on iPhones/iPads. Further costs may arise in keeping the information secure while sending it outside the company’s internal network.

Chapter 3

3. Methodology and Model Development

Maintenance departments face challenges in deciding amongst the various options available for maintenance management. These options supersede each other in different contexts. These alternatives need to be evaluated through the use of some framework in comparison to selecting any one of them based on gut feeling. The decision-making framework developed in this study can be used to sort the data, perform data assessment, retrieve the additional information from other departments, and present them to the decision-maker for an effective decision. This chapter describes the methodology used to develop the decision-making framework along with the development and verification stage of the study.

3.1. Research Methodology

In the initial stage of the framework development, literature related to maintenance practices in the industry was reviewed. Different maintenance management frameworks, along with the maintenance strategies, were reviewed to find available maintenance management options and basic requirements for maintenance management. The study was carried out in three phases. A decision-making framework was developed in the first phase using strut failure as an example. A structured analysis and design technique (SADT) was then used to find out the relationship between different parts of the framework. A process flow diagram was then developed to find out the relationship between the inputs and outputs that had been identified while performing structured analysis and design. Data collection was done in the second phase. Data were collected for two case studies: for the first case study, field data related to tire failure was provided by Syncrude Canada Ltd.; for the second case study, a questionnaire was sent to participants electronically. The questionnaire was targeted to find maintenance and reliability data related to equipment used in the heavy oil production. However, no responses were recorded. Verification of the framework was done using the tire failure data in third phase. Inductive statistics was done on the available tire failure data to find out the framework's applicability. Further results from the reliability analysis performed by Anzabi and Lipsett [32] were also used in the verification of the framework.

3.2. Phase 1—Development of the Framework

The framework was developed with the help of the SADT model. These SADT models are developed with the help of boxes, which are connected with arrows. These boxes can be further decomposed into individual models of required details [74]. In the initial stages of the project, a strut case was analyzed qualitatively for the framework development. The strut is a component of the vehicle suspension system, and is used to provide a dampening effect on the vertical motion of the body, along with support for side-loads during turns [75]. Wear in the seals and control valves occurs in the struts attached to the truck due to their operation in harsh conditions, which leads to struts bottoming out and stops providing the dampening effect [75]. To find a correlation between a sensor value and a failure, data received from the pressure sensor attached to the strut was analyzed. This pressure sensor value could be used for reliability purposes alongside with production monitoring. For production monitoring, these values help in identifying the production quantity by measuring carrying load. And for reliability purposes, probable failures can be identified with the use of properties like mean, variance, or skewness related to pressure sensor values; however, the use of descriptive statistics does not distinguish between different probable faults [75]. Sensor values may see a difference in value depending upon truck operating conditions such as going uphill or downhill [75]. As discussed earlier, this study involved the development of a decision-making framework with the help of the structured analysis and design technique (SADT). In SADT, boxes and arrows are used to create diagrams of the activities involved in a system; a box can be used to represent an activity such as an assembly activity, and arrows can be used to represent the instructions for assembly [10]. A traditional semantic diagram of SADT is given in Figure 3-1.

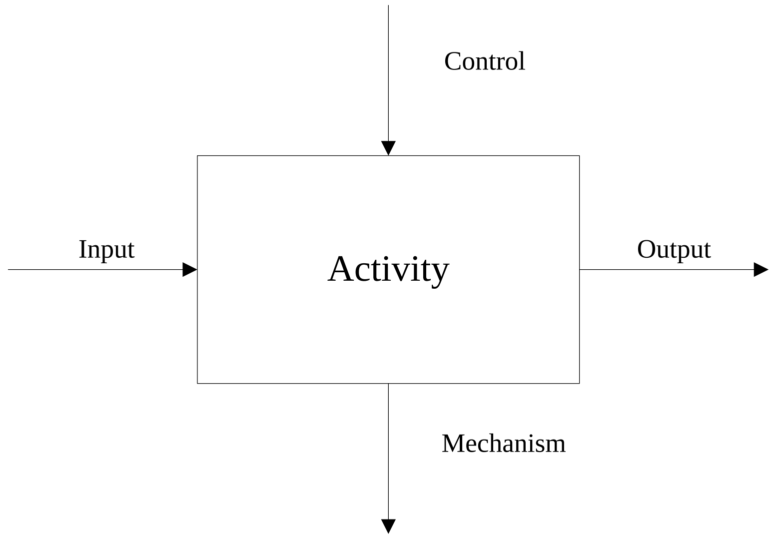

Figure 3-1 Traditional Semantic Diagram for SADT [10]

SADT starts with a high-level view of the system that describes the complete subject in consideration. These high-level diagrams are then detailed with many low-level diagrams [76].

Figure 3-2 shows the first-stage decision-making framework, which was drafted at a higher level.

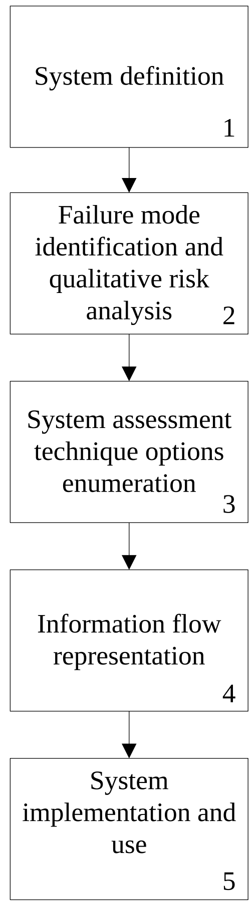

Figure 3-2 High level model for decision making framework

As shown in Figure 3-2, the decision-making framework for maintenance works in five steps:

1. System definition
2. Failure mode identification and qualitative risk analysis
3. System assessment technique options enumeration
4. Information flow representation
5. System implementation and use

The first four steps set up the foundation of the system, and the final one helps the decision-maker make a decision based on the available system assessment and information. Decision analysis is performed to assess the available competitive solutions on the basis of decision criteria, and these solutions can take different rankings depending upon the criteria importance [77]. This framework is developed to help organizations:

- rank failures according to qualitative risk analysis in light of external factors, such as safety or environmental, and internal factors, such as production loss or quality problems;
- relate data trends with failure modes in order to reduce decision-makers' intuition;
- bring information from different departments to the same place in order to maximize the benefit by achieving opportunity cost of lost production; and
- develop a learning module to help improve the system.

In the second stage of SADT, low-level diagrams for blocks 2, 3, and 4 were developed. These diagrams, along with an explanation of the model, are as follows.

3.2.1. System Definition

A system of interest helps develop a boundary line around the system or subsystem [75]. Some of the inputs in defining a system of interest are job requirements/responsibility, production targets, operator's skill chart, maintenance requirements, KPIs for production, reliability and maintenance, quality manuals describing any quality requirements, client and consultant requirements, and information technology requirements. A system of interest could be as simple as a sensor attached to a cold storage for the purpose of temperature monitoring, or as complex as an engine of a haul truck that is loaded with numerous sensors to evaluate and predict its performance, or a costing system used to calculate the cost of an individual motorbike produced in a manufacturing plant.

3.2.2. Failure Identification and Qualitative Risk Analysis

This formulation for maintenance decision-making has been developed by using the concepts of failure modes and effects analysis (FMEA), which was developed in the 1980s to bring consistency in "failure identification and risk ranking against that failure" [75], and qualitative risk analysis, which is used for prioritizing risks depending upon their occurrence and impact [38]. The purpose of qualitative risk analysis is to rank the risks in a quick and cost-effective way in order to perform quantitative risk analyses and risk response planning [38]. However, quantitative risk analysis may be done if the organization wants to calculate overall project risk or needs to determine cost and schedule reserves [40]. Quantitative risk analyses require additional time and resources compared to qualitative risk analyses. For the aforementioned reasons, this formulation is developed by performing qualitative risk analyses only. Other techniques can also be used to rank failures according to their risks. For example, risks can be ranked by using only the guidelines to do FMEA. A graphical representation is given in Figure 3-3.

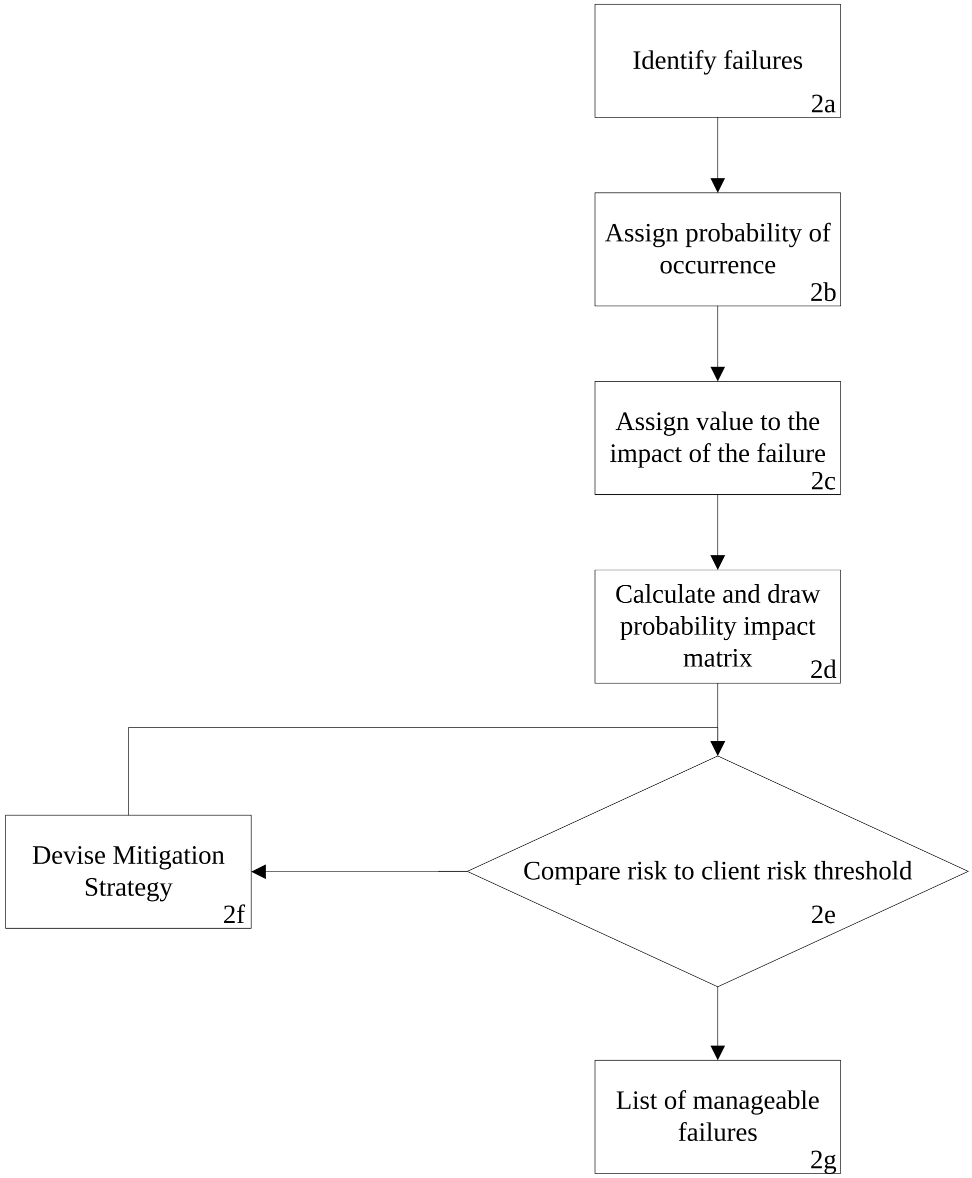

Figure 3-3 Failure identification and qualitative risk analysis

Failure needs to be identified in different operating conditions. Lipsett and Hajizadeh [75] performed a sensitivity analysis by varying the road condition in their experiment on haul truck suspension fault identification. The test was performed using half-car numerical simulation. The results of the sensitivity analysis performed by Lipsett and Hajizadeh [75] showed that by changing the road bed conditions, significant changes in the results were noted, and road condition is an important input for effective fault detection and identification. Failure modes can be defined in certain operating conditions by using a quality technique, such as an Ishikawa diagram [75]. An Ishikawa diagram is developed with the help of lines and symbols in order to find out causes and their effects [78]. An example of Ishikawa diagram is given in figure 3-4.

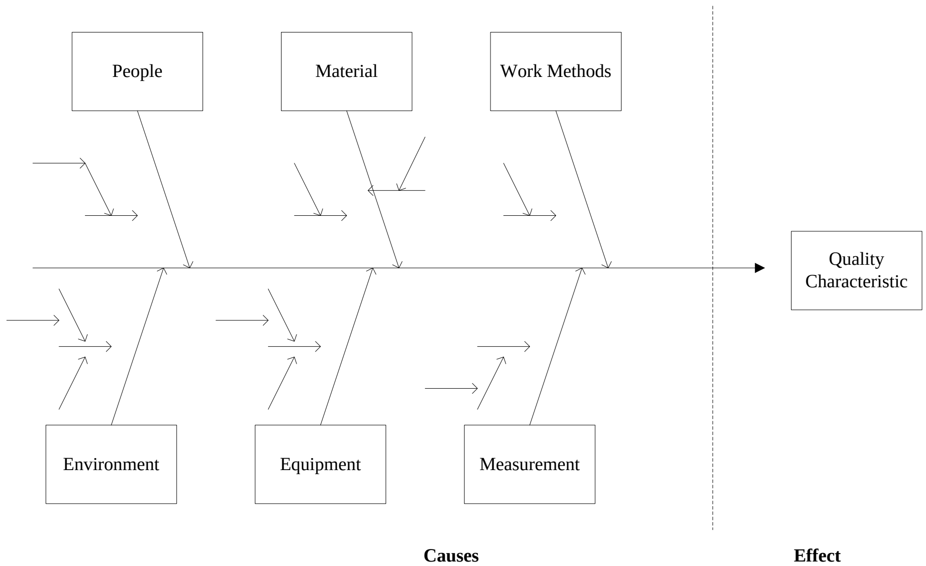

Figure 3-4 Example of Ishikawa diagram [78]

These major causes can be further divided into minor causes by using the brainstorming technique [78]. Historical data, technical specifications of the equipment, maintenance manuals, operating conditions, equipment failure rates, safety requirements, and cause-effect analyses are some of the elements that can help in identifying failure modes and effects.

The importance of each failure mode is then assessed. The probability and impact matrix is a technique used in qualitative risk analysis for risk classification by looking at the probabilities of occurrence and their impacts. Moreover, it helps rate individual risks in particular circumstances [38]. When assigning probabilities and impact values, expert opinion is one of the best strategies to use. Supporting information such as operating conditions, equipment conditions, failure history, mean time between failures (MTBF), production plans, safety issues, and operator competency issues can facilitate the process of assigning values for failure probabilities. Likewise, a database of possible impacts, a product manual, operating conditions, the degree of sensitivity of the failing part, and MTBF can help in assigning values for the severity of impact. The degree of sensitivity of a failing part can significantly change its impact value from minimum to maximum. As discussed earlier in the reactive maintenance case, a bulb can be left to fail without preventive maintenance in a case where it is not critical. However, a bulb failure can result in higher impact if it is used for alarm purposes.

The probability and impact matrix can be developed once probability and impact values are assigned. An example of the matrix is shown in Figure 3-5.

Probability	Impact				
0.90	0.05	0.09	0.18	0.36	0.72
0.70	0.04	0.07	0.14	0.28	0.56
0.50	0.03	0.05	0.10	0.20	0.40
0.30	0.02	0.03	0.06	0.12	0.24
0.10	0.01	0.01	0.02	0.04	0.08
	0.05	0.10	0.20	0.40	0.80

	High
	Moderate
	Low

Figure 3-5 Probability and impact matrix [38]

An important part of the process is to compare the results of the qualitative risk assessment with company's risk threshold values, and then to devise mitigation strategies for the failures that exceed the threshold. A company's risk threshold can be dependent on several factors, such as overall project risk, minimum profit margin, the company's willingness to take risks, and the nature of the business. If the overall project risk is already higher due to other functions of the organization such as procurement or quality, management might want to stay safe from the failures that might add more to the overall risk, and may decide to lower the acceptable risk for operations and maintenance. If an organization is working on a project that has a very thin profit margin, they might want to lower the acceptable value for impact. That is, they might want to avoid failures, which can lead to higher impacts, or in some cases, higher maintenance costs. The company's willingness to accept risk can vary depending upon its history of dealing with risk and how comfortable management is while dealing with risk.

Their acceptance for risk may change according to the available workforce and other technical resources such as maintenance equipment. The nature of the business can also affect the choice of taking risk or not. If a company is operating in a business where reputation is related to safety and failures matter significantly, then the policy makers might lower the acceptable risk thresholds. A simple form of a mitigation strategy could be simply to run to failure. Some of the inputs that can affect the strategy are a list of failures, internal organizational constraints on doing maintenance, external constraints, resource requirements, availability of alternative options, maintenance requirements to restore reliability, mean time to repair (MTTR), MTBF, warehouse information, and logistic availability. Internal constraints can include, but are not limited to, different priorities for maintenance, and approval required from senior management. Resource requirements can include the availability of technical resources and tools. External constraints include import procedures and duration in case a spare part is to be imported into the country. External constraints can also include the availability of technical experts from vendors in cases where maintenance is outsourced. MTTR and MTBF can help in deciding how to adjust equipment maintenance in the maintenance and production schedule. Warehouse information, such as the availability of spares currently in the inventory, as well as incoming schedules for parts along with the number of available parts at the vendor's location, can also affect the mitigation strategy. A list of manageable and ranked failures is an important output of this step.

3.2.3. System Assessment Technique Options Enumeration

System assessment develops relationships between data that is being collected and the possible failure modes. In an operational environment, most decisions are made on a real-time basis, and are a reflection of the manager's experience in that domain. Intuition plays an important role in the decision-making process. Managers rely on their judgement to make decisions, and it has been estimated that forty percent of major decisions are based on gut feelings instead of relying on facts, which can lead to significant errors [79]. The answers from 254 participants with the title of manager or higher were recorded, and the reasons given by the participants for making decisions based on their judgment were the non-availability of good data, that historical data related to the decision and the presence of innovation in the decision were not available, and the fact that decisions are based on qualitative and subjective aspects [80]. This section helps the decision-maker to know some of the facts and historical data prior to making any decision, in addition to the information gleaned from expert opinions. A graphical representation is given in Figure 3-6.

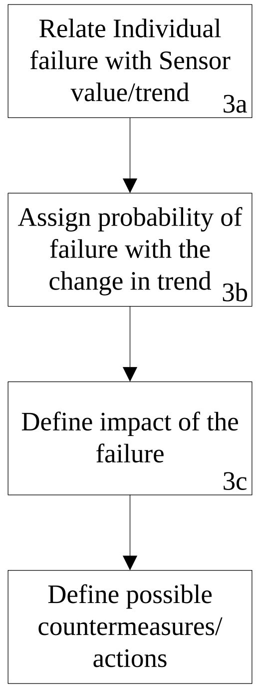

Figure 3-6 System assessment technique options enumeration

The first step in the system assessment is to develop the relationship between a failure and the data set or trend. One of the challenges in the development of these relationships is to have quality data that truly reflect the process. Techniques such as control charts can be used to verify the data quality by observing the process means and value trends. An example of a control chart is given in figure 3-7.

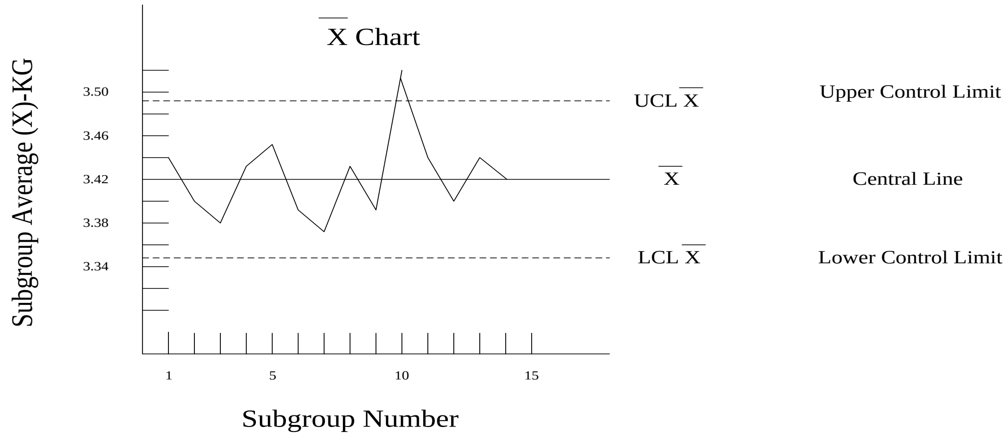

Figure 3-7 Example of a control chart [78]

These observations can further be used to point out the sources of the fault, such as operator incompetency. This quality data can be used to draw frequency distribution diagrams that identify relationships, along with mean calculations and the standard deviation of the population. Mean depicts the average failure rate, and its standard deviation can be used to develop a range for high probability of failure. If these parameters show similarity amongst the data taken over different periods of time or different locations, then assumptions can be made about the existence of a relationship. In order to develop these relations, some of the inputs need to be made constant, such as operating conditions, equipment classification, and operator competency. Advanced modeling and statistical techniques, such as Weibull analysis, can be used to develop and verify these relationships. However, use of these analysis techniques may be more appropriate compared to others in different scenarios.

Once this relationship is developed, probability will be defined for the failures to occur in different ranges for the data values. Some of the inputs that will help to define probability of occurrence are historical data of failure, failure list, failure trend relationship, operating condition, equipment location, equipment conditions, recent usage of equipment, and operator skill chart. Initially, this probability assumption will be based on the expert judgement; however, it can be transformed into more specific numbers once the relationship is tested. A more accurate number of the probabilities can be determined by using reliability modeling. Once a distribution that fits the failure data is found, the probability of the equipment failing within a particular time period can be found using the probability distribution function.

Once the probability of occurrence of any failure is defined, the next step is to define the impact of the failure. The outcome of this process can be a short-term or long-term impact on the asset. A short-term impact could be to stop production in order to replace a failed component such as a fuse, and its downtown time can be calculated from MTTR found in historical data. An example of a long-term impact could be the unavailability of an asset for a longer period of time due to the failure of a critical component that needs to be ordered from the manufacturer of the machine. The MTTR of a system can be calculated by incorporating the time required for the corrective and preventive maintenance activities needed for the different levels of the system [81].

The last step in the system assessment is to define the countermeasures that can be taken against those impacts in case they occur. This process is similar to devising mitigation strategies for any risk. One simple example of countermeasure against the failure of a fuse is to replace it; however, two decisions can take place in different conditions. The first decision is to replace the fuse right away, under the condition that MTTR is low and production is not critical. The second decision is to wait until the shift is over and the truck is free for repair. This decision can be a result of high production demands and/or unavailability of qualified electrician (keeping in mind the case in which a failed fuse does not affect safety of operations). In order to evaluate such decisions, a decision-maker needs information that is outside of his department, such as production breaks, machine idle time, and setup times. The next step in the framework helps the decision-maker to access this required information from other departments depending upon the situation. Warehouse information may be important in a situation where maintenance activity requires spares in order to bring equipment back into operating condition, whereas some maintenance decisions only need information related to production schedule considering all resources are available with the maintenance department.

3.2.4. Information Flow Representation

Decisions are highly dependent on how information is presented to the decision-maker [17]. This part of the framework deals with information flow requirements and the feedback system. A graphical representation of information flow is given in Figure 3-8.

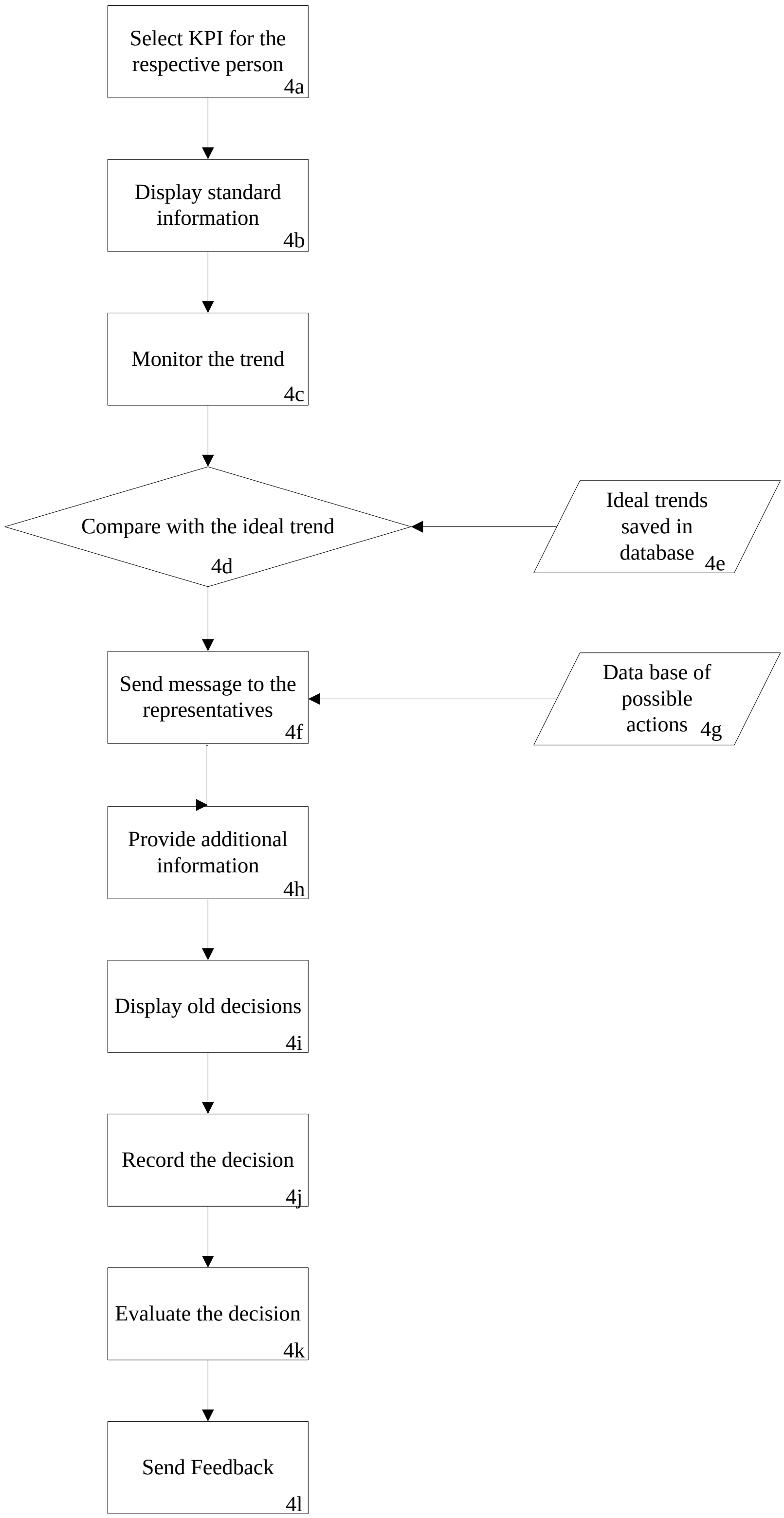

Figure 3-8 Information flow representation

Performance indicators are used to monitor and report performance for technical and management purposes. These indicators are used to monitor the development against certain targets [82]. Selection of these criteria is dependent on the job nature and the company's targets. A company targeted to make profit will have something like "pre-tax profit" as its key performance indicator (KPI), while on the other hand, schools will be more interested in a KPI such as "graduation rate" [82].

To monitor any KPI trend, a system needs to visually provide data from the operations to the decision-maker, along with a ready access to databases where ideal trends are saved. These recent trends are then compared with the ideal trends, and a message is pushed with a potential failure and associated countermeasures in is the event that they are required. One of the methods to present the information package is by using the "dashboard" technique; however other techniques can also be used for visualization, annunciation, and reporting.

A dashboard is a concise summary of current key variables that are important to the business [83]. Dashboards can be used by the managers for decision-making purposes, allowing them to look at the present value in comparison to the targeted value [84]. A dashboard can reduce the amount of wait time for approvals from higher management, as the message can be conveyed easily.

A dashboard can be selected based on the following five criteria [85]:

1. *Data visualization* helps in deciding how much information is needed and how to present it.

2. *Performance indicator* shows the monitored value against the targeted value according to the role.

3. *Dashboard personalization* helps the user adjust the screen and notifications according to requirements and preference.

4. *Audit capability* helps in storing the historical data, and helps the user relate the real-time data with historical data to build their predictive analysis.

5. *Alert/notification* helps in reducing the level of effort required to monitor a job, as monitoring is done only when it is required.

The decision-maker needs to be given the right amount of information, which is dependent on the requirement of the system and the context. Too much information can lead to extra cost, and too little increases the risks involved in decision-making [17]. If not optimum, the best possible maintenance decision needs to take many parameters into consideration, which include data outside the boundaries of the maintenance department. This is possible in a case where a best-possible maintenance strategy would be to run to failure in order to optimize the profit. Some of the additional information parameters that might help in making a maintenance decision are procurement information, incoming quality assurance, warehouse, maintenance schedule, logistics availability, MTTR, MTBF, and production plans [1].

A feedback system needs to be in place once the implementation of the system is successful. This feedback loop can evaluate the decisions, by either a formal review by a maintenance committee, or by a physical inspection of the replaced parts. Upon their approval from the review committee, these evaluations need to be recorded and updated in the database for future use. The review committee may comprise a combination of maintenance technicians, maintenance engineers, and managers.

In the third stage, each of these boxes was further analyzed to figure out its inputs, outputs, controls, and mechanism as required by SADT. These details are given from Figure 3-9 to Figure 3-31.

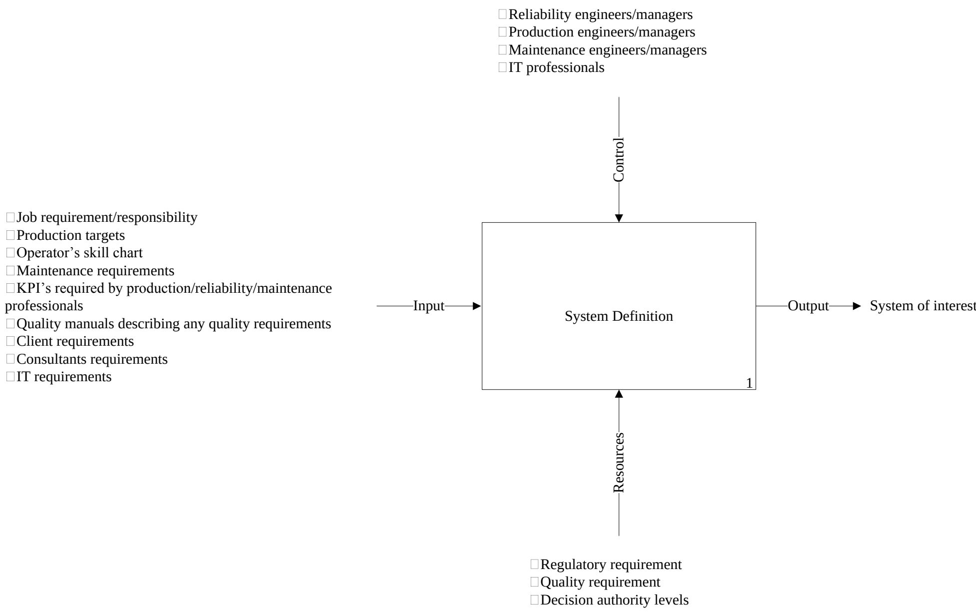

Figure 3-9 SADT element for block 1

The element shown in figure 3-9 is the first part of the framework. It helps define the boundary around the systems. Items listed on the left side of the block are inputs to the block, and are used to produce the output shown on the right side of block. The list shown below the block represents the resources required for the input-to-output transition, and the list on the top mentions the controls required during the process. Not only are the requirements from maintenance and production important in defining the system, but so too are the requirements for maintaining quality. Other stakeholders, such as information technologist and consultants, are also important in defining the system. Furthermore, regulatory requirements also play an important role in defining the boundaries of a system. They help in defining how much risk is acceptable for any operating company, as too much risk may lead to higher profits, but it might affect the reputation of the company.

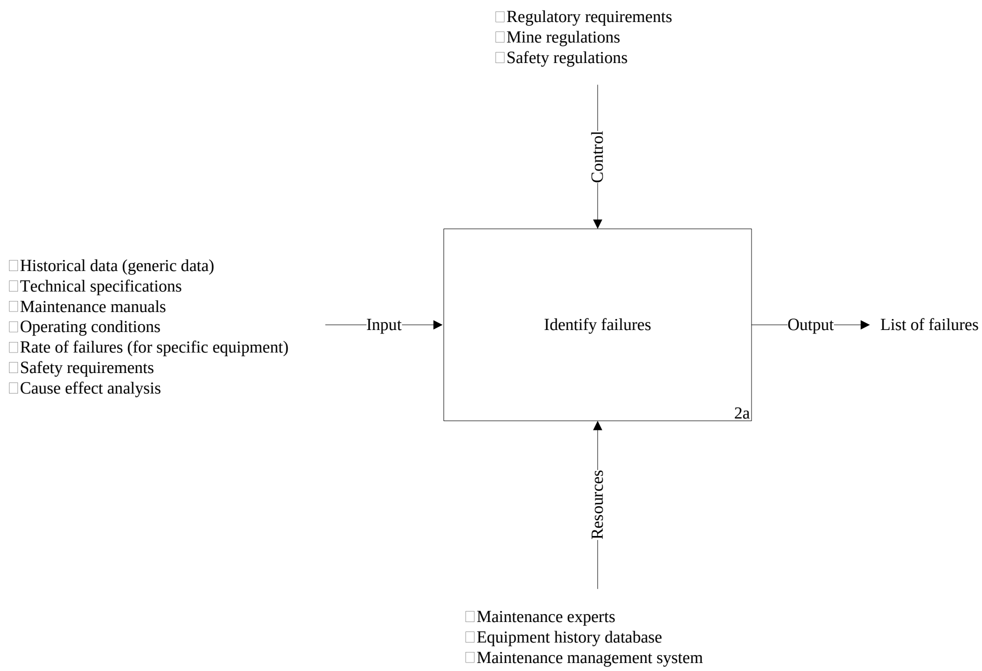

Figure 3-10 SADT element for block 2a

The element shown in figure 3-10 is used for the identification of failures. Failure can be identified by looking at relevant documentation, such as historical data and technical specifications. Some of the failures can also be specific to certain operating conditions, and can be identified by comparing technical specifications with operating conditions. It is necessary to compare these potential failures with safety requirements in order to identify them as soon as possible.

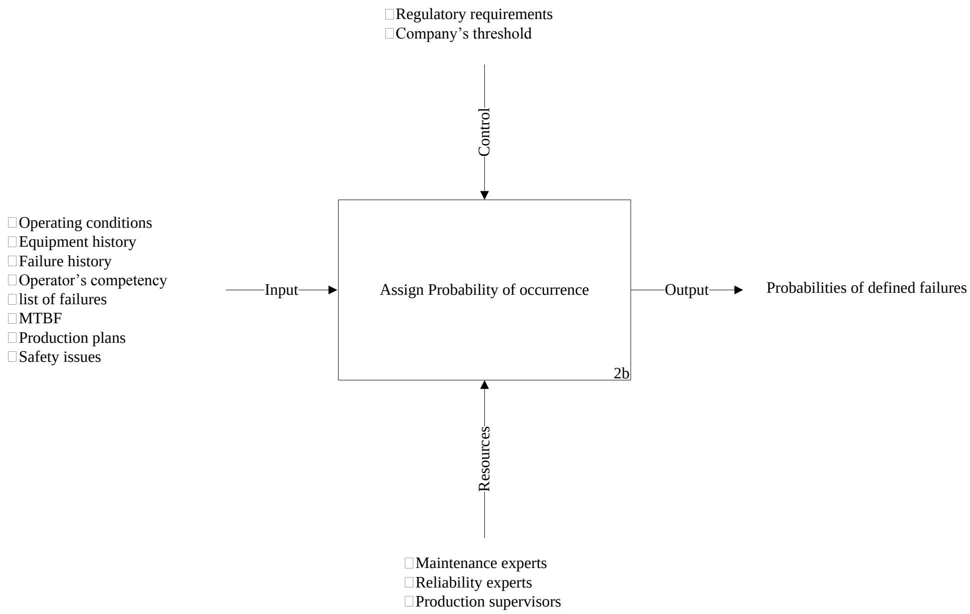

Figure 3-11 SADT element for block 2b

The element in figure 3-11 is used for predicting the probability of occurrence of potential failures. A qualitative or quantitative approach can be adopted depending on the availability of the historical data and its parameters. Some of the failures might be dependent on how equipment is operated; in such cases, operators' competency can play an important role in assigning a value to the probability of occurrence.

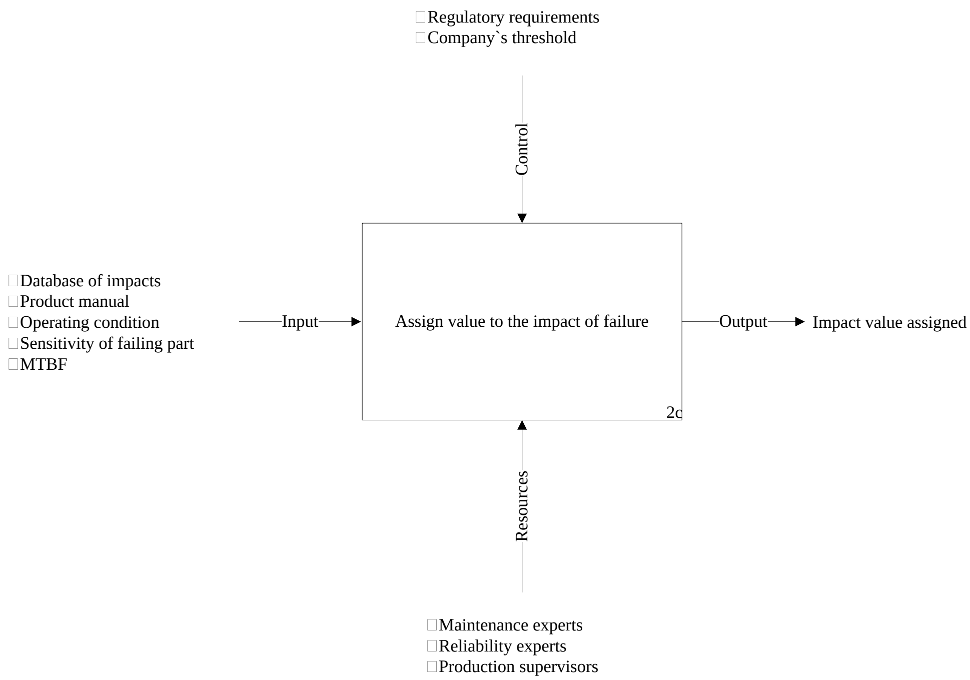

Figure 3-12 SADT element for block 2c

The element in figure 3-12 is used to assign value to the impact in case the failure occurs. Impacts can be defined as loss of operating hours. Sensitivity of the failing part is an important input here, as the failing part may lead to a safety issue.

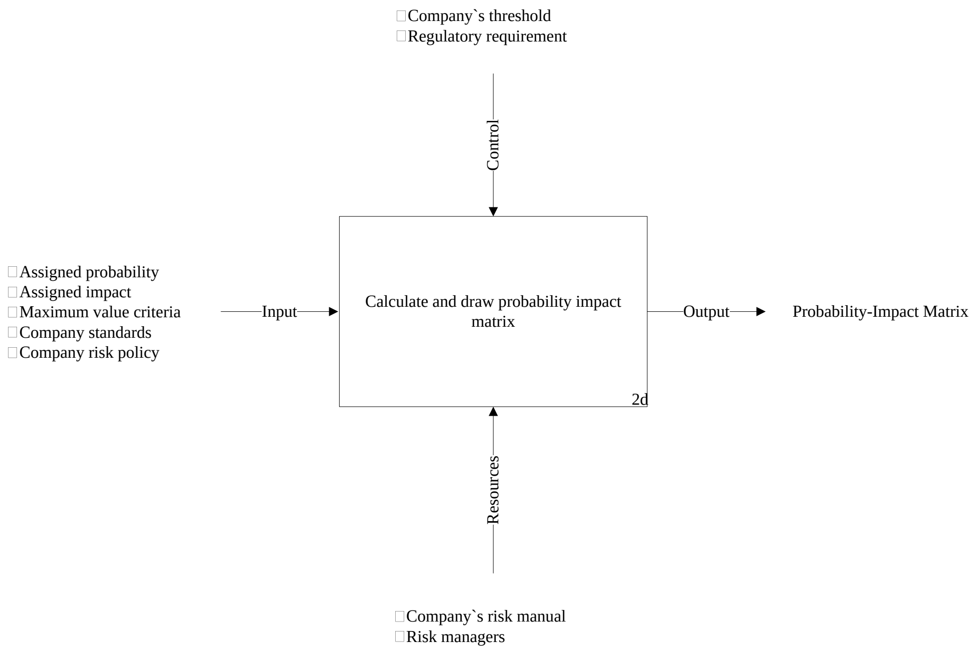

Figure 3-13 SADT element for block 2d

The element in figure 3-13 is used to define the process of calculating and drawing the probability impact matrix. An important input here is the company risk-taking policy, and the definition of how much risk is acceptable to an organization.

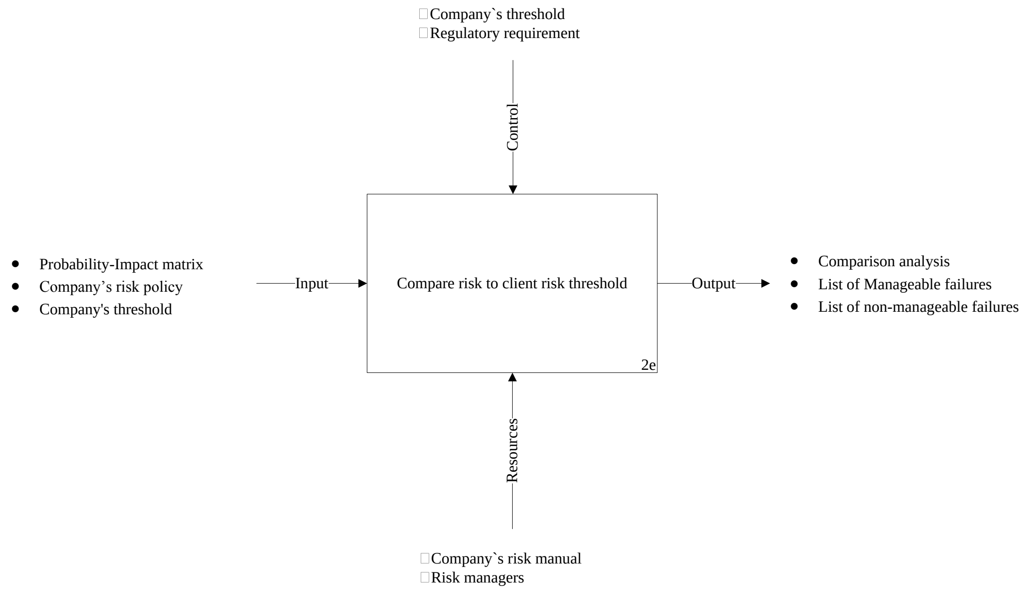

Figure 3-14 SADT element for block 2e

The element in figure 3-14 shows the process of comparing risk associated with failures to the client's risk threshold. The output of this process is very important as it prioritizes the risks, and this prioritized list can then be used to identify the severe risks and resolve any major or safety issues first.

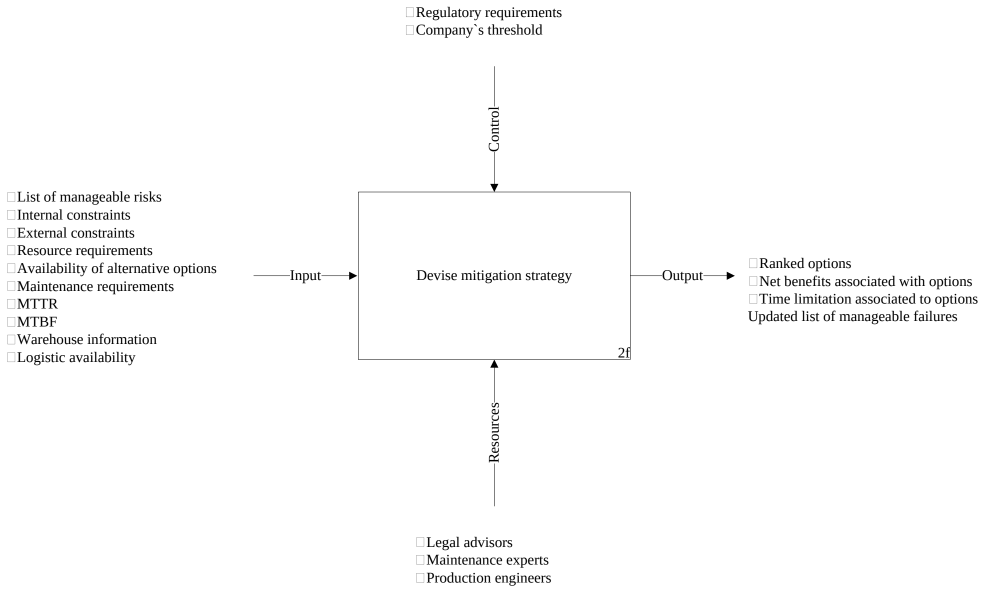

Figure 3-15 SADT element for block 2f

The elements in figure 3-15 show the process of devising a mitigation strategy. Alternative options related to non-manageable failures are evaluated in light of external and internal constraints, availability of maintenance logistics, and resources required. Lists of manageable and non-manageable failures are important outputs. This whole process, from the identification of failures to devising a mitigation strategy against the potential failures, is an iterative process. New potential failures can be identified during the iteration of the process, along with the updated mitigation strategies.

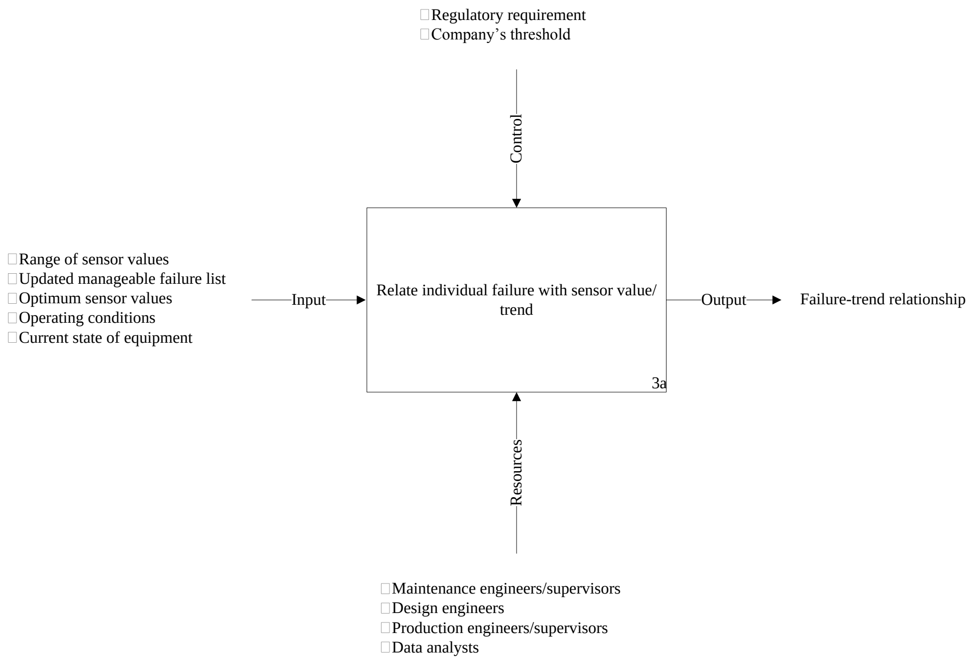

Figure 3-16 SADT element for block 3a

The element in figure 3-16 demonstrates the requirement to find out the relationship between the data and potential failures. Statistical techniques, such as reliability modeling, can be used to identify the relationship between data and failures. An important input is the operating condition, as it may change some of the sensor values. It is important to filter such kinds of data in order to find the right relationship between failures and collected data.

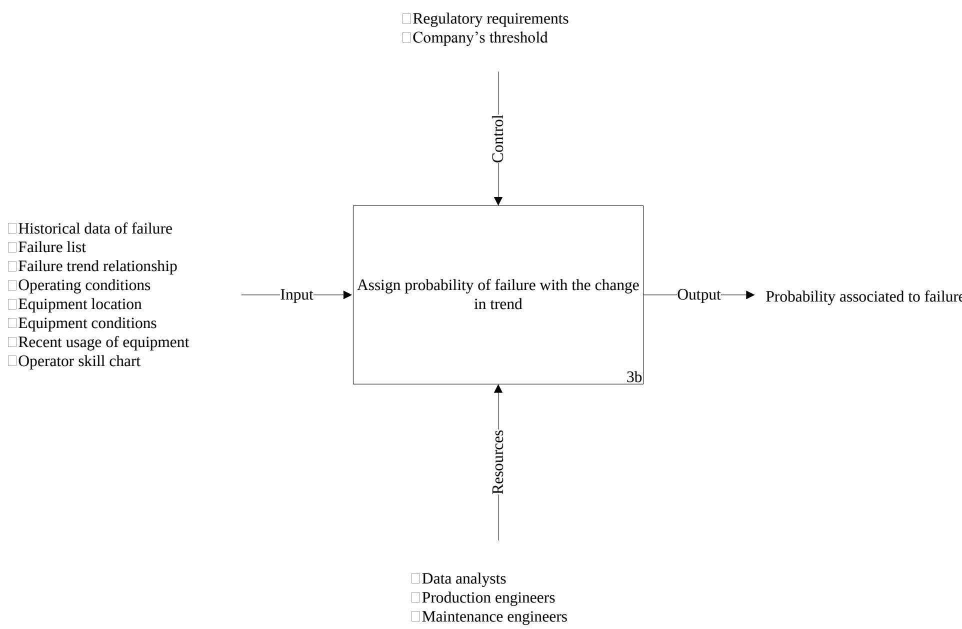

Figure 3-17 SADT element for block 3b

The elements shown in figure 3-15 describe the process of assigning the probability of failure along with the change in the value of the sensor or with the useful life of the equipment. Probability can be assigned by looking at the historical data of failures. This failure data can be analyzed qualitatively or quantitatively to assign the value of probability that the equipment will fail when it reaches a certain useful life or when it will have a sensor value. A probability distribution function can be found by using reliability modeling, which can then be used to assign the probability of failure.

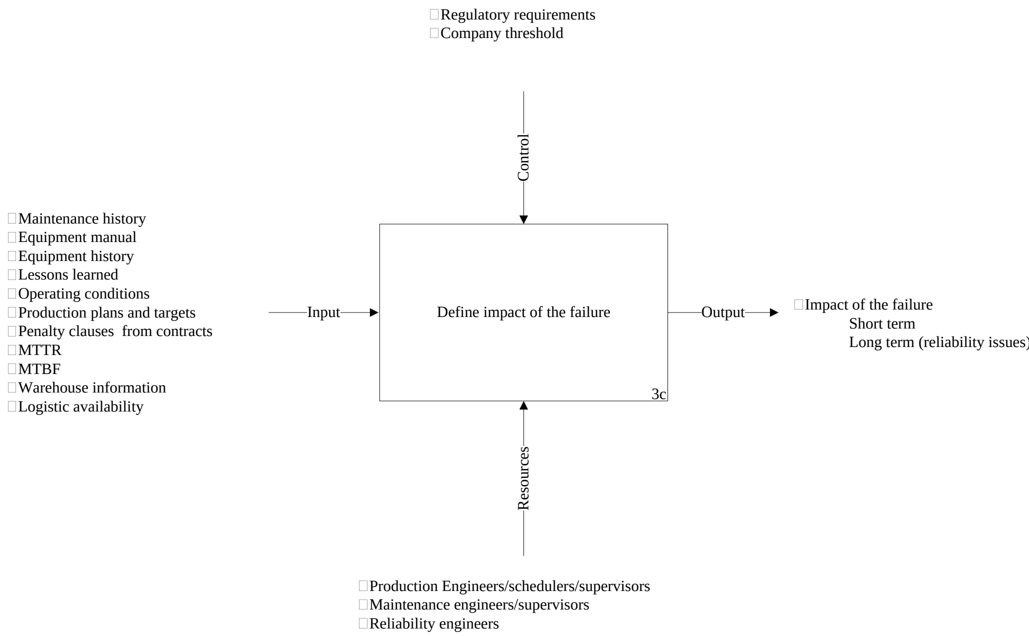

Figure 3-18 SADT element for block 3c

The element in figure 3-18 is used to define the impact of a failure. These impacts can be short-term or long-term. Impacts can be defined from the historical data related to unavailability of the equipment, resultant loss in production due to non-availability of equipment, availability of spares, and availability of maintenance logistics.

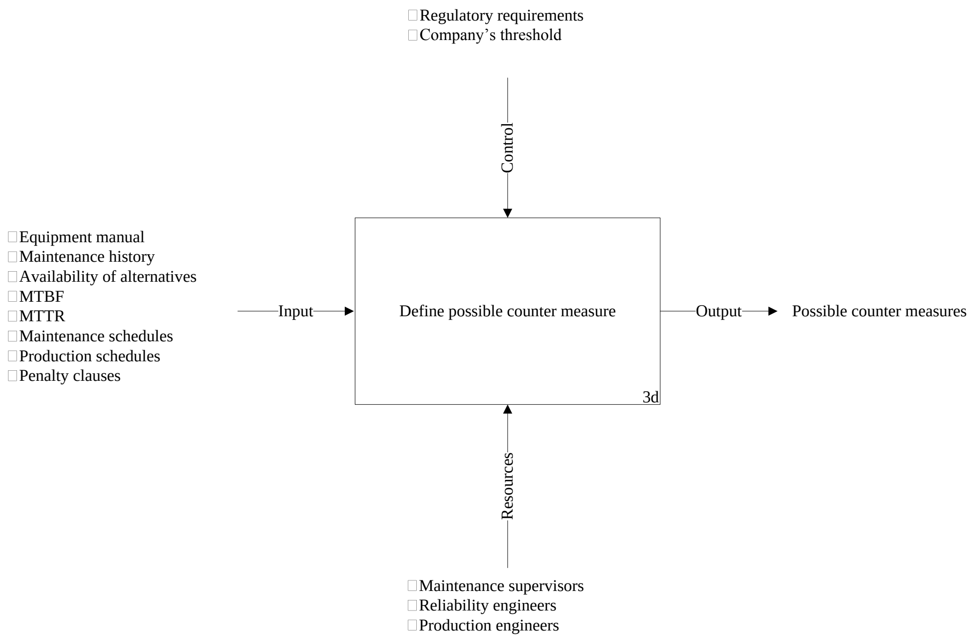

Figure 3-19 SADT element for block 3d

The element in figure 3-19 is used to define the possible counter-measures in cases where the data shows that the equipment is reaching close to failure. These counter-measures can be defined according to production and maintenance schedules, depending if the maintenance can be carried out without disturbing the production or at least with lesser effect on the production. An important input here is the penalty clauses, if there are any. Penalty clauses can lead to changing the decision, such as using the equipment in its current state to meet production targets, although more resources may be required to repair it later.

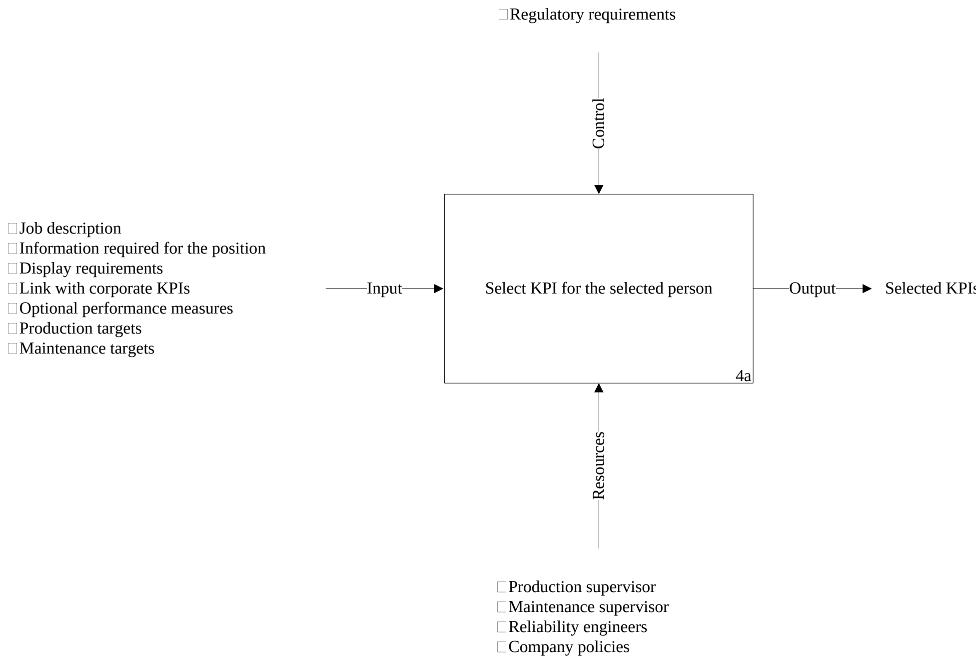

Figure 3-20 SADT element for block 4a

The element in figure 3-20 is the first process in information flow representation. This element describes the procedure for selecting key performance indicators (KPIs). These KPIs are dependent on the job description of the person looking at them, and must be in relation with corporate KPIs. Information from the related departments that may affect the KPIs should be present.

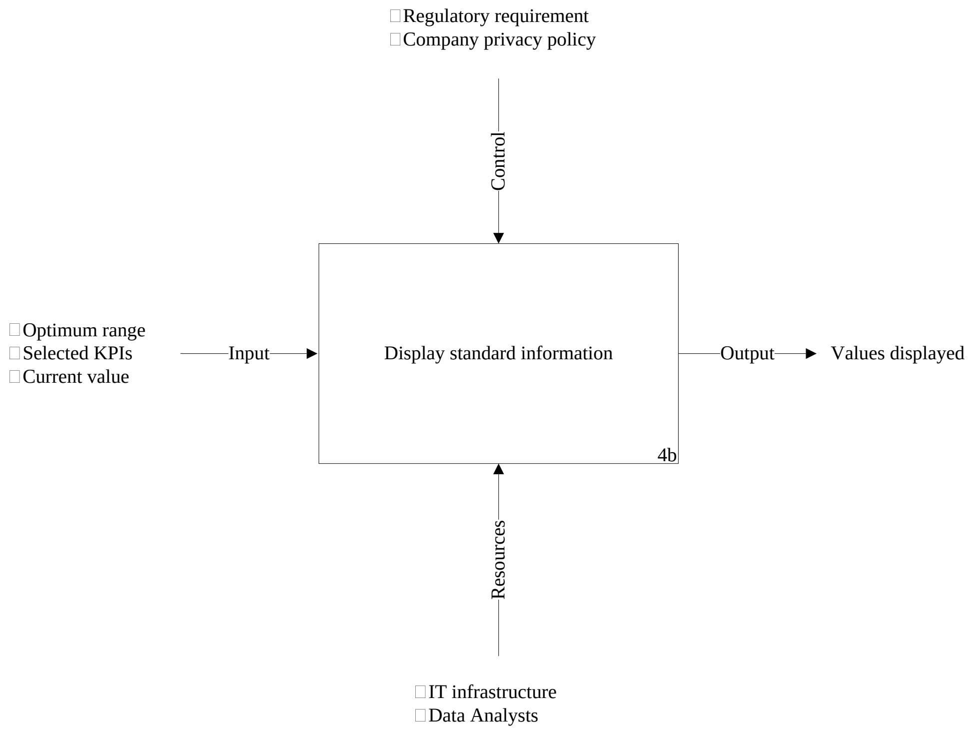

Figure 3-21 SADT element for block 4b

The element in figure 3-21 shows the requirements for displaying standard information on the dashboard. Standard information includes the selected KPIs, and equipment-related information, such as their useful life in comparison with their total useful life.

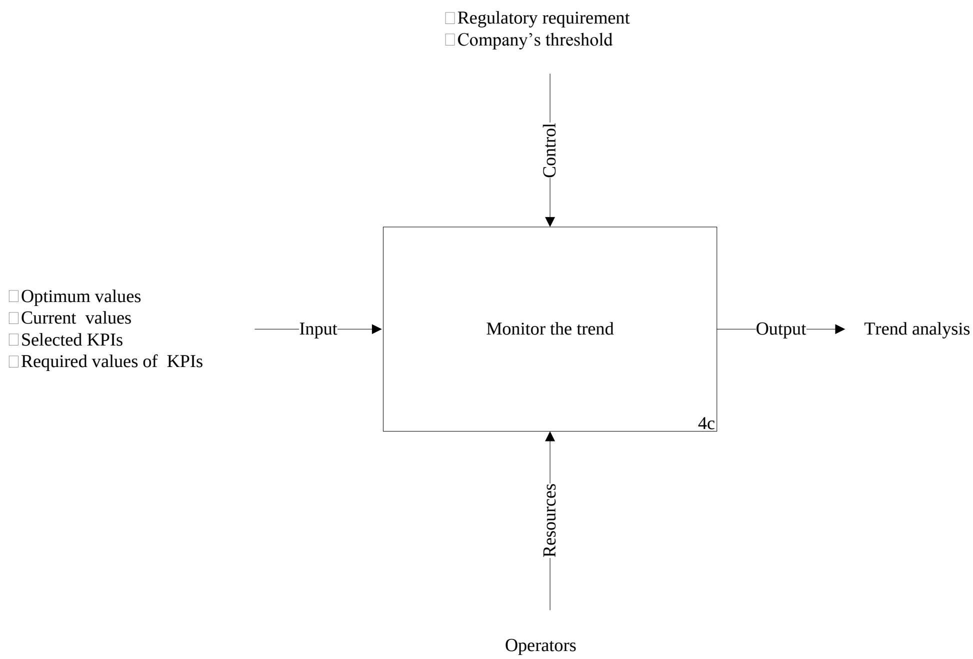

Figure 3-22 SADT element for block 4c

The element in figure 3-22 represents the process of monitoring the trend. Trends related to equipment under observation and KPIs are monitored from the operations.

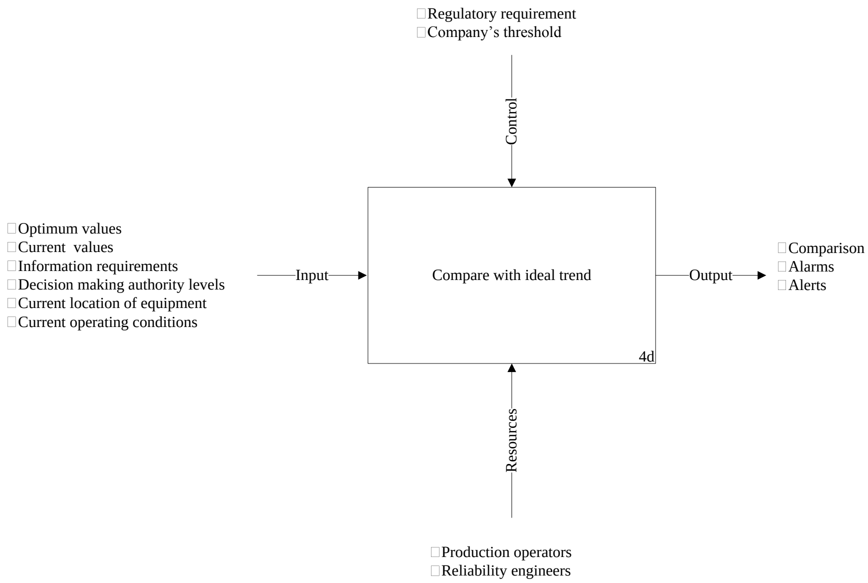

Figure 3-23 SADT element for block 4d

The element in figure 3-23 shows the process of comparing the values with the ideal or optimum values. These trends are compared in the presence of the current location of equipment and current operating conditions. This process generates alarms/alerts related to variations in the trend.

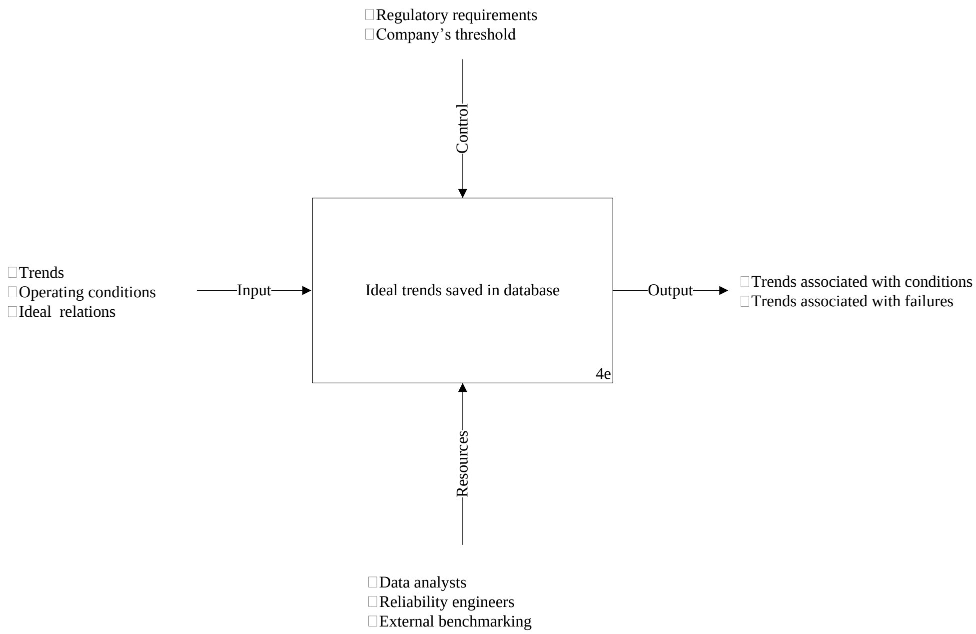

Figure 3-24 SADT element for block 4e

The element in figure 3-24 shows the process of storing the ideal trends in the database. Trends in the form of an ideal relationship to operating conditions are stored in the databases, along with the information of how these trends lead to failures.

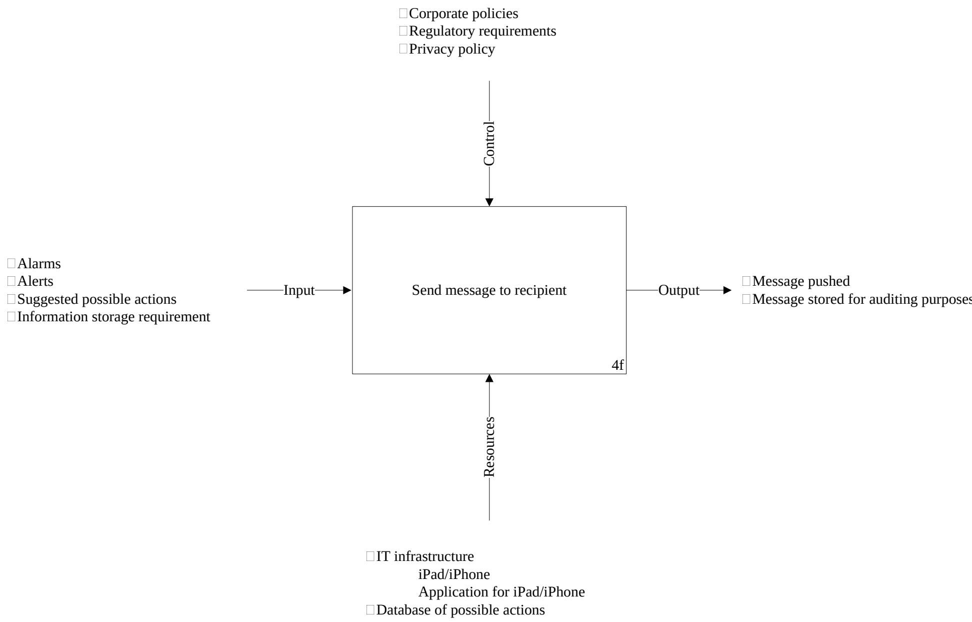

Figure 3-25 SADT element for block 4f

The element in figure 3-25 shows the process of sending a message to a recipient. Alarms/alerts generated in block 4d, along with the suggested possible actions, are pushed to the decision-makers using the decided-upon technology. Messages can be pushed via the iPad/iPhone application.

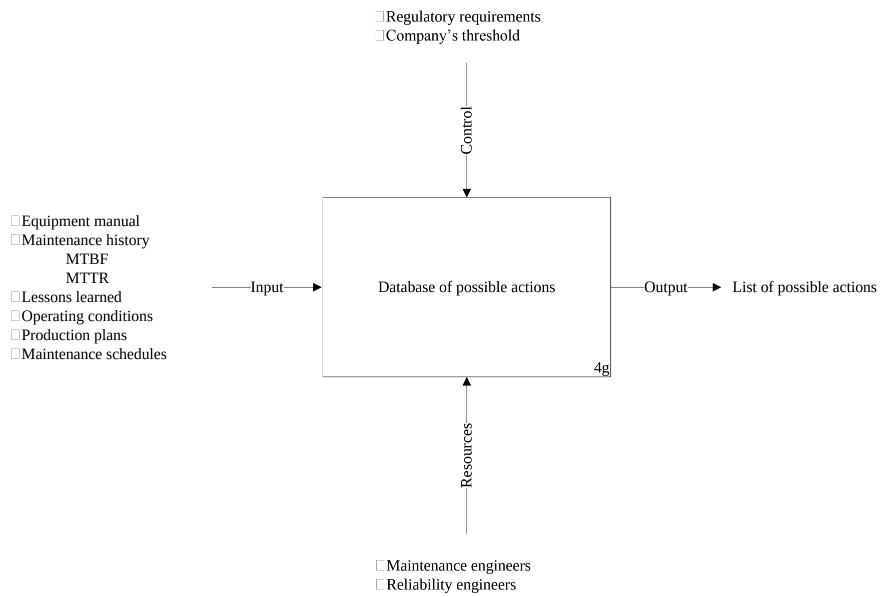

Figure 3-26 SADT element for block 4g

The element in figure 3-26 shows the definition of a database of possible actions. These possible actions are developed in light of production and maintenance schedules, and operating conditions. These options are screened from the available possible actions found in equipment manuals, and from maintenance history.

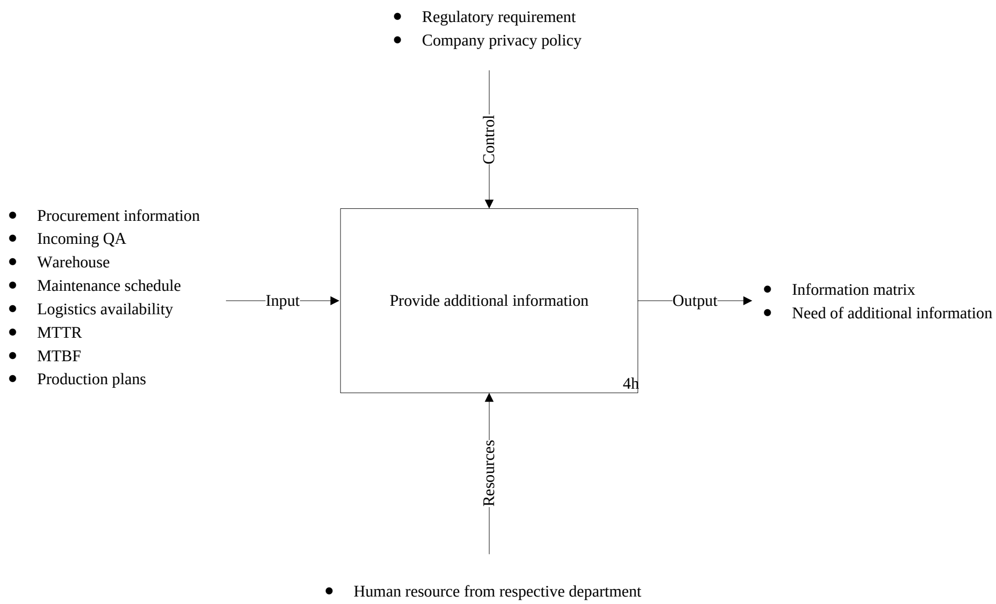

Figure 3-27 SADT element for block 4h

The element in figure 3-27 highlights the importance of additional information that includes information not related to equipment or sensor values. This additional information can come from the warehouse, production, maintenance function, and incoming quality.

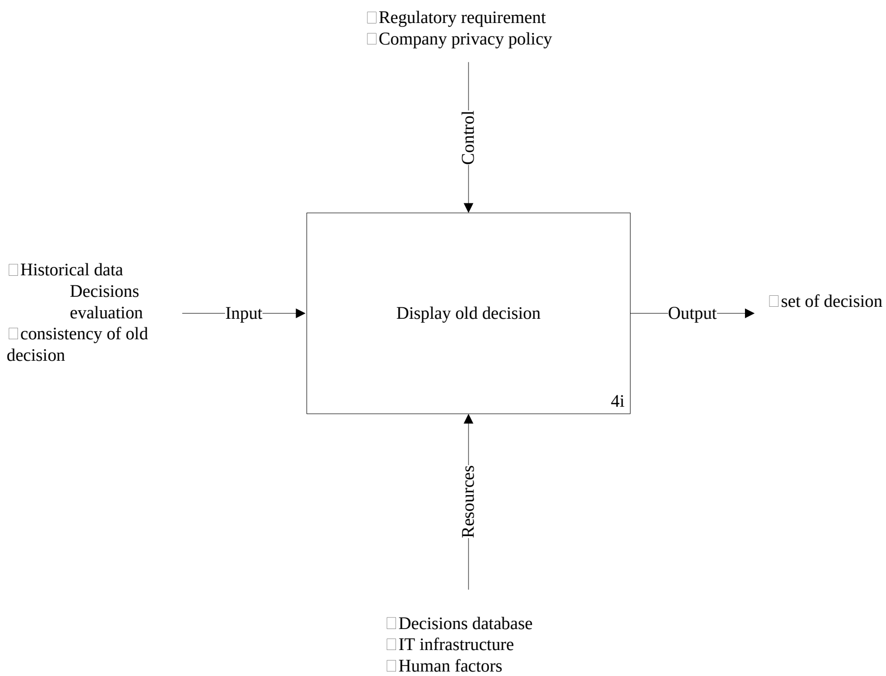

Figure 3-28 SADT element for block 4i

The element in figure 3-28 shows the process of forwarding the decisions from the past. This decision set is forwarded to the decision-maker along with the additional information. These decisions are sent along with its evaluation, which contains details such as under what circumstances this decision was taken and information related to the effectiveness of the decision in the past.

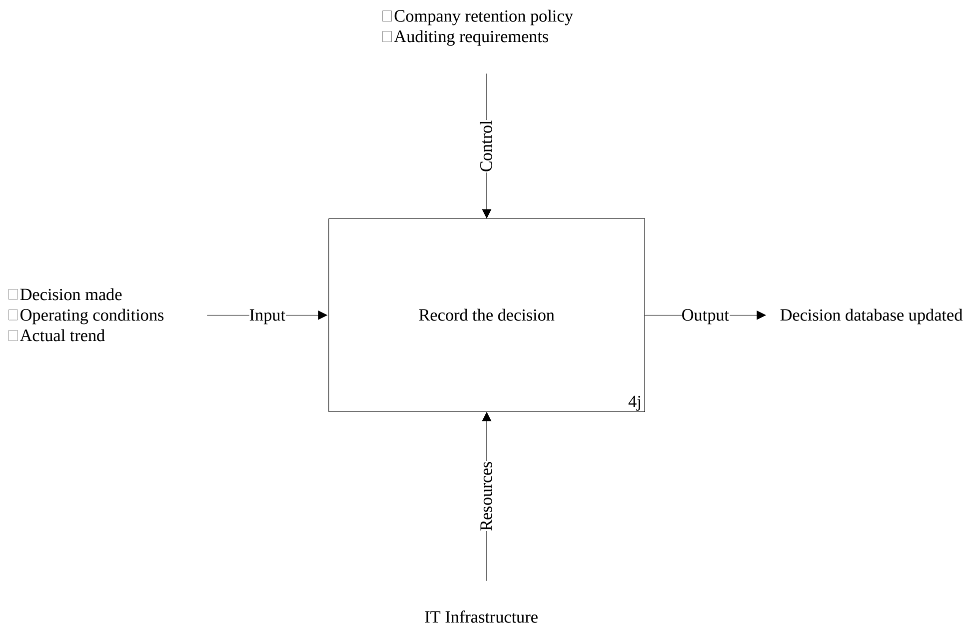

Figure 3-29 SADT element for block 4j

The element in figure 3-29 is used to record the final decision. This process not only records the decision, but also stores information related to operating conditions, as well as the actual data value, along with the trends that lead to failure.

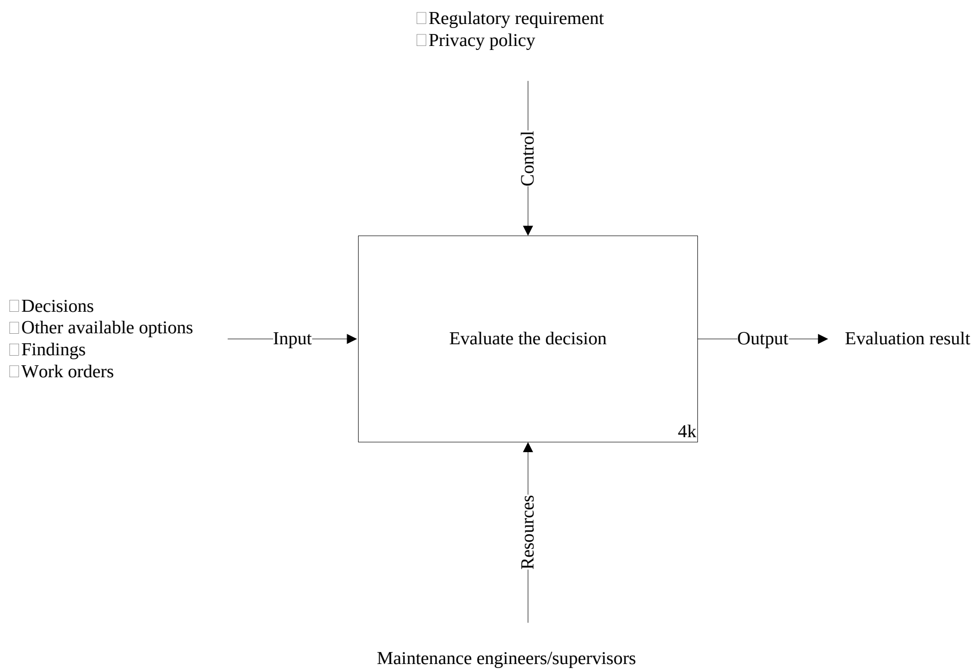

Figure 3-30 SADT element for block 4k

The element in figure 3-30 explains the process of evaluation of the decision. This evaluation is performed by using the information found during the maintenance, and the data present in the work orders. This information is then used to analyze the applicability of the decision, and to see how an alternative decision could have been better in that moment of time.

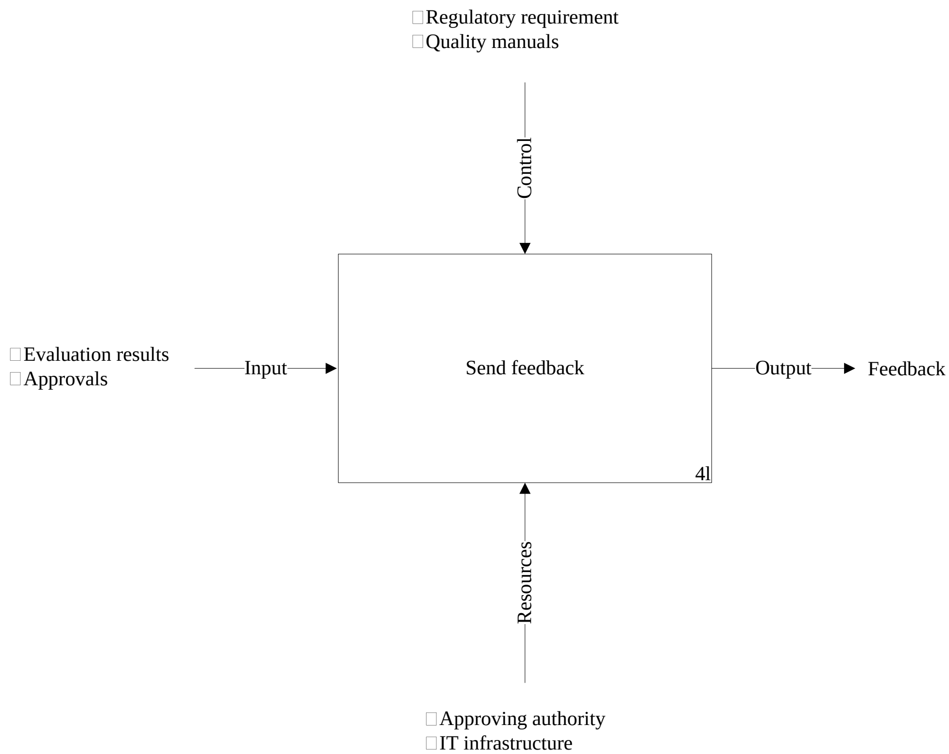

Figure 3-31 SADT element for block 4l

The element in figure 3-31 completes the framework by finalizing the decision and approving the evaluation results. These results can then be stored in the database and presented to the decision-maker, along with the available alternative if a similar situation arises again during the operations.

After the completion of the SADT activity, all of the boxes were mapped together to find out the relation between their inputs and outputs, and to figure out the most common inputs. A map representing all the inputs and outputs can be found in figure 3-32.

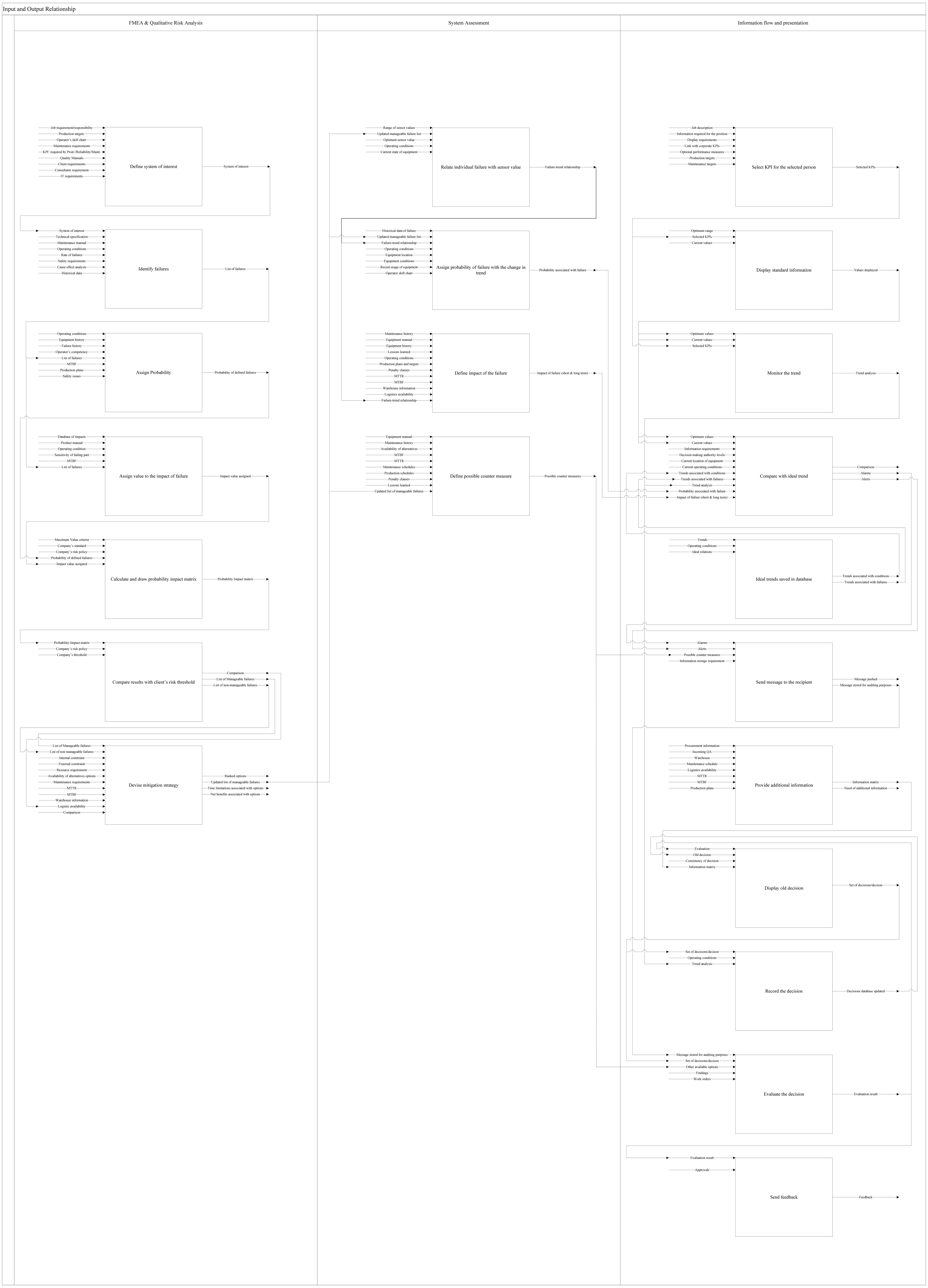

Figure 3-32 Input and output relationship

Figure 3-32 not only shows the input and output relationship between the steps in low level diagram of the framework, but also shows how different outputs move to the different steps in framework. Based on the system of interest, list of failure that can be managed during the operations are developed with the use of second step of framework, which is failure identification and qualitative risk analysis. It also shows how an initial list of failures is updated after performing probability impact assessment. Base on the list of failures identified in the second step, system assessment is carried out in the third step. Probability associated with failure, impact of the failure, and possible counter measures are the outputs that go into fourth step that is information flow representation. Final decisions along with its evaluation are the important output for information flow representation. Techniques used in the framework development are examples of possible approaches for carrying out these activities; however, a range of techniques and procedures may be used, depending upon the industrial application and the equipment under consideration.

3.3.Phase 2—Data collection for Case Study 1

Shovels and trucks are used in opencast mines [86]. To achieve the production targets, it is particularly important to focus on the reliability and availability of the shovel-truck system [86]. Haul trucks with the capacities up to 400 tonnes are used in large operations due to the economy of scale and reduced personnel costs [32]. Reliability of truck tires plays an important role in achieving production targets in opencast mines [86]. Bias ply and radial are two main types of tires [87]. Truck tires have the following characteristics: they are 4 m in diameter, have a mass of up to 5 tonnes, and can cost around USD $60,000 [32]. Some of the main components of tire are tread, carcass, belts, and bead [87]. Under-inflation, over-inflation, tire bleeding, heat generation, speed, and haul length are some of the factors that can affect tire life [86]. Tread cut, tread separation, and sidewall cut are considered to be three common failure modes [32]. The importance of haul truck tires can be seen from the fact that a single tire can take 20% to 25% of the operating cost associated with haul trucks [87]. Along with the operating cost, failure of a tire can result in losing control of vehicle, and in the case of an explosive loss of pressure, it can raise safety issues for drivers and the maintenance team [32].

This case study was done with the help of data supplied by Syncrude Canada Ltd., which were collected at two of their operational locations: the Aurora mine and the Base mine. Data were provided for the tire failures over the period of the year 2005 to 2010. It appeared from the data analyses that the majority of the failures occurred between 3000 and 8000 hours of operation. Tire failures that occurred between 3000 and 8000 hours were then used in the framework verification phase.

3.4. Phase 3—Verification of the Framework by Case Study 1

Data from the first case study was used to map the framework.

3.4.1. System Definition

The following sections of the case study will be looking at tire lifespan and associated failures. On average, a tire is supposed to last for 8000 hours or more [88]. Failure of tires can lead to an increase in downtime of the truck fleet, which can limit the production capacity in the oil and gas industry.

3.4.2. Failure Identification and Qualitative Risk Analysis

Failure identification can be done in many ways; however, in this case study, historical data were analyzed to find different failure modes. A reliability study on the same data was carried out by Anzabi and Lipsett [32]. From the data, the top five failure modes were selected and shown below in the charts of Figure 3-33 for the Aurora and Base mines.

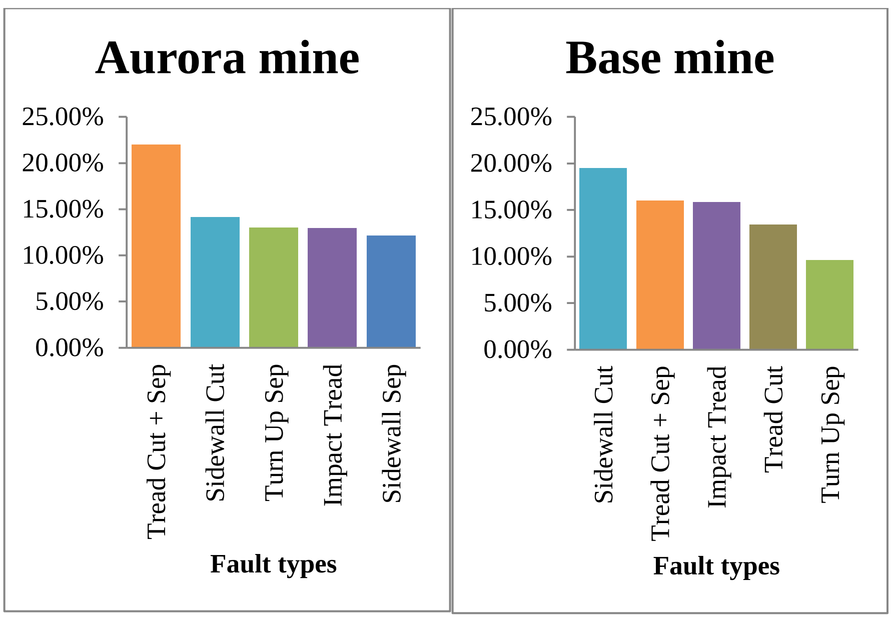

Figure 3-33 Top five failures for Aurora and Base mines

The above graphs do not show consistency amongst the failure distributions in the population in the two different mines. Possible reasons for these variations include operator skill level, operating conditions, and maintenance practices.

Since there is only historical data available to assign the probabilities, it is not possible from the data to determine the root causes of the failure distributions. From the derived data, the probability that these failures will occur in the future is high, and the operating company should have a well-defined strategy in place for these failures. An interesting finding is that these top five failure modes cover almost 75% of the time population in both mines. Considering that operating conditions and operator skill levels remain the same, it can be assumed that during operation, these failures will occur again, and the probability of failure for the Aurora and Base mines could be as shown in Table 3-1.

Table 3-1 Probability of occurrence of failure

Aurora mine		**Base mine**	
Failure	**Probability**	**Failure**	**Probability**
Tread Cut + Sep	0.7	Sidewall Cut	0.7
Sidewall Cut	0.65	Tread Cut + Sep	0.65
Turn Up Sep	0.6	Impact Tread	0.65
Impact Tread	0.6	Tread Cut	0.6
Sidewall Sep	0.6	Turn Up Sep	0.6

Impact values are calculated according to where and in which conditions equipment will be used. However, knowledge of operating conditions, maintenance logistics availability, and mean time between failures were unknown; therefore, a specific value to impact cannot be assigned. Impact on production is defined based on the criticality of meeting production targets and

MTTR. Impact can take the following values depending upon the situation described in Table 3-2.

Table 3-2 Impact value based on production criticality and MTTR

Impact Value	Situation	
	Production Criticality	**MTTR**
0.8	High	High
0.7	High	Low
0.6	Low	High
0.5	Low	Low

For this case study, it is assumed that production criticality and MTTR were low; therefore, an impact value of 0.5 can be assigned. By using this value of impact, probability-impact values displayed in Table 3-3 were calculated for comparison with the company's threshold.

Table 3-3 Probability-impact values

Aurora mine			Base mine		
Failure	**Probability**	**Prob-Impact**	**Failure**	**Probability**	**Prob-Impact**
Tread Cut + Sep	0.7	**0.35**	Sidewall Cut	0.7	**0.35**
Sidewall Cut	0.65	**0.325**	Tread Cut + Sep	0.65	**0.325**
Turn Up Sep	0.6	**0.3**	Impact Tread	0.65	**0.325**
Impact Tread	0.6	**0.3**	Tread Cut	0.6	**0.3**
Sidewall Sep	0.6	**0.3**	Turn Up Sep	0.6	**0.3**
	Impact	0.5		**Impact**	0.5

As the company's threshold for taking the risk was not available and these values appear low in comparison to any probability-impact matrix, all these failures were considered manageable failures for the company.

3.4.3. System Assessment Technique Options Enumeration

This part of the framework was developed to find the relation between the tire life in operation and selected tire failures. For this purpose, the top three common failures, namely tread cut + sep, sidewall cut, and impact tread, were selected. As mentioned earlier, the estimated tire life is 8000 hours in operation [88]; however, from data analysis it appears that this was not true in most of the cases. Failure percentages of the selected three failures over the lifespan of tires are given in Table 3-4.

Table 3-4 Percentage of failures over lifespan of tires

	Tread Cut + Sep		**Sidewall Cut**		**Impact Tread**	
Hours	Aurora	Base	Aurora	Base	Aurora	Base
0–3000	13%	27%	5	16%	17%	27%
3000–8000	**82%**	**68%**	**93%**	**76%**	**80%**	**67%**
8000+	6%	5%	2%	9%	2%	6%

Table 3-4 depicts that less than 10% of these failures occur after the tire reached its nominal useful life. Another important piece of information that can be derived here is that the majority of these failures occur between the range of 3000 to 8000 hours of usage. As seen earlier, the same failures at two different sites had a different share in the population. A similar observation can be made here that same failures have a different percentage share in the same denominations at different sites. Operating conditions and operator skill level can be the reasons for this variation. Before proceeding for trend analysis for the 3000 to 8000 hours denomination, it was assumed that the failures that occurred in the range up to 3000 hours were caused by severe operating conditions or due to lack of operator skill. Furthermore, failures that occurred after the completion of expected life will not be considered.

To relate the trend of tire failures with tire life, frequency distribution graphs were developed for the selected three failures against the hours in operation for the Aurora and Base mines. A bin size of 100 hours was selected to plot these graphs in accordance with a weekly inspection carried out by the organization. These graphs are shown in Figures 3-34 to 3-39.

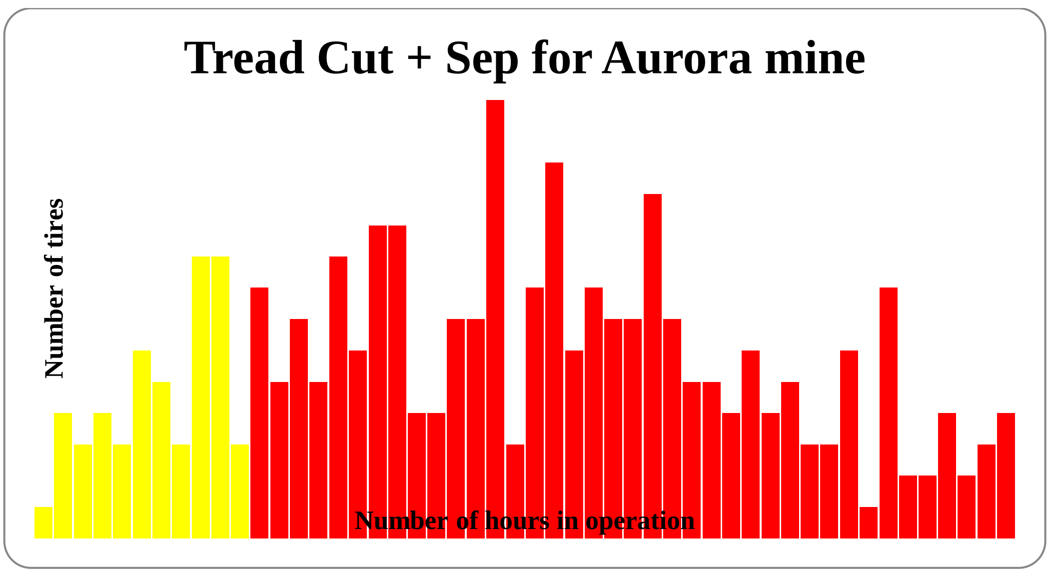

Figure 3-34 Frequency distribution for Tread Cut + Sep for the Aurora mine

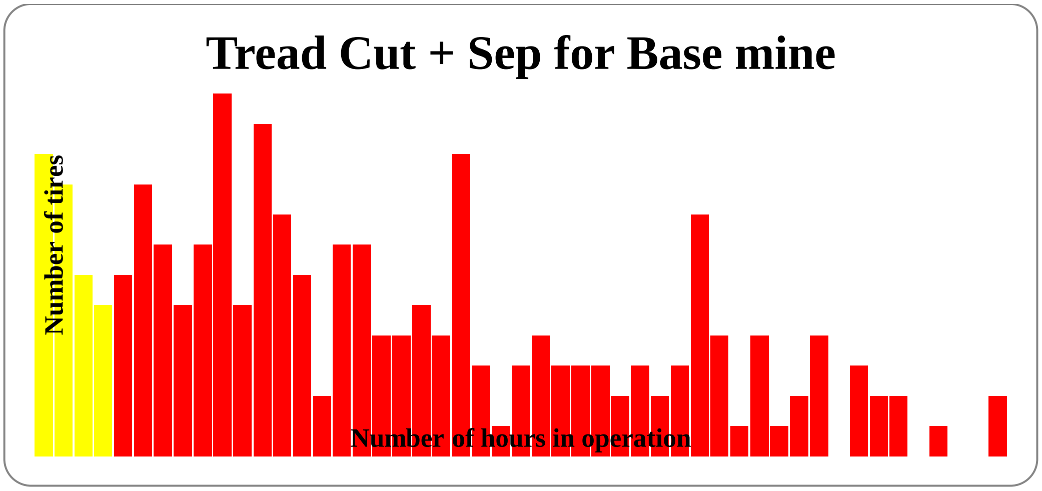

Figure 3-35 Frequency distribution for Tread Cut + Sep for the Base mine

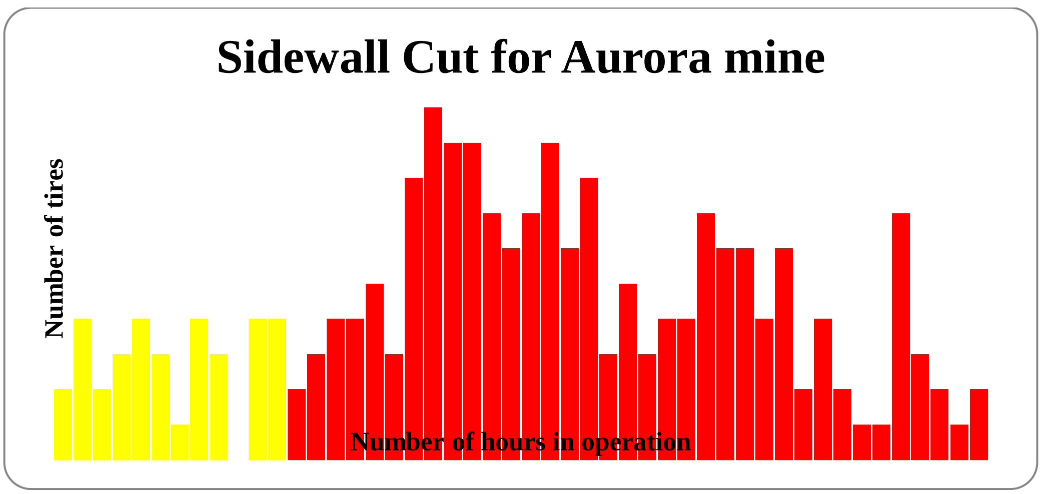

Figure 3-36 Frequency distribution for Sidewall Cut for the Aurora mine

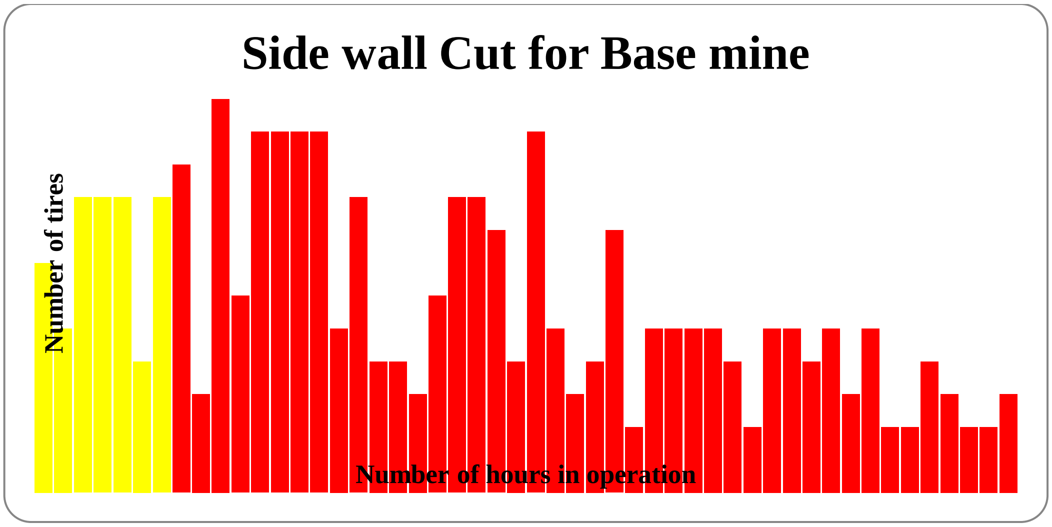

Figure 3-37 Frequency distribution for Sidewall Cut for the Base mine

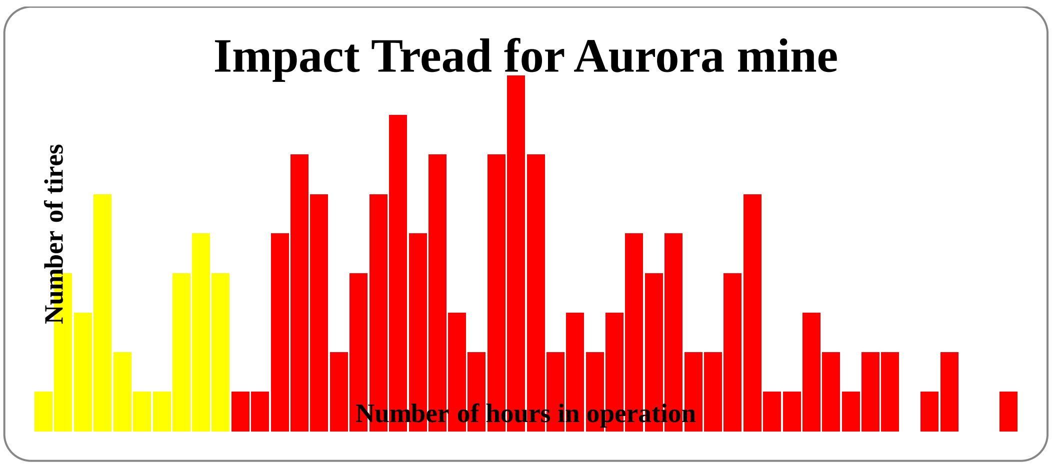

Figure 3-38 Frequency distribution for Impact Tread for the Aurora mine

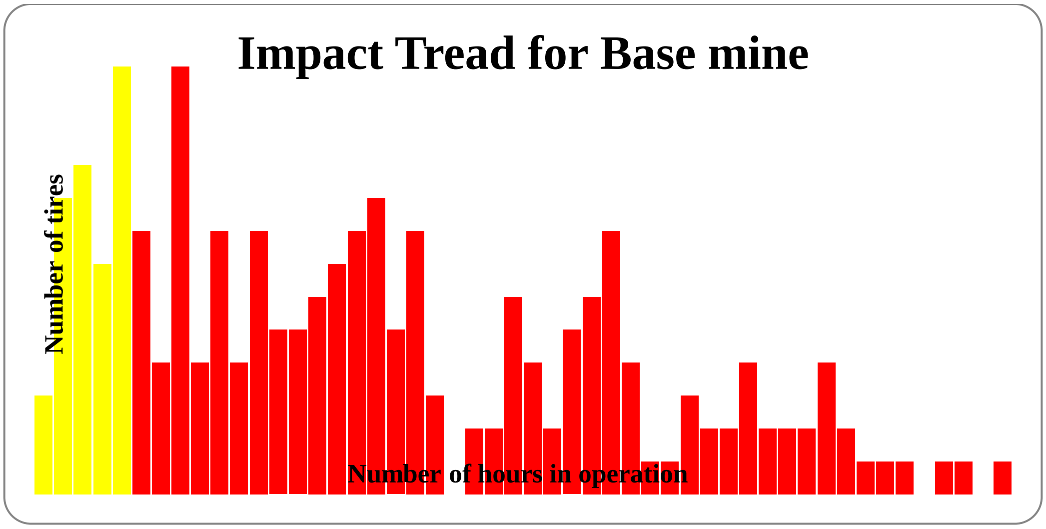

Figure 3-39 Frequency distribution for Impact Tread for the Aurora mine

Operating conditions and operator capabilities play an important role in developing the relationship; however, knowledge about these parameters was not available. In the absence of these parameters, the mean and standard deviation of these graphs were calculated, and are presented in Table 3-5.

Table 3-5 Mean and standard deviation for Figures 3-34 to 3-39

	Tread Cut + Sep		**Sidewall Cut**		**Impact Tread**	
	Aurora	Base	Aurora	Base	Aurora	Base
Average (hours)	5398	4763	5505	5044	5173	4705
Std. Dev. (hours)	1236	1258	1147	1324	1158	1197

Columns in Figures 3-31 to 3-36 were colored in red and yellow, which depict two different ranges for probability of failure. Red was given to the range from mean minus one standard deviation of the data to the end of the tire's useful life, and the life prior to mean minus one standard division was given yellow. The red color reflects that if the tire life is within the range, it has a high probability that it will fail. If it is in the yellow range, then it has a medium probability of failure. One can consider the high probability value between 0.7–0.8, and medium probability value between 0.6–0.7. These probabilities are given considering that a tire will follow a slow-aging failure trend, as discussed in the literature review [1].

In order to assign the probability that a tire failure will occur when in the yellow or red range of its usage, operating conditions, equipment locations, recent use of tires, an operator skill chart, and historical data are required. In this case, an important report that can help in assigning the probability of failure is the visual inspection done by the maintenance crew. However, in the absence of this information, we will assign a probability of 0.7 to the yellow range and 0.8 for the red range of hours used.

Anzabi and Lipsett [32] applied reliability modeling on the same set of data. The results from Anzabi and Lipsett's [32] data analysis show that the data follows the 3-parameter Weibull distribution. A probability distribution function of a 3-parameter Weibull distribution is given in equation 3-1 [32].

$$f(t) = \frac{\beta}{\alpha}\left(\frac{t-\gamma}{\alpha}\right)^{\beta-1} \exp\left(-\left(\frac{t-\gamma}{\alpha}\right)^{\beta}\right) \quad \textbf{3-1}$$

Where:

α – Scale parameter (α >0)

β – Shape parameter (β>0)

γ – Location parameter (γ ≤ t < ∞)

From the analysis performed by Anzabi and Lipsett [32], the values of α, β, γ were found to be 5399.0033, 2.5219, and 34.6234, respectively. These results can be used to find the probability of any tire failing in certain time range. From the maintenance point of view, the impact of tire failure is downtime, but from the production standpoint, it is loss of production units and the safety of the operator. Production loss can further lead to penalties for not meeting the set targets. Warehouse information plays an important role in the definition of countermeasures, and availability or scarcity of tires can lead to different decisions in collaboration of criticality of production, which together can help in getting benefit from the opportunity cost of lost production. The warehouse can provide information, such as the current stock of available tires or the incoming schedule for the next shipment of tires, which can help in the decision about the timing in replacing the tires. A decision-maker can decide if the tire needs to be replaced earlier than it is supposed to be in a case where there are production breaks available immediately, along with the availability of maintenance resources. Another decision alternative that a decision-maker can make here is to replace the tire later; for example, in cases where a tire can be used for some extra time safely and production is at its peak, such decisions can help in taking advantage of the opportunity cost of lost production.

3.4.4. Information Flow Representation

Increasing production rate by reducing downtime, doing the correct and minimum possible maintenance, and cutting down warehouse inventories by collaborating with suppliers can be some of the maintenance targets [1]. Availability of sales products should be increased along with a decrease in the stocks in order to run a business without impacting cash flow [89], which is also true for maintenance departments. Therefore, an important KPI for the maintenance department to consider is the availability of assets and increasing the availability by reducing downtime. Downtime can be reduced by decreasing the amount of time spent on scheduled maintenance or by increasing reliability [1]. Specific to this case study, downtime can be reduced by predicting the tire failure in advance and managing the schedule maintenance in a way that least disturbs regular production. This can be done by replacing the tire either in production break times or when the truck is idle. Such cases may include when the truck is down for scheduled maintenance apart from the tire replacement, or when wait time for trucks is high in production.

A maintenance supervisor dashboard should display the total number of available haul trucks along with the total number of “down” haul trucks, while specifying the reason for the latter being “down,” such as tire failure. Furthermore, it should give details about the tires, which are under the lifespan of yellow or red tags. Some of the examples of a maintenance dashboard are given from figure 3-40 to figure 3-44. Data used in these figures is only meant for illustrative purposes, and is not part of the data used in the case study. The system should send a message to the user that a tire lifespan has entered the red tag. If a possible failure is detected, some of the possible countermeasures can be to replace the tire immediately or wait until its next scheduled maintenance. Along with the benefits of using dashboard, there are some issues concerning its use: even though a dashboard identifies the area of concerns, it may not display the reasons for things going wrong; the dashboard's focus is on a limited number of variables, while due to the nature of business, these variables may change; and the dashboard will not be able to cope with strategic changes in the business [83].

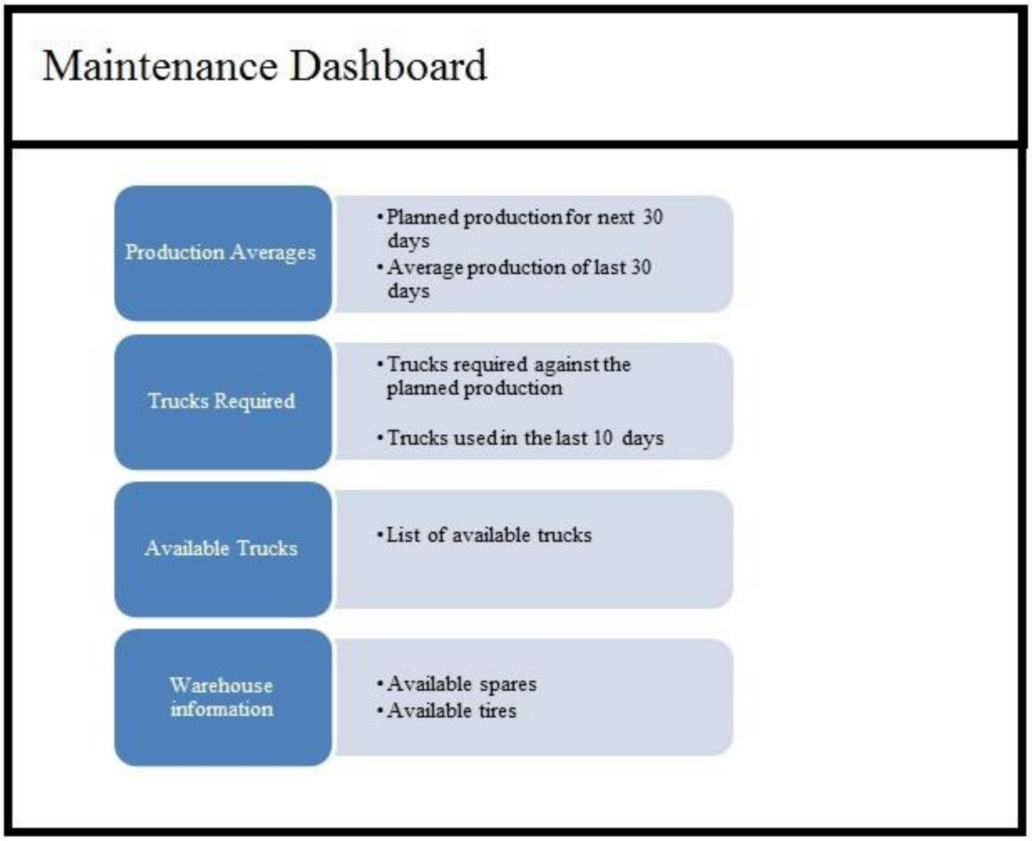

Figure 3-40 Maintenance dashboard example

Figure 3-40 shows an example of the main screen for the maintenance dashboard. This screen will help maintenance personnel select the information he needs from the tabs on the right.

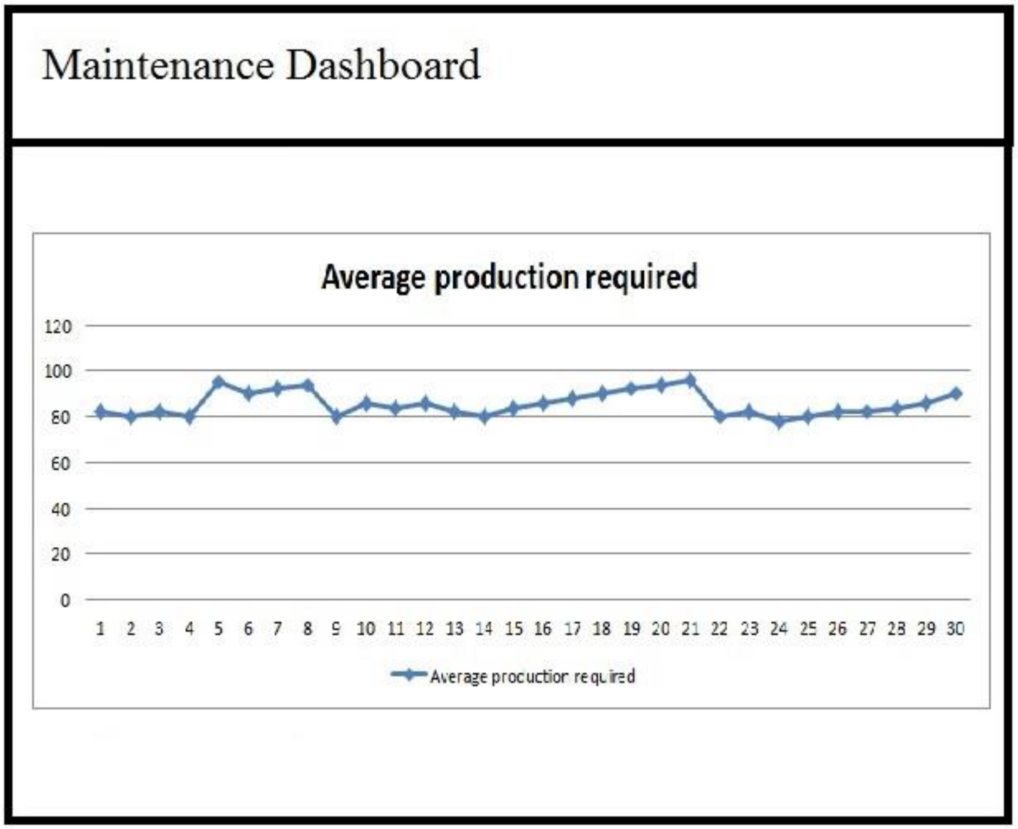

Figure 3-41 Production data example

Figure 3-41 shows an example of an average production required for a month.

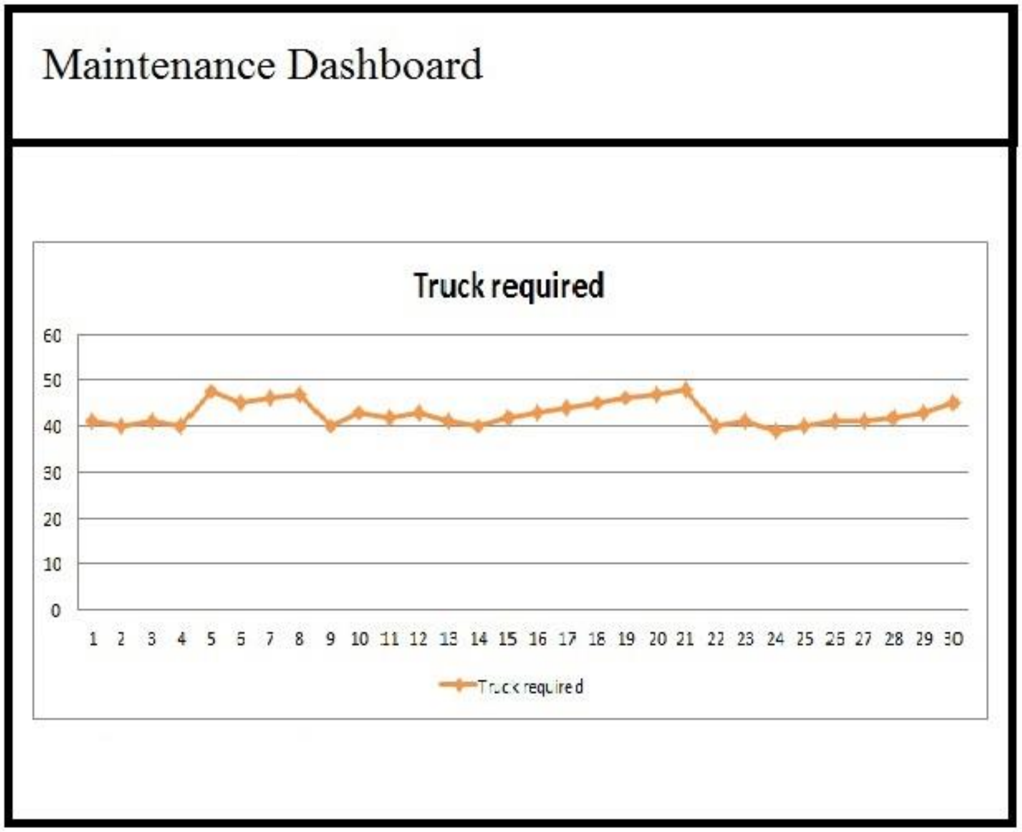

Figure 3-42 Truck requirement against production example

Figure 3-42 shows the relative requirement of trucks in comparison with the planned production on a particular day.

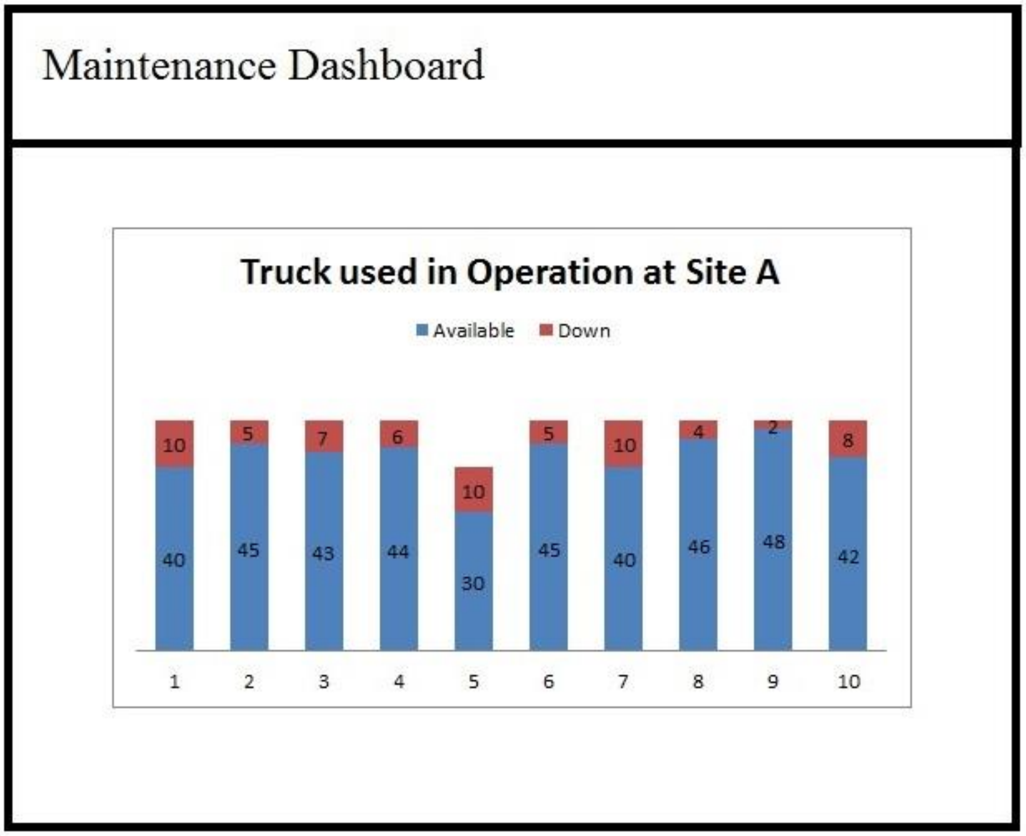

Figure 3-43 Truck usage data example

Figure 3-43 gives the details of trucks' availability for the past 10 days.

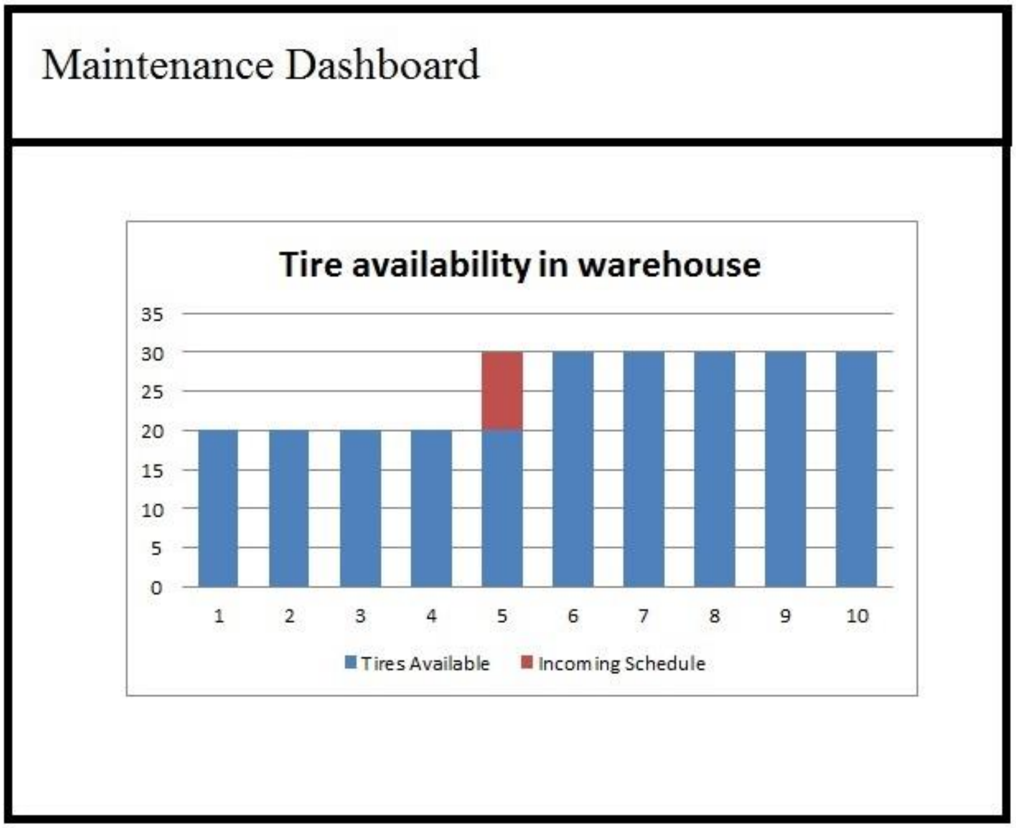

Figure 3-44 Warehouse information example

Figure 3-44 shows the information that can be collected from the warehouse.

To make a decision against the failure, the maintenance supervisor cannot rely on the trend only. One main reason in this case is the widespread nature of the population. However, a good decision can be made in the presence of some additional information. Additional information includes, but is not limited to:

- tires available in the warehouse,
- the current maintenance schedule,
- the availability of the maintenance crew,
- the mean time to repair or replace the tire,

- the current production plan, and
- the next scheduled delivery of tires, if they are out of stock.

Along with the aforementioned information, case-specific information can be forwarded to the decision-maker, including the report prepared by the inspector, who visually inspects the tires on a weekly basis. Only a few types of tire fault progress over time, such as tire tread wear and fatigue. Most faults give little observable indication before the tire is compromised and has to be removed from service. Further, the system should be able to display the old decisions made in similar situations and add visual inspection report similarity as well.

Once a decision is made to repair or replace the tire, it should be recorded, and an evaluation should be done later on the basis of work order closures. These work orders should mention whether the replacement or repair decision made was appropriate, or whether it could have been made earlier or later. Once the evaluation phase is over, the system should be updated with the evaluation record. These evaluations can help the decision-maker to make more safe decisions in case the tire condition was critical when it was replaced. These evaluations will further help the decision-maker to see if decisions made in the past were effective or not. One of the problems with the tire failure is that tires degradation model do not show any sign of wear and it is hard to measure tires damage rate.

3.5. Phase 2—Data collection for Case Study 2

The need for reliability of heavy oil production equipment has increased over the years. Production from the oil sands reserves in Alberta contributes to meet the global energy requirement [90], and by the year 2015, it is forecasted that production will reach a level of 3 million b/d [91]. A combination of sand, water, and bitumen can be classified as oil sands [90]. According to crude oil API Gravity, crude oils can be arranged according to the classification shown in Table 3-6.

Table 3-6 Classification of crude oil according to API Gravity [92]

API Gravity	Crude Oil Classification
>31	Light
21–31	Medium Heavy
1–-21	Heavy
1–14	Extra Heavy
<10	Bitumen

Oil sands can be recovered in two ways: in-situ production is used for 80% of the recovery, and mining is used for 20% of the recovery [90]. Cyclic steam stimulation (CSS) and steam-assisted gravity drainage are considered to be the most verified techniques for in-situ recovery [90] [93]. Some of the problematic areas related to processing and transporting heavy oil are artificial lift, handling issues, the requirement to heat, and the inclusion of solid produce [92].

The objective this case study was to find and rank failure modes related to heavy oil production equipment and devise a maintenance strategy to increase reliability. Furthermore, this case looks at the maintenance practices followed by heavy oil producers, and their information flow, and standardization needs. Such a study would be of immediate use to companies to focus on key reliability issues and establishing best practices for chronic and high-risk failure modes, helping operators to prevent down-hole failures of equipment and reduce risk to personnel, thereby improving the production of heavy oil in Western Canada.

This case study was conducted in three steps: (1) survey development, (2) data collection, and (3) data analysis and recommendation. Data collection was done with the benchmarking technique in mind.

Benchmarking can be defined as a reference point used to measure and improve an organization's performance against a global market leader by following their best practices [94] [95]. Conclusive outcomes, achievable goals, and employee satisfaction are some of the benefits of benchmarking [95].

The benchmarking technique has been used in several industries, and is applied in this case by using these steps:

- Identification of the area of interest
- Preparation of the survey questions
- Identification of the potential participants
- Obtainment of the formal ethics approval
- Data collection through online surveys
- Analysis of the data
- Recommendations for areas of improvement [94] [95] [96].

To understand the applied maintenance practices and equipment reliability issues found in the heavy oil production industry, a questionnaire survey was conducted during the period from November 2012 to March 2013. The questionnaire was sent electronically to five member companies of the STEPS organization. The survey had seven different sections with a combination of open-ended and closed-ended questions. A scale of 1–5 was used in the Likert-type questions. To successfully collect the data for comparison, 25 percent of the survey questions were mandatory to answer. The first section of the survey asked questions related to the expert who was filling out the survey, such as his or her name and contact information. Information collected apart from the contact details in this part is the responsibility of the participant and his or her respective department. The second part of the questionnaire targeted company-related questions, such as size of the company with respect to the number of employees, products, production methods used by the company, location of operations, and capacity-related data. The third part of the survey contained questions that could help in getting knowledge about the procedures that each company follows to maintain its asset information management and monitoring system. It collected information such as methods of storing information, whether they have a formal procedure to collect information, important parameters related to accessing asset information, details of the asset information management software if they are using any, the condition-monitoring system and its parameters, and the condition-monitoring system's usability. The fourth part of the survey asked questions related to equipment maintenance that could lead to information on formal maintenance strategies, maintenance data and triggers, maintenance procedures, and maintenance management software and its attributes, if used. The fifth part of the questionnaire was aimed at finding out information about maintenance decision-making and what kinds of information are available during the process of decision-making, along with what other information the respondents would want in order to make a better decision. The sixth section of the survey collected information related to how a company measures maintenance performance, and whether it is measured against budget. It also determined how the maintenance records are kept in the organization. The seventh and final part of questionnaire was targeted to find out which equipment reliability is of interest to the participants, and which equipment they consider critical to their operations. It also looked for answers in case they do reliability analyses for any of the equipment they use for operations. Table 3-7 presents a brief description of the seven sections.

A copy of the survey can be found in Appendix 1. In order to collect data from the STEPS organization, all the requirements needed from the education institute (i.e., the University of Alberta) were fulfilled as required by the University of Alberta's Research Ethics Office. An application was submitted to the ethics board through their online module. A copy of the approved application, approval letter, and consent form can be found in Appendices 2, 3, and 4 respectively.

Table 3-7 Components of survey questionnaire

No.	Section	Description
1	The Expert	This section collected information related to the person who was filling out the survey. This information was collected in order to clarify any ambiguity in the responses.
2	The Company	This section covered the operational details of the participating companies, such as products, production methods, and size of the company, in order to compare it with other companies.
3	Machine and Equipment Information Management and Monitoring	This section asks questions related to the information requirement and its availability. It also asks questions about the software used for asset information management.
4	Equipment Maintenance	This section asked the participants about maintenance strategies, triggers, and scheduling.
5	Maintenance Decision-Making	This section was targeted to gather data related to information availability against any

		maintenance triggers and information requirements for good maintenance decision-making.
6	Maintenance and Reliability Performance Measurement	This section was developed to address the area of performance measurement procedures adopted by the participating organization.
7	Equipment Reliability	This part of the survey collected data from the participants, related to the equipment that they thought was critical to the organization.

3.6. Phase 3—Verification of the Framework by Case Study 2

Unfortunately, data collection for the second case study was not successful due to the lack of commitment from the sponsors; however, data from the first case study was utilized to map the framework.

Chapter 4

4. Conclusions and Future Work

4.1. Conclusions

This study was carried out to develop a decision-making framework for maintenance decision-making related to remote assets. A total of 135 inputs were identified in the structured analysis. 24 out of 135 input parameters were repeated more than once. Input parameters with a frequency of more than 2 can be found in Table 4-1.

Table 4-1 Inputs frequency in structured analysis

#	Input Parameters	Frequency
1	Operating condition	8
2	MTBF	6
3	MTTR	4
4	Current values	3
5	Logistic availability	3
6	Production plans	3
7	Production targets	3
8	Warehouse information	3

The inputs mentioned in Table 4-1 can be considered the most important parameters for the decision-making framework, as the decision-making framework is dependent on these inputs, and knowledge of these components is critical for the successful implementation of the framework. Operating conditions help in deciding the failures that can be handled with the framework, whereas MTBF and MTTR are an important knowledge related to equipment, and help in devising the mitigation strategy along with the definition of countermeasures in the case of failure. Current values of data, in addition to the operating condition, help in deciding the current state of the equipment. Logistic availability, production plans, production targets, and warehouse information help the decision-maker in deciding on the option that will be best in the current situation.

The proposed framework builds its structure by sorting the defined failures according to their risk level, and has the capability to perform quantitative analysis if required by the customer. The framework also has the ability to integrate data assessment through the use of statistical analysis or machine learning, depending upon the nature of failure.

The proposed framework integrates production, warehouse, and maintenance information, and presents it to the maintenance decision maker in order to get maximum benefit from the opportunity cost of lost production. Furthermore, this framework will help the decision maker to make decisions based on the system assessment and additional information from concerned or interlinked departments through the use of a dashboard, in contrast to a decision made by gut feeling.

4.2.Limitations of Results to Date

This framework is applicable in industries that collect data as part of their routine work and have specialized maintenance departments or maintenance vendors with certain equipment competencies. Implementation of this work is more feasible in the areas of operation where operating conditions stay relatively the same or do not change over a long period of time. This continuity in operating conditions is required, as data need to be collected under the same operating conditions and then need to be tested.

Validation of the model could have been more significant if the case data was collected from the second case study. The second case study would have helped to get the maintenance manager's and/or engineer's perspective on the foundations of a decision-making framework. Furthermore, it would have provided an expert opinion about different inputs upon which the decision-making framework is based.

The data was only related to tire failure. If production data along with some of the weekly inspection reports were available, it would have been beneficial to look at some specific days to check how a different decision would have been able to benefit from the opportunity cost of lost production. The dataset used in the case study can have uncertainties associated with errors in fault identification. Also, relationships between faults and conditions leading to these faults are missing from the data set. Measurements should be taken in order to reduce such uncertainties. Model-based analysis can give insight into what measurements may be required, and how uncertainties can be reduced.

4.3. Recommendations for Future Work

Some of the works that can be done based on the study are:

- A study of the framework application can be carried out to find out its impact on the lead time and maintenance cost.

- An integration of the decision-making framework with the material requirement modules can be studied along with its effect on reduction in inventory.
- A study can be performed to look into the effects of dashboard use in reducing wait time and other aspects of waste
- System analysis can be incorporated into simulations for scenario analysis and sensitivity analysis
- An integration of the analytical hierarchy process technique can be studied to compare the different available decisions.
- The survey from the second case study could be sent out to a larger population to collect data, and a verification of the study could be performed.

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Appendix 1

Heavy Oil Production Equipment Reliability Benchmarking Survey

This survey is to collect data related to the reliability and maintenance of heavy oil production equipment from the participating companies. The data will be processed at Dr. Michael Lipsett's research group at the Mechanical Engineering department of the University of Alberta. The purpose of this survey is to provide the participants with useful statistics that can be used for benchmarking their reliability and maintenance processes and practice, with the objective of improving equipment operations and performance.

Please fill the form as complete as possible, and note, that the quality and usefulness of this project highly depends on the extent to which we receive complete data, including non-mandatory data. In case a question is not clear, pleas e kindly leave us a note or contact us.

Thank you for your input,

1. The Expert

Information related to the person taking the survey.

1.1. Name *

1.2. Title *

1.3. Department

1.4. Responsibility Level *

Check all that apply

- ○ Consulting
- ○ Technical
- ○ Supervisory
- ○ Management
- ○ Other:

1.5. Telephone

1.6. Fax

1.7. Email *

2. The Company

Information related to the company of the expert taking the survey.

2.1. Name *

2.2. Location *

2.3. Number of employees

- 0-50
- 50-200
- >200

2.4. Team or department size

(Estimate number)

2.5. Select all the products that apply to your company *

- Light oil
- Medium heavy oil
- Heavy oil
- Extra heavy oil
- Bitumen/oil sand
- Shale oil
- Conventional natural gas
- Tight gas
- Coal bed methane
- Shale gas
- Other:

2.6. Production methods used by your company *

Select all that apply

- Cold heavy oil production with sand (CHOPS)
- Steam as s is ted gravity drainage (SAGD)
- Electric - SAGD
- Cyclic steam stimulation (CSS)
- Steam flood
- In-situ combustion
- Other:

2.7. Your company’s total production capacity per day

Estimate

2.8. Your company’s maximum production from a field

Estimate

2.9. Your company’s minimum production from a field

Estimate (excluding non-producing ones)

2.10. Where are your field operations?

Specify if it's a field, basin, township...

Asset Information Management and Monitoring

3. Machine and Equipment (Asset) Information Management and Monitoring

3.1. Where is asset information stored at your organization? *

- Paper notes, forms, and folders
- Electronic documents (e.g. MS-Word) and spread sheet (e.g. MS-Excel) files on individual computers
- Electronic documents (e.g. MS-Word) and spread sheet (e.g. MS-Excel) files on s hared folders, drives, and servers
- In special desktop computer software (please specify in other)
- In a web application (please specify in other)
- Other:

3.2. Is equipment asset information formally managed at your organization, i.e. a process is in place for collection, documentation, organization, and retrieval of asset information?*

- Yes, we have a highly formalized process that is under a management system standard (e.g. ISO 9000) Yes, we have a highly formalized process
- Yes, some processes are there, but not formal
- No
- Other

3.3. Regarding accessing and using asset information, please rate the importance of the following parameters to you.

Criteria	**Not Important**	**Somewhat important**	**Important**	**Critical**
Fast and prompt access	○	○	○	○
Complete information	○	○	○	○
Accurate information	○	○	○	○
Reliable access	○	○	○	○
Secure access	○	○	○	○
Mobile access	○	○	○	○
Easy access (low complexity in getting information)	○	○	○	○

3.4. Regarding accessing and using asset information:

Criteria	**I'm not sure**	**No**	**Yes**
I have fast and prompt access	○	○	○
I can get complete information	○	○	○
I get accurate information	○	○	○
My access is reliable	○	○	○
My access is secure	○	○	○
My access is/can be mobile	○	○	○
Using the system for accessing information is easy for me	○	○	○
	○	○	○

3.5. Do you use any asset information management software? please specify *

○ Yes

○ No

○ I don't know

3.6. What is the name of the software that you use for asset information management? *

If you answered "I don't know" or "No" to the previous question, pleas e answer "N/A"

3.7. What features of this software do you find useful?

3.8. What features do you find not so useful, redundant, or counterproductive?

3.9. Overall, what is your level of satisfaction with your asset information management system? *

Disappointed	1	2	3	4	5	Very satisfied
	◯	◯	◯	◯	◯	

3.10. Are there any condition (health) monitoring systems used for your equipment (assets)? Please specify *

You m ay also indicate "I don't know"

3.11. What are the typical parameters that get monitored? (list some parameters)

You m ay also indicate "I don't know" or "N/A" if you don't us e a monitoring system.

3.12. Is this monitoring system included in the asset information management system?

◯ Yes

◯ No

◯ I don't know

3.13. If not, is this monitoring system integrated with asset information management?

◯ Yes

◯ No

◯ I don't know

3.14. How much do you rely on the data from your monitoring system for making day to day operational decisions?

- Highly rely
- Somewhat rely
- The system is only to alert us of critical issues
- Very low reliance, the system is redundant

3.15. What features of this monitoring system do you find useful?

3.16. What features of the monitoring system do you find not so useful, redundant, or counterproductive?

3.17. Overall, what is your level of satisfaction with your asset condition monitoring system? *

Disappointed	1	2	3	4	5	Very satisfied
	○	○	○	○	○	

Maintenance Management

4. **Equipment Maintenance**

4.1. Do you have a formal maintenance strategy in place?

- Yes
- No
- I don't know

4.2. Do you have separate maintenance strategies for different classes of equipment?

- Yes
- No
- I don't know

4.3. Do you use any of the following strategies in your company? Please select all

- Run to failure (or break down maintenance)
- Preventive maintenance (reduction of maintenance through company culture of res possibility and care for assets at all levels of operations)
- Reliability centric maintenance
- Predictive maintenance
- Condition based maintenance (maintenance response based on specific asset condition which is being monitored)
- Scheduled maintenance (maintenance performed at regular schedules)
- Shutdown maintenance (or opportunity based maintenance, is batch maintenance performed at planned or unplanned shutdowns)
- Other:

4.4. Who performs maintenance work for your company:

- Individual departments or units are responsible for their equipment, and general technicians perform the work
- Individual departments or units are responsible for their equipment, and specific maintenance units within the departments perform the work
- A central, in-house, maintenance department
- Maintenance work is contracted out
- A combination of above (check all that applies)
- Other:

4.5. What data is collected during maintenance procedures:

- Operational e.g. flow rate of a pump
- State of the equipment, e.g. failed, faulty, eroded, etc.
- Technician observations
- Technician recommendations
- Fault/failure mode
- Fault/failure effect
- Fault/failure cause
- Other:

4.6. Do you look for maintenance triggers during operations?

- Yes
- No
- I don't know

4.7. In case your answer is yes to the above question, please list the top three triggers in your case:

4.8. Do you have work instructions available for maintenance?

- Yes
- No
- I don't know

4.9. Do you have a list of countermeasures available with you in case of any maintenance trigger occurs?

- Yes
- No
- I don't know

4.10. Do you use a maintenance management software for planning, scheduling, and providing logistics for maintenance work? (please name the software) *

You m ay also indicate "No" or "I don't know"

4.11. If answer to above question is yes, what features of this software do you find useful?

4.12. What features do you find not so useful, redundant, or counterproductive?

4.13. If you use an asset information management system, is the maintenance software a component of that system?

- ○ Yes
- ○ No
- ○ I don't know

5. Maintenance Decision making

5.1. Do you have sufficient information available to you at the time of decision making for a maintenance response?

Please select all that applies

- State of the equipment requiring maintenance
- Proper procedure and knowledge required for maintaining the equipment
- The required operational state of the equipment after maintenance work is completed
- Availability of spare parts and replacement equipment
- Availability of required tools for maintenance
- Availability of maintenance crew
- Availability of logistics
- Mean time to repair
- Constraint on maintenance time
- Constraints on maintenance costs
- HSE requirements
- Regulatory requirements
- Documentation requirements
- Other:

5.2. In your opinion, what other information can help make a good maintenance decision?

Please select all that apply:

- ◯ An effective information system
- ◯ Mobile devices with maintenance information system software
- ◯ Time and cost constraints
- ◯ Safety and environmental constraints
- ◯ Regulations Production plans Procurement information
- ◯ Incoming quality assurance
- ◯ Warehouse information
- ◯ Maintenance schedule
- ◯ Mean time between failures
- ◯ Mean time to repair
- ◯ Other:

6. Maintenance and Reliability Performance Measurement

6.1. Do you measure the performance of your maintenance procedures and work? *

- Yes, it is a formal and required part of our maintenance process
- Yes, we always do, but informally
- Yes, sometimes
- No
- I don't know

6.2. How do you measure maintenance performance?

Please select all that apply in your case

- Availability
- Reliability
- Maintainability
- Process rate
- Quality rate
- Overall equipment effectiveness
- Cost index
- Performance index
- Labor performance index
- Planned vs unplanned hours calculation
- Inventory value analysis
- Other:

6.3. Please list any other specific key performance indicators used for assessing your maintenance processes:

6.4. Do you keep detailed record of the maintenance work done? *

- Yes, always
- Yes, sometimes
- No
- I don't know

6.5. How is record keeping performed:

- Paper notes and forms
- Electronic documents (e.g. MS-Word) and spread sheet (e.g. MS-Excel) files
- In special desktop computer software (please specify in other)
- In a web application (please specify in other)
- Other:

6.6. Is there a fixed budget for maintenance activity?

- Yes, always
- Sometimes
- No
- I don't know

6.7. Does this budget include direct equipment replacement or parts costs?

- Yes
- No
- I don't know

6.8. Are the actual costs against the budget audited?

- Yes, always
- Yes, sometimes
- No
- I don't know

7. Equipment Reliability

7.1. Which of the following equipment would you consider to be critical to your surface operations? *

In determining the criticality of an equipment, consider its effect on disrupting the operations, direct production losses, and safety and environmental hazards, against replacement or repair costs, and the required time and effort for replacements and repairs

- ◯ Pumps
- ◯ Valves
- ◯ Actuators
- ◯ Control and communications systems
- ◯ Monitoring systems
- ◯ Compressors
- ◯ Pipes and piping components
- ◯ Exchangers
- ◯ Boilers
- ◯ Heaters
- ◯ Vaporizers
- ◯ Regulators
- ◯ Well head
- ◯ Other:

7.2. You are interested in the reliability analysis of which of the following equipment? *

- Pumps
- Valves
- Actuators
- Control and communications systems
- Monitoring systems
- Compressors
- Pipes and piping components
- Exchangers
- Boilers
- Heaters
- Vaporizers
- Regulators
- Well head
- Other:

7.3. If you assess the reliability of any equipment, please indicate below. *

- Pumps
- Valves
- Actuators
- Control and communications systems
- Monitoring systems
- Compressors
- Pipes and piping components
- Exchangers
- Boilers
- Heaters
- Vaporizers
- Regulators
- Well head
- We don’t assess equipment reliability
- Other:

7.4. In your opinion, the responsibility of assessing equipment reliability belongs to? *

- Operator
- Vendor
- Third party service provider (e.g. maintenance, rental, etc.)
- Joint project under third party supervision
- Other:

Pumps

7.5. If you selected pumps, which parameters do you know to highly affect its reliability?

Check all that applies

- Equipment priming and s tart up procedure
- Procedures for routine operations of equipment
- Equipment s hut down procedures
- Maintenance crew service quality
- Quality of tools used for service
- The maintenance practice and procedures
- Temperature
- Pressure
- Solids
- Flow rate
- Gas ratio
- Viscosity
- Density
- Wax/paraffin/asphaletenes
- High fluid corrosivity
- Chemical composition
- Other reservoir parameters
- The field location
- Well type (e.g. vertical, horizontal, etc.)
- Duration under operation (including off time)
- Actual run time (excluding off time)

- Water
- H2S
- CO2
- Power (source, quality, voltage, current, frequency, cables)
- Vendor
- Vendor location
- Alloy
- Specific equipment type/model
- Other:

7.6. Please list the top three failure modes you have found associated with pumps. Indicate with the order of occurrence from most observed to least from left to right.

Failure mode is the way in which a failed component or equipment is observed, e.g. "eroded pipe wall at connection" or "broken pump impeller". (For more information: http://en.wikipedia.org/wiki/Failure_m ode_and_effects _analys is) (Or: http://as q.org/learn-about-quality/process-analysis-tools/overview/fmea.html)

Valves

7.7. If you selected valves, which parameters do you know to highly affect its reliability?

Check all that applies

- Equipment priming and s tart up procedure
- Procedures for routine operations of equipment
- Equipment s hut down procedures
- Maintenance crew service quality
- Quality of tools used for service
- The maintenance practice and procedures
- Temperature
- Pressure
- Solids
- Flow rate
- Gas ratio
- Viscosity
- Density
- Wax/paraffin/asphaletenes
- High fluid corrosivity
- Chemical composition
- Other reservoir parameters
- The field location
- Well type (e.g. vertical, horizontal, etc.)
- Duration under operation (including off time)
- Actual run time (excluding off time)

- Water
- H2S
- CO2
- Power (source, quality, voltage, current, frequency, cables)
- Vendor
- Vendor location
- Alloy
- Specific equipment type/model
- Other:

7.8. Please list the top three failure modes you have found associated with valves. Indicate with the order of occurrence from most observed to least from left to right.

Actuators

7.9. If you selected actuators, which parameters do you know to highly affect its reliability?

Check all that applies

- Equipment priming and s tart up procedure
- Procedures for routine operations of equipment
- Equipment s hut down procedures
- Maintenance crew service quality
- Quality of tools used for service
- The maintenance practice and procedures
- Temperature
- Pressure
- Solids
- Flow rate
- Gas ratio
- Viscosity
- Density
- Wax/paraffin/asphaletenes
- High fluid corrosivity
- Chemical composition
- Other reservoir parameters
- The field location
- Well type (e.g. vertical, horizontal, etc.)
- Duration under operation (including off time)
- Actual run time (excluding off time)

- Water
- H2S
- CO2
- Power (source, quality, voltage, current, frequency, cables)
- Vendor
- Vendor location
- Alloy
- Specific equipment type/model
- Other:

7.10. Please list the top three failure modes you have found associated with actuators. Indicate with the order of occurrence from most observed to least from left to right.

Control and communication systems

7.11. If you selected Control and communication systems, which parameters do you know to highly affect its reliability?

Check all that applies

- Equipment priming and s tart up procedure
- Procedures for routine operations of equipment
- Equipment s hut down procedures
- Maintenance crew service quality
- Quality of tools used for service
- The maintenance practice and procedures
- Temperature
- Pressure
- Solids
- Flow rate
- Gas ratio
- Viscosity
- Density
- Wax/paraffin/asphaletenes
- High fluid corrosivity
- Chemical composition
- Other reservoir parameters
- The field location
- Well type (e.g. vertical, horizontal, etc.)
- Duration under operation (including off time)
- Actual run time (excluding off time)

- Water
- H2S
- CO2
- Power (source, quality, voltage, current, frequency, cables)
- Vendor
- Vendor location
- Alloy
- Specific equipment type/model
- Other:

7.12. Please list the top three failure modes you have found associated with Control and communication systems. Indicate with the order of occurrence from most observed to least from left to right.

Monitoring systems

7.13. If you selected monitoring systems, which parameters do you know to highly affect its reliability?

Check all that applies

- Equipment priming and s tart up procedure
- Procedures for routine operations of equipment
- Equipment s hut down procedures
- Maintenance crew service quality
- Quality of tools used for service
- The maintenance practice and procedures
- Temperature
- Pressure
- Solids
- Flow rate
- Gas ratio
- Viscosity
- Density
- Wax/paraffin/asphaletenes
- High fluid corrosivity
- Chemical composition
- Other reservoir parameters
- The field location
- Well type (e.g. vertical, horizontal, etc.)
- Duration under operation (including off time)
- Actual run time (excluding off time)

- Water
- H_2S
- CO_2
- Power (source, quality, voltage, current, frequency, cables)
- Vendor
- Vendor location
- Alloy
- Specific equipment type/model
- Other:

7.14. Please list the top three failure modes you have found associated with monitoring systems. Indicate with the order of occurrence from most observed to least from left to right.

Compressors

7.15. If you selected compressors, which parameters do you know to highly affect its reliability?

Check all that applies

- Equipment priming and s tart up procedure
- Procedures for routine operations of equipment
- Equipment s hut down procedures
- Maintenance crew service quality
- Quality of tools used for service
- The maintenance practice and procedures
- Temperature
- Pressure
- Solids
- Flow rate
- Gas ratio
- Viscosity
- Density
- Wax/paraffin/asphaletenes
- High fluid corrosivity
- Chemical composition
- Other reservoir parameters
- The field location
- Well type (e.g. vertical, horizontal, etc.)
- Duration under operation (including off time)
- Actual run time (excluding off time)

- Water
- H2S
- CO2
- Power (source, quality, voltage, current, frequency, cables)
- Vendor
- Vendor location
- Alloy
- Specific equipment type/model
- Other:

7.16. Please list the top three failure modes you have found associated with compressors. Indicate with the order of occurrence from most observed to least from left to right.

Pipes and piping components

7.17. If you selected pipes and piping components, which parameters do you know to highly affect its reliability?

Check all that applies

- Equipment priming and s tart up procedure
- Procedures for routine operations of equipment
- Equipment s hut down procedures
- Maintenance crew service quality
- Quality of tools used for service
- The maintenance practice and procedures
- Temperature
- Pressure
- Solids
- Flow rate
- Gas ratio
- Viscosity
- Density
- Wax/paraffin/asphaletenes
- High fluid corrosivity
- Chemical composition
- Other reservoir parameters
- The field location
- Well type (e.g. vertical, horizontal, etc.)
- Duration under operation (including off time)
- Actual run time (excluding off time)

- Water
- H2S
- CO2
- Power (source, quality, voltage, current, frequency, cables)
- Vendor
- Vendor location
- Alloy
- Specific equipment type/model
- Other:

7.18. Please list the top three failure modes you have found associated with pipes and piping equipment. Indicate with the order of occurrence from most observed to least from left to right.

Exchangers

7.19. If you selected exchangers, which parameters do you know to highly affect its reliability?

Check all that applies

- Equipment priming and s tart up procedure
- Procedures for routine operations of equipment
- Equipment s hut down procedures
- Maintenance crew service quality
- Quality of tools used for service
- The maintenance practice and procedures
- Temperature
- Pressure
- Solids
- Flow rate
- Gas ratio
- Viscosity
- Density
- Wax/paraffin/asphaletenes
- High fluid corrosivity
- Chemical composition
- Other reservoir parameters
- The field location
- Well type (e.g. vertical, horizontal, etc.)
- Duration under operation (including off time)
- Actual run time (excluding off time)

- Water
- H2S
- CO2
- Power (source, quality, voltage, current, frequency, cables)
- Vendor
- Vendor location
- Alloy
- Specific equipment type/model
- Other:

7.20. Please list the top three failure modes you have found associated with exchangers. Indicate with the order of occurrence from most observed to least from left to right.

Boilers

7.21. If you selected boilers, which parameters do you know to highly affect its reliability?

Check all that applies

- Equipment priming and s tart up procedure
- Procedures for routine operations of equipment
- Equipment s hut down procedures
- Maintenance crew service quality
- Quality of tools used for service
- The maintenance practice and procedures
- Temperature
- Pressure
- Solids
- Flow rate
- Gas ratio
- Viscosity
- Density
- Wax/paraffin/asphaletenes
- High fluid corrosivity
- Chemical composition
- Other reservoir parameters
- The field location
- Well type (e.g. vertical, horizontal, etc.)
- Duration under operation (including off time)
- Actual run time (excluding off time)

- Water
- H2S
- CO2
- Power (source, quality, voltage, current, frequency, cables)
- Vendor
- Vendor location
- Alloy
- Specific equipment type/model
- Other:

7.22. Please list the top three failure modes you have found associated with boilers. Indicate with the order of occurrence from most observed to least from left to right.

Heaters

7.23. If you selected heaters, which parameters do you know to highly affect its reliability?

Check all that applies

- Equipment priming and s tart up procedure
- Procedures for routine operations of equipment
- Equipment s hut down procedures
- Maintenance crew service quality
- Quality of tools used for service
- The maintenance practice and procedures
- Temperature
- Pressure
- Solids
- Flow rate
- Gas ratio
- Viscosity
- Density
- Wax/paraffin/asphaletenes
- High fluid corrosivity
- Chemical composition
- Other reservoir parameters
- The field location
- Well type (e.g. vertical, horizontal, etc.)
- Duration under operation (including off time)
- Actual run time (excluding off time)

- Water
- H2S
- CO2
- Power (source, quality, voltage, current, frequency, cables)
- Vendor
- Vendor location
- Alloy
- Specific equipment type/model
- Other:

7.24. Please list the top three failure modes you have found associated with heaters. Indicate with the order of occurrence from most observed to least from left to right.

Vaporizers

7.25. If you selected vaporizers, which parameters do you know to highly affect its reliability?

Check all that applies

- Equipment priming and s tart up procedure
- Procedures for routine operations of equipment
- Equipment s hut down procedures
- Maintenance crew service quality
- Quality of tools used for service
- The maintenance practice and procedures
- Temperature
- Pressure
- Solids
- Flow rate
- Gas ratio
- Viscosity
- Density
- Wax/paraffin/asphaletenes
- High fluid corrosivity
- Chemical composition
- Other reservoir parameters
- The field location
- Well type (e.g. vertical, horizontal, etc.)
- Duration under operation (including off time)
- Actual run time (excluding off time)

- ◯ Water
- ◯ H2S
- ◯ CO2
- ◯ Power (source, quality, voltage, current, frequency, cables)
- ◯ Vendor
- ◯ Vendor location
- ◯ Alloy
- ◯ Specific equipment type/model
- ◯ Other:

7.26. Please list the top three failure modes you have found associated with vaporizers. Indicate with the order of occurrence from most observed to least from left to right.

Regulators

7.27. If you selected regulators, which parameters do you know to highly affect its reliability?

Check all that applies

- Equipment priming and s tart up procedure
- Procedures for routine operations of equipment
- Equipment s hut down procedures
- Maintenance crew service quality
- Quality of tools used for service
- The maintenance practice and procedures
- Temperature
- Pressure
- Solids
- Flow rate
- Gas ratio
- Viscosity
- Density
- Wax/paraffin/asphaletenes
- High fluid corrosivity
- Chemical composition
- Other reservoir parameters
- The field location
- Well type (e.g. vertical, horizontal, etc.)
- Duration under operation (including off time)
- Actual run time (excluding off time)

- Water
- H2S
- CO2
- Power (source, quality, voltage, current, frequency, cables)
- Vendor
- Vendor location
- Alloy
- Specific equipment type/model
- Other:

7.28. Please list the top three failure modes you have found associated with regulators. Indicate with the order of occurrence from most observed to least from left to right.

Well head

7.29. If you selected well head, which parameters do you know to highly affect its reliability?

Check all that applies

- Equipment priming and s tart up procedure
- Procedures for routine operations of equipment
- Equipment s hut down procedures
- Maintenance crew service quality
- Quality of tools used for service
- The maintenance practice and procedures
- Temperature
- Pressure
- Solids
- Flow rate
- Gas ratio
- Viscosity
- Density
- Wax/paraffin/asphaletenes
- High fluid corrosivity
- Chemical composition
- Other reservoir parameters
- The field location
- Well type (e.g. vertical, horizontal, etc.)
- Duration under operation (including off time)
- Actual run time (excluding off time)

- Water
- H2S
- CO2
- Power (source, quality, voltage, current, frequency, cables)
- Vendor
- Vendor location
- Alloy
- Specific equipment type/model
- Other:

7.30. Please list the top three failure modes you have found associated with well head. Indicate with the order of occurrence from most observed to least from left to right.

Others

7.31. If you selected others, which parameters do you know to highly affect its reliability?

Check all that applies

- Equipment priming and s tart up procedure
- Procedures for routine operations of equipment
- Equipment s hut down procedures
- Maintenance crew service quality
- Quality of tools used for service
- The maintenance practice and procedures
- Temperature
- Pressure
- Solids
- Flow rate
- Gas ratio
- Viscosity
- Density
- Wax/paraffin/asphaletenes
- High fluid corrosivity
- Chemical composition
- Other reservoir parameters
- The field location
- Well type (e.g. vertical, horizontal, etc.)
- Duration under operation (including off time)
- Actual run time (excluding off time)

- Water
- H2S
- CO2
- Power (source, quality, voltage, current, frequency, cables)
- Vendor
- Vendor location
- Alloy
- Specific equipment type/model
- Other:

7.32. Please list the top three failure modes you have found associated with others. Indicate with the order of occurrence from most observed to least from left to right.

Appendix 2

Approved Application

Date: 3/6/2013 3:37:17 PM

Print Close

ID: Pro00034171

View: 1.1 Study Identification

Status: Approved

ID:Pro00034171

Status:Approved

1.1 Study Identification

*All questions preceded by a red asterisk * are required fields. However, answering only the required fields may not provide sufficient information for the REB in order to evaluate your application. Please answer all presented questions that will reasonably help to describe your study or proposed research.*

1.0 * **Short Study Title** *(restricted to 250 characters)*:
BENCHMARK STUDY OF FAULT MODES AND EFFECTS IN HEAVY OIL PRODUCTION EQUIPMENT

2.0 * **Complete Study Title** *(can be exactly the same as short title)*:
Benchmark Study of Fault Modes and Effects in Heavy Oil Production Equipment

3.0 * **Select the appropriate Research Ethics Board (***Detailed descriptions are available by clicking the HELP link in the upper right hand corner of your screen***)**:
REB 2

4.0 * **Is the proposed research:**
Funded (Grant, subgrant, contract, internal funds, donation or some other source of funding)

5.0 * **Name of Principal Investigator** *(at the University of Alberta, Covenant Health, or Alberta Health Services)*:
Waqas Awan

6.0 **Investigator's Supervisor** *(required for applications from undergraduate students, graduate students, post-doctoral fellows and medical residents to Boards 1, 2, 3. HREB does not accept applications from student PIs)*

Michael Lipsett

7.0 * **Type of research/study:**
Graduate Student - Thesis, Dissertation, Capping Project

8.0 **Study Coordinators or Research Assistants:** People listed here can edit this application and will receive all HERO notifications for the study:

Name	Employer
There are no items to display	

9.0 **Co-Investigators:** People listed here can edit this application but do not receive HERO notifications unless they are added to the study email list:

Name	Employer
Alireza Farahaninia	EN Mechanical Engineering

Michael Lipsett TEMP

10.0 **Study Team** *(Co-investigators, supervising team, other study team members):* People listed here cannot edit this application and do not receive HERO notifications:

Last Name	First Name	Organization	Role	Phone	Email
There are no items to display					

ID: Pro00034171 View: 1.3 Funding Information

Status: Approved

1.3 Study Funding Information

1.0 *** Type of Funding:**
Grant (external)

If OTHER, provide details:

2.0 *** Indicate which office administers your award.** *(It is the PI�s responsibility to provide ethics approval notification to any office other than the ones listed below)*
University of Alberta - Research Services Office (RSO)

If OTHER, provide details:

3.0 *** Funding Source**

3.1 Select all sources of funding from the list below:
Petroleum Technology Research Centre 7442

3.2 If not available in the list above, write the Sponsor/Agency name(s) in full (you may add multiple funding sources):
View Sustainable Technologies for Energy Production Systems

4.0 *** Indicate if this research sponsored or monitored by any of the following:**
Not applicable

If applicable, indicate whether or not the FDA Investigational New Drug number or FDA Investigational Device Exception is required:

The researcher is responsible for ensuring that the study complies with the applicable US regulations. The REB must also meet particular review criteria and this application will likely receive full board review, regardless of level risk.

ID: Pro00034171 View: 1.4 RSO Managed Funding

Status: Approved

1.4 RSO Managed Funding

1.0 **If your funds are managed by Research Services Office (RSO), select the Project ID and title from the list below to facilitate release of your study funds.** *(Not available yet)*

*** To connect your ethics application with your funding: provide all identifying information about the**

2.0 **study funding � multiple rows allowed. For Project ID, enter a Funding ID provided by RSO/PeopleSoft Project ID** *(for example, RES0005638, G018903401, C19900137, etc).* **Enter the corresponding title for each Project ID.**

	Project ID	Project Title	Speed Code	Other Information
View	RES0008380	Benchmark Study of Fault Modes and Effects in Heavy Oil Production Equipment	ME 323	

ID: Pro00034171 View: 1.5 Conflict of Interest

Status: Approved

1.5 Conflict of Interest

1.0 *** Are any of the investigators or their immediate family receiving any personal remuneration (including investigator payments and recruitment incentives but excluding trainee remuneration or graduate student stipends) from the funding of this study that is not accounted for in the study budget?**

○ ○ Yes ◉ **No**

If YES, explain:

2.0 *** Do any of investigators or their immediate family have any proprietary interests in the product under study or the outcome of the research including patents, trademarks, copyrights, and licensing agreements?**

○ ○ Yes ◉ **No**

3.0 **Is there any compensation for this study that is affected by the study outcome?**

○ ○ Yes ◉ **No**

4.0 **Do any of the investigators or their immediate family have equity interest in the sponsoring company? (This does not include Mutual Funds)**

○ ○ Yes ◉ **No**

5.0 **Do any of the investigators or their immediate family receive payments of other sorts, from this sponsor (i.e. grants, compensation in the form of equipment or supplies, retainers for ongoing consultation and honoraria)?**

○ ○ Yes ◉ **No**

6.0 **Are any of the investigators or their immediate family, members of the sponsor�s Board of Directors, Scientific Advisory Panel or comparable body?**

○ ○ Yes ◉ **No**

7.0 **Do you have any other relationship, financial or non-financial, that, if not disclosed, could be construed as a conflict of interest?**

○ ○ Yes ◉ **No**

If YES, explain:

Important

If you answered YES to any of the questions above, you may be contacted by the REB for more information or asked to submit a Conflict of Interest Declaration.

ID: Pro00034171 View: 1.6 Research Locations and Other Approval

Status: Approved

1.6 Research Locations and Other Approval

1.0 *** List the locations of the proposed research, including recruitment activities. Provide name of institution or organization, town, or province as applicable** (e.g. On campus, Alberta public elementary schools, shopping malls, doctors' offices in Lesser Slave Lake and Lac La Biche, AHS facilities in Zone 5, post-secondary students at UBC, UA, UT, McGill and Dalhousie, internet websites, etc.)**:**
On campus using Google documents

2.0 *** Indicate if the study will utilize or access facilities, programmes, resources, staff, students, specimens, patients or their records, at any of the sites affiliated with the following** *(select all that apply):*
Not applicable

List all facilities or institutions as applicable:

3.0 *** Indicate if the proposed research has or will receive ethics approval from other Research Ethics Board or institution. Choose all that apply:**
Not Applicable

If OTHER, list the REB or Institution:
Name
There are no items to display

4.0 **Does this study involve pandemic or similar emergency health research?**
○ ○ Yes ○ ◉ **No**

If YES, are you the lead investigator for this pandemic study?
○ ○ Yes ○ ○ No

5.0 **If this application is closely linked to research previously approved by one of the University of Alberta REBs or has already received ethics approval from an external ethics review board***(s)***, provide the HERO study number, REB name or other identifying information. Attach any external REB application and approval letter in Section 7.1.11 � Other Documents.**

ID: Pro00034171 View: 2.1 Study Objectives and Design

Status: Approved

2.1 Study Objectives and Design

1.0 **Date that you expect to start working with human participants:**
10/1/2012

2.0 **Date that you expect to finish working with human participants, in other words, you will no longer be in contact with the research participants, including data verification and reporting back to the group or community:**
9/30/2013

*** Provide a lay summary of your proposed research suitable for the general public** *(restricted to*

300 words). **If the PI is not affiliated with the University of Alberta, Alberta Health Services or Covenant Health, please include institutional affiliation.**

Because of the continual contact of moving sand particles, production equipment's such as pumps are highly prone to wear damage. Interaction between sand and moving parts accelerates wear, which leads to breakdowns. Breakdowns incur greater costs and opportunity cost of lost production. To avoid these breakdowns, equipment such as pump internal components needs to be replaced periodically. Maintenance and replacement schedules must be conservative in order to minimize production losses due to breakdowns. . Predictive maintenance can only be done if there is good understanding of damage mechanisms.

3.0

This research is carried out to understand the reliability issues and challenges in heavy oil production equipment in order to recommend maintenance strategies and reliability methods against that. The reliability and maintenance challenges will be identified through literature review and by collecting data from the participants. A survey will be sent to members of STEPS for the purpose of data collection. This survey will further collect information about maintenance strategies and information systems used by the organizations. The purpose of this study is to provide the participants with useful metrics and statistics that can be used for benchmarking their reliability and maintenance processes and practice, with the objective of improving equipment operations and performance. The survey will be used to develop a preliminary fault modes and effects analysis (FMEA), which will be of immediate use for companies to focus on key reliability issues. Consistent definitions and measurement practices for reliability and maintenance metrics may be of benefit for establishing best practices for chronic and high-risk failure modes. This understanding will help operators to prevent downhole failures of equipment, reduce risk to personnel, and thereby improve production of heavy oil.

*** Provide a description of your research proposal including study objectives, background, scope, methods, procedures, etc)** *(restricted to 1000 words)*. **Footnotes and references are not required and best not included here. Research methods questions in Section 5 will prompt additional questions and information.**

Introduction & Background

Because of continual contact with moving sand particles during the course of normal operation, slurry pumps are highly prone to wear damage. Interactions between sand and the moving parts include rolling, sliding, low-angle impact, and high-angle impact. These interactions result in accelerated wear of the pump surfaces, in varying combinations of abrasion, erosion, corrosion (depending on the chemistry of the slurry), erosion-corrosion, and cutting. As a result of these wear processes; pump internals must be replaced periodically. Breakdowns incur greater costs and opportunity costs of lost production. The current state of knowledge regarding wear processes within slurry pumps is still based more on operator experience and mean time between failures than good understanding of the damage mechanisms. Maintenance and replacement schedules must be conservative in order to minimize production losses due to breakdowns. Predictive maintenance can only be done if there is good understanding of damage mechanisms.

R&D into improved productivity for upstream production often ignores the effects of equipment failures and other maintenance and reliability issues. The PI has experience in industry and academia conducting FMEAs, developing condition-based maintenance programs, and developing advanced condition monitoring and diagnostic techniques. The PI's laboratory is set up for characterization of damage in slurry pipelines, pumps, and oil/water separation units, and for visualization of impact damage through transparent viewing sections. As well, students in the PI's group can conduct structured analysis of failures, and model system reliability using various software tools.

This combination of real-world experience and theoretical knowledge of reliability of systems gives this initial project on reliability of heavy oil systems a high chance of yielding useful results.

Project Scope

1) Develop benchmarking survey questions on reliability and maintenance of heavy oil equipment, and set up nondisclosure agreements to deal with any proprietary information that may be shared by companies on a voluntary basis.

2) Conduct survey.

3) Analyze survey results and construct fault modes and effects analysis.

4.0

4) Investigate condition monitoring and fault detection methods for most important faults identified in the survey.

5) Write final report on FMEA results and potential condition monitoring and fault prevention strategies, reporting aggregate results only in a form that does not identify specific organizations.

6) Present findings at STEPS stewardship meetings and at an academic conference.

Following the survey, a fault modes and effects analysis (FMEA) report will be drawn up and released to the STEPS participating companies. This FMEA will be of immediate use for companies to focus on key reliability issues and establishing best practices for chronic and high-risk failure modes. This understanding will help operators to prevent downhole failures of equipment, reduce risk to personnel, and thereby improve production of heavy oil in Saskatchewan.

Project Work Plan

1)Conduct literature review on heavy oil fault modes, and develop preliminary survey questions. Survey questions will ask no personal or private information of respondents.

2) Set up nondisclosure agreements to deal with any proprietary information that may be shared by companies on a voluntary basis.

3) Establish protocol for conducting survey (on-site or on-line) in consultation with STEPS industry partners, get university ethics approval, and conduct survey.

4) Analyze survey results and construct fault modes and effects analysis using standard FMEA approaches.

5) Write and submit report

6) Investigate condition monitoring and fault detection methods for most important faults identified in the survey.

7) Write final report on potential condition monitoring and fault prevention strategies, reporting aggregate results only in a form that does not identify specific organizations.

5.0 **Describe procedures, treatment, or activities that are above or in addition to standard practices in this study area** *(eg. extra medical or health-related procedures, curriculum enhancements, extra follow-up, etc)*:

6.0 **If the proposed research is above minimal risk and is not funded via a competitive peer review grant or industry-sponsored clinical trial, the REB will require evidence of scientific review. Provide information about the review process and its results if appropriate.**

7.0 **For clinical research only, describe any sub-studies associated with this application.**

ID: Pro00034171 View: 3.1 Risk Assessment

Status: Approved

3.1 Risk Assessment

1.0 *** Provide your assessment of the risks that may be associated with this research:**
Minimal Risk - research in which the probability and magnitude of possible harms implied by participation is no greater than those encountered by participants in those aspects of their everyday life that relate to the research (TCPS2)

*** Select all that might apply:**

Description of Potential Physical Risks and Discomforts

No Participants might feel physical fatigue, e.g. sleep deprivation

No Participants might feel physical stress, e.g. cardiovascular stress tests

No Participants might sustain injury, infection, and intervention side-effects or complications

No The physical risks will be greater than those encountered by the participants in everyday life

2.0

Potential Psychological, Emotional, Social and Other Risks and Discomforts

No Participants might feel psychologically or emotionally stressed, demeaned, embarrassed, worried, anxious, scared or distressed, e.g. description of painful or traumatic events

No Participants might feel psychological or mental fatigue, e.g intense concentration required

No Participants might experience cultural or social risk, e.g. loss of privacy or status or damage to reputation

No Participants might be exposed to economic or legal risk, for instance non-anonymized workplace surveys

No The risks will be greater than those encountered by the participants in everyday life

3.0 *** Provide details of the risks and discomforts associated with the research, for instance, health cognitive or emotional factors, socio-economic status or physiological or health conditions:**
The questions are objective, technical, and expert judgement related and we have not identified any potential risk or any discomfort associated with the questions as they relate to the participants' disclosure. More

precisely, the questions do not inquire about and are not affected by any matters related to the health cognitive or emotional factors, socio-economic status or physiological or health conditions of the participants.

4.0 *** Describe how you will manage and minimize risks and discomforts, as well as mitigate harm:**
Not applicable

5.0 *** If your study has the potential to identify individuals that are upset, distressed, or disturbed, or individuals warranting medical attention, describe the arrangements made to try to assist these individuals. Explain if no arrangements have been made:**
Not applicable

ID: Pro00034171 View: 3.2 Benefits Analysis

Status: Approved

3.2 Benefits Analysis

1.0 *** Describe any potential benefits of the proposed research to the participants. If there are no benefits, state this explicitly:**
This FMEA will be of immediate use for companies to focus on key reliability issues and establishing best practices for chronic and high-risk failure modes. This understanding will help operators to prevent downhole failures of equipment, reduce risk to personnel, and thereby improve production of heavy oil in Saskatchewan.

2.0 *** Describe the scientific and/or scholarly benefits of the proposed research:**
A detail report will be available for the scholars to study the FMEA for the heavy oil production equipment that will contain best and worse practices in the industry.

3.0 **Benefits/Risks Analysis: Describe the relationship of benefits to risk of participation in the research:**
Since no considerable risks were identified related to the survey questions. The outcome of the survey would only provide benefits to the participants in improving their understanding of the subject matter in exchange for their participation time.

ID: Pro00034171 View: 4.1 Participant Information

Status: Approved

4.1 Participant Information

1.0 *** Who are you studying? Describe the population that will be included in this study.**
All participants will be part of STEPS organization and their details will be provided by PTRC.

2.0 *** Describe the inclusion criteria for participants (e.g. age range, health status, gender, etc.). Justify the inclusion criteria (e.g. safety, uniformity, research methodology, statistical requirement, etc)**
Participants need to be the part of STEPS industry and recommended by PTRC representative. The background and characteristics of the participants may be diverse and the only criterion for inclusion for the participants in the study is their exposure or interest in the subject matter under investigation.

3.0 **Describe and justify the exclusion criteria for participants:**
Not applicable

*** Will you be interacting with human subjects, will there be direct contact with human participants, for this study?**
◉ **Yes** ○ No

4.0 *Note: No means no direct contact with participants, chart reviews, secondary data, interaction, etc.*

If NO, is this project a chart review or is a chart review part of this research project?

◯ ◯ Yes ◉ ◉ **No**

Participants

How many participants do you hope to recruit *(including controls, if applicable)*

30

5.0 **Of these how many are controls, if applicable** *(Possible answer: Half, Random, Unknown, or an estimate in numbers, etc).*

unknown

If this is a multi-site study, for instance a clinical trial, how many participants *(including controls, if applicable)* **are expected to be enrolled by all investigators at all sites in the entire study?**

Justification for sample size:

6.0 Sample size is dependent on the recommendations made by PTRC and the number of STEPS organization members.

7.0 **Does the research specifically target aboriginal groups or communities?**

◯ ◯ Yes ◉ ◉ **No**

ID: Pro00034171 View: 4.3 Recruit Potential Participants

Status: Approved

4.3 Recruit Potential Participants

Recruitment

1.1 How will potential participants be identified? Outline how you will identify the people who will be approached for participation or screened for eligibility.

A list of participants will be provided by PTRC. A participant needs to be a member of STEPS.

1.0 **1.2 How will people obtain details about the research in order to make a decision about participating? Select all that apply:**

Researchers will contact potential participants

1.3 If appropriate, provide the locations where recruitment will occur *(e.g schools, shopping malls, clinics, etc.)*

Pre-Existing Relationships

2.1 Will potential participants be recruited through pre-existing relationships with researchers *(e.g. Will an instructor recruit students from his classes, or a physician recruit patients from her practice? Other examples may be employees, acquaintances, own children or family members, etc)*?

2.0 ◉ ◉ **Yes** ◯ ◯ No

2.2 If YES, identify the relationship between the researchers and participants that could compromise the freedom to decline *(e.g. professor-student)*. **How will you ensure that there is no undue pressure on the potential participants to agree to the study?**

A contract already exists between the research team, PTRC, and STEPS. An email request will be sent to participants to fill out the survey, it's their own decision to participate or stay out.

3.0 **Outline any other means by which participants could be identified, should additional participants be needed** *(e.g. response to advertising such as flyers, posters, ads in newspapers, websites, email, listservs; pre-existing records or existing registries; physician or community organization referrals; longitudinal study, etc)*

Not applicable

4.0 **Will your study involve any of the following** *(select all that apply)***?**

None of the above

ID: Pro00034171 View: 4.5 Informed Consent Determination

Status: Approved

4.5 Informed Consent Determination

1.0 *** Describe who will provide informed consent for this study (select all that apply). Additional information on the informed consent process is available at: http://www.pre.ethics.gc.ca/eng/policy-politique/initiatives/tcps2-eptc2/chapter3-chapitre3/#toc03-intro**

All participants have capacity to give free and informed consent

2.0 **Provide justification for requesting a Waiver of Consent (Minimal risk only, additional guidance available at: http://www.pre.ethics.gc.ca/eng/policy-politique/initiatives/tcps2-eptc2/chapter3-chapitre3/#toc03-1b**

How is participant consent to be indicated and documented? Select all that apply:

Implied by overt action (i.e. completion of questionnaire)

Except for �Signed consent form� use only, explain how the study information will be communicated and participant consent will be documented. Provide details for EACH of the option selected above:

We will be sending them updates about the study procedures via email and when submitting their questionnaire form at appropriate submission spots notices will be added, which will notify the participant that by submitting the form they consent to their information being used in the study.

3.0 **Authorized Representative, Third Party Consent, Assent**

3.1 Explain why participants lack capacity to give informed consent *(e.g. age, mental or physical condition, etc.).*

NA

3.2 Will participants who lack capacity to give full informed consent be asked to give assent?

○ ○ Yes ◎ ◉ No

Provide details. IF applicable, attach a copy of assent form(s) in the Documentation section.

3.3 In cases where participants (re)gain capacity to give informed consent during the study, how will they be asked to provide consent on their own behalf?

NA

4.0 **What assistance will be provided to participants, or those consenting on their behalf, who have special needs?** *(E.g. non-English speakers, visually impaired, etc)***:**

NA

5.0 *** If at any time a participant wishes to withdraw, end, or modify their participation in the research or certain aspects of the research, describe how their participation would be ended or changed.**

By sending an email and removing their information from the study and sending them an acknowledgement that their information has been removed from our storage devices.

6.0 **Describe the circumstances and limitations of data withdrawal from the study, including the last point at which it can be done:**

Participants can withdraw their data two weeks after their submission.

7.0 **Will this study involve any group(s) where non-participants are present? For example, classroom research might involve groups which include participants and non-participants.**

Yes **No**

ID: Pro00034171 View: 5.1 Research Methods and Procedures

Status: Approved

5.1 Research Methods and Procedures

Some research methods prompt specific ethic issues. The methods listed below have additional questions associated with them in this application. If your research does not involve any of the methods listed below, ensure that your proposed research is adequately described in Section 2.0: Study Objectives and Design or attach documents in Section 7.0 if necessary.

1.0 *** This study will involve the following** *(select all that apply)*
The list only includes categories that trigger additional page(s) for an online application. For any other methods or procedures, please indicate and describe in your research proposal in the Study Summary, or provide in an attachment:

Surveys and Questionnaires (including internet surveys)

2.0 *** Is this study a Clinical trial? (Any investigation involving participants that evaluates the effects of one or more health-related interventions on health outcomes?**

Yes **No**

3.0 **If you are using any tests in this study diagnostically, indicate the member(s) of the study team who will administer the measures/instruments:**

Test Name	Test Administrator	Organization	Administrator's Qualification

There are no items to display

4.0 **If any test results could be interpreted diagnostically, how will these be reported back to the participants?**

ID: Pro00034171 View: 5.7 Interviews, Focus Groups, Surveys and Questionnaires

Status: Approved

5.7 Interviews, Focus Groups, Surveys and Questionnaires

1.0 **Are any of the questions potentially of a sensitive nature?**

Yes **No**

If YES, provide details:

2.0 **If any data were released, could it reasonably place participants at risk of criminal or civil law suits?**

Yes **No**

If YES, provide the justification for including such information in the study:

Will you be using audio/video recording equipment and/or other capture of sound or images for the

3.0 **study?**

Yes **No**

If YES, provide details:

ID: Pro00034171 View: 6.1 Data Collection

Status: Approved

6.1 Data Collection

1.0 *** Will the researcher or study team be able to identify any of the participants at any stage of the study?**

Yes No

2.0 **Will participants be recruited or their data be collected from Alberta Health Services or Covenant Health or data custodian as defined in the Alberta Health Information Act?**

Yes **No**

Important: Research involving health information must be reviewed by the Health Research Ethics Board.

3.0 **Primary/raw data collected will be** *(check all that apply)*:

Directly identifying information - the information identifies a specific individual through direct identifiers (e.g. name, social insurance number, personal health number, etc.)

All personal identifying information removed (anonymized)

4.0 **If this study involves secondary use of data, list all original sources:**

5.0 **In research where total anonymity and confidentiality is sought but cannot be guaranteed** *(eg. where participants talk in a group)* **how will confidentiality be achieved?**

ID: Pro00034171 View: 6.2 Data Identifiers

Status: Approved

6.2 Data Identifiers

1.0 *** Personal Identifiers:** will you be collecting - at any time during the study, including recruitment - any of the following *(check all that apply)*:

Surname and First Name

Address

Telephone Number

Email Address

If OTHER, please describe:

2.0 **Will you be collecting - at any time of the study, including recruitment of participants - any of the following** *(check all that apply)*:

There are no items to display

If OTHER, please describe:

3.0 *** If you are collecting any of the above, provide a comprehensive rationale to explain why it is necessary to collect this information:**

This information is required to contact the participant in case any clarification is required. Participants are required only to provide their work contact information. This information will only be retrieved if a clarification is required.

4.0 **If identifying information will be removed at some point, when and how will this be done?**

This will be removed from the main file upon the completion of data collection. It will be stored in another electronic file where it can be tracked using a unique code.

5.0 *** Specify what identifiable information will be RETAINED once data collection is complete, and explain why retention is necessary. Include the retention of master lists that link participant identifiers with de-identified data:**

Once data collection is complete and there are no further clarification questions. All identifiable information will be deleted permanently.

6.0 **If applicable, describe your plans to link the data in this study with data associated with other studies (e.g within a data repository) or with data belongong to another organization:**

Not applicable

ID: Pro00034171 View: 6.3 Data Confidentiality and Privacy

Status: Approved

6.3 Data Confidentiality and Privacy

1.0 *** How will confidentiality of the data be maintained? Describe how the identity of participants will be protected both during and after research.**

Once the data collection is done, every participant will be given a unique code that will only be identified by the project team. A separate file will be created, where the contact information can be stored and retrieved if required.

2.0 **How will the principal investigator ensure that all study personnel are aware of their responsibilities concerning participants' privacy and the confidentiality of their information?**

Details regarding data collection and storage method will be provided in the invitation letter to all the participants.

3.0 **External Data Access**

*** 3.1 Will identifiable data be transferred or made available to persons or agencies outside the research team?**

○ ○ **Yes** ○ ● **No**

3.2 If YES, describe in detail what identifiable information will be released, to whom, why they need access, and under what conditions? What safeguards will be used to protect the identity of subjects and the privacy of their data.

3.3 Provide details if identifiable data will be leaving the institution, province, or country ***(eg. member of research team is located in another institution or country, etc.)***

ID: Pro00034171 View: 6.4 Data Storage, Retention, and Disposal

Status: Approved

6.4 Data Storage, Retention, and Disposal

1.0 *** Describe how research data will be stored, e.g. digital files, hard copies, audio recordings, other. Specify the physical location and how it will be secured to protect confidentiality and privacy.** (For example, study documents must be kept in a locked filing cabinet and computer files are encrypted, etc.)

Research data will be stored electronically with the research team in password protected computers.Electronic record of survey results will be kept on a secure departmental server, not on a hard drive of an individual computer. Data will be accessed from 5-8J and 6-29 Mechanical Engineering Building.

2.0 *** University policy requires that you keep your data for a minimum of 5 years following completion of the study but there is no limit on data retention. Specify any plans for future use of the data. <u>If the data will become part of a data repository or if this study involves the creation of a research database or registry for future research use, please provide details.</u>**

There are no plans for the use of data in future.

3.0 **If you plan to destroy your data, describe when and how this will be done? Indicate your plans for the destruction of the identifiers at the earliest opportunity consistent with the conduct of the research and/or clinical needs:**

ID: Pro00034171 View: 7.1 Documentation

Status: Approved

7.1 Documentation

Add documents in this section according to the headers. Use Item 11.0 "Other Documents" for any material not specifically mentioned below.

Sample templates are available in the HERO Home Page in the **Forms and Templates**, or by clicking HERE.

1.0 **Recruitment Materials:**

Document Name	Version	Date	Description
There are no items to display			

2.0 **Letter of Initial Contact:**

Document Name	Version	Date	Description
There are no items to display			

3.0 **Informed Consent / Information Document(s):**

3.1 What is the reading level of the Informed Consent Form(s):

3.2 Informed Consent Form(s)/Information Document(s):

Document Name	Version	Date	Description
draft_consent_121002.docx | History	0.01	10/2/2012 6:13 PM	

4.0 **Assent Forms:**

Document Name	Version	Date	Description
There are no items to display			

5.0 **Questionnaires, Cover Letters, Surveys, Tests, Interview Scripts, etc.:**

Document Name	Version	Date	Description
Survey.pdf | History	0.01	10/2/2012 6:13 PM	

6.0 **Protocol:**

Document Name	Version	Date	Description
There are no items to display			

Investigator Brochures/Product Monographs *(Clinical Applications only)*:

	Document Name	Version	Date	Description
7.0	There are no items to display			

Health Canada No Objection Letter *(NOL)*:

	Document Name	Version	Date	Description
8.0	There are no items to display			

Confidentiality Agreement:

	Document Name	Version	Date	Description
9.0	There are no items to display			

Conflict of Interest:

	Document Name	Version	Date	Description
10.0	There are no items to display			

Other Documents:

11.0 *For example, Study Budget, Course Outline, or other documents not mentioned above*

Document Name	Version	Date	Description
There are no items to display			

ID: Pro00034171 View: SF - Final Page

Status: Approved

Final Page

You have completed your ethics application! Please select "Exit" to go to your study workspace.

This action will NOT SUBMIT the application for review.

Only the Study Investigator can submit an application to the REB by selecting the "SUBMIT STUDY" button in My Activities for this Study ID:Pro00034171.

You may track the ongoing status of this application via the study workspace.

Please contact the REB Administrator with any questions or concerns.

Appendix 3

Approval Letter

Notification of Approval

Date:	November 5, 2012
Study ID:	Pro00034171
Principal Investigator:	Waqas Awan
Study Supervisor:	Michael Lipsett
Study Title:	Benchmark Study of Fault Modes and Effects in Heavy Oil Production Equipment
Approval Expiry Date:	November 4, 2013

Approved Consent Form:	Approval Date	Approved Document
	11/5/2012	draft_consent_121002.docx

Sponsor/Funding Agency:	Petroleum Technology Research Centre	7442
Sponsor/Funding Agency:	Sustainable Technologies for Energy Production Systems	

Thank you for submitting the above study to the Research Ethics Board 2 . Your application has been reviewed and approved on behalf of the committee.

A renewal report must be submitted next year prior to the expiry of this approval if your study still requires ethics approval. If you do not renew on or before the renewal expiry date, you will have to re-submit an ethics application.

Approval by the Research Ethics Board does not encompass authorization to access the staff, students, facilities or resources of local institutions for the purposes of the research.

Sincerely,

Dr. Stanley Varnhagen

Chair, Research Ethics Board 2

Note: This correspondence includes an electronic signature (validation and approval via an online system).

Appendix 4

Consent Form

INFORMATION LETTER and CONSENT FORM

Study Title: Benchmark study of fault modes and effects in heavy oil equipment

Research Investigators:
Waqas Awan and Rezsa Farahani

6-29 Mechanical Engineering Building
University of Alberta
Edmonton, AB, T6G 2G8
wawan@ualberta.ca
780-492-5635

Supervisor:
Dr. Michael Lipsett
Ph.D. P.Eng
5-8J Mechanical Engineering Building
University of Alberta
Edmonton, AB, T6G 2G8
mlipsett@ualberta.ca
780-492-9494

Background

Dear ABC,

My name is Waqas Awan and I am a graduate student working on a PTRC-STEPS research project with Dr. Michael Lipsett in the Mechanical Engineering Department at University of Alberta. We are sending out this survey to collect data related to the reliability and maintenance of heavy oil production equipment, as part of a study on how to conduct benchmarking of maintenance on heavy oil equipment and systems. This project is jointly funded by the Sustainable Technologies for Energy Production Systems (STEPS) program and the Petroleum Technology Research Centre (PTRC). You are contacted as you are a member of the STEPS organization, and PTRC provided us with your contact information to be included as a study participant. The results of this study will be used to prepare a report, which will be shared with the participants in aggregate form, without revealing specific company information. Information specific to your organization will also be available upon request. Aspects of the study will contribute to an academic thesis chapter and potential academic/industrial publications, which will also be shared with the participants. The study results will be presented at STEPS stewardship meetings and possibly at academic conferences.

Purpose

The purpose of this survey is to provide the participants with useful metrics and statistics that can be used for benchmarking their reliability and maintenance processes and practice, with the objective of improving equipment operations and performance.

Study Procedures

This study asks you to fill out an online survey that can be accessed through the link provided in the email. The survey will not take more than thirty minutes. Please fill the form as completely as possible, and note that the quality and usefulness of this project highly depends on the extent to which we receive complete data, including non-mandatory data. If you are not comfortable with a particular question, you have the option to leave that answer blank. Not private or personal information is asked. In case a question is not clear, please kindly contact us.

Benefits

The survey will be used to develop a preliminary fault modes and effects analysis (FMEA), which will be of immediate use for companies to focus on key reliability issues. Consistent definitions and measurement practices for reliability and maintenance metrics may be of benefit for establishing best practices for chronic and high-risk failure modes. This understanding will help operators to prevent downhole failures of equipment, reduce risk to personnel, and thereby improve production of heavy oil.

Risk

The questions are objective, technical, and related to expert judgment on technical matters. We have not identified any potential risk to you associated with the survey.

Note, that there may be risks to being in this study that are not known. If we learn anything during the research that may affect your willingness to continue being in the study, we will tell you right away

Voluntary Participation

You are under no obligation to participate in this study. The participation is completely voluntary. Even if you agree to be in the study you can change your mind and withdraw. In case you want to withdraw from the application, please write an email within one month of receiving this letter and we will not include your data for analysis.

Confidentiality & Anonymity

Data collected throughout the research will only be accessible to research team and will not be shared with anyone outside the research team. Personal information will not be shared in any form during the presentation of research findings or in the reports produced from the research findings. Results derived from the research will be used in the preparation of report for STEPS, conference/journal articles, and thesis chapters. Data collected during the research will be kept electronically after the study is completed for the retention period of five years on a password protected server. Participants will receive the report as per the protocols of STEPS organization. We may use the data gathered in this study in future research; but if we plan to do further work, then the new scope will have to be approved by a Research Ethics Board.

Further Information

If you have any further questions regarding this study, please do not hesitate to contact us on the above mentioned email addresses. The plan for this study has been reviewed for its adherence to ethical guidelines by a Research Ethics Board at the University of Alberta. For questions regarding participant rights and ethical conduct of research, contact the Research Ethics Office at (780) 492-2615.