Freedom of conscience

Freedom of speech

Equal opportunity

Entitlement to private property and privacy

Protection of all conscious life and their private properties

Fair and free market

University of Alberta

Design, Simulation and Evaluation of Effective Industrial Information Systems: Case of Machine Condition Monitoring and Maintenance Management Information Systems

by

Rezsa Farahani

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Dedicated to my father and mother

Abstract

Industrial information systems can improve the management of industrial operations by providing relevant and timely information on the status of physical assets via condition and process monitoring systems, and by enabling the effective use of data by systems and processes that restore proper functionality via control and maintenance systems. A framework and methods have been developed that extend current information system design methods for design and evaluation of effective industrial information systems, as a method for more concretely demonstrating the value of system features prior to system design, and for assessing system performance after implementation for continuous system improvement. An effective system from the framework's perspective is first, performance-based, i.e. benefits due to the system are balanced with associated costs. Second, it is fit for the system owner's purpose, i.e. it has been designed with respect to organizational business strategy, objectives, and constraints. And third, it is holistic, i.e. it addresses various performance criteria that are important to the system stakeholders, e.g. operational excellence, financial, safety and environmental. This thesis describes the development and application of the framework and methods, and verifies their effectiveness using data from an industrial operation. The application case is on the development of a machine condition monitoring and maintenance management information system for mobile machine management of mining and production operations. Evaluation methods have been developed to assess several candidate systems and to select the most effective alternative as part of the framework. The first method is a risk assessment method for analytical performance evaluation of the system using a time-based, event-risk tree model. The second method involves simulating the system for evaluating system performance based on a developed probability model linked, stochastic, discrete event simulation method, which includes machine events, operations

workflow, information flow, and decision making related to the case operations. After system alternatives are evaluated, the process for selecting the most effective system is then demonstrated using the analytical hierarchy process (AHP) method coupled with the framework as a multi-criteria decision analysis method. Verification of the case description, models, and the assumed parameter values has been achieved by subject matter expert review.

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Contents

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Lowercase letters:

f: probability mass function (p.m.f.) or probability distribution function (p.d.f.)

h: hazard function

t: time

Uppercase letters:

F: cumulative distribution function

P: probability

S: severity measure

Greek letters:

α: Weibull distribution scale parameter

β: Weibull distribution shape parameter

γ: Weibull distribution location parameter

ε: error

σ: standard deviation

Ɽ: risk value

Abbreviations

AHP: Analytic Hierarchy Process

BDM: Breakdown Maintenance

BIS: Business Information System

BPMN: Business Process Model and Notation

DCF: Discounted Cash Flow

DES: Discrete Event Simulation

EIS: Enterprise Information System

ERP: Enterprise Resource Planning

CBM: Condition-Based Maintenance

CRM: Customer Relationship Management

CMMIS: Condition Monitoring and Maintenance Management Information System

CMMS: Computerized Maintenance Management System

DAG: directed acyclical graphical model

DOE: Design Of Experiment

FIFO: First-In-First-Out

HR: Human Resources

IDE: Integrated Development Environment

IIS: Industrial Information System

IT: Information Technology

KBS: Knowledge Base System

KM: Knowledge Management

MIS: Management Information System

MIMOSA: Machinery Information Management Open Systems Alliance

MMRIS: Maintenance Management and Reliability Information System

MMRS: Maintenance Management and Reliability System

MMS: Maintenance Management System

MSS: Management System Standard

NPV: Net Present Value

OPM: Opportunity Planned Maintenance

PM-DES: Probability model linked, discrete event simulation

PPM: Preventive Planned Maintenance

QMS: Quality Management System

RCM: Reliability-Centric Maintenance

SAW: Simple Additive Waiting

SCADA: Supervisory Control And Data Acquisition

SCM: Supply Chain Management

SOA: Service Oriented Architecture

TCO: Total Cost of Ownership

TPM: Total Productive Maintenance

TQM: Total Quality Maintenance

UML: Unified Modeling Language

VAR: Value-at-Risk

WAN: Wide Area Network

WLAN: Wide Area Local Network

WMAN: Wide Metropolitan Area Network

WWAN: Wireless Wide Area Network

1. Introduction

The productivity, efficiency, and safe performance of industrial processes and operations have been greatly enhanced using industrial information systems (IIS) (Clemons, 1986; Swan et. al., 1999; Melville et. al., 2004; Berchet and Habchi, 2005; Ravichandran and Lertwongsatien, 2005; Boucher and Yalcin 2006; Groover, 2007; Hendricks et. al., 2007; Izza, 2009). Industrial processes highly depend on reliable functionality of their subsystems and assets. IIS are critical to optimal performance of operations since they can provide relevant and timely information on the status of assets according to their acceptable level of functionality via condition and process monitoring systems. Furthermore, IIS enable effective use of information by systems, processes, and procedures that restore proper functionality via control and maintenance systems.

This thesis is on the development of a framework for design, simulation, and evaluation of effective IIS, with the purpose of improving IIS implementation practices by providing a systematic method for guiding the design, development and performance evaluation activities. An effective system, based on the framework, is fit-for-purpose, performance-based and holistic. The research objectives for this work were to explore the need for effective IIS and what constitutes an effective system, and then to develop a framework that can be used for designing, selecting, and evaluating the performance of such a system. The main hypothesis of the research is that the developed framework and its methods are effective in designing and evaluating the performance of industrial information systems that are fit-for-purpose, performance-based, and holistic. This thesis describes the application of the framework and verifies it as a hypothesis using a hypothetical case. The case is on designing, evaluating, and selecting a condition monitoring and maintenance management system (CMMIS) for implementation in natural resource mining and production operations for a hypothetical organization.

Academic studies and practical implementations have shown that systems that are not aligned with an organization’s objectives and operations perform sub-optimally or are counter-productive to an industrial organization’s objectives (cited in Chapter 2), i.e. in practice, achieving systems that are fit for the organization’s purpose has been a challenging topic. Moreover, it has been shown that many systems miss or neglect factors that affect the organization's performance. Additionally, organizations have been moving increasingly towards performance-based system implementations where the strategic advantages, increase in profits, and cost savings due to the system are balanced with the development (or purchase), maintenance, and upgrade costs. Acquiring and implementing an IIS is an investment decision. Validation of an investment decision requires measurement of system performance, and since this measurement is typically done after system implementation and utilization, it is often difficult to perform the initial design and development activities with foresight to the business value of what is required from the system, and thus difficult to confirm an investment decision. Hence, it is proposed in this work that demonstrating the value of an effective IIS prior to making an investment decision should be achieved by "pre-evaluating" the performance of its various components in achieving organizational objectives and in creating value, in accordance with its costs and implementation options, and prior to the design and development activities.

Another major motivation for this work was the lack of research on holistic performance measurement of IIS for performance-based system implementations. The need for a framework that enables the design and evaluation of effective IIS is argued in Chapter 2, along with a review of the state of the art.

This work aims to address these matters by developing and verifying a framework for designing, evaluating, and selecting of IIS that is fit for an industrial organization's purpose, performance-based, and holistic. The framework guides the design and development activities based on the expected system performance and organizational needs that are to be fulfilled by the system. Note, that the notion of a performance-based system implies the importance of value trade-off. A fit-for-purpose system implies the requirement for a system that is expected to achieve clear organizational business objectives. A holistic framework addresses various performance criteria for the system that are critical to the business, i.e. in addition to monetary measures of performance and value such as increase in production and decrease in costs, this includes "intangible" benefits, such as adhering to the organizational strategy, achieving operational excellence, minimizing safety and environmental risks, and improving operational decision quality.

The developed framework is described in Chapter 4. Demonstration of the framework's applications, in part to verify it, is described in Chapters 5, 6 and 7, using a hypothetical case that involves the design and evaluation of CMMIS for mobile machine management and maintenance in surface mining operations.

The developed framework is composed of three phases, two of which are pre-design and development activities. The needs assessment phase provides a systematic means for defining the current state of the industrial application of the system (related to the implementing organization), the requirements for implementing the intended IIS, the resources and methods for design and development activities, and the system performance measurement criteria. The performance criteria development phase involves activities that are related to designing performance evaluation methods, metrics, or important performance indicators for pre-evaluating potential system performance and measuring performance after implementation. The pre-evaluation of alternatives and choice selection phase is on assessing the performance of designed system alternatives based on the performance criteria and metrics developed during the last two phases, by means of relevant, comparative, analytical or simulation methods.

The framework has been developed to be used for demonstrating the value of various choices and system features for IIS design and implementation as investments for an organization, i.e. to demonstrate the business value of various aspects of the system, and how each component or functionality of the system creates value, affects the organization, and potentially achieves business objectives.

The hypothetical case is used to test and verify the application of the developed framework, with a specific focus on the design, implementation, and performance measurement of a CMMIS. For this purpose, hypothetical CMMIS are designed at a high-level using the framework, after which the functionality and the potential performance of the designed hypothetical systems are evaluated using the developed evaluation methods as part of the framework.

The evaluation methods were developed to evaluate the performance of the alternative designed systems and to select the most effective alternative for implementation, as part of the framework’s methods. The first method is a risk assessment method for analytical evaluation of system performance using a transient event-risk tree model. The second method involves simulations for evaluating system performance based on a developed stochastic discrete event simulation method that uses a stochastic model of the case operations. These evaluation methods are described in

Chapter 6, and their application shown in Chapter 7. As part of the framework, and based on the system comparison results, the most effective system is selected using the analytical hierarchy process (AHP). The procedure for system alternative choice selection and decision analysis is described for both evaluation approaches in Chapter 7.

Verification of the case description, models, and the assumed parameter values are achieved by subjecting them to the review of a subject matter expert. The expert was selected for being highly acquainted with the case operations. This expert verification process is described in Chapter 8.

In summary, Chapter 2 describes the need for effective industrial information systems with a focus on condition monitoring and maintenance management systems. It also explains what constitutes an effective system. Chapter 3 describes the research method used in this work. Chapter 4 is dedicated to describing the developed framework for effective industrial information system design and evaluation, and the two different methods for demonstrating the application of the framework and verifying its effectiveness using an industrial application case in Chapters 5, 6, and 7.

The framework was developed as a tool and method for designing and evaluating IIS, and to address the design and performance assessment issues of IIS in general. However, specific problems, methods, processes, concepts, practices, issues, challenges, etc. are different from one business function and industry to another. When using the hypothetical case and the developed evaluation methods for studying and verifying the framework, these differences were acknowledged. However, the intention was not to fully validate the framework's ubiquitous effectiveness, rather it was to verify its potential for resulting in an effective system implementation that is holistic, fit-for-purpose, and performance-based, and to make generalizations where possible.

In the end, it was shown by the verification process that the framework can be used to design effective systems, and to compare the performances of these alternative systems against an existing system for system choice selection prior to implementation, hence supporting the main hypothesis stated in this thesis.

2. The Need for Effective Industrial Information Systems: A Review of Performance Criteria for Designing and Evaluating Holistic Systems

2.1 Problems in Achieving Effective IIS

IIS are often a subset of an organization's enterprise information system (EIS) that mainly serve as an information technology (IT) system for the organization's specific industrial production and operational activities. In turn, EIS are generally regarded as IT systems that are dedicated to providing computerized information flow within an organization, for the purpose of providing business services, achieving business objectives, and enabling specific functionalities required by a business (Brown and Magill, 1994; Davenport, 1998; Shang and Sedon, 2002; Boudreau and Robey, 2005; Hendricks et. al., 2007). In this work, IIS is defined as a system that combines IT, information, business methods and processes, people, and resources in order to enhance decision making, enable control and monitoring of operations, expand production, and increase overall production and operations efficiency according to the industrial organization's business strategy. IIS are sometimes referred to as business information systems (BIS) or management information systems (MIS) in some business contexts, which are all subsets of EIS. However, in this text, IIS is distinguished from BIS and MIS in that IIS are technologically equipped and specifically designed to support engineering, manufacturing, production and industrial processes. This clarification of semantics is meant to distinguish IIS from systems that are commonly employed in businesses with no such industrial capacities.

Benefits of suitable IIS on various organizational business activities are widely documented (Powell, 1997; Pepperd, 2004; Devaraj, 2007; Hendricks, 2007). These systems can result in cost reductions, strategic advantages, avoidance of production losses, production expansion and, mitigation of safety and environmental risks. However, an unsuitable IIS may not be effective in providing the intended level of performance (Shao and Lin, 2002; Carr, 2003; Bendoly and Jacobs, 2004; Osei-Bryson and Ko, 2004; Tiernan and Peppard, 2004; Chan and Reich, 2007; Hendricks et. al., 2007; Bendoly et. al., 2009).

In pursuit of implementing effective IIS, numerous design, development, deployment, and adaption methods and strategies have been developed. In general, to assess IT investment choices, there is no shortage of investment decision methods, some that are quite complex for practical purposes (Clemons, 1991; Balasubramanian et. al., 1999; Benaroch, 1999; Campbell, 2002; Shwartz, 2003; Fichman, 2004; Irani et. al., 2006; Ordoobadi, 2008; Wu et. al., 2010). On the other hand, many organizations assess choices for IIS implementation based solely on the total cost of ownership (TCO) of a particular system (Ferrin and Plank, 2006). This has shown to be an inadequate valuation and system selection method since IIS is not a commodity, and effective performance of a system in a particular business setting is highly dependent on the specific needs of an organization and its context and conditions (Tiernan and Peppard, 2004). This usually is a result of the common misperception that IIS are necessary cost drivers, as opposed to them being viewed as high return investments that provide significant efficiency and bottom line cost reduction (Tiernan and Pepppard, 2004).

But organizations have been moving increasingly towards performance-based (performance balanced) system implementations where the benefits obtained from the system, such as strategic advantages, increase in profits, and cost savings are balanced with the costs associated with the system, such as development (or purchase), usage maintenance, and upgrade costs. Also, validation of system investment and implementation decisions requires measurement of system performance, and since this measurement is typically done after system implementation and utilization, it would be difficult to perform the initial design and development activities with foresight to the business value of what is required from the system, and thus difficult to confirm that an investment decision has been towards achieving an effective one.

Without systematic analysis of expected system performance based on suitable metrics, it is difficult to concretely demonstrate the value creation of a system prior to implementation (often after implementation as well), and hence difficult to achieve effective systems. For example, successful implementations of enterprise resource planning (ERP) systems have been associated with their proper alignment with the respective organization’s business (Brown and Magill, 1994; Davenport, 1998; Markus et. al., 2000; Sommers et. al., 2000). Alignment essentially means that a system is fit for the organization’s purpose, and it is achieved when an implemented system creates value for the organization and contributes to the organization’s objectives. In this sense, the effectiveness of the system must be judged based on various performance criteria that are important the organization.

Thus, the problem in implementing effective systems, in part, relates to a system design not being fit for the organization’s purpose. It is also related to the system not being performance-based, i.e. the value of the system is disregarded when the focus is solely on costs. The other major aspect to the problem is the focus of design and system performance evaluation on only one, or a limited, arbitrarily selected set of criteria, i.e. the system not being holistic.

There is a lack of research on holistic design and performance measurement of IIS for effective system implementations. Efforts in this area have been focused on evaluating a specific IIS component for specific applications, or on measuring the general improvement of an organization due to these systems (Martinsons et. al., 1999; Gordijn and Akkerman, 2001; Hitt et. al., 2002; Shang and Seddon, 2002; Kleist, 2003; Fichman, 2004; Kumar, 2004; Chand et. al., 2005; Uwizeyemungu and Raymond, 2009; Asosheh et. al., 2010).

On the other hand, decades of research work does exist on performance measurement of specific business or management methods. However, such work is very scarce when the methods are enabled by an information system. For example, a specific IIS is a condition monitoring and maintenance management information system (CMMIS), which is employed to enable monitoring and maintaining proper functionality of subsystems and assets (Iung and Crespo-Marquez, 2006; Crespo-Marquez et. al., 2007; Muller et. al., 2008; Isermann, 2011). In this case, holistic design and performance measurement research related to the method, i.e. asset and maintenance management, have been mainly focused on evaluating and comparing the performance of different maintenance methods and strategies for different industrial applications (Tsang et. al., 1999; Moore and Star, 2006; Muchiri et. al., 2010; Bana et. al., 2012). Research on CMMIS design has been mainly prescriptive and in favor of certain implementation and integration methods, e.g. in Holmberg (2001), Bangemann et. al. (2006), Crespo-Marquez (2007), and Holmberg and Helle (2008). However, aligned and performance-based design and evaluation of CMMIS have not been addressed.

It is proposed in this work that in order for a system to be an effective system, it should be fit-for-purpose, performance-based, and holistic. The notion of a performance-based system implies the importance of value trade-off. A fit-for-purpose system implies the requirement for a system that is expected to achieve clear organizational business objectives. A holistic system addresses various performance criteria for the system that are critical to the organization, i.e. in addition to monetary measures of performance and value such as increase in production and decrease in costs, this includes “intangible” benefits, such as achieving business strategy, operational excellence, safety and environmental risk minimization, and decision quality improvement.

The performance criteria that result in a holistic system, as a requirement for achieving effective systems, can be grouped in three categories: (1) criteria pertaining to the specific domain, (2) information system performance criteria, and (3) organizational performance criteria. All three categories together allow for holistic design and performance measurement of an IIS. In this Chapter, a review is provided on some important performance criteria that are related to these three performance categories.

2.2 Holistic Performance Criteria for an Effective System

Holistic performance measurement of an IIS, first, requires evaluating its performance as an information system, i.e. a system that enables information management within an industrial operation. Some very important performance criteria come to light when focus is on the performance of the information system aspect of an IIS, such as matters related to the generation, flow, and persistence of data, system intelligence and automation, information security, user interaction, and presentation of information.

On another dimension, performance of an IIS should not only be assessed with criteria related to its own domain and information system, but should also involve criteria related to the organization and the enterprise system. These criteria involve metrics and indicators beyond the customary financial and specific IIS domain ones. This includes topics that have been acknowledged to be important to an organization’s performance and sustainability, but are often neglected when a system is evaluated solely based on narrow criteria. These important topics include organizational learning, system capability in handling uncertainty, decision quality, decision flexibility, user adaption, and knowledge management.

Even niche, application specific IIS are now becoming more coordinated with other organizational business and production activities, with a key enabler being more effective integration of information and communication systems. IIS have moved from being applications that support specific industrial functionalities, to influencing high-level business objectives. Increasingly, certain capabilities and concepts are required to be supported by IIS, such as decision making, learning, knowledge management, collaboration, analysis and intelligence, risk awareness and alerting, visualization, mobility and dispersed operations, flexibility, interoperability, etc.

In the following, several performance criteria and their respective metrics for holistic IIS performance measurement, including its enterprise system, are discussed.

2.3 **Specific IIS Domain**

An important set of metrics for assessing system performance are metrics related to the specific domain of an IIS. Specific domains are organizational practices or technical concepts that an IIS is to support or enable, e.g. asset management, maintenance management, reliability engineering, supply change management, production control, inventory management, resource planning, etc..

For example, metrics related to maintenance management are often availability, serviceability, and repair time (Campbell 1995; Jardine and Tsang, 2006; Crespo-Marquez, 2007). Metrics related to reliability engineering are often survivability, hazard rate, failure rate, and mean time to failures (MTTF) (Ben-Daya and Duffua, 1995; Campbell, 1995; Moubray, 1997; Tsang et. al., 1999; Kuo and Zuo, 2003; Jardine and Tsang, 2006; Moore and Starr, 2006; Parida and Kumar, 2009; Muchiri et. al., 2010; Ayyoub and McCuen 2011; Simoes et. al., 2011; Bana-e-Costa et. al., 2012). These metrics are used by default to evaluate the performance of such organizational practices, which are also used to measure the improvements gained due to using an IIS that is focused on a specific practice.

2.4 **Financial**

The primary performance criterion for business practices and applications has been financial, and various financial metrics are used to evaluate the performance of business investments, operations, and decisions as measured and expressed in monetary terms. Since an IIS is an organizational investment, with expectations of benefits from its function, the financial criterion is a key performance criterion for assessing the value of an IIS as a whole and its various features in specific.

Not only can typical organizational performance metrics such as production, consumption, and costs be expressed using financial metrics, but also a variety of holistic performance criteria can use financial metrics for measuring the performance of the system and the organization related to each such criterion. Although it is sometimes difficult (or meaningless) to translate all aspects of performance in terms of monetary figures, if done properly, financial figures can be used to more readily calculate and demonstrate the value of investments and the value of various system performance levels. Some areas that traditionally financial metrics have been used are:

- production value;
- production opportunity losses;
- machine operational costs;
- maintenance costs and cost overruns;
- risk costs;
- lost revenue due to down-time;
- lost revenue due to inefficiencies in operations;
- labour costs; and
- improvements on operations cost savings.

These metrics would typically be expressed in monetary figures and calculated including discount cash flow (DCF) methods (Berk and DeMarzo, 2010).

2.5 **Environmental**

Organizations have become increasingly sensitive to the environmental impact of their operations. This concern extends to the IIS, where there is great value in assessing the performance of the system based on environmental metrics (Moubray, 1997; Rantnayake and Markeset, 2010).

- number regulatory environmental penalties;
- number of environmental constraints met;
- quantity of use of environmentally damaging material;
- quantity of discharge of environmentally damaging material; and
- environmental restoration and remedial activities and costs.

2.6 Safety

Safety is perhaps the most important consideration in business decisions, and is typically one of the main criteria considered in system design and engineering (Sorensen, 2002; Petersen, 2003). Hence safety is an important candidate as one of the main performance criteria for an IIS (Hamilton and Chervani, 1981; Kartan, 1997; Bates and Gavande, 2003; McMeekin et. al., 2006). Metrics that can measure how the system improves safety are greatly valuable to an organization, and can include:

- potential for decrease in false negative alerts;
- simulated decrease in safety incidents and injuries;
- potential for increase in overall safety alertness level; and
- potential for achieving high ratings on third party safety inspections.

2.7 Information Management

Business value creation in the modern economy is information driven, however, possession and storage of information does not mean that it would be effectively used to create value. The most fundamental function of an IIS is to provide effective information management, from the point where data and information is generated, to where it is retrieved and used, including all the provisions for storing, preserving, and securing it (Strong, 1997; Candell et. al, 2009; Yu et. al., 2010; Data and Christopher, 2011; Wong and Cheng, 2011). Metrics for measuring the effectiveness and efficiency of information management by an IIS can be related to the:

- ability to collect and store more asset, equipment, and system data as needed, i.e. be appropriately scalable;

- increase in the quality and better conditioning of data;
- the frequency of software service use if the system has a service architecture; and
- efficiency in retrieving data.

Understanding information dynamics and flow within an organization is valuable for understanding both the existing system of an organization for requirements definition, and for defining system architecture and information dynamics for a new IIS. Any new system, to various degrees, can use the information that already exists in the system. Existing information in an organization's information system can be regarded as a foundational element of the organization's knowledge and competitive advantage. In general, information can exist in many forms, e.g. explicitly in enterprise data and content sources and stores, and implicitly, as the knowledge of employees, in organizational and operational decisions, and in an organization's strategy and objectives. In this regard, e.g., organizational information can be grouped into different classes based on their proximity to the IIS. Proximity can be defined as how relevant the information is to the IIS functions, and how frequently the information is utilized by it.

2.8 **Risk Awareness**

All businesses face various types and levels of risk. An effective IIS is able to cast light on the sources and types of risks that can threaten an organization. This makes IIS particularly valuable since it can monitor types and levels of risks arising from critical assets and processes which an organization is most sensitive to. e.g. general reduction of organizational risks for manufacturing organizations (Akomode et. al., 1997).

For example, CMMIS are particularly valuable in this sense, since they enable monitoring types and levels of risks arising from critical assets and processes which an organization is the most sensitive to. Hence it is valuable to measure the effectiveness of an IIS in this regard. Typically the higher priority risks considered in organizations are related to production, costs, environment, and safety, e.g. in the context of CMMIS, risks are associated with asset and machine reliability and availability.

Risks and uncertainties facing an organization are related, and many of the metrics related to the risk awareness performance of a system have much in common with metrics related to system performance in uncertainty handling (next section). In this text the difference between uncertainty and risk is that although both can be expressed with the probability axioms, risk has a negative connotation, and is associated with costs, i.e. expressed as the probability of an event multiplied by the cost (negative consequence) of that event. Measurement of system performance is providing risk awareness may be challenging, which might require subjective perceptions of systems performance in this regard, however, some specific metrics can be related to:

- sending or displaying to the users risk alerts that can affect their decisions and actions;
- calculation of risk values related to costs, schedule, and profit;
- risk uncertainty estimation and quantification of subjective risk estimations (Durbach and Stewart, 2011; Payzan-LeNestour and Bossaerts, 2011);
- risk classification and determining its correlations with other risks; and
- assignment of risk ownership and context.

2.9 **Uncertainty Handling**

An effective IIS is driven by effective information flow, and thus affected by information uncertainties, i.e. the system not only relies on effectively managing information and its flow in an organization, but also relies on uncertain knowledge and judgement of experts and decision makers, and sources of information uncertainty. IIS can add great value by pointing to the sources of uncertainty and by demonstrating the effect of uncertainties on business decisions and operations. In this sense, IIS can be extremely useful by readily relating uncertainties to decisions and actions (Henn and Ottomanelli, 2003; Data and Christopher, 2011). When the environment is uncertain, information can have value since it eliminates or reduces uncertainty. However the nature of uncertainties and the extent to which they affect decisions and actions must be understood in order to collect and allocate effective information.

The sources of uncertainty and their properties are diverse. In general, sources of uncertainty can be technical, environmental, economy and market, technology, social and political, behavioral (individual and organizational), and regulations. Many provisions and functionalities that can increase the effectiveness of an IIS in handling uncertainty are usually independent from the uncertainty source type. Some of these provisions are common with the ones described as part of the risk performance criterion, which were mainly related to improving uncertainty identification, quantification and estimation.

However, not all information and event uncertainties that the system must manage or account for are related to risk events.

The metrics related to an IIS in handling uncertainty can be related to measuring improvements on:

- identification of the areas and factors of uncertainty;
- understanding how these uncertainties are quantified and expressed;
- clarifying the relation between uncertainties and business risks;
- understanding the relations and correlations between uncertainties and propagation of uncertainty from equipment and maintenance floor to high level performance indicators;
- identification, elicitation, and separation of subjective beliefs of experts from data driven uncertainties in a decision model to increase the decision maker's understanding of the decision model (Meyer and Booker, 2001); and
- determination of value of information, or cost-benefit of uncertainty reduction.

2.10 **Operational Excellence, Strategic Directives, and Quality**

Operational excellence may be an integral part of an organization’s management system, which can be greatly enhanced by an IIS (Forza, 1995), and hence suitable metrics are required to evaluate the performance of an IIS in this regard. Metrics may be related to concepts such as lean operations and continuous quality improvement principles, e.g. related to production operations, may involve measuring the role of IIS in lean production increase and expansion, and “just-in-time” product or service delivery. Related to strategic advantages, metrics may be related to product time-to-market and customer satisfaction.

For example in the case of CMMIS, performance measurement of process quality and operational excellence in maintenance has been an integral part of the total quality management practice in operations, and addressed by practitioners and academics (Nakajima, 1988; Willmott et. al., 1994; Ben-Daya and Duffua, 1995; Sharp et. al., 1997; Tsang, 2002).

2.11 **System Machine Intelligence and Automation**

A distinguishing feature of an effective IIS can be in its value creation capability by employing system intelligence to provide relevant information to users and enable automation. With significant advances in machine learning and data mining algorithms and software, and facing large amounts of data that require the decision maker's attention, an intelligent IIS can provide greater value by, e.g., enabling knowledge discovery from large amounts of data, or in the case of CMMIS, employing models learned from data for reliability and failure predictions, and allowing for online anomaly detection (Dash and Venkatasubramanian, 2000; Juricek et. al., 2001; Venkatasubramanian et. al., 2003; Emmanouilidis, 2006; Uraikul et. al., 2007; Chan and McNaught, 2008; Hajizadeh and Lipsett, 2011). Measuring the value added by system intelligence can be related to:

- determining the priority of data sources, and the priority and importance of maintenance actions and decisions;
- discovering knowledge and learning models from collected data;
- classification of collected data; and
- automated and intelligent detection and alerting.

Performance of prediction and control models, algorithms, or methods are typically measured by observing the deviation of their outputs from a true outcome, i.e. their error. So a typical metric for performance is prediction and control accuracy. On the other hand, other tangible metrics that translate to business value can be:

- reduction in human activity time on tasks;
- increase in human value-added activity;
- decrease in instances of human intervention in tasks; and
- instances of successful intelligent detection and alerting.

2.12 **Knowledge Management**

Another aspect of IIS performance measurement is its capability in enabling knowledge management (Davenport and Prusak, 2000) and how effectively it uses and organization's knowledge base. Metrics in this regard can be related to:

- assignment of process and business context to data;
- inclusion of meta data associated with data;
- knowledge extraction from unstructured data;
- capturing tacit knowledge in processes; and
- effective visualization of knowledge.

2.13 **Decision Quality**

An effective IIS enables good decision making at various levels of an organization. All the discussed aspects of a IIS so far may be required to work in concert to enhance the decision making process, and to improve decisions.

The extent to which an IIS improves the decision making process and increases the quality of decisions is itself an important performance criterion for consideration. The system may enhance decision making by having the capability to technically analyze decisions as problems with multiple attributes, trade-offs, and uncertainties (Howard, 1988; Keeney and Raiffa, 1993), and account for cognitive issues in human decision making (Tversky and Kahneman, 1974; Schwartz, 2004).

In the field of decision studies, it is generally conceded that there are three aspects to decision making and decision analysis, namely, qualitative, quantitative, and behavioral. These aspects require different metrics for performance evaluation. The qualitative aspect of decision making is focused on defining the problem and modeling the action of decision making into a process (Howard, 1988). The quantitative studies on decision making are concerned with mathematically modeling decisions, e.g. discussed by Keeney and Raiffa (1993). The behavioral aspect of decision research is concerned with studying behavioral and psychological issues with regards to decision making both from individualistic and organizational perspectives (Tversky and Kahneman, 1974; Goldstein and Hogarth, 1997; Schwartz, 2004).

For example, performance metrics related to an IIS affecting decision quality can be related to how the system handles uncertainty and provides risk awareness, e.g. whether right questions have been asked to assign the right subjective uncertainties to inputs, or if there have been proper understanding of relative probabilities and conditional probabilities. Furthermore, consistency in use of quantification and decision making methods can be measured as a metric for decision quality.

2.14 **Decision Options and Flexibility**

There usually exists flexibility and options in making decisions, such as delaying, modifying, upgrading, reversing, or abandoning actions, where such flexibility has itself intrinsic value. IIS can aid in providing options for decision and actions, and the extent to which it allows options and the type of the allowed options may influence the effectiveness of the system (Wu et. al., 2010). Performance of an IIS in allowing for flexibility and having options in decision making could be measured by comparing it with the case where such flexibility does not exist.

Hence it is also important to measure system performance with respect to the availability, extent, and type of decision and action flexibility and options in an IIS. Metrics in this regards can be related to:

- Number of decision points when options were needed but were not available; and
- Financial improvement resulting from applying an option.

2.15 **Organizational Adaption and User Interaction**

Many technology products and systems fail to get adopted and used by the intended users, despite careful considerations and sophisticated efforts in designing, engineering and developing the technology.

The issues have been shown to be mainly sociological, organizational and psychological rather than technical (Dixon, 1999; Rogers, 2003). E.g. Rogers (2003) proposed that five factors affect personal decisions on adoption of innovation, known as "Roger's 5 factors". He argued that for a technology innovation to be successfully adopted, it should demonstrate:

1. Relative advantage: the relative advantage and improvement of the innovation over similar established options;
2. Compatibility: how compatible the innovation is with the person's behavior, preferences, and activities;
3. Complexity (or simplicity): the degree of complexity or simplicity in using the innovation, which simplicity is often preferred;

4. Trialability: the extent to which the innovation can be readily tested and tried; and
5. Observability: the degree which the innovation and its advantages are tangible and visible to an individual and others.

Performance metrics for an IIS related to its adaption can be based on such factors, and other topics related to diffusion of innovation and technology adaption such as peer network effects, adaption decisions (i.e. optional, collective, authority), and incentives, e.g.:

- System utilization satisfaction survey;
- User logged in time;
- Number of messages sent in the system; and
- User sign-up/drop-out rate.

2.16 **System Security and Privacy**

Information security and privacy is among the most important considerations in designing and implementing an IIS (Kizza, 2009; Das et. al., 2012). Security issues can be external or internal. External security is concerned with defending against attacks on the system for sabotaging its performance, and against theft of valuable information. The main focus becomes to fix vulnerabilities and implement provisions that guard against intrusions, which can occur against various parts of IIS architecture. Internal security is concerned with protecting data storage and quality, i.e. avoiding data loss. Various data back-up strategies can be used that depend on the system architecture. The concept of information privacy is also among top organizational priorities. The capability of an IIS to protect information, both the organization’s and that of third parties trusted with the organization, from both government and individual intruders is valuable, and the performance of the IIS in this regard can also be evaluated.

System security performance has been research extensively. Some commonly used metrics related to performance measurement of IIS security in general are:

- instances of intrusion;
- frequency of intrusion detections;

- number of activities related to arranging and dealing with authentication issues; and
- amount of data loss.

2.17 **Presentation of Information**

Effective performance of an IIS not only depends on how the system collects and processes information and facilitates its flow, but also on how it presents relevant information to various users of the system. Many information systems have failed to provide their intended level of performance due to inadequate or ineffective presentation of information and user interaction despite technical sophistication in their functionality features (Dixon, 1999; So and Smith, 2003). Performance metrics for presentation and reporting in the context of IIS can be related to:

- decrease in the amount of time spent on training users;
- increase in user ratings related to using the system and understanding information presented;
- timely alerting related to sensitive productivity or quality loss;
- clear reception and comprehension of the level of safety risks and environmental hazard alerts; and
- reporting and alerting in the case of non-compliance with regulations.

2.18 **Organizational Learning**

Improvement in a system occurs when a learning mechanism is present. From a complex systems perspective, this includes memory and feedback (Sterman, 1994). Leaning occurs by comparing outcomes to ideals, or by comparing two consecutive outcomes. For example in improving the quality of a decision making process, the quality of uncertainty estimates can be measured after the decision outcome has been observed. In this case, the quality of estimates for uncertainties in the decision models can be measured after enough projects have been conducted based on those estimates, and if statistically significant data is obtained to state the probability distribution in parameters of successful projects.

Effective organizational learning is effectively using an organization’s systems, resources, and knowledge to improve present and future performance based on past information (Levitt and March, 1988; Simon, 1991; March, 1992; Dodgson, 1993; Nevis et. al., 1995; Spender, 1996; Crossan et. al., 1999). Organizational learning also includes learning from IIS development and implementation failures and success experiences (Lyytinen and Robey, 1999).

Achieving continuous organizational learning and improvement of the organization’s performance based on past data, decisions, and actions is challenging, and since IIS have to potential to greatly facilitate organization learning (Stein and Zwass, 1995), the organization may want to employ its IIS to aid in this goal. Effective organizational learning may be premised on effective system performance based on many of the criteria that was previously discussed.

2.19 **Other Criteria and Criteria Priority**

In addition to the mentioned criteria, others can be used as well for system design and evaluation. The performance criteria required for holistic system evaluation, ultimately, stem from the special characteristics, environment, business, and objectives of an organization, and it is a responsibility of the organization to clearly define its set of performance criteria.

Once the criteria for IIS performance evaluation are established by the organization, the priority of the criteria, their relationships, and how they relate to the organization’s strategy should be developed. This becomes an exercise in determining the importance, priority, and urgency of criteria compared to one another as it pertains to the organization.

2.20 **Design and Evaluation of Effective Systems**

In this chapter, the key aspects of an effective IIS were discussed. An argument was laid out in favour of the need for holistic assessment of system performance with respect to its information system characteristics, and the business context of the organization and its processes, i.e. the organization’s enterprise system.

The idea for holistic evaluation of IIS can extend to system design and development activities. This approach, as a design and evaluation method, has been formalized in this work resulting in the proposed framework, i.e. a framework for design and evaluation of an effective system discussed in Chapter 4.

It is proposed here that demonstrating the value of an effective IIS prior to making an investment decision should be achieved by “pre-evaluating” the performance of its various components in achieving organizational objectives and in creating value, in accordance with its costs and implementation options, and prior to the design and development activities. One of the research objectives has been to develop the framework as a method for achieving this purpose.

3. Research Method

The research work described in this thesis is on developing a framework for the design, evaluation, and performance measurement of effective IIS. The research method for this work is hypo-deductive and descriptive. It is focused on exploring the concept of effective IIS, developing a framework for achieving effective systems, and describing and verifying various aspects of the developed framework using a hypothetical case. For this purpose, a qualitative verification approach is taken to verify that the framework, including its qualitative and quantitative methods, follow the research objective, and can be used to design and evaluate effective IIS. Based on this research method, the research objective of this work is developed (Bouma and Ling, 2004; Phillips and Pugh, 2005). Note, that the framework itself is a method for producing system alternatives as effective system hypotheses, and testing their effectiveness in comparison to one another in order to select the most effective system. This chapter describes the research method for the development and verification of the framework. The framework's methods are described in the next chapters.

The need for effective IIS design and performance evaluation what an effective system entails was discussed in Chapter 2. The research objectives of this work summarized as a statement are:

To explore the need for effective IIS and what constitutes an effective system, and then to develop a framework that can be used for designing, selecting, and evaluating the performance of IIS for achieving an effective system.

To achieve these research objectives, the framework was developed based on the observations on what constitutes an effective IIS, and then applied within the scope of an industrial case as part of its verification work. This thesis falls under engineering research, however, based on familiar terms in business and social science research methodology, this work takes a descriptive, qualitative, research approach (Bouma and Ling, 2004; Creswell, 2009). The qualitative, verification aspect of the research is inductive, in that a specific case is used to verify the asserted philosophical statements (research objectives) in order to strengthen those statements. This involves, first, the description of the need for effective information systems, the shortcomings in current system design and performance evaluation methods and frameworks, the need for a design and performance evaluation framework that can result in an effective system, and what constitutes an effective system. Second, the development of the framework and its phases, activities, and other components are described based on evidence in the literature showing the importance and need for these components. Thirdly, it is not attempted to prove or validate the useability of the framework as a hypothesis that results in a universal law, rather it is verified (in contrast with validation) by demonstration that the framework and its constituting methods can be used for designing, selecting and evaluating the performance of IIS within the scope of a studied case, while bringing to attention the findings that can be generalized for effective IIS design and evaluation. This approach complies with the strategy of strengthening arguments by inductive research. For this purpose, a hypothetical industrial case, along with the application of the framework to the case are described, mainly as part of the hypothesis verification process. Finally to increase confidence in the case-based verification work, the framework methods and case data, including its description, models, parameters, and assumptions are verified by a subject matter expert for plausibility, consistency, and accuracy.

In summary, the hypo-deductive research process of the scientific method (Popper, 1959) can be described as forming hypothesis from observations (inductive reasoning process), and testing the hypothesis to either reject it, which can result in the “falsifying” of the hypothesis, or strengthening it, but never proving it as a universal fact (Figure 3-1). The research approach in this work takes the first steps of hypothesis formation, resulting in the development of the framework, and then using a case study to refine and verify the application of the framework to the case in this exploratory, descriptive research. This concept has been shown in Figure 3-2 and distinguished by the dash-line boxes. This hypothesis development and verification process is considered as a prelude to further research for deductively testing hypotheses based on the framework. However, this thesis has been developed with respect to the field of engineering research. Based on the definition that engineering is the field of applying scientific principles and skills of art to propose and develop solutions in the form of any design, product, artifact, system, or method for a specific problem or need, then an engineering research method in accordance to the scientific method can be shown in Figure 3-3. The aspects of this research method addressed in this work have been shown in the aforementioned figure by the dash-line boxes.

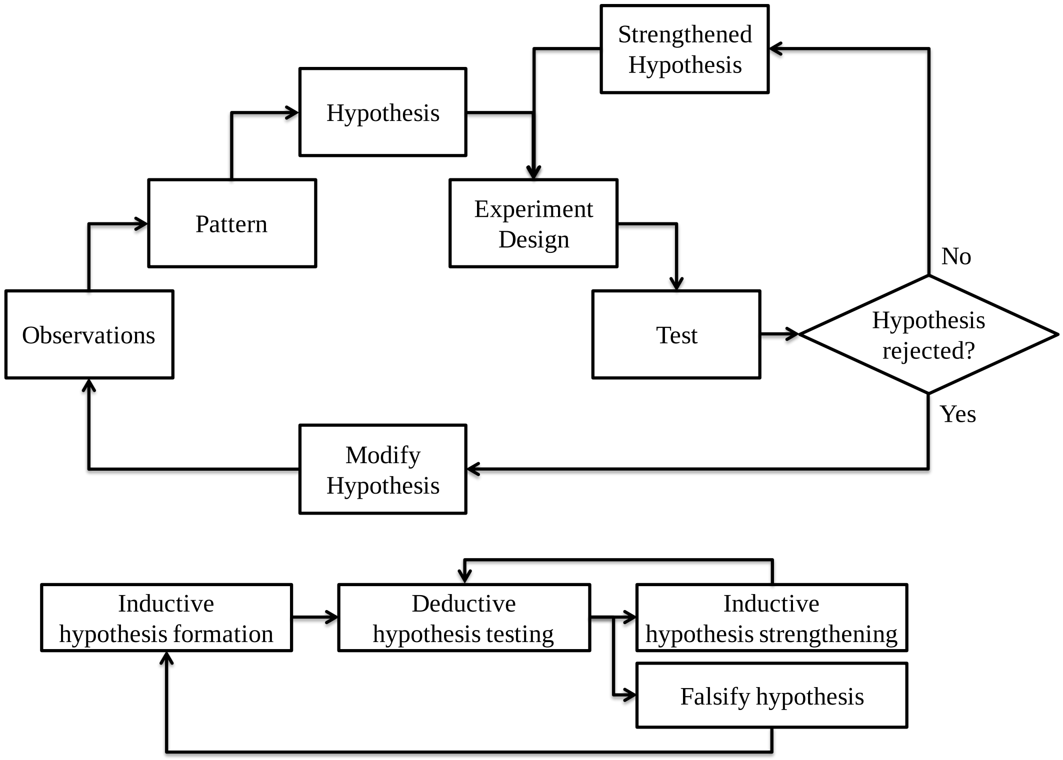


Figure 3-1. The hypo-deductive approach of the scientific method

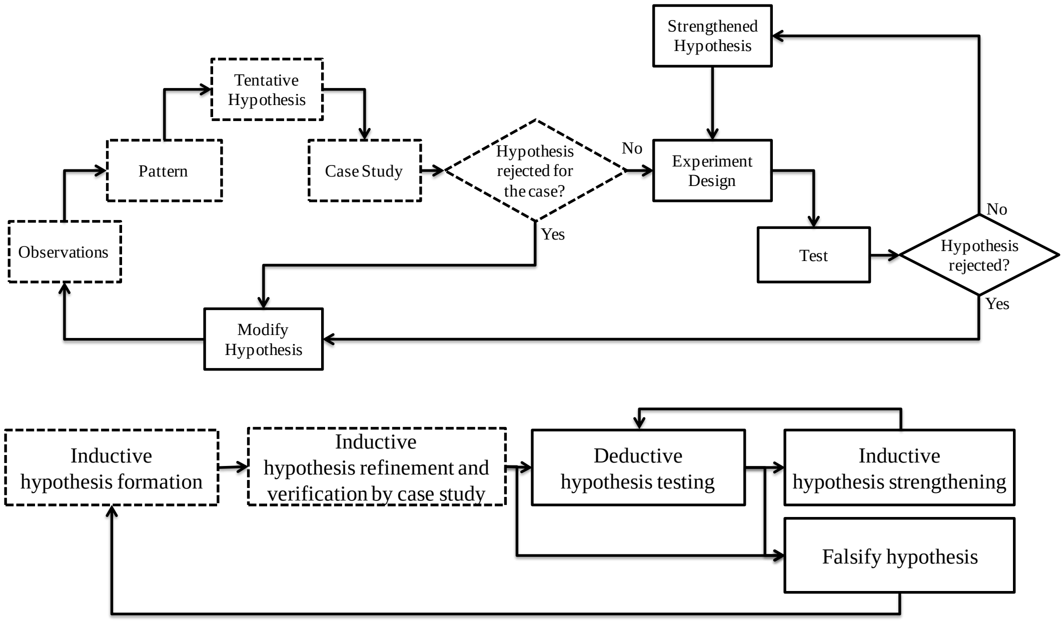


Figure 3-2. Hypothesis refinement and verification using a case study as part of the hypo-deductive approach and as the prelude to the deductive hypothesis testing process

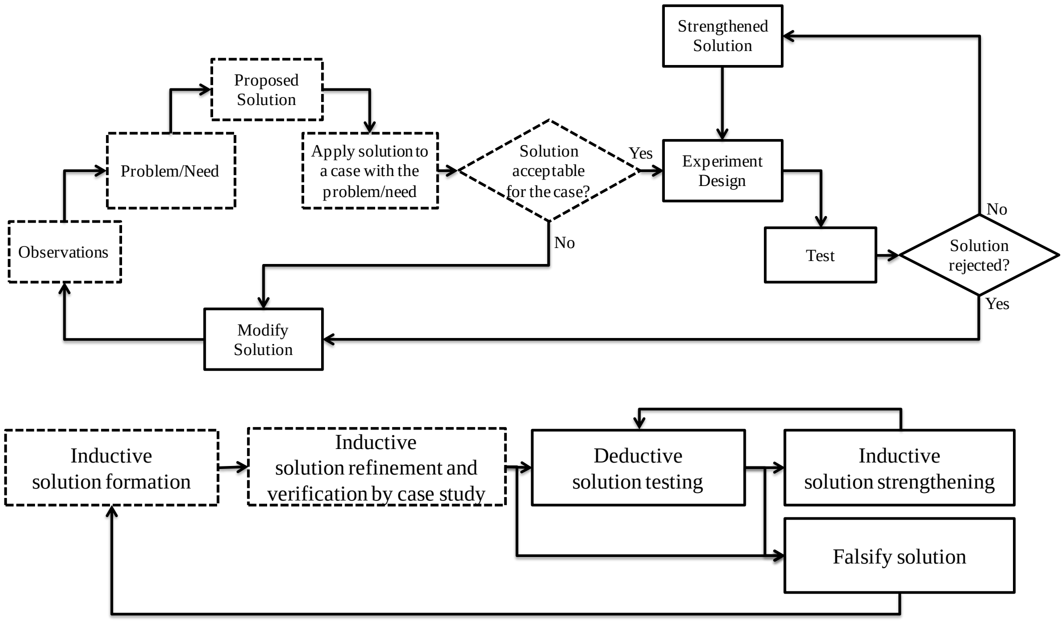


Figure 3-3. Solution refinement and verification using a case study as part of the problem solving method of engineering research methodology

The used hypothetical case is structured based on an industrial application for which the case data is verified by a subject matter expert. To demonstrate the application of the framework and to verify that it can be used to achieve effective systems, the framework is applied to produce alternative system choices for implementation. The system alternatives are then evaluated and compared against the existing system of the case using the developed evaluation methods that are part of the contributions of this work. Demonstration of the useability of the framework as the research objective would then be deemed achieved when the potential for effective system implementation after applying the framework based on the studied case can be demonstrated and verified by the subject matter expert (Carter-Steel and Al-Hakim, 2009).

Due to the exploratory nature of this work and the descriptive approach taken, the research method involves both quantitative and qualitative methods for demonstrating the application of the framework to the case and its verification as the research objective (Clarke and Lehaney, 2000; Creswell, 2009). For this purpose the framework's evaluation methods are used as quantitative methods for verifying the useability of the framework in achieving an effective system when applied to a specific case. Due to the complexity of information systems and their involvement with complex human, organizational, and business systems, it is not feasible to identify and control all the relevant parameters that can affect the system design and performance when studying a system. Hence, using cases is an effective means for studying information systems because a case contains many parameters that are common within the same family of cases, and therefore, findings involving such parameters can be generalized, while providing the opportunity for noting and discussing the limitations of such generalizations. Case studies have been used extensively in information systems research for studying both system design (Clarke and Lehaney, 2000; Middleton, 2007; Moscoso, 2007; Laitinen et. al., 2009) and performance measurement (Irani, 2002; Detlor, 2003; Uwizeyemungu and Raymond, 2009). The qualitative aspect of the research method relates to using a case to conduct inductive research (“bottom-up”), and verifying the consistency and plausibility of the case description and parameters within the chosen application domain. This verification is achieved by subjecting the case to the review of a domain subject matter expert.

The case used in this work has been selected to contain sufficient information on an organization that has the objective of implementing some form of an IIS. The goal was to apply the framework to the case study so that it could be demonstrated how the framework can clarify the value proposition of an IIS based on an organization’s needs and required performance criteria, and how it can result in an effective system, i.e. a fit-for-purpose, performance-based, and holistic system that is superior to the existing practice of the case, based on relevant metrics. In this work, the specific IIS domain selected for the case is a CMMIS. The candidate case is related to machine and maintenance management of mining truck operations in the resource production industry where an organization has the objective of implementing an effective CMMIS.

The path and activities that are intended for the verification work are illustrated in Figure 3-4.

Initially, the needs assessment activities of the framework are performed to analyze the existing state and to establish the requirements of the case organization for a CMMIS. The metrics and evaluation factors based on the established performance criteria are then developed for design, development, and implementation of the system. From these results, hypothetical CMMIS alternatives are considered for the case at a high level (e.g. in Section B of the Appendix).

Performance of the hypothetical CMMIS alternatives resulting from the application of the developed framework (i.e. “the framework CMMIS”) is compared with the existing practice of the case organization. These comparisons are conducted according to the selected performance criteria metrics, and by using the developed evaluation methods on workflow, information flow, decision making based on decision options, and system business dynamics, based on the case operations. The comparisons are performed to measure the degree to which the framework performs better than the existing practice, and its effectiveness in resulting in a fit-for-purpose, holistic, and performance-based system.

Hence by applying the framework, the needs assessment activities work towards developing a fit-for-purpose system, diversity of the performance criteria enable a holistic system, and accommodation of value trade-off and performance metrics development and measurement by the framework steer towards a performance-based system. Then the framework evaluation activities determine the most suitable candidate to be compared against the existing practice of the organization.

To evaluate the performance of the alternative systems and to select the most effective alternative for implementation, as part of the framework, two methods have been developed and used. The first method is a risk assessment method for analytical evaluation of system performance using a transient event-risk tree model. The second method involves simulations for evaluating system performance based on a developed stochastic discrete event simulation method that uses a stochastic model of the case operations. These methods are described in Chapters 6.

The studied case involves events that result in undesirable outcomes. These events are machine faults and failures, and safety and environmental incidents. Tire maintenance data existed for the case. Reliability models based on this data were used to model tire faults and failures. All other events were modeled based on verified assumptions.

Simulations on work flow and information flow is based on a code that was developed to simulate case operations, production, occurrence of fault and failure events, fault detection and prediction, maintenance activities, human and system decisions, task scheduling, and other discrete events. A range of distributions for the input variables are considered representing variable uncertainty, resulting in a monte carlo type simulation. Simulation output is expressed based on relevant performance metrics, discussed in the next sections. The work flow, information flow, and decision models underlying the simulations are described by use case scenarios and depicted in diagrams.

Both methods were developed to assess system performance of the framework CMMIS alternatives against the existing system of the case. The final, pre-implementation step of the framework, i.e. the application of the decision making process for selecting the most effective system among the alternatives is demonstrated using the AHP multi-criteria decision making method in Chapter 7.

There are four aspects to the verification work. The first aspect involves verification of the application of the framework and its usefulness for designing and evaluating effective IIS. The second aspect is about verifying that the case description represents, at a high-level, a real industrial operation for which the application of the framework is demonstrated. The third aspect is to verify that the methods for evaluating system performance, i.e. the analytical risk assessment and the simulation methods are based on models that represent the case operations with the objective of achieving meaningful comparative analysis. The fourth aspect is on verifying that the values assumed for the parameters that are involved in the models are plausible in real operations.

The first aspect of the verification work is achieved by defining the case and demonstrating the application of the framework in the case. Verification of the case description, models, and the assumed parameter values are achieved by subjecting them to the review of a subject matter expert that is acquainted with the operations which the case is based on. Matters related to the expert review work and the expert’s opinions are described in Chapter 8.

It should be emphasized that, the intention has not been to fully validate the framework’s ubiquitous effectiveness, rather to verify its potential for resulting in an effective system implementation that is holistic, fit-for-purpose, and performance-based, and to make generalizations where possible.

The procedure of applying the framework to the case, in order to verify the hypothesis, is performed with the objective of verifying that the resulting system is first, fit-for-purpose by adhering to the requirements set for it; second, performance-based, by balancing the system benefits with the associated costs; and third, holistic, by addressing a variety of performance criteria deemed important by the case organization.

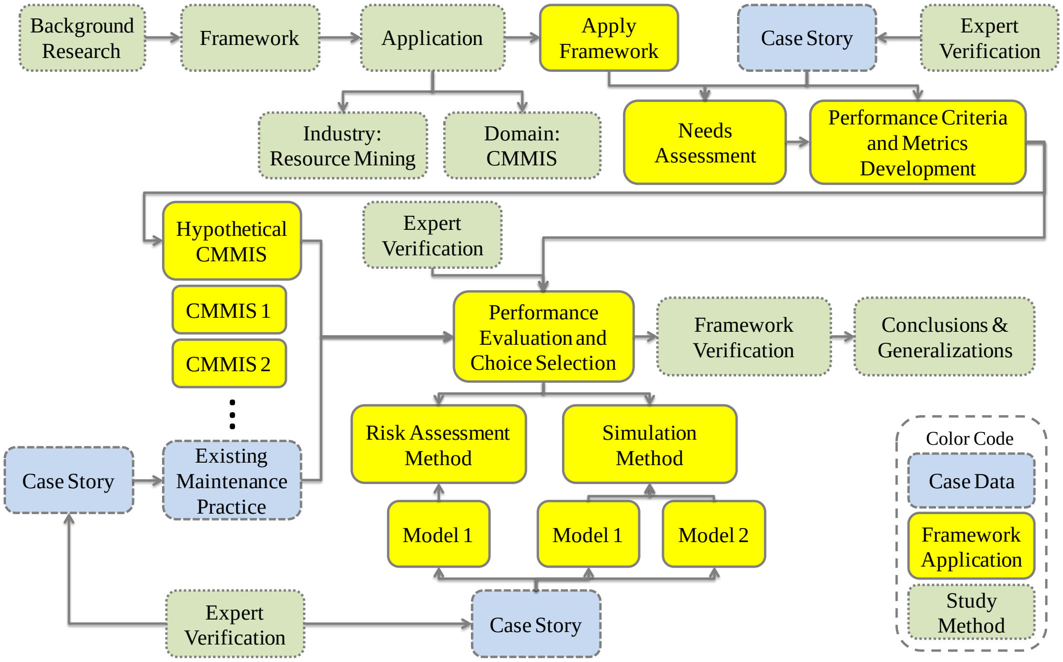


Figure 3-4. Research path and activities for verifying the framework

4. The Framework

4.1 Introduction

This Chapter describes the developed framework for implementation of effective IIS. The framework has been developed with the purpose of enhancing the existing IIS implementation practice by providing a systematic method for guiding the design, development and performance evaluation of a fit-for-purpose, performance-based and holistic system. Note, that the notion of a performance-based system implies the importance of value trade-off. A fit-for-purpose system implies the requirement for a system that is expected to achieve clear organizational business objectives. A holistic framework addresses various performance criteria for the system that are critical to the business, i.e. in addition to monetary measures of performance and value.

It is also proposed in this work that, demonstrating the value of an effective IIS prior to making an investment decision can be achieved by "pre-evaluating" the performance of its various components in achieving organizational objectives and in creating value, in accordance with its costs and implementation options, and prior to the design and development activities. Thus the framework has been developed with the purpose of demonstrating the value of various choices for IIS design and implementation investments for an organization. i.e. demonstration of the business value of various aspects of the system, and how each component or functionality of the system creates value, affects the organization, and potentially achieves business objectives.

4.2 Anatomy of the Framework

The main purpose of the framework is for it to be used as a tool for effective IIS design (or selection), implementation, and performance assessment. To serve this purpose, the framework has a strong focus on the information system aspect of the overall system. It emphasizes that the performance of IIS must be evaluated with respect to its underlying information system, and with respect to the business context of the implementing organization, i.e. its enterprise system.

The current practice of equipping an industrial organization with IIS typically involves a requirements gathering phase (specification) followed by design, development and implementation phases based on some assessed requirements, e.g. in Van Horn et. al. (2006). During development, software tests are performed at various levels of granularity. Functionality of the completed system is then verified after implementation by comparing against the design specifications. These activities can be performed using various information system development methodologies, such as waterfall or agile (Ambler, 2002), indicated by the blocks in the grey area in Figure 4-1. The framework extends and complements the existing practice as a continuous improvement system (Figure 4-1). The framework is intended to be generally applicable to all IIS at a high-level, and to provide a rigorous, systematic assessment process for providing a fit-for-purpose system.

The developed framework is composed of three phases, two of which are pre-design and development activities (outside of the grey area in Figure 4-1) in addition to the typical specification gathering, design, development and evaluation activities of the existing practices.

The first phase is needs assessment, which provides a systematic means in defining the existing state of the business and industrial operations of an organization, the requirements expected from the intended IIS for an organization, the resources and methods for design and development, and the system performance measurement criteria.

The second phase is performance criteria development, which encompasses the activities related to defining metrics or performance indicators for pre-evaluating potential system performance, and assessing performance after implementation. During this phase, the priority and relationship of the selected performance criteria and metrics are also determined.

The third phase is pre-evaluation of alternatives and choice selection. This phase is related to assessing the performance of designed system alternatives based on the performance criteria and metrics developed during the last two phases, by means of suitable, analytical or simulation methods for comparative studies of designed alternative systems and selecting the most effective one.

To achieve the framework objectives, the needs assessment phase works towards developing a fit-for-purpose system. The framework’s emphasis on the inclusion of a diverse set of performance criteria via both needs assessment and the performance criteria development enables a holistic system. And the framework's accommodation of value trade-off analysis and design alternative performance assessment based on the established performance criteria metrics during the pre-evaluation phase steer the design towards a performance-based system. These phases are described in more detail in the next sections.

The needs assessment phase is focused on information collection, problem definition, and determination of the direction for conceiving system solutions. The next phase, i.e. performance criteria development, finalizes the selection and ranking of performance criteria and metrics for system performance assessment. Based on these two phases, system design is then performed to generate alternative systems, i.e. formulation of hypothetical systems as hypotheses that have the potential to meet the organization's IIS requirements. At this phase, after the alternatives are specified, they are examined to verify whether they address the specifications and demands of the first two phases. If any adjustment is required, the needs assessment and performance criteria development activities are performed again to make any necessary modifications to the requirements, and to re-design the alternative systems. Once the alternative systems are determined, they are comparatively evaluated during the pre-evaluation phase to select the best alternative using an appropriate multi-criteria decision making method. The selected system is then developed, implemented in the organization, and verified to confirm that it meets the requirements expected from it. If no adjustment is necessary, the system is released for utilization in the organization. After utilization, the system performance is then evaluated based on the performance metrics, determined from the first two phases of the framework, to validate whether the system meets the objectives set for it. If the implemented system falls short in meeting its organizational objectives, the framework is used again starting from the needs assessment activities to determine the gaps (and the problem roots of the existing gap) and closing the gaps by performing the rest of the framework activities. The dashed lines in Figure 4-1 imply that the performance evaluation for continuous improvement of a system under utilization is only optionally done in existing system development practices. The framework emphasizes the importance of this step.

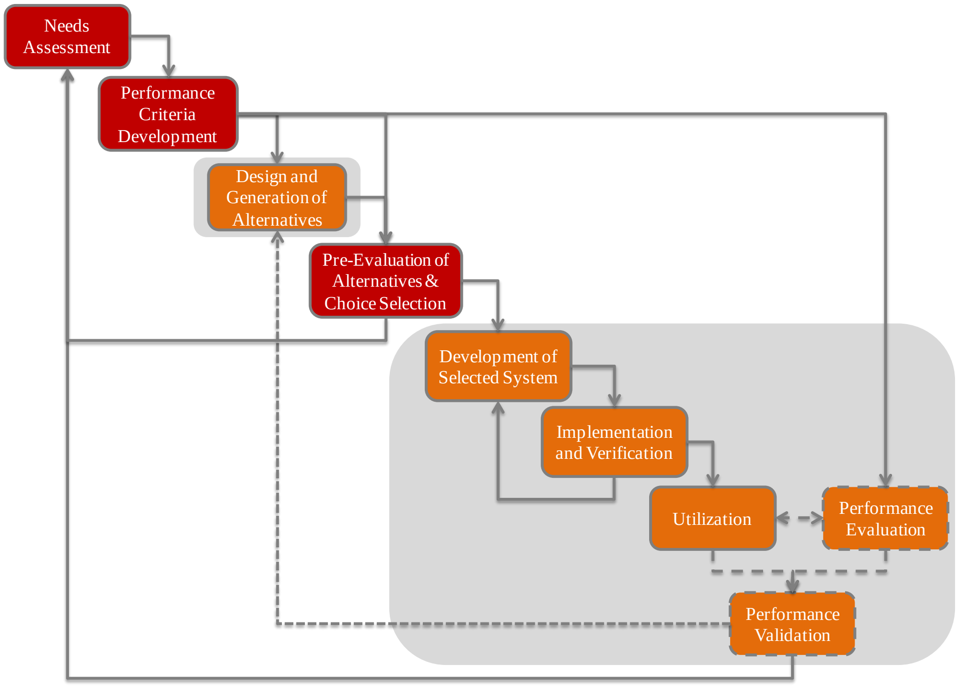


Figure 4-1. The framework: a continuous improvement process

It should be noted that the framework phase layout shown in Figure 4-1 is more aligned with the traditional waterfall approach in system development. However, the framework is applicable and can extend other development methodologies as well, such as the agile method that can result in quicker iterations through the process instead of long and detailed phases of the waterfall approach.

4.3 Needs Assessment

The needs assessment activities are intended to provide a systematic process for establishing the IIS system requirements, its expected performance, and the existing state of the user organization with the purpose of implementing an effective system. These activities, first, facilitate practice consistency and the elimination of any arbitrariness in determining the needs of the organization. It then provides a reliable assessment process with clear orientation towards an organization's objectives, and with the purpose of clarifying the system value and the gaps that could be filled by the system for all stakeholders, so that all requirements that are critical to the organization's objectives would be addressed by the IIS without costly future modifications and re-work. In other words, the needs assessment phase is the first step in achieving a fit-for-purpose system. The framework's needs assessment activity involves five assessment topics.

Requirements assessment is for defining the business strategy to be respected and enabled by the system, the objectives that are expected to be achieved by the system, and the design and implementation constraints.

Existing system assessment is for understanding the organization's business model, operations, information system, and information flow and usage.

Resource assessment is for identifying the resources available and required for system design, development and implementation, which primarily includes financial capital, human capital, information, and technology.

Domain assessment is for assessing processes, instructions, procedures, and logic for achieving the objectives of the specific domain that the IIS is to be designed for. Examples of domains for an industrial operation include asset information and maintenance management, process control, resource planning and management, and supply chain management. This may involve the business system, management systems, engineering or specific function systems, and industrial process systems required for the specific domain.

Performance criteria selection is for selecting performance criteria that are critical to effective performance of a fit-for-purpose IIS, which have been deemed important or of high priority by the organization. The criteria include all the criteria determined during requirements assessment, the criteria related to the maintenance management method, and other criteria (colors orange, brown, and red in Figure 4-2, under Performance Criteria Selection, respectively).

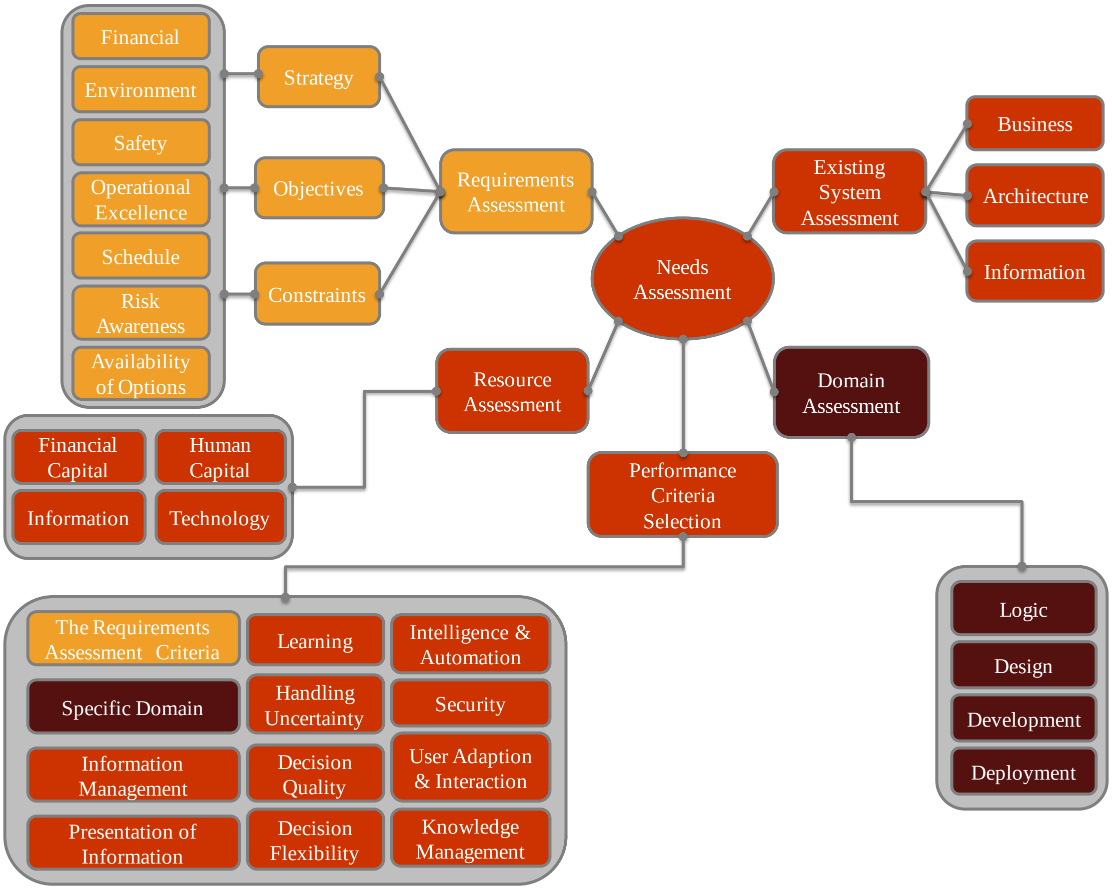


Figure 4-2. Assessment topics of the framework's needs assessment phase

4.3.1 Requirements Assessment

System requirements assessment is performed to define the objectives which the organization wishes the system to achieve, to determine constraints and limitations for the system, and the business strategy that would guide and affect these objectives and constraints. Strategy also determines the priority and the importance of the objectives and constraints for the organization.

The main criterion for setting objectives and constraints for a new system design and implementation has traditionally been financial. In worst cases, this means objectives that are vague and constraints that narrowly only focus on the total cost of ownership (TCO) of the system (Ferrin and Plank, 2006). An example of such an objective can be "comprehensive and large data collection" along with a TCO constraint set at some maximum cut-off value. In the best cases that use financial metrics, the objectives may include more specific metrics such as increase in production and reduction in costs, equipment downtime, and labor utilization, accompanied by detailed cost constraints on the various aspects of the system design and implementation project, which is complemented by a clear definition of organizational project strategy such as “to achieve lean operations”, “minimum operations costs”, etc..

However, even such a best case is not holistic. If the system is required to address other non-financial and critical issues in addition to financial objectives and constraints, then the objectives, constraints, and strategy for the IIS should also be based on other criteria that may be deemed critical to the organization’s performance such as safety, environment, risks, etc. as well. Note that objectives, constraints, and strategy can be based on one or more of these criteria. For example an organization’s objectives may be financial, environmental, and safety related, along with financial, environmental, risk, and time constraints, under a strategy based on project economics, availability of options, and time sensitive operations.

4.3.2 Existing System Assessment

The existing system assessment topic of the framework is to clarify the context of the organization for IIS implementation. While assessing the organization’s requirements for an IIS, the existing state and system of the organization must also be determined. Assessing the existing state is the basis of determining the gap between the IIS that the organization already has, and what it requires to obtain so that an effective system can be designed to close the gap. This phase is generally concerned with gathering information about the organization and its existing system, which may include the organization’s:

1. overall values and objectives of the business;
2. industrial processes and operations;
3. general financial indicators such as production, revenue, costs, and profits;
4. relevant business and organizational dynamics and stakeholder relations;
5. immediate, short term, and long term competitive strategies;
6. business market, industry, competitors and stakeholders;
7. organizational factors such as size, structure, culture, and location;
8. e.g. for a CMMIS, maintenance management practice including its maintenance procedures and maintenance costs; and

9. existing IIS architecture, e.g. whether it's a silo system, fully integrated service oriented architecture (SOA) system, existence of web-applications, communication network, etc.

Understanding the existing system is an imperative aspect of designing an effective system. Many functionalities of an existing system may be re-used or served as a foundation for new features and functionalities. On the other hand, it might be necessary to discard many aspects of an existing system after the realization that they are not supporting the requirements set for the system. Furthermore, improvements and value due to a new system can be more effectively determined by comparing a potential candidate system to an existing one, i.e. comparing "what we want" to "what we have".

In assessing the existing system, the existing information dynamics and flow in the organization should also be determined. This is critical in defining the system architecture and information dynamics for a new IIS, since the new system must effectively and efficiently use the information that already exists in the system, which generally is the foundation of the organization's knowledge and competitive advantage.

The overall performance of an IIS depends on its information and communication system, which affects information flow and dynamics, which in turn affect operational decision making. Decisions are made based on available data and knowledge within the entire system. The timing, speed, and probability of decisions are affected by information dynamics and communications within the system. Communication among different parties takes time, and depends on the communication system.

4.3.3 **IIS Domain Assessment**

This aspect of the framework is about assessing the specific IIS domain requirements and considerations, which in this context can be a set of processes, instructions, procedures, and logic for achieving certain objectives and accomplishing certain tasks within a specific industrial application. This includes business systems, management systems, engineering or specific function systems, and industrial process systems.

Typical information system domains for an industrial operation are asset information and maintenance management (as the case study of this work), process control, resource planning and management, and supply chain management.

This topic also includes the determination of any required general or application specific IIS design, development, and deployment methods. Design and development methods may vary for different business systems, for example an agile development method might be more suitable for one application, and a waterfall development model may be best suited for another (Fox and Patterson, 2012).

Specific domain assessment also includes laying out options considered suitable or required for system design, with respect to results from existing system assessment, requirements assessment, and resource assessment activities. System options can be related to architecture, infrastructure, hardware, software, services, programming languages, platform, models, features and functionalities.

During IIS domain assessment, the methods for pre-evaluating system performance are also determined. These methods may involve both quantitative and qualitative evaluation. For example quantitative system risk modeling or simulations can be used for evaluation of IIS design alternatives. As part of the domain assessment activity, the decision making methods for comparing the designed IIS alternatives and selecting the most effective system is determined.

4.3.4 **Resources Assessment**

The resource assessment topic of needs assessment is to identify the resources that are available and required to the organization for system design, development and implementation. In general, the resource categories are financial capital, human capital, information, and technology. Other tangible and non-tangible assets may be included under information and technology categories.

4.3.5 **Selection and Definition of Performance Criteria**

In order to design an effective system, and to be able to perform meaningful performance evaluation after its implementation, the framework calls for designation of the criteria that are critical to the organization and which are expected to be addressed by the IIS as part of the needs assessment phase. Several such criteria were mentioned in Chapter 2.

Once the performance criteria are determined, suitable metrics can be proposed and defined for each criterion. The criteria and the defined metrics would then guide system design, implementation, and performance measurement activities.

4.4 Performance Criteria and Metrics Development for Performance Evaluation

After selecting suitable system performance criteria during the needs assessment phase, the performance criteria development activity of the framework is intended to explore these criteria as they relate to the organization’s objectives and business operations, and to select or develop metrics for each criterion so that effective design and performance measurement can be achieved.

During this phase, the priority of the criteria, their relationships, and how they relate to the organization’s strategy is also developed. Note, that the framework calls for development of performance criteria and their metrics prior to design, so that the design phase can be goal-oriented and the expectations for performance can be clarified and laid out in advance. Determination of performance criteria may be done at the discretion of the organization, and solely depends on the organization’s existing circumstances, its requirements, and its general strategy. Several performance criteria and their respective metrics for system performance measurement are discussed in Chapter 2, as examples of holistic performance criteria that have been generally found to affect an organization’s overall performance.

Once the criteria for IIS performance evaluation are established by the organization, the priority of the criteria, their relationships, and how they relate to the organization’s strategy should be developed. The organization may broadly categorize its required performance criteria in terms of implementation priority or urgency, e.g. by a priority pyramid as illustrated in Figure 4-3. In this model, the right arrows indicate the ascendance in the pyramid building blocks that means decreasing priority but increase in importance. The left arrows indicate that the top portions affect the lower parts of the pyramid, implying that although the top categories may be rated with less urgency (or priority) than the foundational criteria (the base of the pyramid), but they are the most important in terms of achieving an effective system and that should eventually be addressed by the organization.

Note, that the particular ranking of criteria in Figure 4-3 is illustrated only as an example, and ultimately, each organization should set and assess its own performance criteria and rank their priority and urgency based on factors that are relevant to the organization. This requires careful consideration and balancing of organizational needs at different times and situations to determine the set of performance criteria. For example, when the relation between choices and the organization's strategy is under consideration, multi-viewpoint methods such as the balanced score card approach can be used (Kaplan and Norton, 1996). In using the criteria for assessing alternative IIS choices, the criteria can be evaluated and ranked with more quantitative methods such as the analytic hierarchy process (AHP) (Saaty, 1980) or PROMETHEE (Brans et. al., 1984, Brans & Mareschal, 1995).

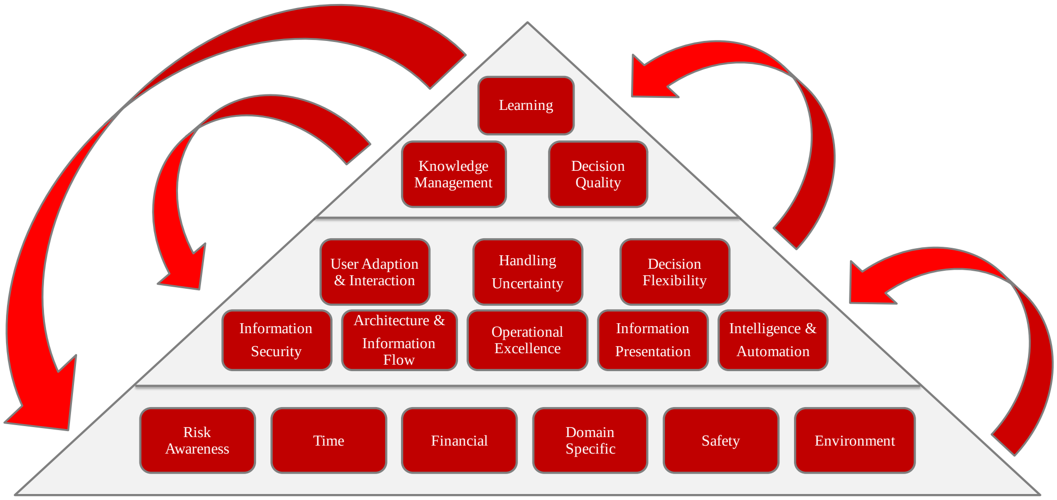


Figure 4-3. Criteria ranking: the performance criteria pyramid

4.5 Pre-Evaluation of Alternatives and Choice Selection

After the needs assessment and performance criteria development topics of the framework are addressed, the first step of the next phase, i.e. pre-evaluation and choice system selection, is to design hypothetical IIS alternatives as candidates for implementation. The systems can also be selected among commercially available options.

Once the alternatives are determined, then the second step of this phase is to evaluate the performance of the system candidates based on the specified performance criteria, and by using an appropriate method to perform comparative analysis of the systems. The method can range from a purely subjective ranking of each system based on each criterion an according to its perceived performance by an assessor or assessors, to a full simulation of the operations of the organization employing the hypothetical IIS.

Whether subjective estimation, mathematical analysis, or simulation, the purpose is to comparatively demonstrate the performance of system alternatives so that the best system can be selected for implementation. Once comparative analysis of systems is done, the decision has to be made to select the best system. To achieve this, multi-criteria decision making methods such as AHP or PROMETHEE can be used to rank the alternatives for selecting the best system.

Multi-criteria decision analysis methods have been developed and used extensively in the past few decades to solve decision problems in engineering, economics, business, finance, energy, manufacturing, government, politics, sociology, medicine, and military (Keeney and Raiffa, 1993, Steuer and Na, 2003, Pohekar and Ramachandran, 2004, Mendoza and Martins, 2006, Wallenius, 2008). In practice, the AHP (Saaty, 2005, Vaidya and Kumar, 2006) and PROMETHEE (Behzadian et. al., 2012) families of methods have been used extensively since they can be more readily applied by a decision practitioner for practical purposes without challenging mathematical and computational complexities.

Selection of any system evaluation or decision analysis method, based on the specific needs and the application of the implementing organization, is done during the IIS domain assessment activity of the needs assessment phase, mentioned in section 4.3.3.

4.6 Application of the Framework

In the next chapter, the application of the framework is described using a hypothetical case that is on developing a CMMIS for implementation in natural resource mining and production operations.

The case is used to test and verify the application of the developed framework for design, evaluation, selection, and performance measurement of a CMMIS. For this purpose, hypothetical CMMIS are designed at a high level, and the functionality and the potential performance of the designed systems are evaluated using evaluation methods as part of the framework. The analyses are performed by comparing the performance of the designed system with the existing practice of the case, with the objective of observing the effectiveness of the framework.

5. Application of the Framework: Designing a CMMIS

The framework has been developed as a means for achieving a fit-for-purpose, holistic, and performance-based CMMIS. One approach for verifying the effectiveness of the framework is by demonstrating its application using case studies (Clarke, S. and Lehaney, B., 2000; Carter-Steel and Al-Hakim, 2009). With this approach, effectiveness of the framework as a hypothesis can be verified based on the following outcomes:

1. when the main aspects of the framework have been applied and used for designing, evaluating, and selecting systems related to a case;
2. when potential for improved system implementation after applying the framework to a case can be demonstrated; and
3. when confirmation is granted by a case expert that the used methods are consistent with the industry's needs for a CMMIS, the case representation of a real life scenario is acceptable, and the evaluation method outcomes for identification and selection of an effective system are plausible.

A case study can entail applying the framework to design and evaluate CMMIS for an organization, to demonstrate how the framework can clarify the value proposition of a CMMIS based on the organization's needs and required performance criteria, and how it can result in a fit-for-purpose, performance-based, and holistic system that is superior to the existing practice of the case organization. This exercise is carried out in this chapter to demonstrate the application of the needs assessment and performance criteria development phases of the framework to the case for designing alternative CMMIS. Description of the system evaluation methods and their application within the case are carried out in Chapters 67, respectively.

The case used in this study was developed based on real-world industrial operations and parameters. Both the developed case and the application of the framework within the case were studied and affirmed by a subject matter expert from the case industry, as a user of the potential system resulting from the framework. The expert was deemed (based on his educational and professional background) to be experienced and knowledgeable about the industry, application, organization, and operations related to the case. The expert review part of the verification work is discussed in Chapter 8.

5.1 CMMIS as a Specific IIS

IIS are designed and implemented to provide a specific functionality, mainly to provide a certain management system, business service, engineering service, decision support, or for the purpose of monitoring and controlling processes or activities. Although various levels of integration promote effective information flow in an organization’s IIS, systems related to specific domains are seldom completely integrated and implemented together. Various systems also provide different functionalities that may be very different in their design, development, and deployment requirements and methods. Hence the special requirements of a specific IIS domain that supports a specific industrial function or system should be distinguished for the purpose of system design and evaluation. In this work, the specific domain of physical asset condition monitoring and maintenance management is selected as an applied instance of IIS to discuss the topic of fit, holistic, and performance-based system design and evaluation.

Industrial processes require available and reliable functionality of their subsystems and assets to various degrees. Effective and reliable system performance requires monitoring of system health and timely detection of faults, anomalies and undesired functionality, along with proper alerting at both the component and the system level. This applies to both smaller systems, e.g. the operations of a few excavation machines, to very large, highly complex systems such as aerospace systems (Johnson et. al., 2011). At the organizational level, the procedures and practice of handling the reliability and availability of devices and systems constitutes the organization’s maintenance management and reliability system (MMRS). IIS can significantly enhance the performance of an MMRS by providing relevant and timely information on asset status and health via condition and process monitoring systems, and trigger appropriate responses based on suitable information via control and maintenance systems. An MMRS that incorporates some form of computer facility is known as CMMS (also known as maintenance management and reliability information system, MMRIS), and if powered by an IIS that provides advanced monitoring and maintenance system functionalities, it is known as CMMIS. Several key factors have dramatically increased the demand for CMMIS technology, such as:

1. potential for significant cost reductions due, since maintenance costs are among the highest costs for many operations, especially for natural resource production operations;
2. improving sustainability in development and in operations by lowering costs and reducing environmental and safety risks;
3. when reliability and lifecycle of equipment or products can be accurately determined, competitive advantage is gained by improvements in the quality and volume of production; and
4. increase in system and component availability, because for integrated operations, system availability is extremely important since failure in one area can quickly propagate through the system and affect proper functionality of large parts of the operations.

Reliability, operational availability, and lifetime planning of systems, equipment and products are of prime importance in the practice of maintenance management and reliability engineering, with availability being more critical than reliability in some industries. For this purpose, several maintenance management paradigms have been developed and evolved over the past decades, such as run-to-failure (breakdown maintenance or BDM), fixed preventive planned maintenance procedures (PPM), opportunity planned maintenance (OPM), reliability-centered maintenance (RCM) (Moubray, 1997), total productive maintenance (TPM) (Nakajima, 1988), total quality maintenance (TQM), condition based maintenance (CBM), and lifecycle profit planning (LCP) (Ben-Daya et. al., 2009; Iserman, 2011).

Suitability of each method depends on many factors such as the industry, the industrial application, the organizational business objectives and practices, available technology, user attitudes, and demands of stakeholders.

Effective monitoring of system health and timely detection of failures, faults, and anomalies, along with proper alerting at both component and system level aid maintenance practices, specifically, the CBM and RCM maintenance strategies. At the component level, reliability engineering aims to utilize systems engineering, statistical lifetime analysis, component physics modeling, optimization methods, and probability analysis of failures and fault causal relationships to assess the component failure rates and the underlying failure causes, modes, and effects. Implemented as business and workflow processes, maintenance management processes deal with the reliability and availability of components, by responding to failures and events within the context of the functioning system and with respect to the organization's objectives. Due to the sophistication of reliability engineering and maintenance management processes and practices, modern maintenance management systems are increasingly required to be powered by IIS.

Firstly, IIS enables effective machine and maintenance management systems (MMS), and information management of these systems. Information in these systems involves equipment and system information and operational data such as equipment specifications, operational instructions, equipment parts and sources, and vendor information. It also includes information related to the maintenance process, i.e. items to be inspected, repaired or replaced, maintenance schedules, maintenance technician information, and specific maintenance actions to be taken.

Secondly, IIS allows integration of asset lifecycle and inventory information with an MMRS. For all but the most simple asset systems, the amount and context complexity of such information requires the involvement of an IIS.

Thirdly, IIS enables effective condition monitoring to prevent failure by detection and alerting, i.e., by:

1. monitoring assets;
2. predicting the time, severity, probability of their faults and failures; and
3. preventing such undesirable events or minimizing negative outcomes by alerting and sending instructions and procedures to relevant stakeholders, controlling and modifying certain aspects of the equipment and system operations, and preparing to handle any undesirable events.

This is a preferred method in modern maintenance, however, it has been historically expensive due to expensive costs of computers, sensors and information systems. But with the cost of these technologies decreasing very rapidly, CBM has become an extremely viable and effective strategy for maintenance management.

Finally, technical software for machine management and maintenance decision optimization and reliability engineering analyses is another form of IIS used in machine operations. Such software are extremely useful for most practical applications where system complexity, number of parameters, and the amount of data is large enough that it is not feasible to solve problems without computer solver capabilities.

Machine management and maintenance work requires working with various sources of information and large amounts of data, communicating with many stakeholders such as customers, vendors, coworkers, and making complex decisions. An effective maintenance system involves coordination of information, processes, and decisions among several different levels of operation, i.e. equipment, field, plant (operations) and the business (organization). Hence machine and maintenance management methods require the full potential of an IIS to perform effectively and efficiently, resulting in the development of CMMIS. These systems, like other specific IIS, are becoming more coordinated with other organizational business and production activities, with a key enabler being more effective integration of information and communication systems, especially domain specific business applications. CMMIS have moved from supporting crew task management to influencing high-level business objectives. Increasingly, certain capabilities and concepts are required to be supported by a CMMIS, such as decision making, learning, knowledge management, collaboration, analysis and intelligence, risk awareness and alerting, visualization, mobility and dispersed operations, flexibility, interoperability, etc.

Physical assets can now be equipped with telemetry and data acquisition systems, using numerous imaging devices and sensors. Data from machines can be easily transmitted via a form of a wireless wide area network (WWAN) to data bases. CMMIS can facilitate effective use of this data, resulting in effective monitoring, detection, predicting, alerting, and prescribing actions for improving reliability and availability of machines. Furthermore, CMMIS allows for predictive maintenance, optimized maintenance activities, consistency in inspections and decision making, reduced human error, and systematic recording of observations, actions, and decisions.

It is well established that an organization’s maintenance management processes profoundly affects organizational performance on its various business functions and organizational levels (Simoes et. al., 2011). CMMIS affects the top-line financial performance of an organization by improving system availability and reliability, i.e. by reducing or mitigating the disturbing effects of a machine’s undesirable condition on production and operations. On the other hand, the more efficient and effective the machine and maintenance management processes are, the more improvements are observed at the bottom-line financials as costs are reduced and production and operations become leaner. CMMIS also improves overall operational safety and decreases environmental damage, thus supports an organization’s commitments to its employees and other stakeholders.

CMMIS plays a critical role in facilitating and improving the quality of information flow from the level of equipment and operations in the field to other areas of an organization. CMMIS, as one of the key information generation sources and information management engines of an organization, also affects the organizational knowledge management process. A modern CMMIS is also pivotal in enhancing organizational learning, since it can provide context and create connection from the machine and operations level (where changes for improvement are applied) to higher level business performance indicators. It is through such effective connections and via change-measure-learn feedback loops that learning occurs within an organization.

Moreover, modern CMMIS can both enhance or diminish decision quality in an organization. Enhancement is gained when information is organized and presented to decision makers along with the decision problem statement, the decision context, and the outcomes and learnings from past decisions. Quality of decisions is potentially diminished when information has poor quality, is scattered, irrelevant, or without context.

CMMIS affects decision flexibility by the extent to which it provisions for the use of decision options, such as executing, pausing, stopping, abandoning, upgrading, or transferring decisions.

CMMIS also affects handling uncertainty and risk in the organization’s system. Uncertainty in an organization can exist in many forms, from equipment parameter uncertainty to market and business uncertainties. CMMIS can be instrumental in identifying the sources of data uncertainty, the characteristics and relations of uncertain parameters, illustration of uncertainty propagation through the system, the opportunities for uncertainty reduction, and demonstration of the value of information.

The performance of a CMMIS system used by the operations also determines fault and failure prediction capability, and affects the subjective failure risk perception of the operator, the inspection time, maintenance time, and efficiency in ordering service and supplies, etc.

The modern CMMIS has grown from methods of organizing machine information and maintenance activities at a small crew scale, to potentially being an indispensible dimension of an organization's EIS. These systems are expected to use information and communication system technology to work in concert with production, supply chain, inventory, and managerial accounting processes. They are also expected to significantly contribute to the organizations knowledge and learning, and to improve organizational decision quality under various sources of uncertainty.

These diverse performance expectations from a modern CMMIS require effective design and implementation with respect to its performance as an IIS that is holistic within the context of the organization and its enterprise system.

5.2 Asset Reliability and Maintenance Management Performance Criterion

An important set of metrics for assessing system performance are specific metrics related to the application domain of an IIS. In the case of a CMMIS, the key objective of the system is to improve machine management and maintenance along with the reliability engineering practice in an organization. Performance measurement of a CMMIS with respect to these criteria has been studied extensively. Metrics related to maintenance management are often availability, serviceability, and repair time (Campbell 1995; Jardine and Tsang, 2006; Crespo-Marquez, 2007). Metrics related to reliability engineering are often survivability, hazard rate, failure rate, and mean time to failures (MTTF) (Ben-Daya and Duffua, 1995; Campbell, 1995; Moubray, 1997; Tsang et. al., 1999; Kuo and Zuo, 2003; Jardine and Tsang, 2006; Moore and Starr, 2006; Parida and Kumar, 2009; Muchiri et. al., 2010; Ayyoub and McCuen 2011; Simoes et. al., 2011; Bana-e-Costa et. al., 2012).In addition to industry specific metrics, the following performance metrics related to achieving effective maintenance are typical:

- detection instances of processes not performing within specifications;
- serviced items per maintenance downtime; and
- production delays due to untimely outages or maintenance issues.

5.3 Applying the Framework: Case Description

To use the framework for designing and implementing a CMMIS, the context of the case application for employing the system must be clear. In this work, the application of the framework is demonstrated in the context of machine and maintenance management of mining machine operations. The hypothetical case is based on an organization that has the objective of implementing a CMMIS. As part of the framework verification work, the goal is to apply the framework within the context of the case to demonstrate how the framework can result in CMMIS alternatives, and can clarify the value of the systems based on the organization's needs and its required performance criteria. Application of the framework to the case is also intended to demonstrate how the framework can result in a fit-for-purpose and performance-based system that is superior to the existing practice of the case, based on the specified performance criteria and metrics.

The case resembles, at a high-level, the operations of a production business unit of an organization that operates machines for surface mining of oil sands. These operations typically employ truck-shovel mining methods under harsh operating conditions. Trucks are faced with many reliability challenges where proper maintenance is critical to achieve safe operations, decrease in costs, and lower environmental impacts (Forsman and Kumar, 1992; Ercelebi et. al. 1993; Mukhopadhyay, 1999; Roman, 1999; Dhillon, 2008). For example in the case of hauler trucks, various components are susceptible to damage, faults and failures such as its engine, suspensions struts, and tires (Hajizadeh and Lipsett, 2011; Lipsett et. al., 2011; Lipsett and Vaghar Anzabi, 2011). Failures in these components result in significant repair costs and production losses due to downtime.

First, it is assumed that the case involves an organization that is contemplating implementing a CMMIS to increase the availability of machines and the performance of its production business unit's operations. Faced with numerous strategies, methods, and technologies that have been devised and developed for increasing machine availability and reliability, the case organization faces numerous choices for a CMMIS. The remaining of this section describes the various assumptions that build the case for performing the verification work. It should be noted that not all of the information within the case description is used for applying the framework and its methods. This is mainly to simplify the models to a degree that the analytical evaluation methods of the framework can be feasibly applied, meanwhile extracting results that are useful for analysis and verification of the framework and its methods, and that are potentially interesting for organizations that are similar to the hypothetical case organization (and that have the same objective in implementing an CMMIS).

The operation has a number of machines, operators, maintenance technicians, and inspectors involved. Moreover, the operation h

as a target production goal, and has a budget allocated for maintenance activities. In this case, production and maintenance activities are both coordinated and managed within the same department that oversees the operations. It is assumed that the machine fleet is composed of only large hauler trucks.

Machines operate in the field based on production and maintenance schedules, where the machine operating time is referred to as its run-time. During a machine's run-time, they are susceptible to faults, failures, and incidents. When a fault occurs, it might be detected by the operator, inspector, maintenance technician, or the machine via its fault detection system. When faults occur, machines might continue operating, but the fault either negatively affects the machine output, or increases the probability that the related failures or incidents will occur sooner. If a failure occurs, the machine operation is halted. This forces the requirement of proper repair and restoration before the machine can resume normal operations. Depending on the failure type, the cost and duration of maintenance varies. Incidents can also occur during a machine's run-time, namely, safety incidents and environmental incidents. An incident may result in machine downtime and high costs.

Machines may undergo inspection at scheduled times, and/or at the operator's request. The number of inspectors may be limited resulting in increased downtime when several machines request inspection. Inspection tools might also be limited resulting in even longer downtime. The main role of an inspector is to determine whether a machine is faulty, and report to the operator for his decision making to continue operating the machine, or request maintenance.

Similar to inspection, machines may undergo maintenance service at scheduled times, and/or at the operator's request. Maintenance technicians and tools might also be limited causing increased maintenance times.

An important aspect of the operations is the decision making process, habits, and attitudes of various parties. Decision making involves all the decisions related to the operations, maintenance, and business processes of a system of machines in the production operations. The main decision makers may be the machine operators, inspectors, maintenance technicians, or the manager of the operation.

For example, in the case's operations, the machine operator can always make the decision to continue operating the machine at the production site at any time during the machines operation, or to request inspection or maintenance. An operator may have an intuitive or perception or a logical model of when a machine might fail or cause an incident. Based on his perception, he can make the decision to request inspection before the machine fails or causes incidents to avoid extra costs associated with a failure or incident occurring during the scheduled run-time.

In the field, multiple parties communicate related to the machine operations. Communication can be formal, e.g. occurs at specific times, relates to specific matters, uses certain communication devices, and may be required to be recorded and organized, or communication can be ad-hoc, i.e. parties could decide to bypass the formal process in certain situations.

Once a fault is detected by an inspector, or if a failure or incident occurs, a focused maintenance procedure is performed on the machine. On the other hand during routine planned maintenance procedures, a series of maintenance tasks are performed to both inspect and service a machine.

The basic maintenance approach of responding to events and providing maintenance service after a machine immediately requires such service, i.e. the practice of providing a reactionary service only after the occurrence of a machine event, is known as the breakdown maintenance (BDM) approach. When an organization implements a routine scheduled inspection and maintenance service for its equipment and machines, the practice is known as the preventive maintenance (or planned maintenance typically abbreviated PM) approach. In the considered case, it is assumed that the organization already has a preventive maintenance process in place.

It is also assumed that the organization intends to increase production by reducing machine downtime, and decrease costs by improving inspection and maintenance procedures, and by reducing the instances of failures and incidents during run-time. To achieve this, the organization considers implementing a CMMIS to support a condition-based maintenance (CBM) and preventive maintenance approach. CBM and preventive maintenance involves preparing for handling machine faults, failures, and incidents, and providing maintenance service once a need for maintenance is determined by the machine's condition monitoring system, using predictive models and methods.

5.4 Needs Assessment

As part of the verification exercise, the application of the framework for the case is demonstrated with the purpose of designing an effective CMMIS for potential implementation by the case's hypothetical organization, starting from the needs assessment phase.

5.4.1 Requirements Assessment

Requirements assessment is the starting point in applying the framework because of its role in determining the general strategy, objectives, and constraints for system design. System strategy, objectives, and constraints need not be defined from scratch, rather they can be found explicitly or implicitly documented in many sources in the organization, e.g., on the corporate website, in the corporate shareholder's annual reports, press releases, management system standard manuals and records, internal newsletters, corporate policy and bylaws, recruiting criteria, and previously established business unit targets and objectives.

It is assumed that the case organization has the general strategy of producing with high margins, while having the highest reputation in their industry for having a safe working environment, and being a leader in reducing environmental impacts of their operations. Such a high-level organizational strategy can easily be deduced from a single "mission statement" paragraph. Clearly the values of such a statement should be respected by the CMMIS, if it is intended to be a fit-for-purpose system. For example, in this hypothetical case, the case organization may require operational excellence strategies to be implemented at the department level as part of the organization's general strategy. Furthermore, the organization may already have a strategy in place for its information system that expands on the high-level organizational strategy with regards to the potential benefits of the system. For example, this strategy can be "to enable the organization's high-level strategy, enhance operational excellence for the departments, and provide higher awareness of risks facing the organization for better decision making”. Hence, from these statements, the CMMIS strategy in this case can be deduced: to implement a system that increases business margins (financial), decreases environmental impact and improves the safety of operations, enables operational excellence, and increases risk awareness. These form the requirements criteria of the requirements assessment topic of the framework. Each criterion can then be expanded and then listed as specific objectives and possibly constraints for system design, e.g. in this case:

1. Financial
    a. Increase production
    b. Reduce maintenance costs
    c. Reduce equipment failure costs
2. Environment
    a. Reduce incidents
    b. Reduce associated costs and losses
3. Safety
    a. Reduce incidents
    b. Reduce associated costs and losses
4. Operational excellence
    a. Lean operations
    b. Process and service time reduction
    c. Just-in-time service
5. Risk awareness
    a. Existence of risk monitors
    b. Alert stakeholders when risk is high

5.4.2 Existing System Assessment

For designing and implementing a CMMIS, existing system assessment involves assessing the organization’s business model and maintenance management practice, information and communication system, and the general organizational decision making process and those related to reliability, maintenance and asset management. Existing system assessment entails a formalized information collection and structured description of the existing processes and system of the organization.

Information on the existing maintenance practice can be obtained from maintenance procedures and guidelines, quality management standards (QMS), or in general management system standards (MSS) documents.

For the hypothetical case organization, it is assumed that the existing system assessment activity indicates that the organization uses a blend of break down maintenance and preventive maintenance strategies. Preventive maintenance is done through routine inspection and maintenance intervals, and break down maintenance is performed when an incident or failure occurs.

It is assumed that the existing maintenance program of the case organization involves routine visual (manual) inspection of trucks by experienced maintenance staff for finding anomalies. Trucks requiring maintenance are then called off from operations and queued for repair and restoration. This procedure heavily relies on the expert's experience and skill in inspection and recommendation of remedial actions. Only basic documentation is required to record observations and decisions, for compliance with audit programs (Lipsett and Hajizadeh, 2011).

Such basic maintenance program is inherently expensive due to long inspection schedules and downtimes; is prone to large human errors because of significant reliance on situational, expert "seat-of-the-pants" judgments; poor information and decision flow; poor recording and documentation of observations, recommendations, and decisions; and arbitrariness in actions and decisions. These are also among the reasons that the organization of the case decides to implement a CMMIS.

It is assumed for the case that a formal integrated CMMIS does not exist. The machines do not have any fault detection capability, and there are no means to monitor and record the condition of machines during their run-time. Therefore in case of faults, the operator remains unaware until a failure, incident, or change in output occurs, or if the fault is determined by inspection.

Operators communicate with the base using radio phones to report special operational conditions, events, or concerns. The machines are not equipped with condition monitoring systems (CMS), but can be equipped with on-board fault detection instruments for detecting critical component faults and displaying the faults on the machine's dashboard that is observable by the operator.

It is assumed that after each inspection that is performed based on the operator's request in order to determine the condition of the machine, the result is reported to the operator verbally. Paper and electronic documents of the diagnosis are saved under the machine's files. These files can be accessed by maintenance technicians.

The maintenance process includes routines for dealing with specific incident or failure events, and regular maintenance activities. The formal documentation of processes is arbitrary, and many procedures and activities exist only in the "heads" of the technicians. For each machine, the date and duration of maintenance, the brief mention of the performed maintenance activities, and costs are recorded in the machine's file. Any required parts or external services are requested by the maintenance technicians both for routine, constant, requirements and on a special case basis.

Once a fault is detected by an inspector, or if a failure or incident event occurs, a focused maintenance procedure is performed on the machine. On the other hand during routine maintenance procedures, a series of maintenance tasks are performed to both inspect and service a machine.

Inspectors and maintenance technicians have access to computers containing electronic files of their reports related to machines. Only reports that are meant to be used by another party are shared via shared networked folders. The information is saved in text or spreadsheet files. Operators do not have access to this information. The operation's manager is sent monthly aggregated maintenance, inspection, and operations, activity and cost reports.

It is assumed that the case trucks can be equipped with telemetry and data acquisition systems, and wireless wide area network (WWAN) exists in the operations area to access the internet.

5.4.3 **Resource Assessment**

For the studied case, it is assumed that investment budget is available for designing and implementing CMMIS, however, the organization is would like to minimize costs when all other factors are equal.

5.4.4 Specific Domain Assessment for Asset Information, Reliability and Maintenance Management

The domain assessment topic of the needs assessment phase is to determine the logic and methods for designing and implementing an IIS, in this case a CMMIS. This has to be done with regards to the organization’s requirements for the system, and with clear knowledge of the existing system. In the studied case, method assessment is about determining the logic and methods of condition monitoring, maintenance, and management of assets and machines.

The asset information and maintenance management method assessment topic of the framework is to distinguish the special requirements of a CMMIS related to the required maintenance management method and practice for the organization’s specific application.

This includes the required condition monitoring and maintenance management logic for the system, which in this context refers to the rules, processes, methods, procedures, models, and practices of the maintenance management system and the organization’s maintenance strategy. It also includes any ontology or standards which the practice is based on, e.g. including more specific functional standardized specifications such as ISO 13374-1 for machinery diagnostic systems.

The organization has formed the hypothesis that machine condition monitoring and failure prediction capabilities, powered by an effective information system, would accomplish the organization’s requirements for the system. For this purpose, a variety of new technologies and methods that are available to the organization should be assessed during specific IIS domain and methods assessment to select the most suitable options for the CMMIS. For the new CMMIS, the organization intends to implement the CBM and predictive maintenance approach with the goal of discarding its current, costly, preventive maintenance activities.

A CBM approach towards maintenance requires the machines to be equipped with condition monitoring technology for continuous system health monitoring and fault detection. It also requires a communication system to be in place for transferring data out of machines. CBM also requires an information system to be in place for coordinating fault and failure response activities.

Predictive maintenance requires methods and technology for predicting the occurrence of faults and failures. This includes models and methods for failure prediction and a system for collecting and processing machine data.

Moreover, the organization carries the hypothesis that optimization of inspection and maintenance procedures is necessary to improve the financial metrics, and to increase operational excellence. Hence the CMMIS should also fulfill this role.

In summary, it is determined by the specific domain assessment activity for the studied case that the CMMIS should support a combination of BDM, preventive maintenance, CBM and predictive maintenance strategies along with maintenance process optimization.

With regards to selecting an information system development method, it is assumed that during the methods assessment activity, the case organization decides to use the traditional waterfall system development method for developing its CMMIS. This method is more familiar and similar to the project planning and management practice in the resource production industry.

Since machine events and some processes of the operations are stochastic in nature, and since the organization is interested in several risk metrics for performance assessment, it is assumed that the organization selects a transient (time-based), event-risk analysis method, described in Section 6.1, as one of its pre-evaluation methods. It also decides to use a stochastic simulation method, developed and described in Section 6.2, as the second system evaluation method. Furthermore, since the performance measurement is based on several performance criteria and metrics, the method used for choice selection is AHP because of its versatility, relative simplicity, and its accommodation multi-criteria choice selection (described in Section 6.4).

5.4.5 **Performance Criteria Selection**

As the last part of the needs assessment phase, the case organization must select the performance criteria which it intends to use to evaluate the performance of its potential CMMIS. In addition to its previously selected requirements assessment criteria, i.e. financial, environmental, safety, risk awareness, and operational excellence, it is assumed that the organization intends to assess its CMMIS performance with regards to asset and maintenance management, and information management.

5.4.6 The Case's Needs Assessment Outcome

In summary, the needs assessment phase of the framework for the case organization can be seen in Figure 5-1, which compared to the full scope of the framework, is more limited but customized to the needs of the case organization.

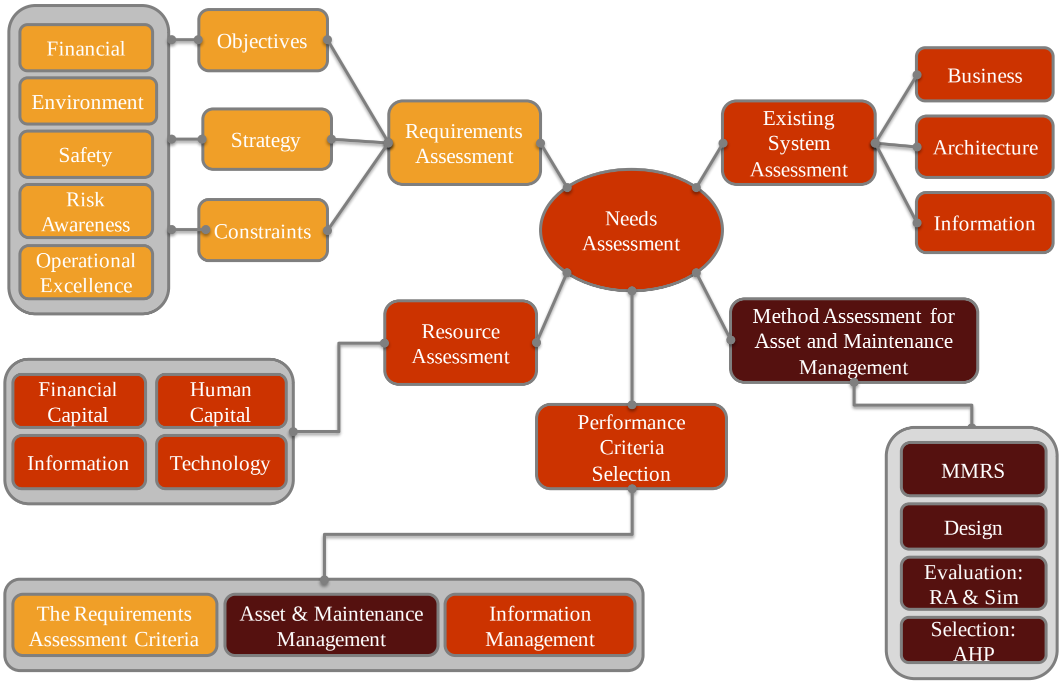


Figure 5-1. The needs assessment phase of the framework for the hypothetical industrial case

5.5 Performance Criteria Development

The case organization's assumed selected performance criteria for evaluating its CMMIS were described during the needs assessment phase. During the performance criteria development phase, the organization must rank the criteria with regards to their priority/importance, and for each criterion, select suitable metrics for formal system evaluation.

5.5.1 Performance Criteria Ranking

At a high-level, it is assumed that the case organization ranks the importance of its selected performance criteria in the following order:

1. Financial

2. Environmental
3. Safety
4. Operational excellence
5. Risk awareness
6. Asset and maintenance management
7. Information management and flow

5.5.2 Metrics Selection

For concrete evaluations, metrics are needed for each performance criterion. Some metrics can be used for both pre-evaluation of system performance, and post implementation performance measurement, for which some metrics may only be suitable for one of those phases. Since metrics are used by the evaluation methods, they are outlined as part of the discussion on pre-evaluation methods in the pre-evaluation analyses sections.

5.6 Application of the Framework and Designing CMMIS Alternatives

By performing the pre-design and development phases of the framework, i.e. the needs assessment and performance criteria development phases, it is assumed that the organization has determined the requirements for a potential CMMIS implementation, the characteristics of the existing system, the available resources for designing and developing the system, the logic and methods of the CMMIS, and the metrics for evaluating system performance. At this stage, the organization is ready to design and develop a CMMIS. The pre-design and development phases serve as guidelines to conceive one or more CMMIS designs as refined hypotheses of systems that have the potential to satisfy the organization’s requirements. In the following, two hypothetical system designs are described at a high-level, as the outcome of the needs assessment phase.

5.6.1 **System 1: Offline CMMIS**

The first hypothetical system is a CMMIS that relies on the machines’ on-board CMS. In this case, on-board sensors collect data from the machine and store it on a data logger. This data is then manually downloaded to computers to be used as inputs to fault detection and reliability models for system health and reliability diagnosis and prognosis.

Moreover, all data collected from the operation are transferred manually to local application server computers for storage and processing. It is assumed that these server computers contain the CMMIS application, where data is conditioned, pre-processed, and processed. It is also assumed that the application contains pre-processed data and the application model including (a) maintenance management rules and logic, and (b) reliability, fault detection, and condition prediction models and algorithms.

It is assumed that as the users of the CMMIS application, maintenance technicians interact with the system by inputting machine data, their observations, decisions, and action results into the system, and requesting information on machine condition and their work processes for repairing and servicing a machine if required.

5.6.2 **System 2: Real-time CMMIS**

The second hypothetical system is a CMMIS consisting of machines with on-board CMS that are connected via a wireless network to a central application server.

It is assumed for this system that, wireless field data collection takes place from the machines, which collect and send data to the main CMMIS application servers either continuously or in short time interval batches.

It is assumed that the application and data server computer in this case are owned by a third party service provider. It is also assumed that data is uploaded directly to the servers from the machines, and accessed by users that have a network connection to the servers at any location where the means for such access exists. The CMMIS application is also accessed and used in this manner.

Using this system, the operators have a mobile computer with wireless network connection to request inspections, to report failures, incidents, and special machine conditions, and to be alerted by the system of any machine fault or messages from the base. It is assumed that once the application detects a fault, both the operator and the service crew are notified by the system where the machine is then queued for service with a high priority.

6. Application of the Framework: Methods for CMMIS Pre-Evaluation and System Selection

After the CMMIS candidates for implementation have been designed, the next phase of the framework calls for pre-evaluating the performance of the candidate systems as considered system alternatives based on the determined performance metrics, followed by selecting the best performing system for implementation. The pre-evaluation and choice selection phase for the case under study is described in this chapter, where the general methods that are used for pre-evaluation and choice selection accommodate the requirements of the case organization.

The first pre-evaluation method described in Section 6.1 is a transient (time-based), event-risk analysis method. The second is a stochastic discrete event simulation method, described in Section 6.2. For choice selection, the AHP method is used because of its versatility, relative simplicity, and its accommodation multi-criteria choice selection (described in Section 6.4).

In demonstrating the application of the framework based on the hypothetical case, the utility of the framework in achieving an effective system is also verified. The case was described in Chapter 5, i.e. an organization that intends to implement a CMMIS for its surface mining operations. Verification, in this approach, involves performing the pre-evaluation analyses as system value analysis based on the determined metrics related to the organization’s selected performance criteria, and selecting the best performing system using the decision making (choice selection) method to verify, by demonstration, the merits of the framework in designing and evaluating an effective system.

6.1 Risk Analysis with Transient Event-Risk Trees (TERT)

Wherever stochastic events exist that may result in costs or other negative outcomes, risk analysis methods can be used to assess the problem involving such events for planning and decision making. Various definitions of risk have been used by academics and practitioners, where the used definition of risk is typically established at the beginning of a work. The notion of risk has been used as the probability of occurrence of a negative (undesirable) event, e.g. in Ostrom and Wilhemsen (2012), where risk is defined as “the probability of an unwanted event that results in negative consequences”. Risk has also been defined as the severity of an uncertain event. However, Aven (2010) has attempted to clarify the improper terminology uses of risk, and to bring consistence in its use. Aven and Renn (2009) define risk associated with an “activity” to be “uncertainty about and severity of the consequences of an activity”. With this definition, a quantitative or qualitative expression of risk must be related to the events that can occur, the probability of the occurrence of an event, and the severity of the outcome of an event all together. If the negative outcome of an event is called the severity of that event, and the magnitude of this severity can be expressed and quantified, then the event risk can be defined as the probability weighted severity of the event, i.e. its severity multiplied by the probability that the event occurs.

In specifying risk events and situations, the objective is not to formulate “the” right questions, rather it is to agree on “meaningful” questions, i.e. questions that allow meaningful comparison of the effectiveness of the system choices according to the framework.

For the hypothetical case, because of the stochastic nature of the events in the operation, the value of the probable negative outcome of a given event situation is the uncertain severity of that situation for which a risk value can be calculated. Event situations can be defined based on an organization’s interest or concern about a certain outcome. For example, an organization might want to study the financial, safety, or environmental risks associated with the failure of a specific number of machines. In this case, the organization may define several risk levels, such as a “good situation”, when none of the machines fail during their designated operation period, an “ugly situation” when all the machines fail at a given point in time, or a “bad situation”, when at least half of the machines fail prior to a specific time.

An important step is for the organization to define and agree upon such situations of interests and the associated risk thresholds or risk values of interest/concern. However, in order to calculate the risk values, stochastic models of risk causes such as failures and incidents must be developed or assumed. Regarding the hypothetical case under study, it is assumed that the organization has collected failure and incident data over time, and that this data has been used to develop failure and incident models. Different probability distribution functions (p.d.f), such as the uniform distribution, the normal distribution, and the Weibull distribution, can be fitted to such data. The data distributions represent the stochastic nature of the event for which the data has been collected (Kuo and Zuo, 2003; Ayyub and McCuen, 2011).

For each risk cause, to calculate risks, e.g. related to a failure or an incident, an event risk tree, based on its corresponding probability tree, can be drawn that shows risk value outcomes of the defined risk situations, based on a specific distribution function for the risk event. To calculate risks using time-based data, a transient (time-based), event risk tree (TERT) can be developed where each node of the tree represents a point in time, each branch of the tree represents an uncertain risk situation including all defined risk events (machine events with an undesirable outcome), and each node section containing a collection of branches represents the set of risks for different risk scenarios.

Let t be an instance of the random variable that represents the operating time of a machine until it fails or causes an event, and $f(t)$, $F(t)$, and $h(t)$ represent the probability mass function (p.m.f., or p.d.f. in case of a continuous distribution), cumulative distribution function, and hazard rate function of the random variable, respectively.

If we assume that all the machines have a maximum life of t_f, and that there is an equal chance that a machine can fail at any given point in time prior to t_f, then this phenomenon can be represented by a continuous uniform distribution. In this case, assuming the machines start operating at time zero, the probability of a machine failing prior to time t is:

$$F(t) = \frac{t}{t_f}$$

The expected value (mean) or mean time to failure (MTTF) is:

$$t_m = \frac{t_f}{2}$$

and the hazard rate, which indicates an exponentially increasing failure hazard rate, is:

$$h(t) = \frac{1}{(t_f - t)}$$

Another distribution that can be used to fit failure or incident data is the normal distribution. In this case, the p.d.f. and CDF are:

$$f(t) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}(\frac{t-t_m}{\sigma})^2}$$

$$F(t) = \int_{-\infty}^{\frac{t-t_m}{\sigma}} \frac{1}{\sqrt{2\pi}} e^{-\frac{\tau^2}{2}} d\tau$$

t_m is the mean of a normally distributed run-time data. $F(t)$ for a normal distribution does not have a closed mathematical function form, but can be determined by numerical solver methods or tables.

A widely used distribution used for the reliability analysis of run-time failure data is the Weibull distribution. If the failure times of machines, which can be related to specific failure modes, can be represented by a Weibull distribution, then the p.d.f, CDF, and hazard rate of machine failure data can be expressed by the following functions, respectively:

$$f(t) = \frac{\beta}{\alpha}\left(\frac{t-\gamma}{\alpha}\right)^{\beta-1} e^{-(\frac{t-\gamma}{\alpha})^\beta}$$

$$F(t) = 1 - e^{-(\frac{t-\gamma}{\alpha})^\beta}$$

$$h(t) = \frac{\beta}{\alpha}\left(\frac{t-\gamma}{\alpha}\right)^{\beta-1}$$

In these functions, α is called the scale parameter, β is the shape parameter, and γ is the location parameter.

For a transient event risk tree, the probability of occurrence of an event can be calculated using any of the mentioned distributions. Each node of this diagram represents a machine event cause at a given point in time, with branches out of each node indicating the probability of a risk situation related to that event occurring at that point in time. To each branch, a measure of magnitude of the undesirable outcome can be assigned, which is also known as the severity of that event (S). This measure can be subjective. However, it should be quantified by some scale in order to calculate quantitative values for the risk of the event. In this case, the risk value (Ɽ) is the probability of an event (P), multiplied by the severity measure (S) of the outcome:

$$Ɽ = P \times S$$

Hence the value of a branch represents the quantified measure of risk of an undesirable outcome, while each tree section represents a set of risks and their values at some point in time.

If we consider the undesirable risk situations to be a certain number of machine failures and incidents for the hypothetical case of study, since for each situation of interest there are two possible outcomes of a machine event occurring or not occurring, the risks for each situation can be calculated using a binomial distribution with the random variable representing the number of failures or incidents occurring by some time:

$$P(X = x) = \binom{n}{x} p^{x}(1-p)^{(n-x)}$$

The probabilities of a specific risk situation occurring or not occurring can be calculated from the assumed failure or incident distributions. Hence the probability that x number of machines fail among n machines, assuming that the probability of failure of a single machine prior to time t is $F(t)$ becomes:

$$\mathcal{F}(x,t) = \binom{n}{x} F(t)^{x}(1-F(t))^{(n-x)}$$

Taking $\mathcal{F}$ as a random variable of interest, the probability of a variety of risk situations can be defined. For example, $\mathcal{F}(0,t)$ is the probability that no machine fails prior to time t, or $\mathcal{F}(n,t)$ is the probability that all of the machines fail prior to time t. Or, similarly the probability that at least five machines fail prior to time t can be expresses as:

$$\sum_{x=5}^{n} \mathcal{F}(x,t)$$

Based on the organization's definition of risk situations, to make decisions with regards to selecting a CMMIS for implementation, it selects four risk situations to be:

1. Ʀ^{g}: "good" situation, or the risk of none of the machines having a failure or incident event. Note that, logically there is no consequence associated with none of the machines failing, hence this risk value can be zero, however, if there exists a baseline cost or consequence associated with operating the machines even if they do not fail, then risk values can be calculated for this situation;
2. Ʀ^{b}: "bad" situation, or the risk of at least five of the machines having a failure or incident event;
3. Ʀ^{u}: "ugly" situation, or the risk of all of the machines having a failure or incident event; and

4. Ɍ^{e}: “expected” situation, or the total average risk of the machines having a failure or incident event, calculated as the mean of the machine failure binomial distribution, i.e. $nF(t)$.

When $\mathcal{F}_k(x,t)$ is the probability of a risk event cause type *k* occurring for *x* machines prior to time *t*, and $S_k(x)$ the severity of risk event cause type *k* for *x* machines, then:

$$\text{Ɍ}_k(x,t) = \mathcal{F}_k(x,t) \times\ S_k(x)$$

The time-based, event risk tree for machine events can then be drawn by calculating $\text{Ɍ}_k(x)$ at each node (Figure 6-1). The collection of all risks for all of the risk event cause types, *k*, for a risk event situation, *i* (a branch), is a set denoted by Ɍ^i.

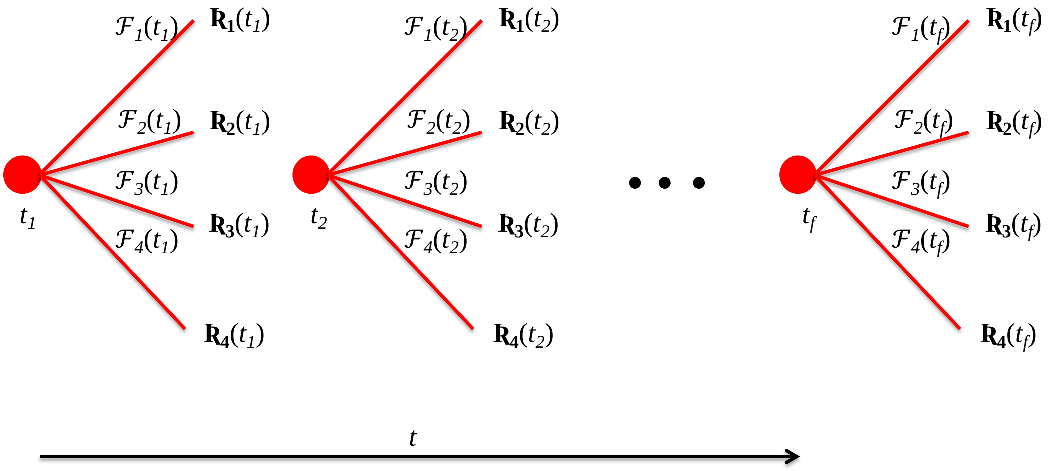


Figure 6-1. Transient risk tree showing four risk situations resulting in a set of risk values for different risk event types

6.2 The Simulation Method for Pre-Evaluation

Any method that can allow for a holistic evaluation of system performance can be used to compare the performance of the different system alternatives against each other. For cases where the system must perform under random occurrences of events and decisions, the method must allow for the stochastic nature of the case. One such method discussed in the previous section is the transient event-risk tree method. Although this method is useful and informative for simpler case scenarios, i.e. provides the means for relative performance comparison of such cases, it is not adequate for more complex cases. Considering the power of currently available computers, the performance of systems can be simulated for comparative analysis given an effective simulation method. Such a method should allow for the simulation of machine operations, work flow, decision making and information flow to simulate production, stochastic occurrence of faults and failures and incidents, fault detection and prediction, maintenance activities, human and system decisions, task scheduling, and other organizational operations, discrete events and processes. Business and industrial operations have been extensively simulated ever since the widespread business use of computers (Nance, 2002; Jahangirian, 2010). More recently, simulations have also been used to study enterprise systems (Rabelo, 2005), and enterprise modeling (Christensen, 1996), including specific systems such as ERPs (Moon, 2005) and SCMs (Kleijnen, 2003; Zee, 2005). Simulations have also been used to analyze information systems (chapter 14 in Altiok and Melamed, 2007).

This section proposes and describes a simulation method that allows for the discrete simulation of industrial operations involving the mentioned aspects of such operations. The method is based on the discrete event simulation (DES) method that includes stochastic events, such as faults, failures, incidents, and decisions, and is linked to a probability model that represents the inter-relationships, dependencies, and mutual influences of the stochastic parameters and events through graph models of prior, conditional, and posterior probabilities. Hence, resulting in a probability model-linked, discrete event simulation (PM-DES) method.

6.2.1 Stochastic Discrete Event Simulation

Discrete event simulation (DES), as opposed to simulation of continuous parameters, is a powerful method that has been used extensively for modeling and simulating dynamic problems that must include the occurrences, relationships, responses, and in general, dynamics of the simulation subject. It is particularly well suited to solve problems that involve queuing, signalling, waiting, triggering, decision making, multiple and parallel processes, stocks and resources, multiple and parallel actions, priorities, and randomness. DES has been used extensively to simulate many events and processes in manufacturing, production, maintenance, decision making, information systems, supply chain management, etc. (Robinson, 2005; Hallocks, 2006; Wainer, 2009; Wainer and Mosterman, 2011). Events can be time dependent and can also be location dependent.

Stochastic DES is a variant of DES where events can occur randomly based on specific probability distributions. Randomness can be applied to any event, including actions, decisions, and environment variables (Ross, 2006). Since one stochastic simulation represents only one instance of many possibilities in occurrence of random variables, meaningful results can be obtained if many simulations are performed by varying the variable values based on their distribution and obtaining the resulting distribution of the unknown variables of interest. This procedure is a Monte Carlo type simulation (chapter 3 in Altiok and Melamed, 2007).

6.2.2 Probability Model

When random events that are modeled are many, or dependent on one another, the relationships, dependencies, and influences of the events can be modeled using probability models including all that fall under the family of probabilistic graphical models (Koller and Friedman, 2009). These models have the advantage of graphically illustrating the relationships and dependencies among the random variables to aid the calculation of probabilities of interest using prior, conditional, and posterior probabilities.

A useful model that can be used to represent the relationships among event probabilities is the directed acyclical graphical model (DAG). Such a model generally starts with independent prior probabilities of random variables and ends in posterior probabilities through conditional probabilities. Therefore when using DES for simulating a stochastic event problem, a DAG can be constructed and used to guide the probability value assignments in the DES model. This method is named a probability model-linked, stochastic, discrete event simulation method (PM-DES) in this work, and is proposed and developed as a method for simulating and comparing the performance of the framework system alternatives.

As an example, a schematic of the structure of the PM-DES method for the hypothetical case of hauler truck machine operations is shown in Figure 6-2. There are six elements to a PM-DES model, data, probability models, uncertain events and parameters, discrete events and processes, and the uncertain outcomes. Data on various features that can affect the uncertain events and parameters are used by probability models, such as reliability models or machine learning models, to predict the probability of occurrence of an uncertain event or parameter. The uncertain events and parameters in turn can be inter-related and affect other uncertain events and parameters. Determined by the operations of a specific case, occurrence of an uncertain event or parameter may trigger a certain response process, which can be modeled by discrete event modeling. Execution of these operational and business processes ultimately affects important higher-level operational and business metrics such as revenue, cost, loss of revenue, and perhaps undesirable outcomes. Uncertain and desirable outcomes, such as revenue or decrease in costs, are opportunities. Conversely, uncertain and undesirable outcomes, such as loss of revenue, increase in costs, or safety and environmental incidents are risks. Ultimately, the goal of the PM-DES method is to use feature data, through probability models, and discrete event models, to calculate uncertain outcomes of interest. In the application case under study, this means linking machine feature data, through machine failure and incident probability models, and the operations discrete events and process models, to higher level business metrics in terms of risks and opportunities.

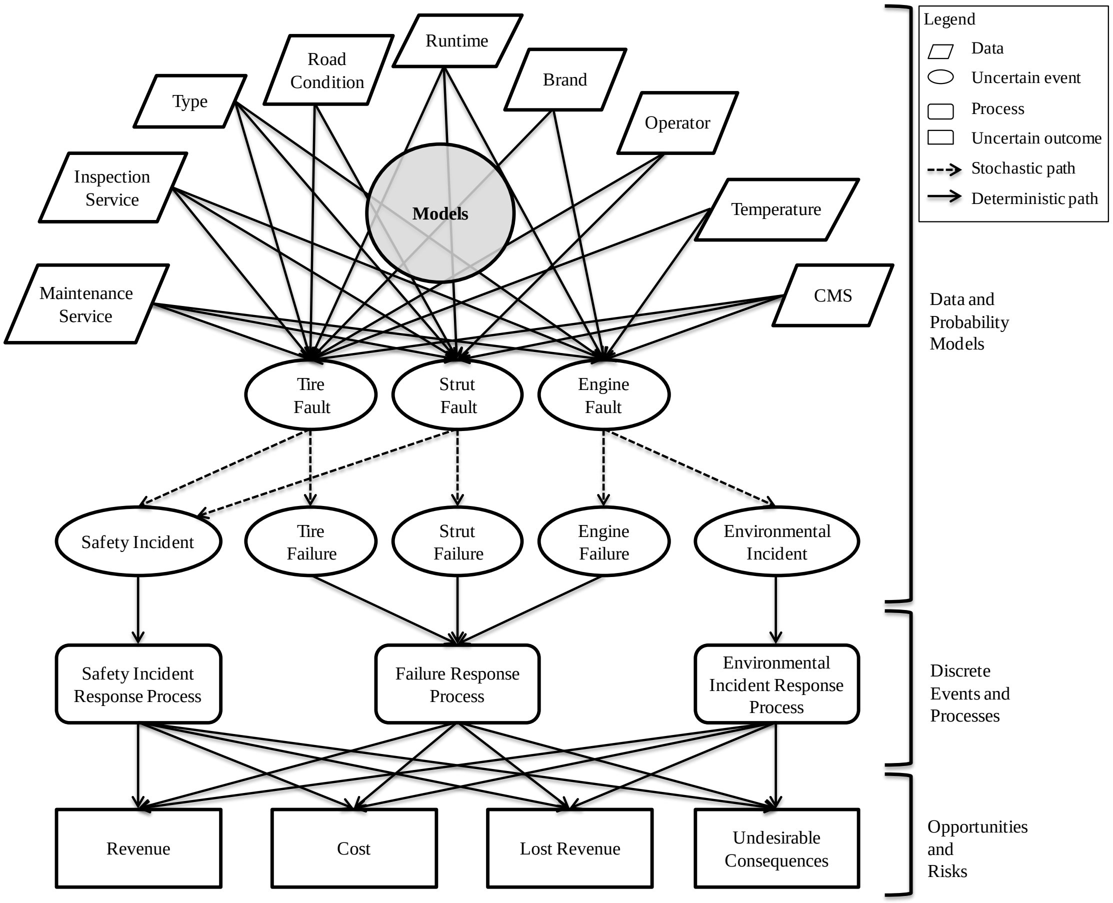


Figure 6-2. Schematic of the structure of an example PM-DES model for hauler truck machine operations

6.2.3 Model Components

The first step for building a PM-DES simulator is to develop a simulation model that adequately represents the application case. It should be noted that adequate does not necessarily imply complexity. The general model that represents the application of interest in this study contains the following components:

1. Machine operations;
2. Business unit operations;
3. Information flow; and
4. Decision making.

The machine operation model includes the machine event models, such as for faults, failures and incidents. It also includes models related to the machine's input, output, side effects, and constraints, e.g. production rates and costs. These models can be stochastic, e.g. faults and failures can be based on reliability models or specific distributions. The stochastic models then serve to generate the parameter values for the simulations.

For example, failures of a machine, or its run-time, can be predicted (with some accuracy) by using reliability models that have been developed based on the features that affect the machines condition. In other words, both a reliability model itself, and its predicted outcome for a machine, depend on the feature set and values that affect the machine. Failure times in a simulation can either be calculated as a random value from the machine's reliability distribution, or by calculating it using the random values directly from the features based on the features' distributions input into a reliability model (Figure 6-3).

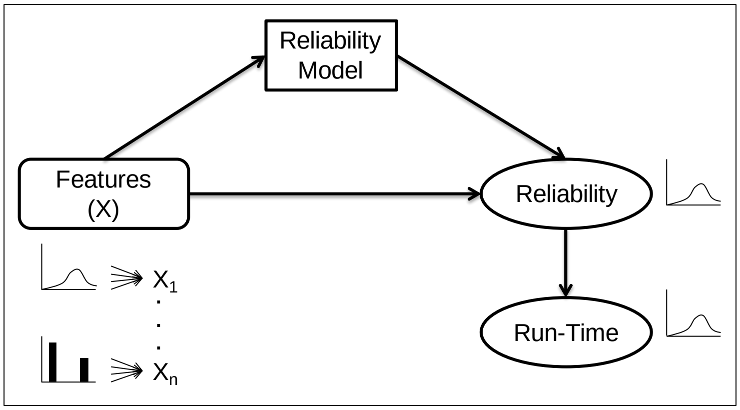


Figure 6-3. Machine run-time calculation from its features and reliability model

The business unit operations model includes modeling the operations of a collection of assets as part of the collective operations of a business unit. It can include both systems modeling and workflow modeling of the system of assets in the operations, including:

- The aggregation of asset production output, input, and costs;
- Constraints;
- Dynamics of a system of assets including cause and effects on each other and on the environment;
- Operations workflow including the machine's and people's schedule;
- Inspection, maintenance, and quality control procedures; and
- Resource and service supply and coordination and inventory management.

Decisions directly affect the performance of a business unit in any organization (as discussed in Appendix A). A significant aspect of a PM-DES simulation involves machine, system, and human decisions in order to observe how alternative systems handle decisions and how their performance affects decisions and hence the operations. Modeling decisions includes defining decision rules, i.e. procedures, criteria, states and methods in which decision making occurs within the system. Decisions affect the operational run-time of an asset, and the change in costs associated with timely actions to avoid, or failing to avoid, the consequences of events.

Figure 6-4 depicts the important decisions that different stakeholders can make in the case under study. The decisions related to the machine operator and the inspector, the machine operator and the maintenance technician, and the CMMIS as described in Section 5.3 are shown in Figure 6-4 in parts A, B, and C, respectively.

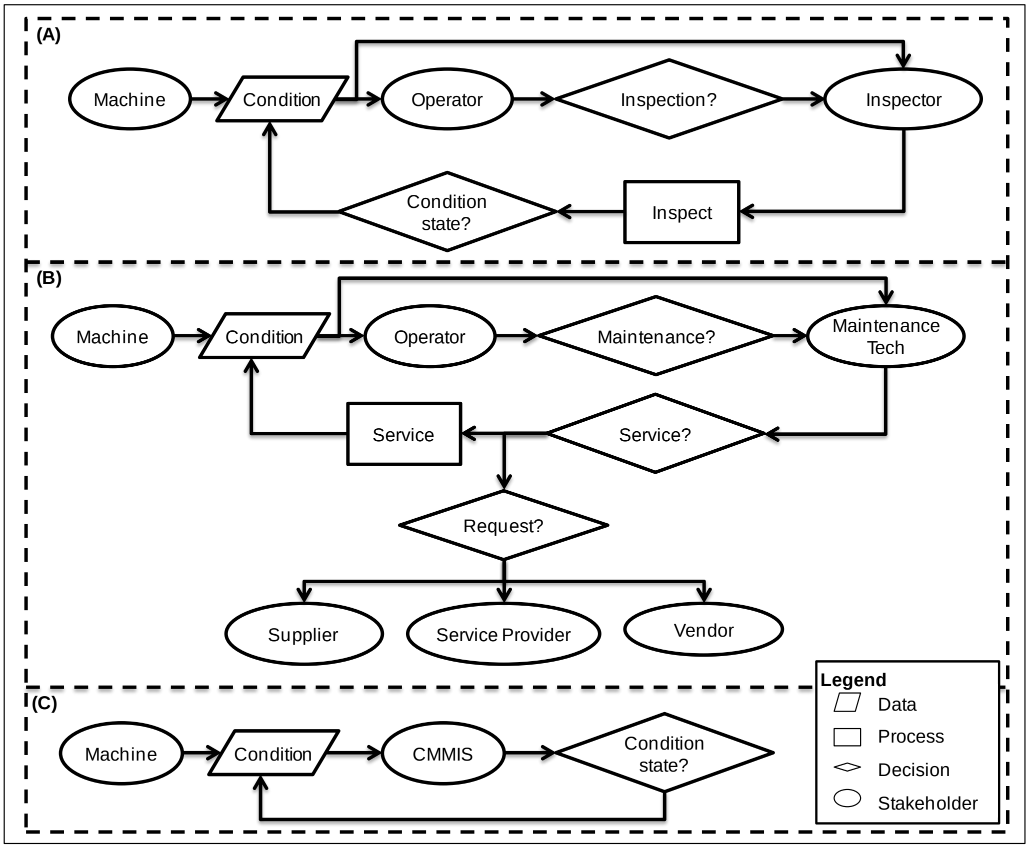


Figure 6-4. Decision making in the operations of the studied case

Information is the input to decision making. The flow of information and its dynamics affect the decision making process, hence affecting a decision outcome and its quality. After all, the benefits and utility of an IIS stems from its ability in managing information among machines, systems, and men. Therefore the simulation model must also allow for directly or indirectly simulating information flow if a meaningful performance assessment and comparison of the alternative systems is to be performed. Direct information flow modeling involves modeling the information unit along with the relevant components, channels, directions, speed, storage, and access of data transfer within a system among the machines and stakeholders. This includes modeling the direction, accuracy, uncertainty, observation time, and presentation of information, which all influence decision making. Indirect modeling does not deal with directly simulating the dynamics of information flow, rather, it aims to indirectly incorporate the effect of different system functionalities on the information flow and manifestation of this effect in other model parameters in the simulations.

Anything that can affect information flow, access to information, or presentation of information can also affect run time and the capability of avoiding (or failing to avoid) the consequences of events. As an example of modeling and simulating information flow, an operator's maintenance request can be mentioned, which is typically done after a machine failure or incident. Two systems can be compared in this regard, one which the operator must use a radio phone to contact and send/receive information related to this matter to the maintenance stakeholder, and another which this information is transmitted automatically when the failure occurs without the involvement of the operator. The information flow for this situation can either be directly modeled and simulated, or indirectly by changing the communication time value which can be implicit in another parameter such as post-failure machine downtime after such an event.

To aid in accounting for information flow in the simulation model, a simple information flow diagram can be drawn with the directions of information flow among the various parties that deal with the information, e.g. as depicted in Figure 6-5. A more complete form of this diagram can include the communication media for each information path, e.g. as shown in Figure 6-6.

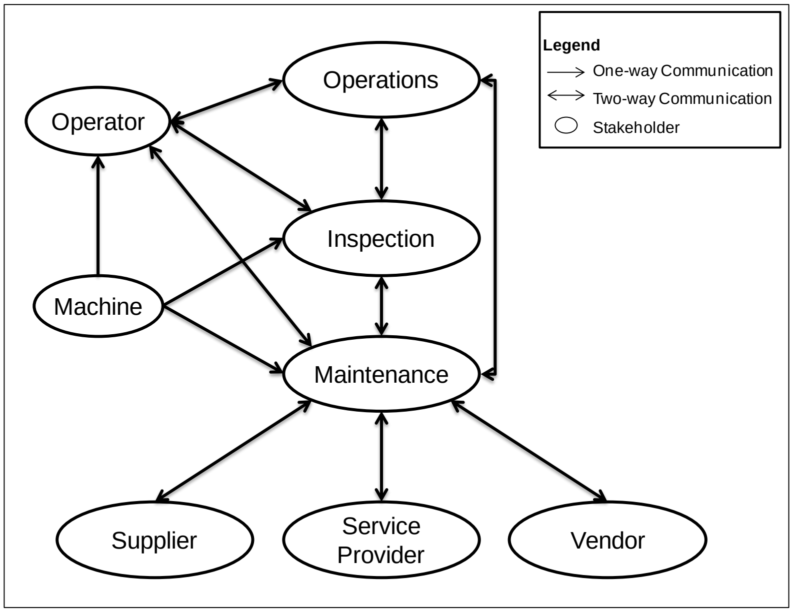


Figure 6-5. Information flow among various parties in the operations of the studied case

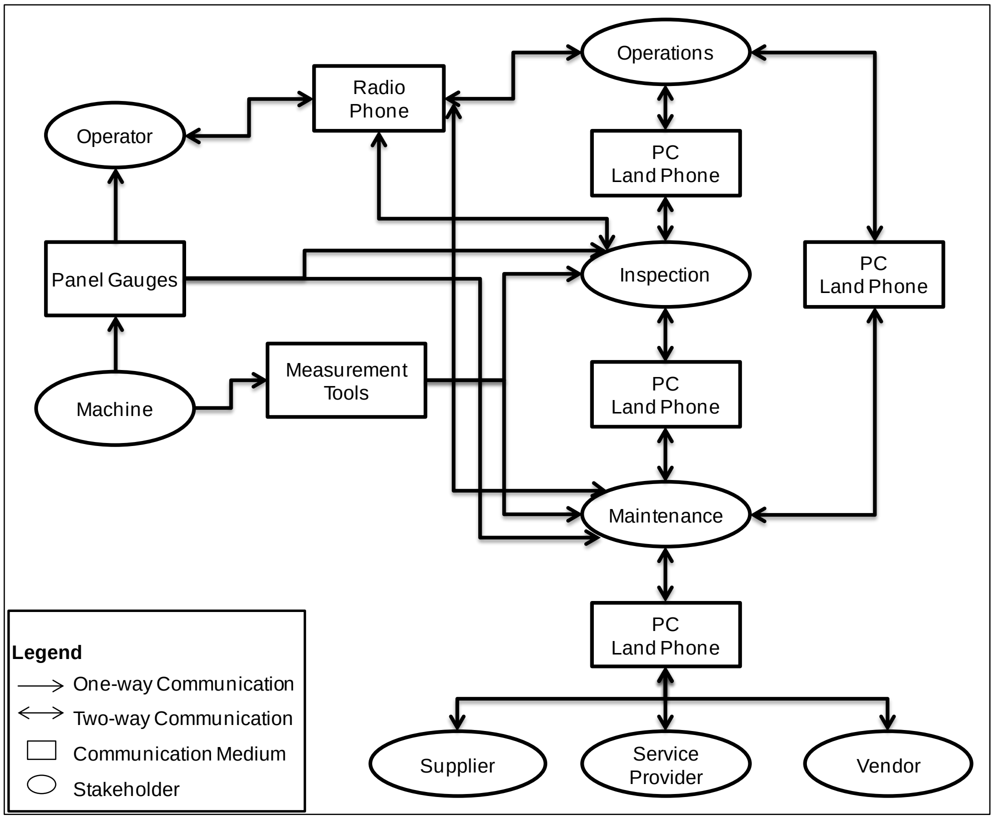


Figure 6-6. Information flow among various parties, including the used communication media, in the operations of the studied case

6.2.4 General Model for the Hypothetical Case of Hauler Truck Operations

The general model that represents the application case of study includes a number of machines, operators, maintenance technicians, and inspectors. Machines operate for a designated duration as part of the overall business unit operations. Machine run-times are determined by a machine operation’s schedule. During their run-time, machines generate a production output which can be translated to revenue. For the application case, the revenue rate is assumed to be constant. Machine’s direct operating cost is not included in the model as it is typically only related to fuel costs and is negligible compared to other costs. When not operating, the machines do not generate revenue and do not incur operating costs. This, however, results in lost revenues.

Machines are assumed to be susceptible to stochastic events that include faults, failures, and incidents during their operation. When faults occur, the machine can continue operating. The fault increases the probability of the failures that are associated with the occurred fault. A fault may also increase the probability of incidents. Faults may be detected by an inspector, maintenance technicians, or the machine fault detection system.

When a failure occurs, machines require immediate maintenance. The maintenance process takes certain repair duration before the machine can resume operations. It is assumed that there are additional financial and time costs if the machine fails during its scheduled operating time. Depending on the failure type, the cost and duration of maintenance varies.

It is assumed that there are two types of incidents that can occur during a machine's operation, safety incidents and environmental incidents. An incident may result in machine downtime, and high costs. Machines also require immediate maintenance after an incident.

Hence in the simulation model, the machines can be in five operating states (Figure 6-7): production, failed, incident, inspection, maintenance. Machines that are in the production state can have two health conditions: healthy or faulty. The faulty condition, and the incident and failed states have associated modes, e.g. strut fault, or tire failure. The "incident" state is that of the machine that has caused an environmental or safety incident.

Machines start operating in the "production" state and in the "healthy" condition until their state changes (Figure 6-8). After the simulation starts from this state, an event can occur. An event can be a fault, a failure, or an incident. An event is characterized by being stochastic in nature and outside the control of the system. The change of state is produced by the simulation. The state and condition of the machine affects the probabilities of events and decisions. Events can occur with different probability distributions.

Machines may undergo inspection at scheduled times, and/or at the operator's request. Inspectors are limited in number and can work on machines only one at a time. Inspection tools might also be limited which may result in waiting times. The role of the inspector is to determine whether a machine is faulty or not, and report to the operator for his decision making. After an inspection, the outcome is that the machine is labelled either healthy or faulty. Inspections cost time and money depending on the fault mode.

Machines may also undergo maintenance at scheduled times, and/or at the operator's request. Maintenance technicians and tools might also be limited, resulting in queuing and waiting downtimes. The role of the maintenance technicians in the model is to repair machines from faulty or failed state to healthy state. Maintenance costs time and money depending on the event type and mode.

The model includes the decision making process in the operations. During a machine's operation, the machine operator can make the decision to continue operating at the site, or to request inspection or maintenance. An operator has a subjective perception of when a machine fails or can cause an incident. Based on this perception, he can make the decision to request inspection or maintenance before the machine fails or causes an incident to avoid extra costs associated with a failure or incident occurring during the scheduled run-time. The time when the operator makes a decision is stochastic and based on a stochastic decision model for the specific operator. The operator's decision model takes into account the known condition of the machine, i.e. if it's known that the machine is faulty or healthy, and the time that has elapsed since the last time this condition was known. The outcomes of the operator's three decisions are:

1. If the decision was to continue, the machine resumes operating whether it's truly healthy or not;
2. If the decision was to get inspection, the operator gets the inspector's diagnosis of whether the machine is faulty or healthy; and
3. If the decision was to get maintenance, the machine undergoes maintenance and will be reinstated to a "healthy" condition of the production state.

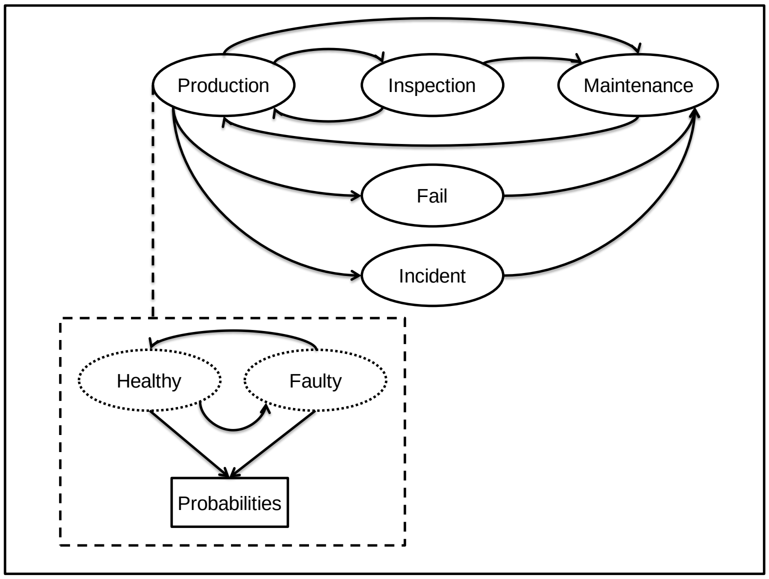


Figure 6-7. State and condition change diagram of the simulation model

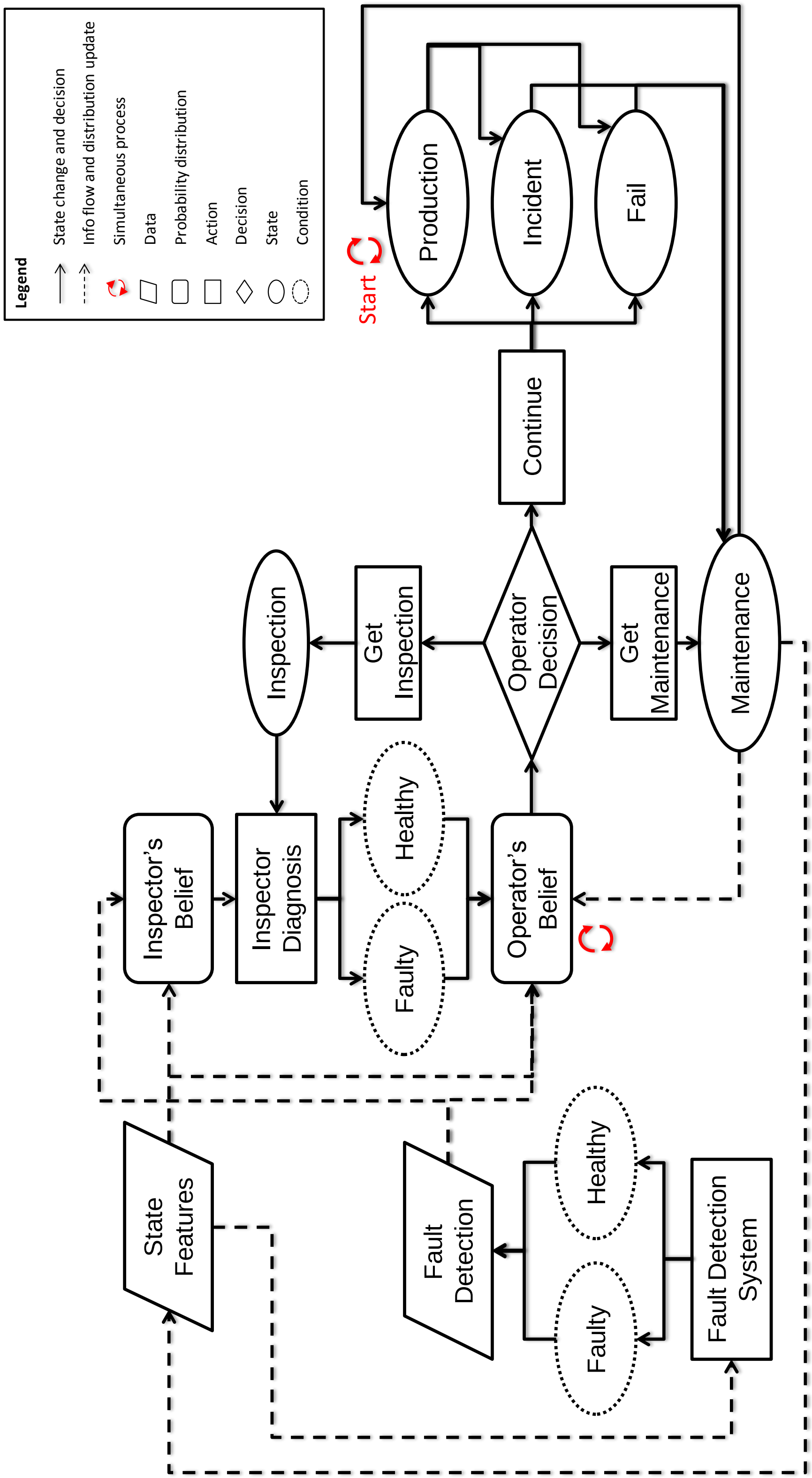


Figure 6-8. High-level diagram of the simulation model

6.2.5 General Considerations for Simulator Algorithms and Programs

Based on the simulator model that was discussed in the previous section, a simulator program (or application) is required to run the simulations.

In general, three methods are used for DES programming. The DES program can be activity-based, event-based, or process-based. The activity-based method involves simulation through discrete time steps. The duration of the simulation is discretized into arbitrary, usually small, time steps. At each time step, the simulator searches through processes, actions, decisions, and other events to find the ones that have occurred at the current simulation time to execute relevant routines related to the found event.

The activity-based method is relatively easier to program because marching in time and looking for events that have occurred is a paradigm that more closely resembles the natural elapse of time and occurrence of events in the real world. However, the downside to this method is that at many simulation instances, no event occurs but the simulator must keep marching in time and searching for events at every discretized simulation instance.

The event-based method involves keeping track of the simulation time based on a list of events and their respective simulation times. This means that the simulator advances through the list of events updating the current simulation time with the next (minimum) event on the list, and executing all the routines related to the current event. In this sense, incremental march in time and check for events is avoided. The event based method is computationally much more efficient than the activity based method.

The process-based method is based on the paradigm that events can be modeled as processes that at appropriate times perform certain routines. Each process is usually programmed as a distinct function (or routine), and runs as a process thread until it terminates or re-runs. One advantage of the process-based method is that each event is individually modeled as a distinct process, making it convenient to trace its behavior. Another advantage of this method is that it is best suited for object-oriented and functional programming paradigms as each event process can be an instant of a more general class of events, with its execution being based on a certain function. The process-based method can also benefit from multi-thread parallel programming algorithms. The process-based method was used to develop the simulator code for the

PM-DES model in this work (the general algorithm underlying the code is described in Appendix C of this thesis). The code was developed using the SimPy 2.3.1 modules for object-oriented, process based, DES programming (Muller et. al., 2011).

The simulator must perform many simulations based on the variation of variables from list or distributions. The output result variables, either as averages or as distributions, generally converge to their true values (based on the input values and the model).

6.3 Metrics Selection

For concrete evaluation of system performance, metrics are needed for each performance criterion designated during the needs assessment phase of the framework. Some metrics can be used for both pre-evaluation of system performance and post implementation performance measurement, and some may only be suitable for one of those phases. All the metrics that are assumed to be selected by the hypothetical case organization are listed below. Each pre-evaluation method uses a specific set of metrics, that are relevant to the method, from this outlined list. The method-specific sets of metrics are mentioned in the pre-evaluation analyses sections in subsections related to each method.

1. Financial:
    a. Revenue
    b. Revenue loss
    c. Machine maintenance cost
    d. Production loss risk
    e. Direct cost of failure risk
2. Environmental:
    a. Average number of incidents on the field
    b. A risk threshold of less than 3 environmental incidents on the field
    c. Production loss risk to the environmental events
    d. Direct cost risk associated with environmental events
3. Safety:
    a. Average number of incidents on the field

    b. A risk threshold of less than 2 safety incidents on the field
    c. Production loss risk to the safety events
    d. Direct cost risk associated with safety events
4. Operational excellence:
    a. Availability (uptime)
5. Risk awareness:
    a. Operators’ risk awareness of machine faults
6. Asset and maintenance management:
    a. Lean service
    b. Average number of failures in the field
7. Information management and flow:
    a. Communication time

6.4 Comparative Evaluation and Choice Analysis

Once the framework-designed systems, along with the existing system (or practice if no system exists) and possibly other system options have been outlined as alternatives for system implementation, the next step is to proceed with a systematic method in selecting the best choice based on the performance criteria and their respective metrics that were determined using the framework. For this purpose, a suitable multi-attribute decision making method can be used. For the case under study, it is assumed that the organization conducts system choice selection using the AHP method, demonstrated in the next chapter.

The AHP method is a scale-based ranking method for multi-criteria decision making. It results in the ranking of decision alternatives based on successive ranking of multiple criteria and multiple levels of sub-criteria for each higher level criterion as they relate to the candidate alternatives (Saaty, 1980, 1990, 2005). Decision alternatives are the alternative choices that are being considered for a decision related to a specific objective(s). Criteria are the attributes by which the decision is intended to be based on. Each objective may have sub-objectives and each criterion may have many sub-criteria and so on.

The AHP method is very useful for practical applications where a rigorous, systematic decision making method is required without the excessive mathematical complexity. This balance is important for practical purposes where the mathematical knowledge or computational resources of the decision analyst may be limited. The AHP method has been applied to a wide range of engineering, manufacturing, medical, social, political, personal applications (Saaty, 2006, Vaidya, 2006). The method is versatile in accounting for subjective ranking based on a defined and agreed upon numerical ranking scale in a consistent manner. One ranking scale that is commonly used by practitioners for subjective pair-wise comparisons is the 1-9 odd number scale (Forman and Selly, 2002). Based on this scale, when two items are being compared, 1 means an item is equal in comparison to the other, 3 means one item is slightly better than another, 5 means strongly better, 7 means very strongly better, and 9 means extremely better. In this sense, the inverse value of the numbers have the inverse subjective meaning, i.e. 1/3 means slightly worse, 1/5 means very strongly worse and so on. Based on this logic, e.g. if item A is 5 compared to B, that means item A is rated strongly better than item B, or item B is 1/5 compared to A, i.e. item B is strongly worse than A. Use of this method of subjective ranking is shown in the application of the AHP method in selecting among alternative CMMIS in the next chapter.

AHP is also very useful as a tool for clarifying the decision alternatives, and the hierarchy of criteria and sub-criteria that are required or relevant to the decision outcome, as part of the formulation stage of the decision analysis process. This is because the relative ranking of all the criteria and the sub-criteria within each higher-level criterion should be determined first for each decision alternative. In simulating and comparing the performance and differences of various multi-attribution decision methods, Zanakis et. al. (1998) concluded that the AHP method was the closest in performance to the Simple Additive Waiting (SAW) method, which was quoted to produce the most instances of acceptable results for single dimensional problems from Triantaphyllou and Mann (1989). For these reasons, the AHP method was selected as the decision method for choice analysis of the CMMIS alternatives.

7. Application of the Framework: Pre-Evaluation and System Selection

The pre-evaluation and choice selection analysis for the hypothetical case organization is based on two application case models and four alternative system scenarios, all deducted from the case context. The alternative system scenarios include the existing system and processes of the organization's operations; a base systems used for analysis control; and two system scenarios each representing an implementation of one of the two designed CMMIS alternatives assumed to be under the organization's consideration, i.e. the offline CMMIS and the real-time CMMIS. Although the main goal of pre-evaluation of system alternatives is to assess the value of these systems compared to the existing system (or practice) of the organization, the base scenario is useful for clarifying and comparing the value added or wasteful activities during the analysis, e.g. it can be used for illustrating the basic processes when using a value analysis method such as value stream mapping (Kaplan and Norton, 1996).

The two application case models are developed to provide the basis for developing the system scenarios and the evaluation methods at different levels of complexity. The two models are:

1. Model 1: machines have only one failure mode, i.e. tire failure, one environmental incident mode, and one safety incident mode; and
2. Model 2: machines have multiple failure and incident modes.

The first application case model (Model 1) was mainly developed for performance evaluation using the transient event-risk tree method. It is also used for performance evaluation using the simulation method, in part, to compare the extent to which the evaluation results using these methods differ (or not). The second, more elaborate model is only used for analysis using simulations.

7.1 Model 1: Single Failure Mode, Environmental Incident, and Safety Incident

Using Case Model 1, both the TERT and PM-DES analysis were performed on the four scenarios. PM-DES analysis is based on 400,000 simulations for each scenario to obtain the distributions and average values for the output variables of interest. The results are deemed converged with this number of simulations (in the section on convergence in Appendix C of this thesis).

7.1.1 Case Model 1: General Description of the Case Operations

For the first case model, i.e. Case Model 1, it is assumed that within the hypothetical case’s operations, machine failures have only one failure mode, i.e. tire failure. Maintenance data for tire faults of large hauler trucks operating in oil sands mining operations were available for this study (Vaghar Anzabi & Lipsett, 2011). The data consisted of the time when the tires were fitted on to the machine, the time when the tire was deemed faulty or failed, and the tire fault mode. It is assumed in this work that all data points are labelled failures, i.e. even if a tire has been labelled faulty in the original data set, meaning that it can still operate until becoming dysfunctional, it is assumed to have failed for the purpose of failure probability model development in this work.

When data on a particular event such as for failures exists, it may be represented with a distribution function. As mentioned earlier, three different failure distributions for the tire failure mode of machines were considered to be used with the pre-evaluation methods, i.e. a uniform, normal, and Weibull, assuming that all three have an equal expected value (mean). The intention for doing so is to seek whether even a simple (“naive”) assumption such as a uniform probability distribution, or a typical, but perhaps less accurate, assumption such as a normal distribution can result in the same case comparison conclusions as a more accurate assumption for a distribution such as a Weibull distribution. For incidents, only uniform distributions are assumed for simplification. The stochastic failure and incident events are modeled using these distributions. The time-based risk calculation method using event risk trees are therefore based on these three different distributions, and the risk calculations based on this method are demonstrated for each operations systems scenario in the next sections.

The tire failure data histogram used for developing the distribution functions is shown in Figure 7-1, which represents the recorded lifetimes of tires. The total number of failure data points in the data set is 3,558. The arithmetic mean of the data is 4,704 h and the maximum recorded run-time is 33,029 h.

Figure 7-2 shows the normalized histogram of the data along with the uniform, normal, and Weibull fitted probability distribution functions. Figure 7-3 shows the respective cumulative distributive functions.

$$F_{uniform}(t) = \begin{cases} \frac{t}{2t_m} = \frac{t}{9408}, & t \leq 9408 \\ 1, & t > 9408 \end{cases}$$

$$F_{normal}(t) = \int_{-\infty}^{\frac{t-4704}{2053}} \frac{1}{\sqrt{2\pi}} e^{-\frac{\tau^2}{2}} d\tau$$

$$F_{Weibull}(t) = 1 - e^{-(\frac{t-35}{5399})^{2.5}}$$

Note, that the normalized histogram is not the probability mass function of the data, and is simply calculated by equating the summation of the rectangular area of the bins to unity.

Safety and environmental incidents are assumed to occur based on a uniform distribution with means of 21,900 h and 8,760 h (i.e. a total period of 5 and 2 years), respectively (Figure 7-4).

$$F_{safety}(t) = \begin{cases} \frac{t}{2t_m} = \frac{t}{43800}, & t \leq 43800 \\ 1, & t > 43800 \end{cases}$$

$$F_{environmental}(t) = \begin{cases} \frac{t}{2t_m} = \frac{t}{17520}, & t \leq 17520 \\ 1, & t > 17520 \end{cases}$$

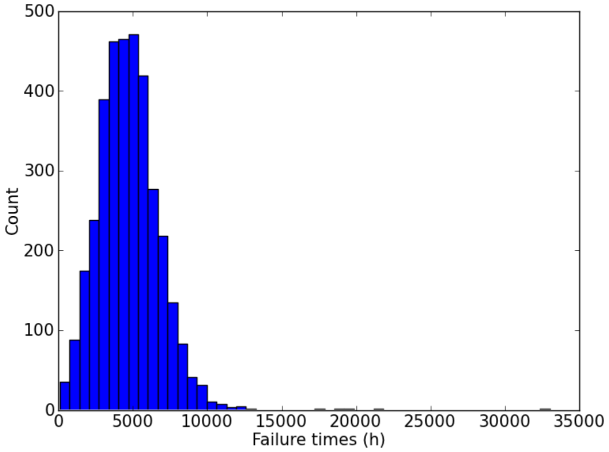


Figure 7-1. Histogram of the tire failure data

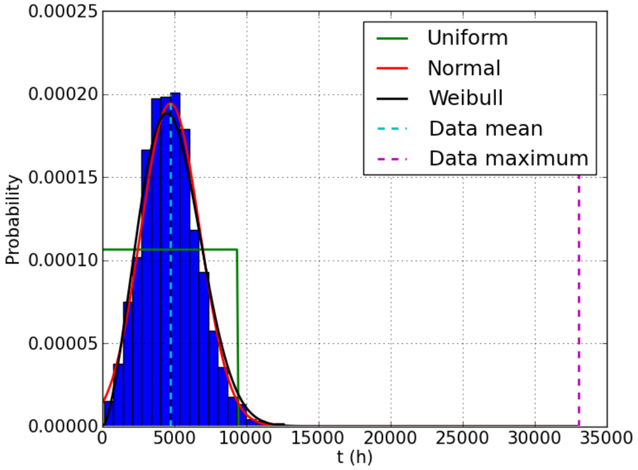


Figure 7-2. Probability density functions fitted to the tire failure data

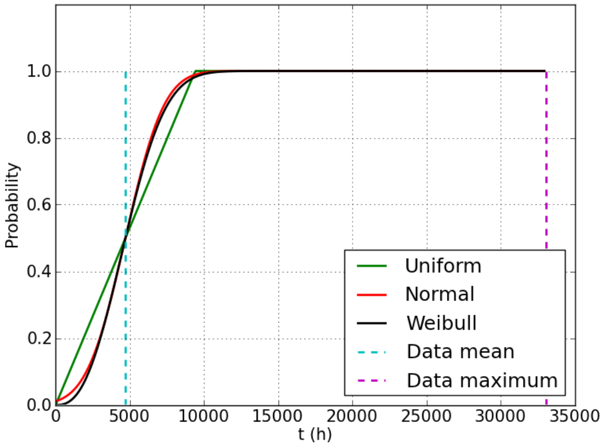


Figure 7-3. Cumulative distribution functions fitted to the tire failure data

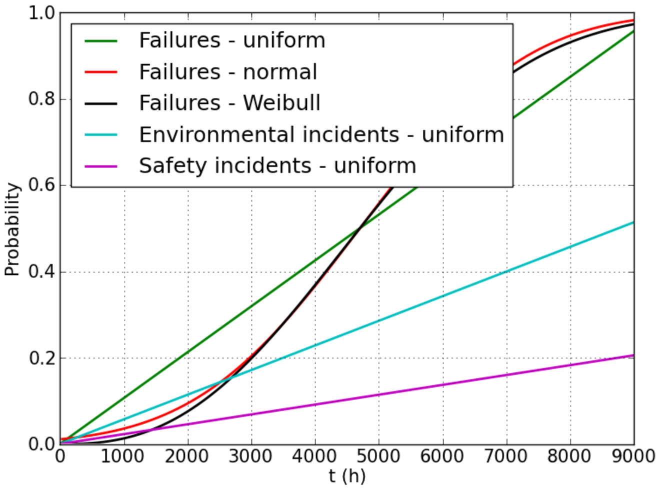


Figure 7-4. Probability of an event occurring prior to t for a single machine

7.1.2 Case Model 1: Base System Scenario (Run-to-Failure)

In this scenario, machines operate in the field according to the operations schedule. Neither a CMMIS nor an on-board CMS for machines exist. When a machine fails or causes an incident, the operator turns off the machine and calls the base via a radio phone to report the event. The machine is then taken off the field for maintenance. The machines do not undergo any periodical inspection or maintenance routine.

Assume the operation involves ten machines of the same kind. The machines operate indefinitely until they fail or cause an incident, after which they are forwarded for maintenance. The machines haul oil sands ore at a value rate of $30,000/h. This rate is roughly calculated based on a truck trip frequency of 3 trip/h, truck capacity of 400 ton/load(trip), each ton of oil sands yielding half a barrel of synthetic crude oil (0.5 bbl/ton), and each barrel of oil priced at $50 (Carroll, 2013). The machines may fail or cause an incident while operating, which will result in a penalty in addition to the planned maintenance cost associated with the failure or incident mode (Figure 7-5).

It is assumed that when a failure or event occurs, it takes 15 minutes to call and book a maintenance procedure for the machine, and 4 h from the time that the base dispatches the means to forward the machine to maintenance until the maintenance procedure is started on the machine. It is further assumed that the maintenance procedure on average takes 6 h for tire failures and 24 h for repairing a safety or environmental incident cause.

It is also assumed that the repair price for a tire failure is $50,000, with an extra $10,000 cost if the machine fails on the field. The process when a machine faces a safety or environmental incident in this case is similar to when it fails, with the difference that the costs associated with incidents are assumed to be much higher than failures. And respectively, safety incidents in the field cost an extra $1,000,000 and environmental incidents cost $10,000 to the estimated average repair cost of $5,000 (planned maintenance cost) for machine problems that can cause such incidents.

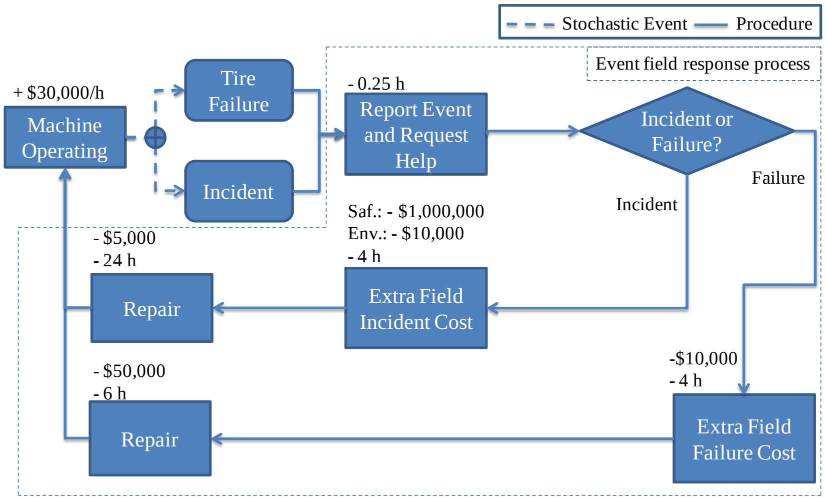


Figure 7-5. Machine event response diagram for the base scenario

7.1.2.1 TERT Calculation Results

Using the TERT method the risk values for the risk situations of interest to the organization are calculated for each risk situation.

TERT evaluation results for this scenario indicates that, in addition to the costs associated with machine failures and events, revenue is also lost when a machine is having downtime. Depending on the event cost, this loss of revenue may be considerably higher than the direct costs of failures or incidents and hence more critical for consideration. Figure 7-6 to Figure 7-8 show the costs and revenue losses associated with failures, environmental incidents, and safety incidents for different number of eventful machines, respectively. Based on the assumed values, it can be seen from Figure 7-6 that revenue losses resulting from a failure downtime are much higher than direct costs. This significant difference should be highlighted when machine availability is important for the case organization. In case of environmental incidents, revenue losses are still higher than costs (Figure 7-7), however, direct costs for this particular case become much more significant in the case of safety incidents (Figure 7-8).

The probabilities of the “good, bad, and ugly” risk situations for the failure and incident events and based on the different distribution functions are shown in Figure 7-9 to Figure 7-14. For example, it can be seen that there is a significant difference among the different distributions for the situation where the probability that none of the machines fail together is being considered (Figure 7-9). While the Weibull and normal distributions indicate that this probability is higher than 0.5 for run-times less than 1,500 h, the uniform distribution shows a much lower probability. At run-times lower than 1,000 h, the probability that none of the machines fail is quite high based on the Weibull distribution (higher than 0.9), however, this is not implied from the uniform distribution curve except for very early run-times. The same observation, though inversely, can be seen from Figure 7-10 where the probability that all of the machines fail at once (“ugly situation”) is depicted. This probability at run-times around 8,000 h is higher than 0.5 for both the normal and Weibull based curves, however, not as considerable (0.2) based on the uniform assumption. Figure 7-11 shows the probability that at least five machines fail prior to some time, where the difference between the distributions is also evident. The normal and Weibull based probability curves closely follow one another. The main increase in probability occurs near the mean point around 4,000 h to 5,000 h. Similar observations in trends and values can be made for the situation probability plots of environmental and safety incidents.

Figure 7-15 to Figure 7-24 show the risk values of the various risk situations and for failure and incident events and based on the different distribution functions. The plots include risks with both the direct costs of events and loss of revenue as their measure of severity.

Based on these plots, the organization can observe many different risk values and trends for various situations and events in order to deduce the most rational decision and course of action that reduces the overall risk associated with the operations. Such information can be used as an objective means for evaluating and comparing the different CMMIS choices specifically, and overall operational tactics in general.

For example consider the risk of revenue losses from downtimes due to failures and basing the stochastic events on the Weibull assumption, shown in Figure 7-22. The total average risk at around 3,800 h is close to $1 million. If this number is a risk threshold for the organization in terms of downtime losses, then the organization can search for ways to reduce this risk. On the other hand, the revenue loss risk of the "ugly" situation, i.e. when all of the machines fail together, should not be of concern until after 7,500 h of machine operations with no failure events. It can be deduced from this observation that the organization can omit provisions for handling the failure of all of the machines until after that time. Similarly, when the revenue loss risk of the "bad" situation is being considered, where at least five machines fail together prior to some time, *t*, the risk figure nears and exceeds $1,000,000 after 4,500 h of run-time. This might prompt the organization to account for servicing more than five machines after this time to reduce the revenue loss risk. Moreover, Figure 7-22 shows that the curve of this situation converges with the total average risk of revenue loss after about 5,000 h of run-time, emphasizing the importance of the decision to account for five machine failures after this time. Similar observations and deductions can be made for environmental and safety events in the risk plots of Figure 7-23 and Figure 7-24.

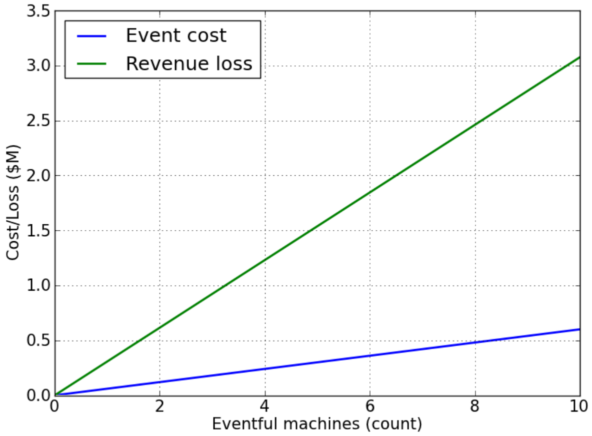


Figure 7-6. Cost or revenue loss (value at risk) due to failures

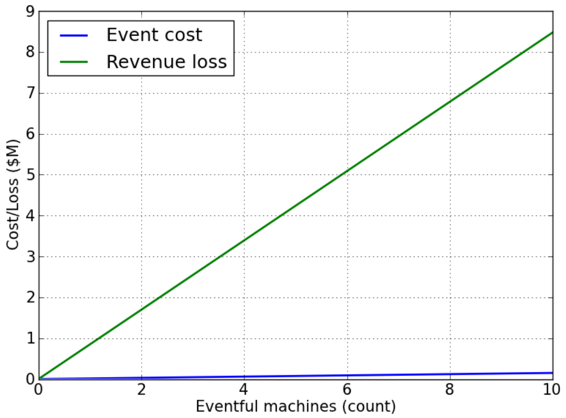


Figure 7-7. Cost or revenue loss (value at risk) due to environmental incidents

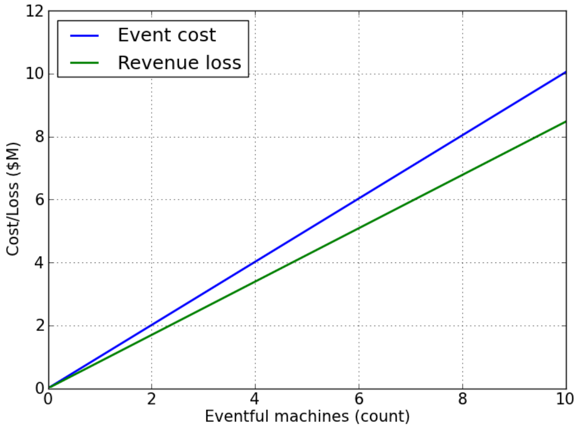


Figure 7-8. Cost or revenue loss (value at risk) due to safety incidents

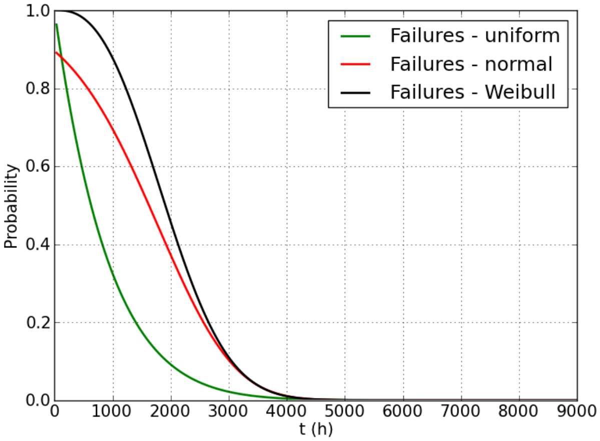


Figure 7-9. Probability that none of the machines fail prior to t

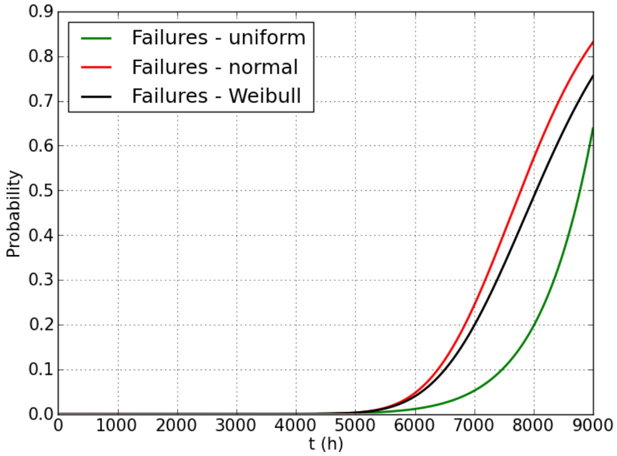


Figure 7-10. Probability that all of the machines fail prior to t

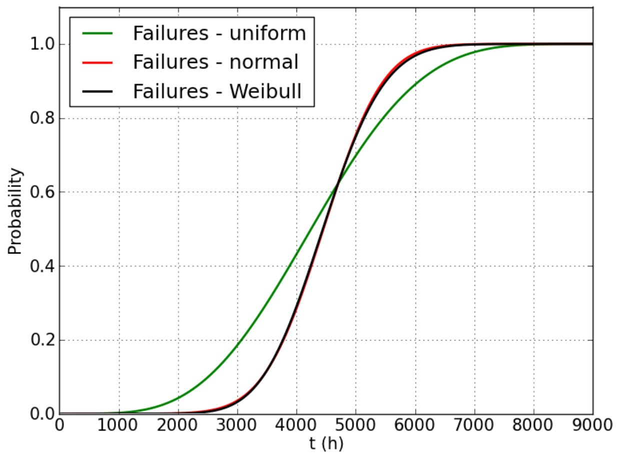


Figure 7-11. Probability that a minimum of 5 machines fail prior to t

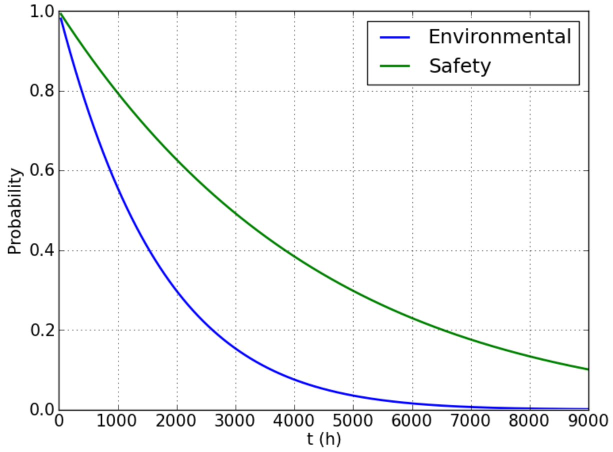


Figure 7-12. Probability that none of the machines have an incident prior to t

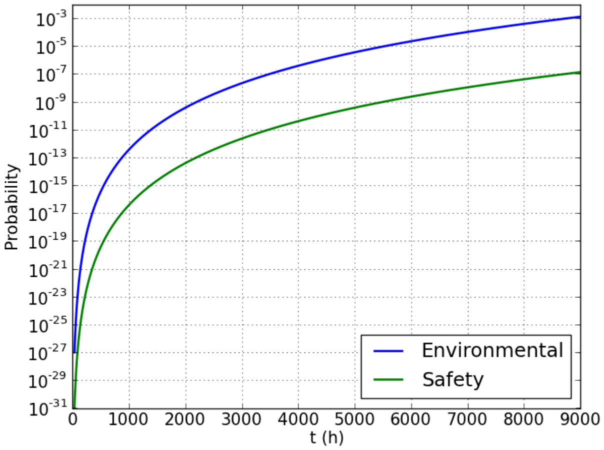


Figure 7-13. Probability that all of the machines have an incident prior to t

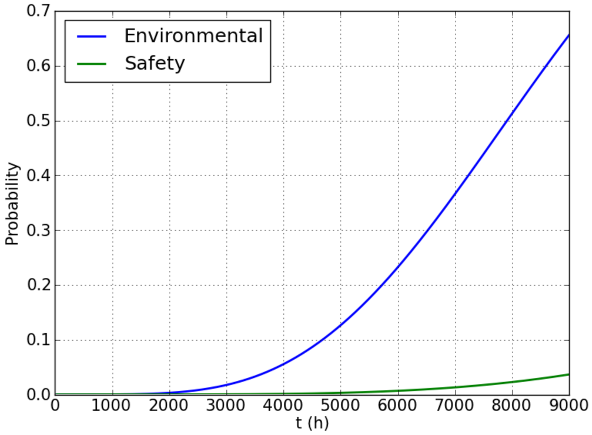


Figure 7-14. Probability that a minimum of 5 machines have an incident prior to t

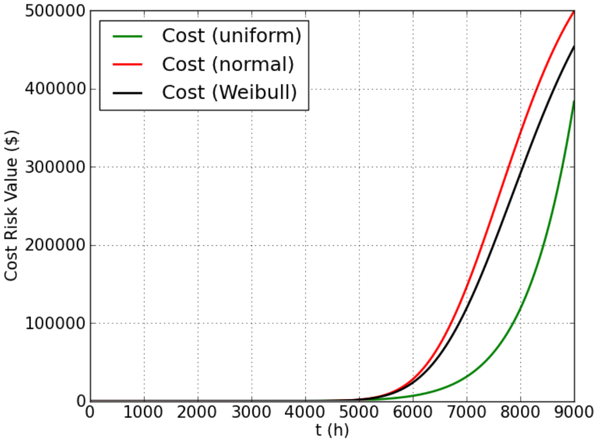


Figure 7-15. Cost risk value if all of the machines fail prior to t

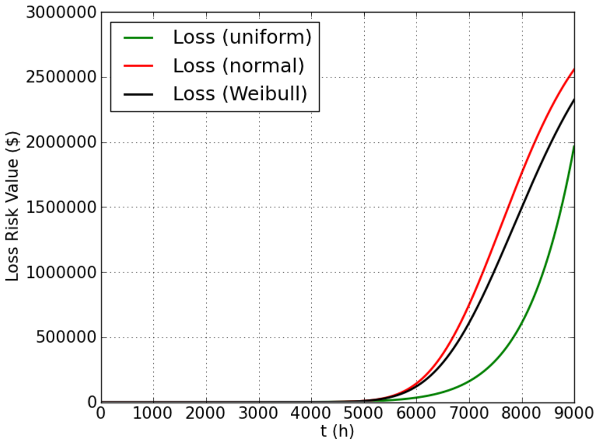


Figure 7-16. Loss risk value if all of the machines fail prior to t

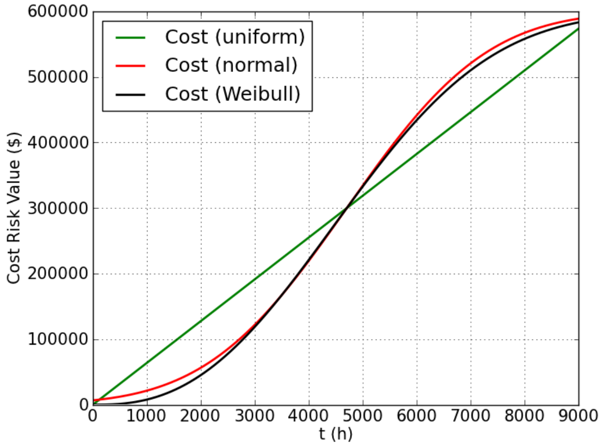


Figure 7-17. Total average cost risk value of machine failures prior to t

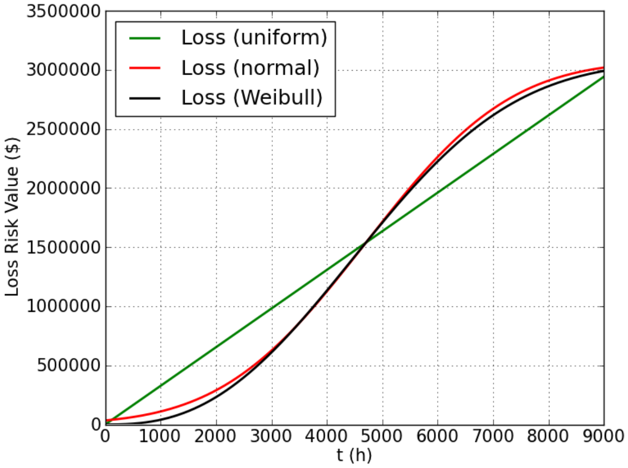


Figure 7-18. Total average loss risk value of machine failures prior to t

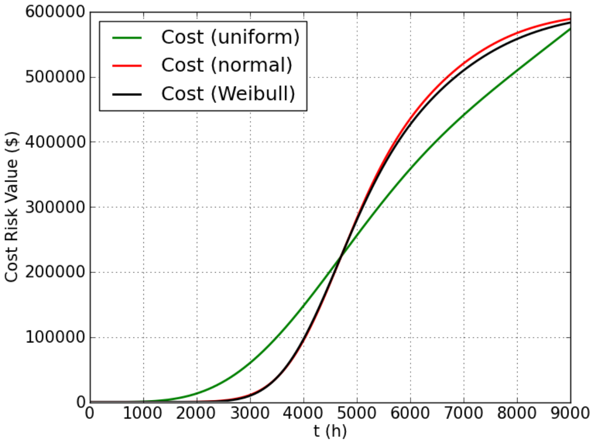


Figure 7-19. Cost risk value if a minimum of 5 machines fail prior to t

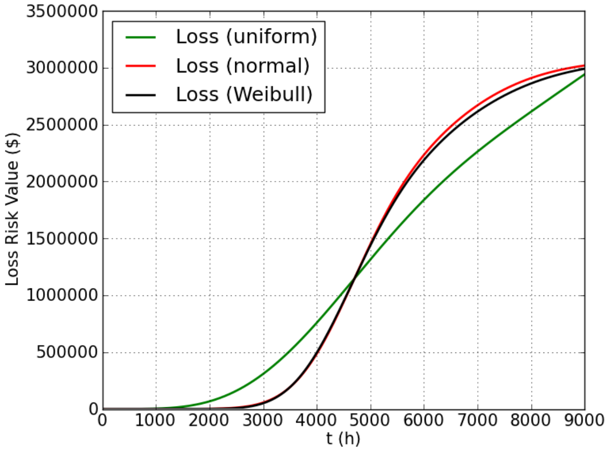


Figure 7-20. Loss risk value if a minimum of 5 machines fail prior to t

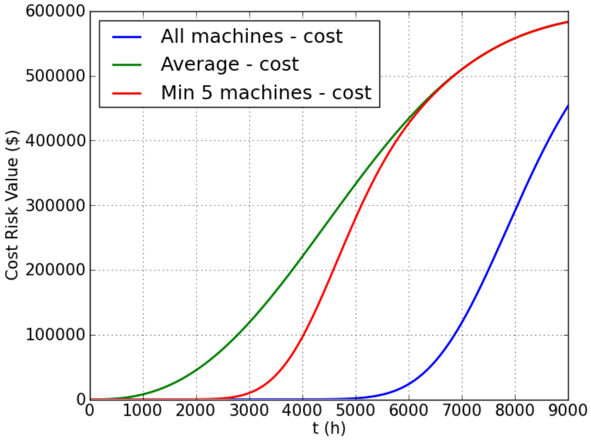


Figure 7-21. Cost risk value of machine failures (Weibull distribution)

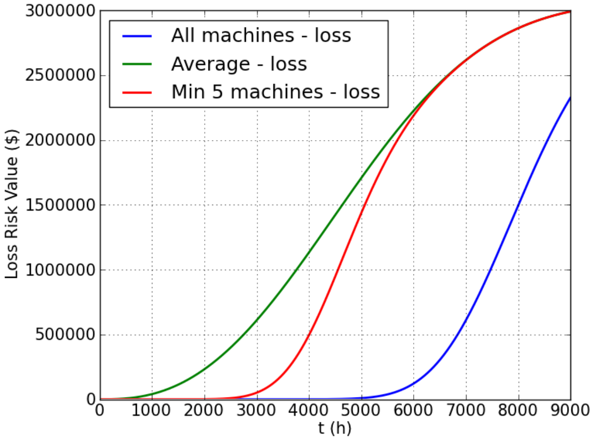


Figure 7-22. Loss risk value of machine failures (Weibull distribution)

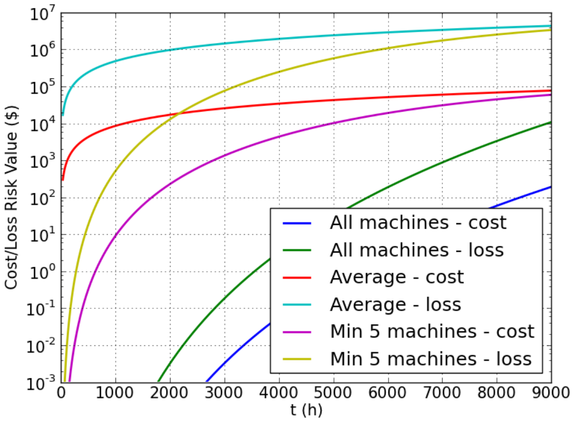


Figure 7-23. Risk value of machine environmental incidents for different risk situations

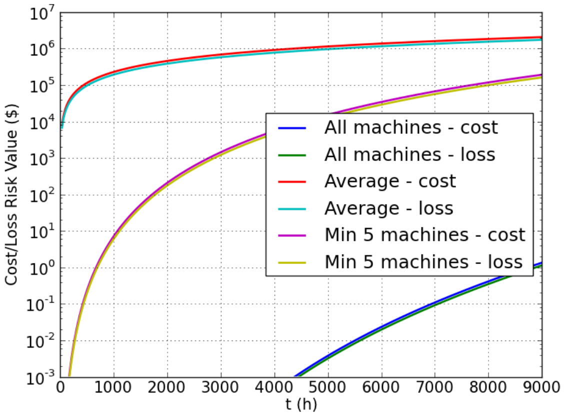


Figure 7-24. Risk value of machine safety incidents for different risk situations

7.1.2.2 **PM-DES Results**

The PM-DES simulations for this system scenario also demonstrated that in addition to the costs associated with machine failures and events, revenue is lost when a machine is having downtime. Figure 7-25 to Figure 7-29 show the simulation histograms of revenue, revenue loss, cost, total availability, average availability, and number of field failures based on the three different machine tire failure models for the 400,000 simulated operations, respectively. Figure 7-30 shows the simulation histograms of the number of safety and environmental incidents for the simulated operations. Each histogram shows the distribution of the output variable.

First, as an example of the type of insights that can be gained using the PM-DES evaluation method for analysis, it can be seen from Figure 7-26 that for this hypothetical case, revenue losses resulting from a failure downtime are much higher than direct costs.

Second, it can be seen from the figures that the histograms based on the different distributions are not significantly different for practical, comparative decision making. Even if the absolute distribution values of the output variables are of interest to the case organization, the difference among the three input failure distributions is not significant.

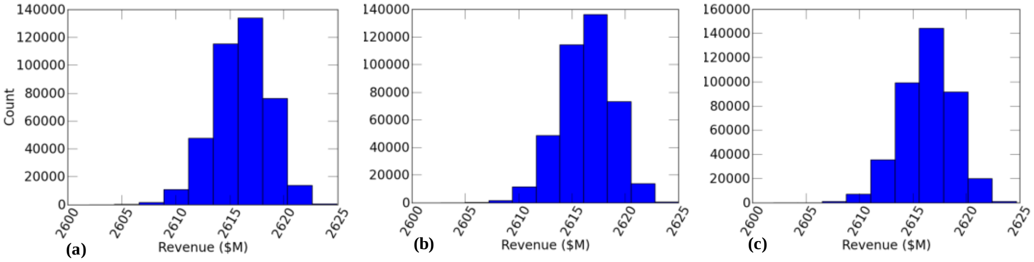


Figure 7-25. Histogram of revenue outcomes for the base system simulations based on three different distributions for machine failures, (a) uniform, (b) normal, and (c) Weibull

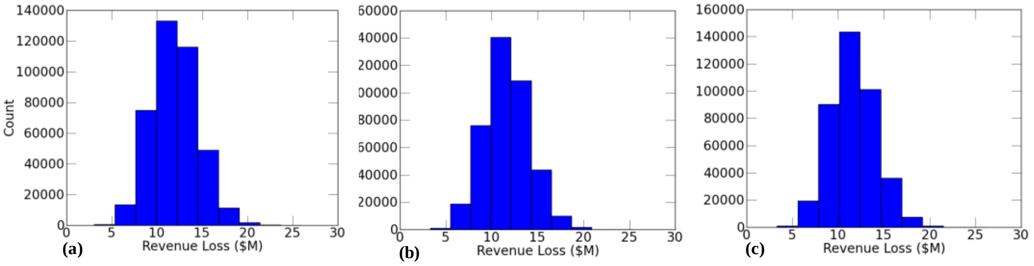


Figure 7-26. Histogram of revenue loss outcomes for the base system simulations based on three different distributions for machine failures, (a) uniform, (b) normal, and (c) Weibull

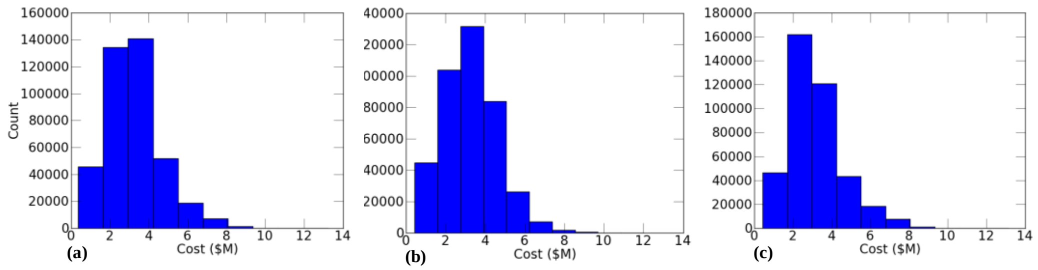


Figure 7-27. Histogram of cost outcomes for the base system simulations based on three different distributions for machine failures, (a) uniform, (b) normal, and (c) Weibull

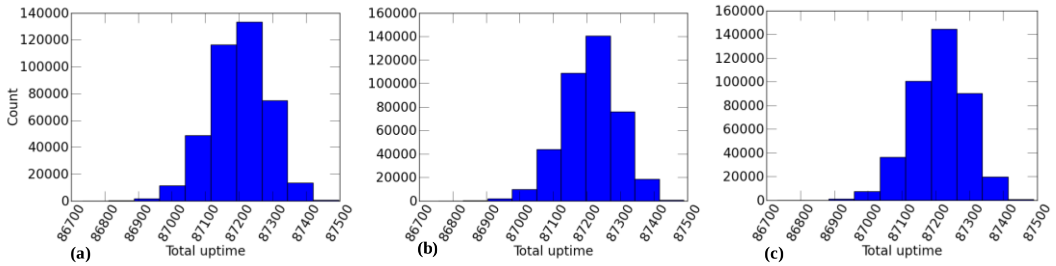


Figure 7-28. Histogram of total availability (h) outcomes for the base system simulations based on three different distributions for machine failures, (a) uniform, (b) normal, and (c) Weibull

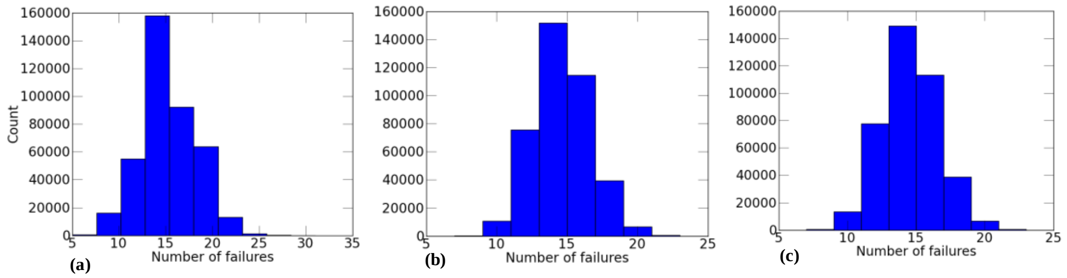


Figure 7-29. Histogram of the number of failure that occurred on the field for the base simulations based system on three different distributions for machine failures, (a) uniform, (b) normal, and (c) Weibull

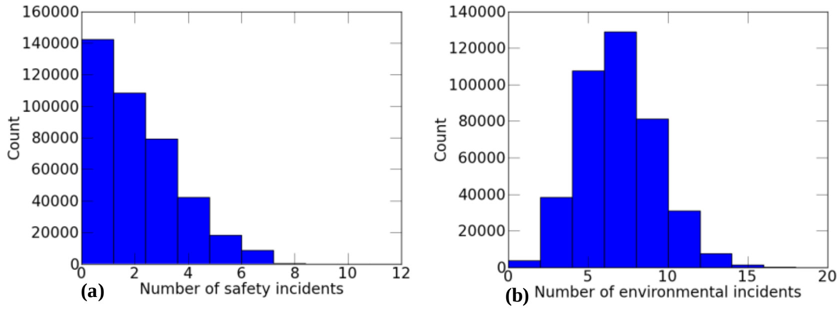


Figure 7-30. Histogram of the number of, (a) safety incidents and (b) environmental incidents that occurred on the field for the base system simulations based on uniform distribution for safety and environmental events

7.1.3 Case Model 1: Existing System Scenario (Routine Major Prevention Service)

It is assumed that the existing system includes the BDM approach for maintenance management of the base scenario, i.e. the machines operate until they fail, and that a CMMIS or on-board CMS does not exist. However, in this scenario, which represents the existing state of the operations of the organization and its existing maintenance and reliability practice, it is assumed that machines are routinely inspected for faults at regular intervals based on a preventive (planned) maintenance strategy. It is assumed that all of the machines are inspected weekly and it is assumed that machines receive service immediately and there is no downtime due to machine queuing. It is further assumed that every inspection procedure costs $2,000 and 5 h to complete. The inspection is to determine whether a machine is faulty or healthy. If healthy, the machine is cleared for resumption of operations. If faulty, however, the machine undergoes a repair or replacement maintenance service that resets the condition of the machine to a healthy state. It is assumed that after each maintenance procedure, machines are restored to their original condition as when they started operating. In this sense, the reliability of the machines after each maintenance procedure is “reset”, i.e. machines start operating from a “like new” state. These repairs are assumed to cost $50,000 and 6 h of repair downtime for faults that cause tire failure, and a cost of $5,000 and 24 h of repair downtime for faults that cause safety or environmental incidents (Figure 7-31). It is also assumed that once a machine becomes faulty, the fault progresses towards failure in two days, hence if a fault is detected during inspection within this time period, the machine’s failure on the field will be prevented, otherwise, a fault will occur and result in a failure without the machine being inspected (Venkatasubramanian et. al., 2003; Carroll, 2013). It is further assumed that if the machine is truly faulty, then there is a chance that the fault is not detected. Hence it is assumed that the conditional probability of detecting or missing a fault given that the machine is truly faulty has been estimated either subjectively, or from data. This conditional probability is assumed to be:

$$P(inspector\ detects\ fault \mid machine\ is\ faulty) = \frac{9}{10}$$

and therefore, the probability that the inspector misses the fault, or a false negative assessment is:

$$P(inspector\ misses\ fault\ |\ machine\ is\ faulty) = \frac{1}{10}$$

Similarly, it is assumed that if the machine is truly healthy, the inspectors can definitely determine this condition with 100% accuracy, or:

$$P(inspector\ deems\ healthy\ |\ machine\ is\ healthy) = 1$$

$$P(inspector\ deems\ faulty\ |\ machine\ is\ healthy) = 0$$

These conditional probabilities must be accounted for when calculating risks for this scenario.

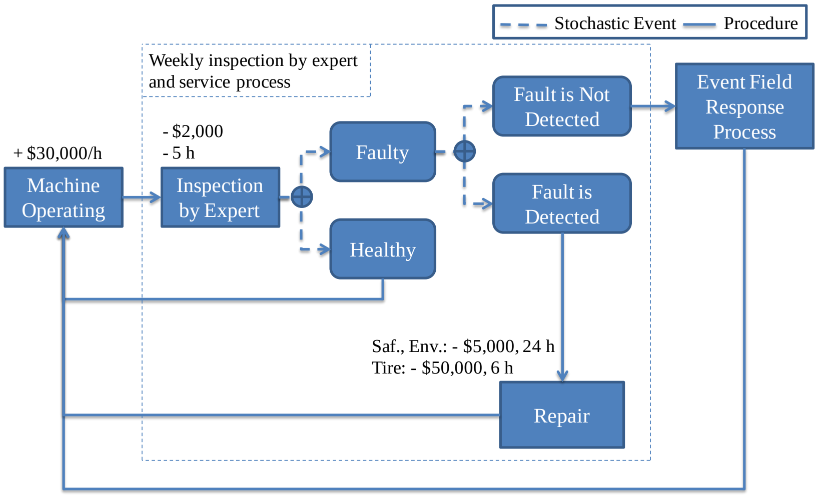


Figure 7-31. Machine event response diagram for the existing system scenario

7.1.3.1 TERT Calculation Results

Assuming the costs and production value rates to be the same as the base scenario, risk values can be calculated for the risk situations for failures and incidents (Figure 7-32 to Figure 7-41) as described in the previous sections. These plots show the significant decrease of risk values as compared to the base scenario, but only during the period of time when a machine fault could be detected before progressing to a failure, i.e. two days before and after inspection time. For three days in a week, the machine is susceptible to becoming faulty and failing in the field. This phenomenon is evident from the indented risk curves in these figures. These figures indicate a drastically lower risk of failures or incidents (reduction in risk) during a period of 48 h before and after an inspection, i.e. if the machine has become faulty during the 48 h period before it is inspected, then there is a chance that it will be detected by the inspector, and similarly, after a machine has been inspected, if it has been determined healthy, it will not become faulty until after 48 h elapses. Outside of this 96 h period (the sum of 48 h before and 48 h after inspection), i.e. 72 h in a week, faults may develop and not get detected by an inspector leaving the machines susceptible to failure in the field, risk values are equal to the base scenario for the three,

Although during four days in a week, risks in this scenario are significantly lower compared to the base scenario, the operation incurs a weekly cost of $2,000 and revenue loss of $150,000 per machine based on the assumed values for service costs.

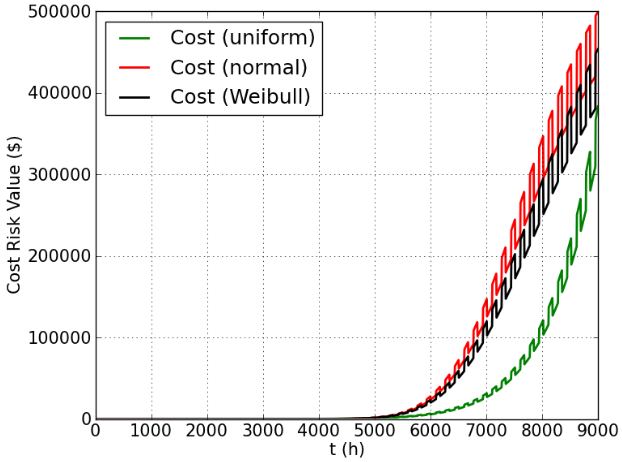


Figure 7-32. Cost risk value if all of the machines fail prior to t

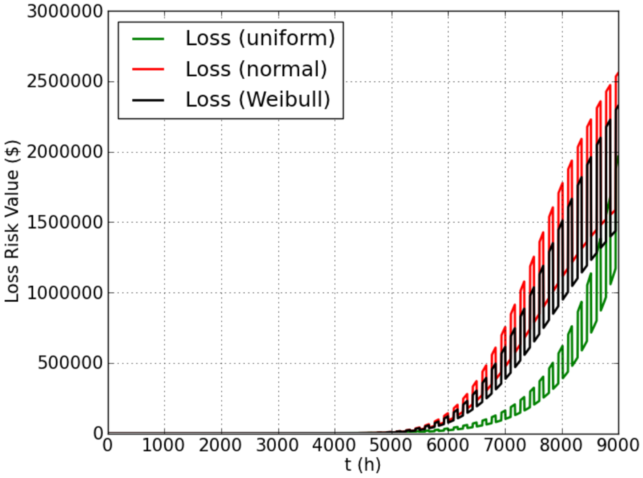


Figure 7-33. Loss risk value if all of the machines fail prior to t

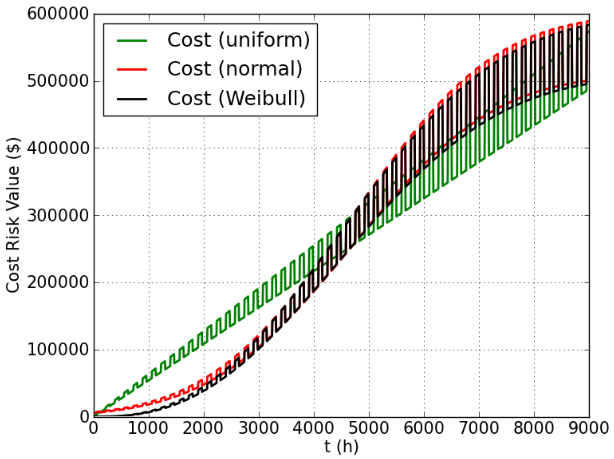


Figure 7-34. Total average cost risk value of machine failures prior to t

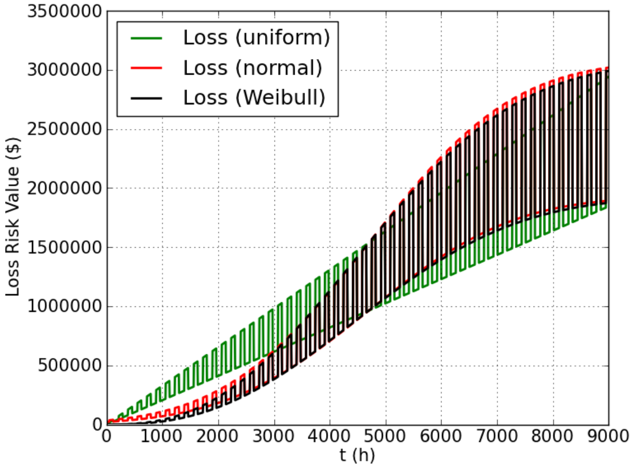


Figure 7-35. Total average loss risk value of machine failures prior to t

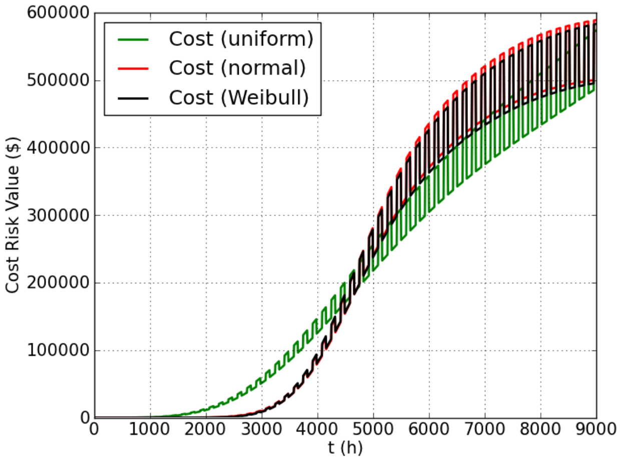


Figure 7-36. Cost risk value if a minimum of 5 machines fail prior to t

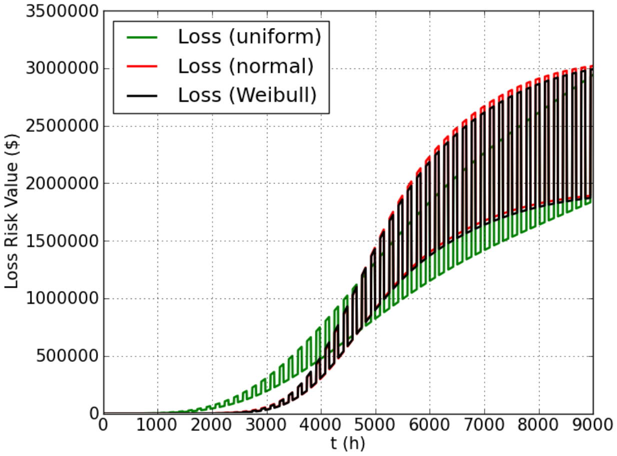


Figure 7-37. Loss risk value if a minimum of 5 machines fail prior to t

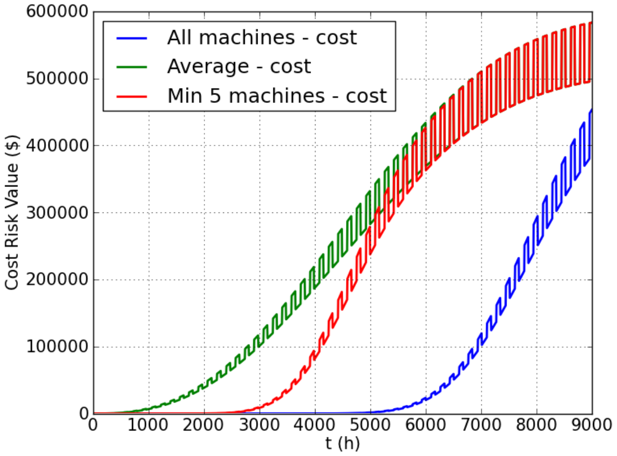


Figure 7-38. Cost risk value of machine failures (Weibull distribution)

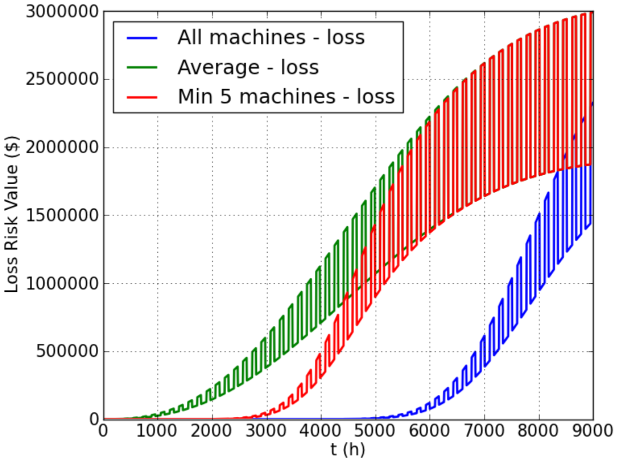


Figure 7-39. Loss risk value of machine failures (Weibull distribution)

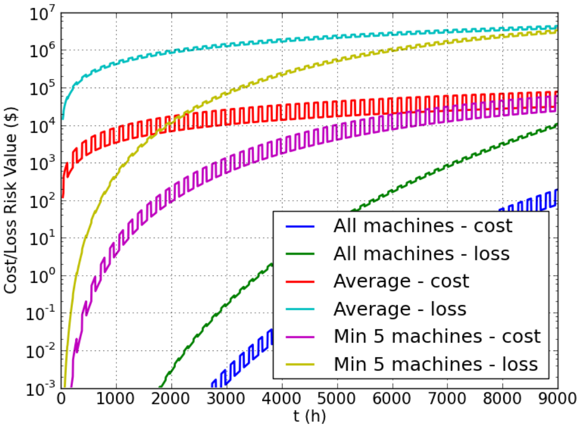


Figure 7-40. Risk value of machine environmental incidents for different risk situations

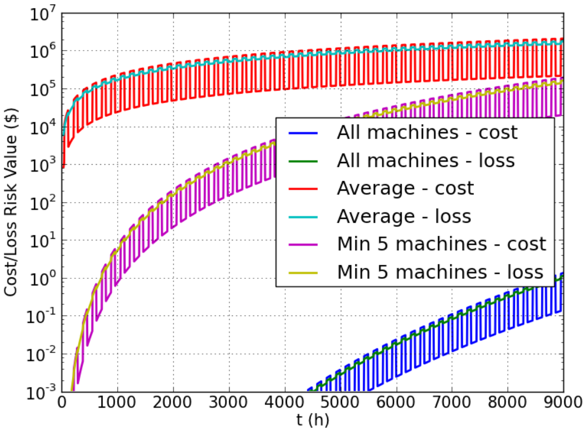


Figure 7-41. Risk value of machine safety incidents for different risk situations

7.1.3.2 PM-DES Results

Figure 7-42 to Figure 7-47 show the simulation histograms of the output variables for 400,000 simulations based on the existing system scenario. Similar to the base scenario simulations, the three different input distributions for machine failures do not result in significantly different results.

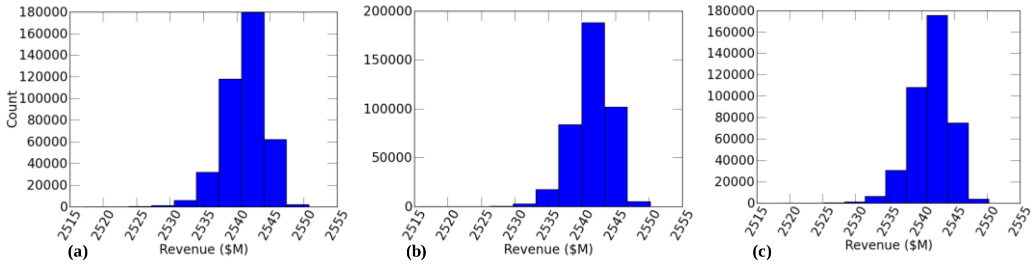


Figure 7-42. Histogram of revenue outcomes for the existing system simulations based on three different distributions for machine failures, (a) uniform, (b) normal, and (c) Weibull

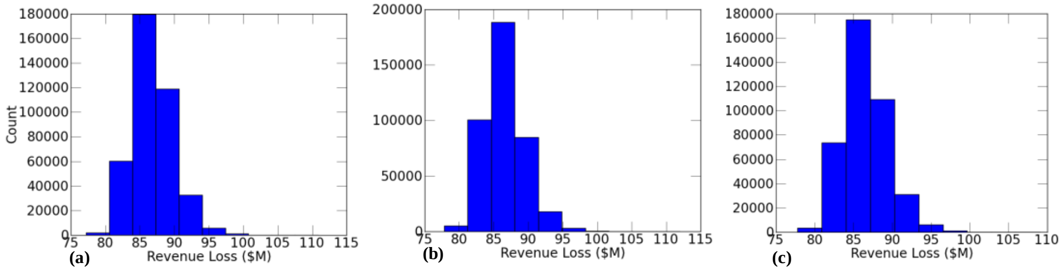


Figure 7-43. Histogram of revenue loss outcomes for the existing system simulations based on three different distributions for machine failures, (a) uniform, (b) normal, and (c) Weibull

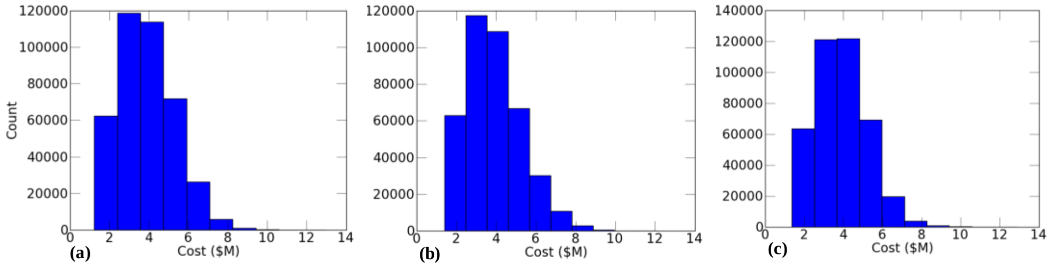


Figure 7-44. Histogram of cost outcomes for the existing system simulations based on three different distributions for machine failures, (a) uniform, (b) normal, and (c) Weibull

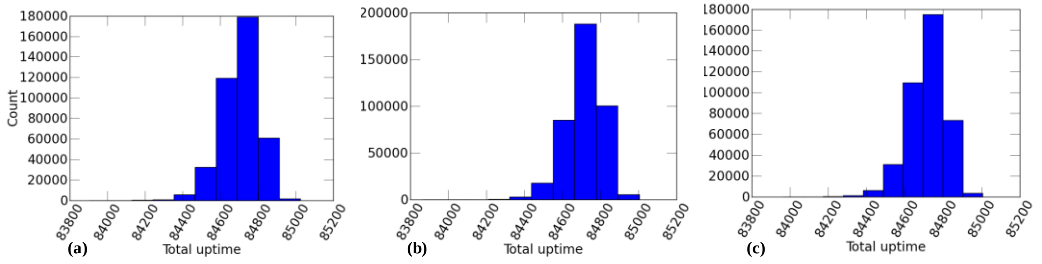


Figure 7-45. Histogram of total availability (h) outcomes for the existing system simulations based on three different distributions for machine failures, (a) uniform, (b) normal, and (c) Weibull

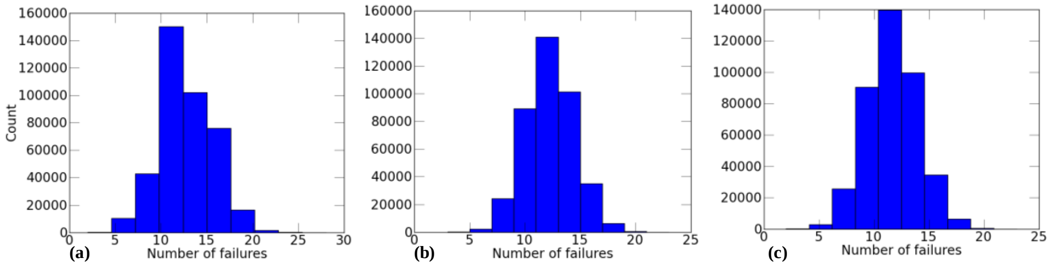


Figure 7-46. Histogram of the number of failure that occurred on the field for the existing system simulations based on three different distributions for machine failures, (a) uniform, (b) normal, and (c) Weibull

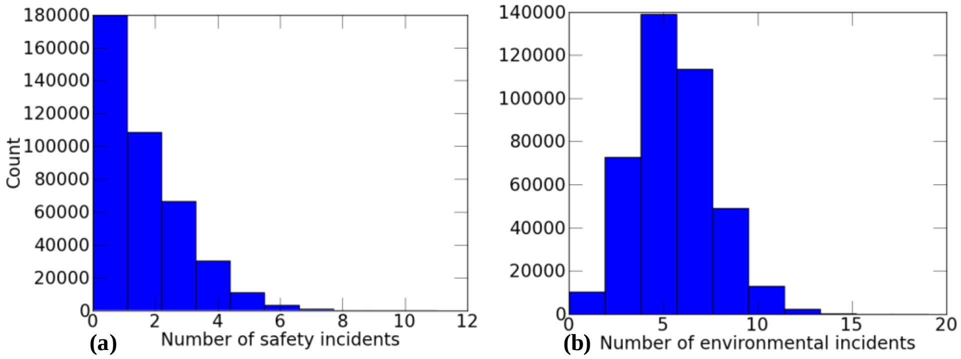


Figure 7-47. Histogram of the number of, (a) safety incidents and (b) environmental incidents that occurred on the field for the existing system simulations based on uniform distribution for safety and environmental events

7.1.4 Case Model 1: Offline CMMIS System Scenario (With Routine Minor Prevention Service)

This scenario involves the application of the offline CMMIS alternative in the operations. It is assumed that the machines in this scenario are equipped with an on-board, non-networked CMS. In this scenario, similar to the existing system scenario, machines are inspected weekly for faults. However, instead of visual inspection by experts, the CMMIS's fault detection application is used for detecting faults using machine condition data. This data is logged by the on-board CMS, and is manually transferred to the fault detection application, which processes the data using relevant models, and reports whether it has deemed the machine to be healthy or faulty (Figure 7-48). This procedure is assumed to cost $50 and 0.5 h for each machine, much lower compared to complete inspection by an expert. Also similar to the existing system scenario, it is assumed that if a fault is not detected during the two day period that takes for it to progress into a failure, the machine may become faulty and fail in the field without reaching its scheduled inspection time.

All the other factors of this scenario are similar to the existing system scenario. Similar to when an expert performs inspection, the condition probabilities associated with detection errors of the CMMIS fault detection application are accounted for. It should be possible for the organization to obtain information regarding the accuracy of the fault detection application from the application developers. It is assumed that the application has a far lower accuracy in correctly determining the condition of a machine when it is truly faulty. These conditional probabilities are assumed to be:

$$P(application\ detects\ fault\mid machine\ is\ faulty) = \frac{6}{10}$$

and hence the probability that the application misses the fault is:

$$P(application\ misses\ fault\mid machine\ is\ faulty) = \frac{4}{10}$$

On the other hand, if the machine is truly healthy, it assumed that the application determines the machine condition with 100% accuracy, as well as an ideal expert:

$$P(application\ deems\ healthy\mid machine\ is\ healthy) = 1$$

$$P(application\ deems\ faulty\mid machine\ is\ healthy) = 0$$

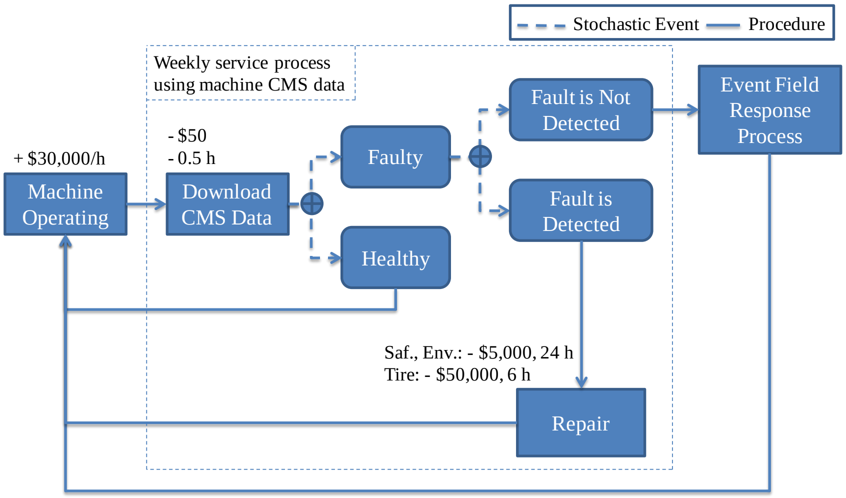


Figure 7-48. Machine event response diagram for the offline system scenario

7.1.4.1 **TERT Results**

The risk plots related to the risk event situations of interest in this scenario are shown in Figure 7-49 to Figure 7-58. Similar to the existing system scenario, the graphs generally show a drastic decrease in cost and revenue loss risk figures during four days in a week when faults could be detected in the inspection routine. Since it has been assumed that the accuracy of the fault detection application is much lower than that of an expert's, this reduction in risk values is less when compared to the existing system scenario. However, the considerably lower weekly cost of inspection ($50) and revenue loss ($15,000) per machine for this scenario should also be taken into account when comparing system values.

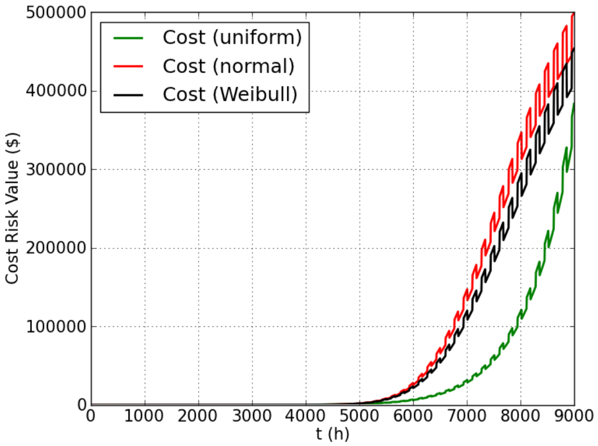


Figure 7-49. Cost risk value if all of the machines fail prior to t

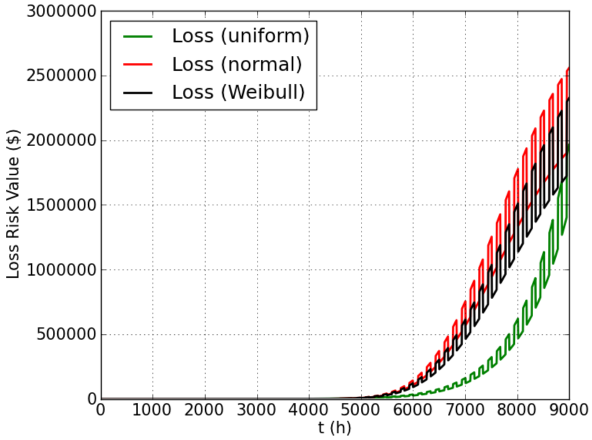


Figure 7-50. Loss risk value if all of the machines fail prior to t

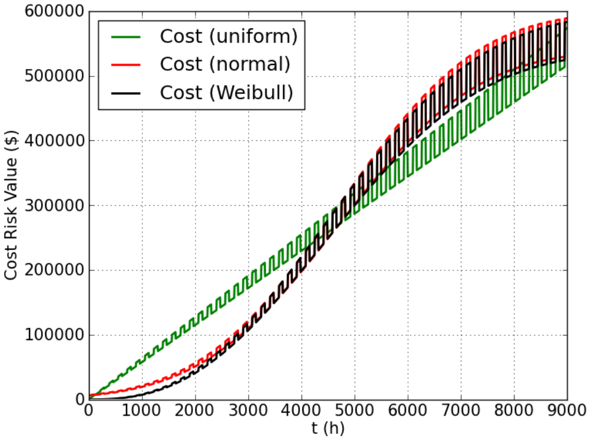


Figure 7-51. Total average cost risk value of machine failures prior to t

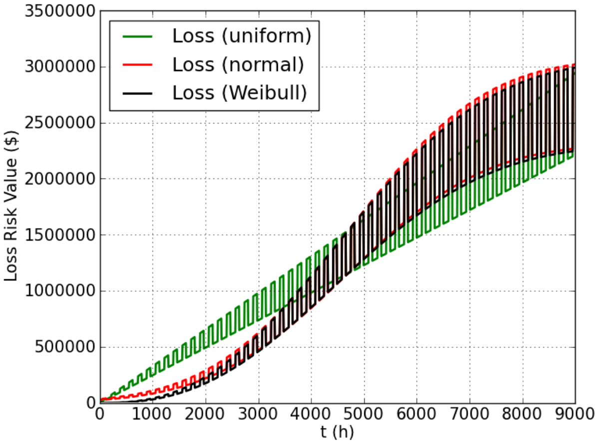


Figure 7-52. Total average loss risk value of machine failures prior to t

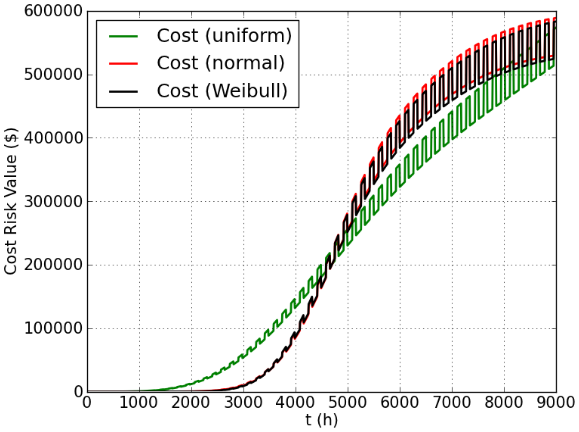


Figure 7-53. Cost risk value if a minimum of 5 machines fail prior to t

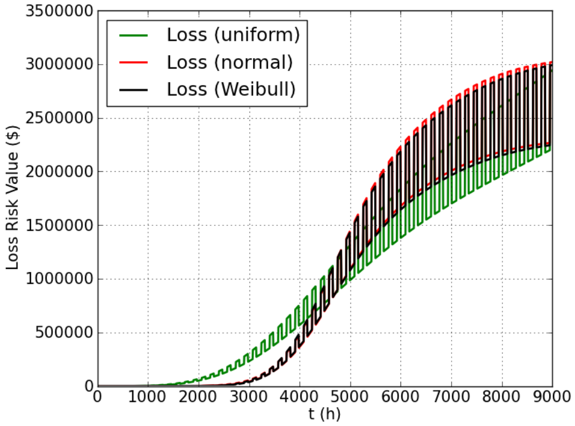


Figure 7-54. Loss risk value if a minimum of 5 machines fail prior to t

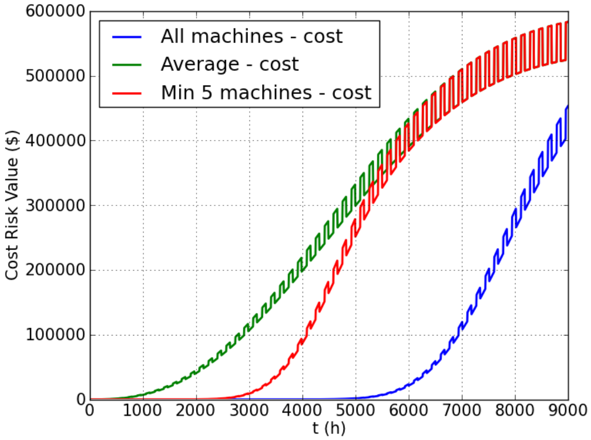


Figure 7-55. Cost risk value of machine failures (Weibull distribution)

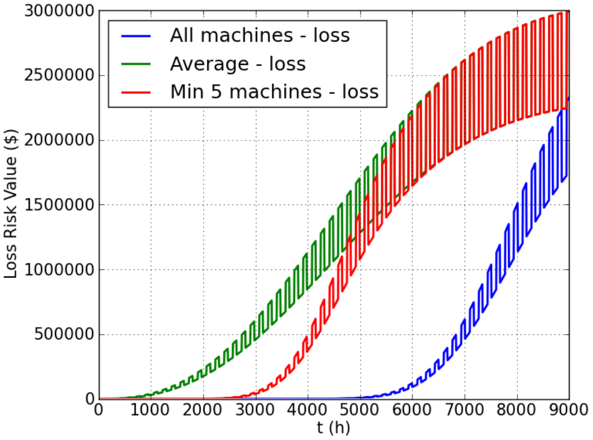


Figure 7-56. Loss risk value of machine failures (Weibull distribution)

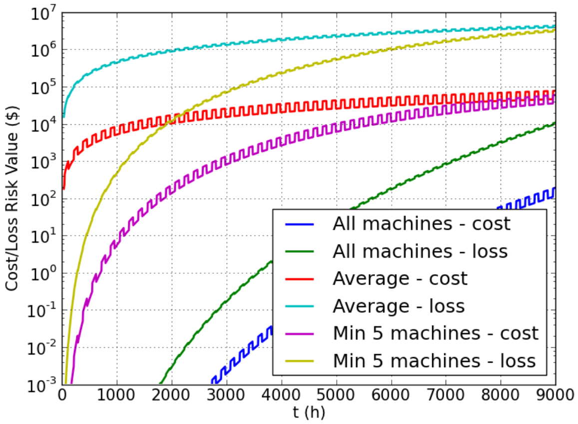


Figure 7-57. Risk value of machine environmental incidents for different risk situations

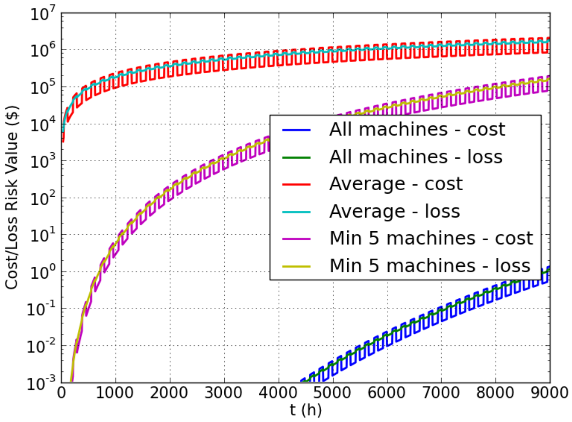


Figure 7-58. Risk value of machine safety incidents for different risk situations

7.1.4.2 **PM-DES Results**

Figure 7-59 to Figure 7-64 show the simulation histograms of the output variables for 400,000 simulations, where the three different input distributions for machine failures do not result in significantly different results.

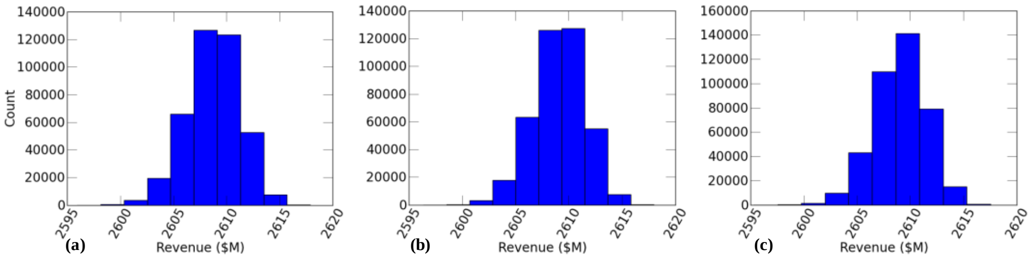


Figure 7-59. Histogram of revenue outcomes for the offline system simulations based on three different distributions for machine failures, (a) uniform, (b) normal, and (c) Weibull

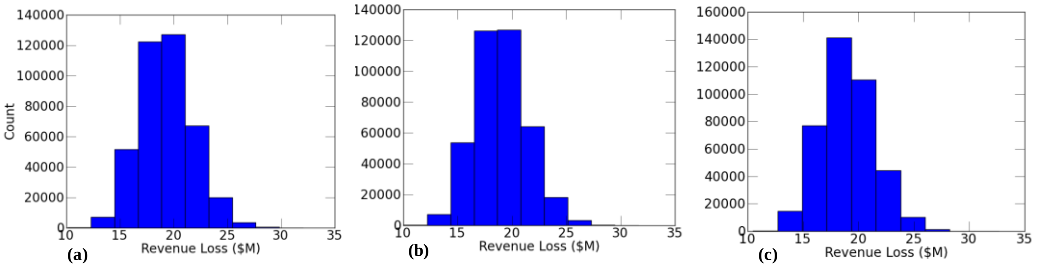


Figure 7-60. Histogram of revenue loss outcomes for the offline system simulations based on three different distributions for machine failures, (a) uniform, (b) normal, and (c) Weibull

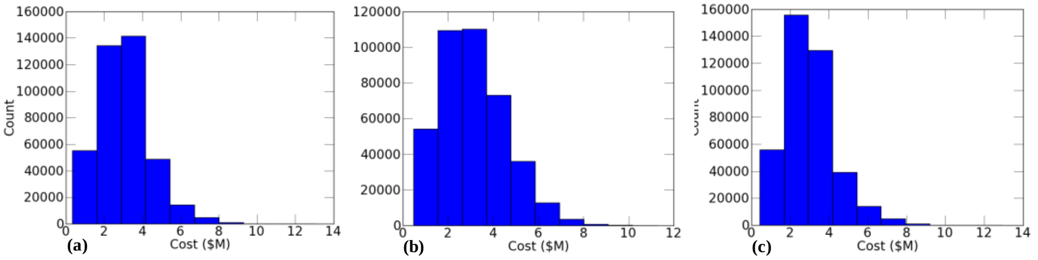


Figure 7-61. Histogram of cost outcomes for the offline system simulations based on three different distributions for machine failures, (a) uniform, (b) normal, and (c) Weibull

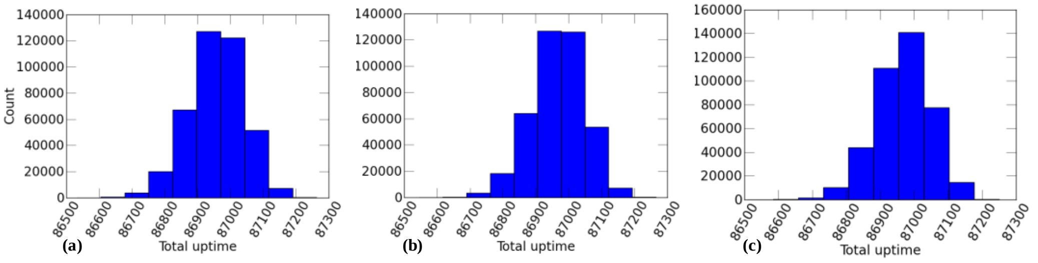


Figure 7-62. Histogram of total availability outcomes for the offline system simulations based on three different distributions for machine failures, (a) uniform, (b) normal, and (c) Weibull

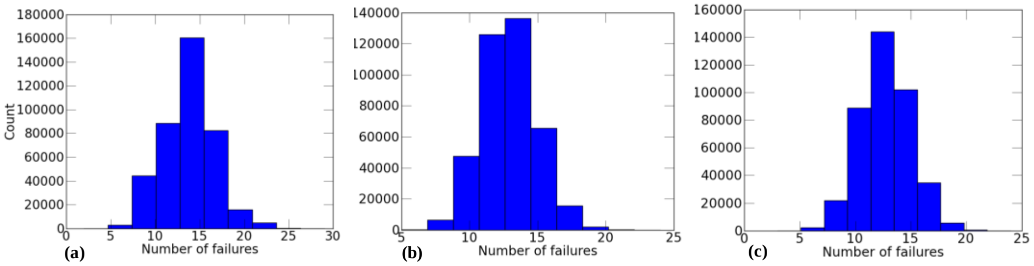


Figure 7-63. Histogram of the number of failure that occurred on the field for the existing system simulations based on three different distributions for machine failures, (a) uniform, (b) normal, and (c) Weibull

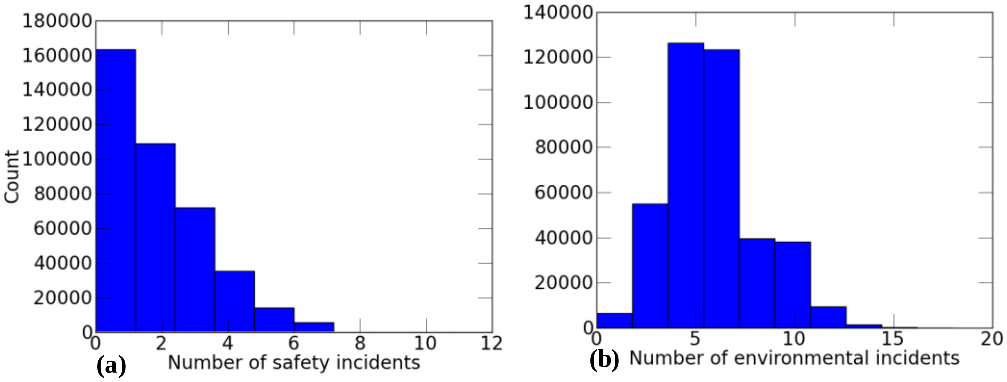


Figure 7-64. Histogram of the number of, (a) safety incidents and (b) environmental incidents that occurred on the field for the offline system simulations based on uniform distribution for safety and environmental events

7.1.4.3 Case Model 1: Real-time CMMIS Scenario (With No Routine Prevention)

In this scenario the operation is equipped with the real-time CMMIS alternative. It is assumed that the system allows real-time condition monitoring of machines, and management of maintenance activities.

The main operation parameters of this scenario are the same as the base case scenario with no routine inspections. The difference is that this scenario is based on a condition-based maintenance (CBM) strategy. The on-board CMS of machines are tasked with collecting and sending machine condition data, in real-time, to the CMMIS application server and receive diagnosis shortly after. Once a fault is detected by the remote application, it is assumed that the maintenance crew is immediately notified of the fault, and the machine is then scheduled for maintenance (Figure 7-65). When a fault is detected, the operator is also notified via the on-board CMS of the occurrence of the fault. It is assumed that once a fault is detected, the operator does not stop the machine's operation and continues until the end of a normal work shift, and the fault is dealt with by the maintenance procedure at that time.

The conditional probabilities associated with detection errors are assumed to be equal to that of the Offline CMMIS scenario, i.e.:

$$P(application\ detects\ fault \mid machine\ is\ faulty) = \frac{6}{10}$$

$$P(application\ misses\ fault \mid machine\ is\ faulty) = \frac{4}{10}$$

$$P(application\ deems\ healthy \mid machine\ is\ healthy) = 1$$

$$P(application\ deems\ faulty \mid machine\ is\ healthy) = 0$$

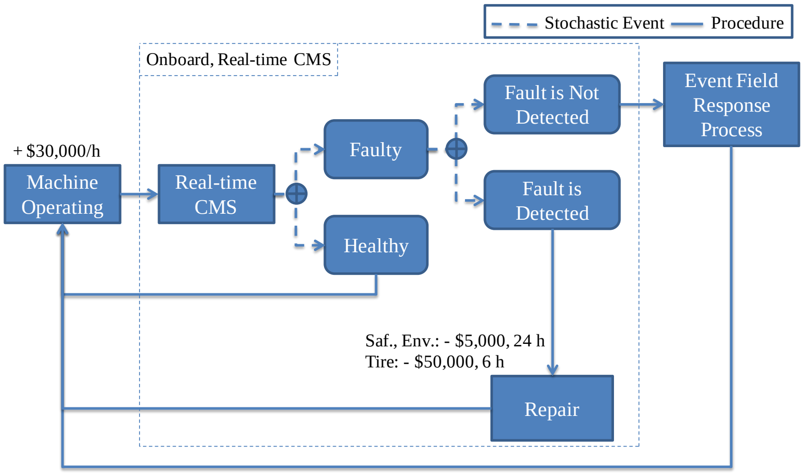


Figure 7-65. Machine event response diagram for the real-time system scenario

7.1.4.4 TERT Results

Figure 7-66 to Figure 7-75 show the risk plots related to the risk event situations of interest in this scenario. Compared to the Base scenario, the risk values are significantly lower, i.e. the CMMIS has reduced these risk values across all risk events. Moreover, unlike the existing system and the offline CMMIS scenarios, this reduction in risk is observed at all times because the machines are under continuous, real-time condition monitoring. Additionally, there is no inspection costs associated with this system.

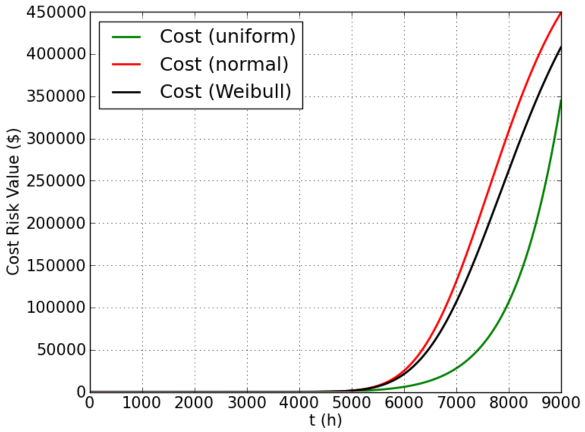


Figure 7-66. Cost risk value if all of the machines fail prior to t

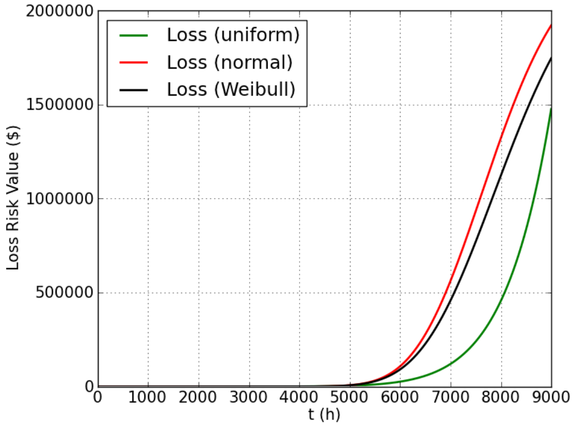


Figure 7-67. Loss risk value if all of the machines fail prior to t

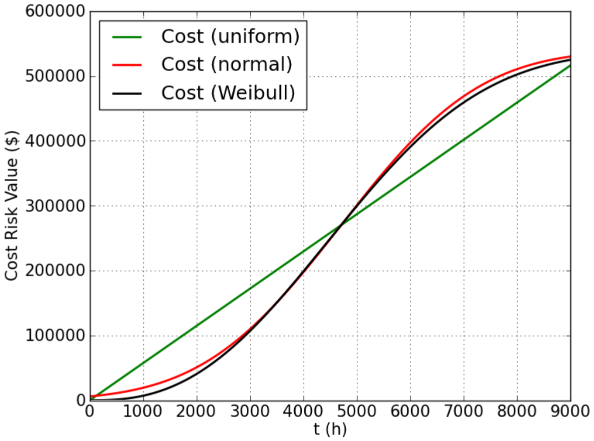


Figure 7-68. Total average cost risk value of machine failures prior to t

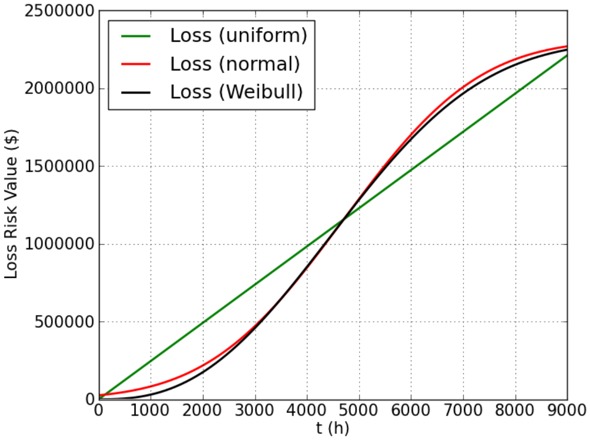


Figure 7-69. Total average loss risk value of machine failures prior to t

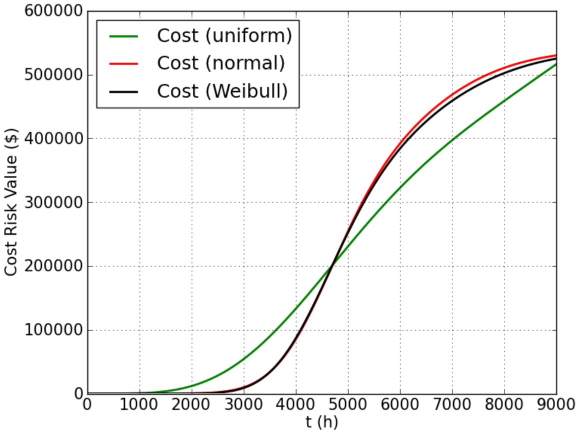


Figure 7-70. Cost risk value if a minimum of 5 machines fail prior to t

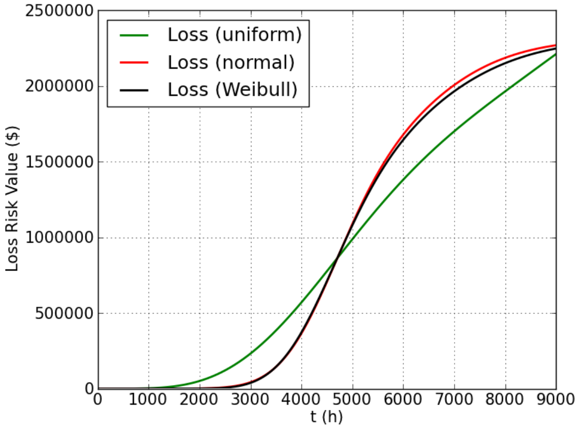


Figure 7-71. Loss risk value if a minimum of 5 machines fail prior to t

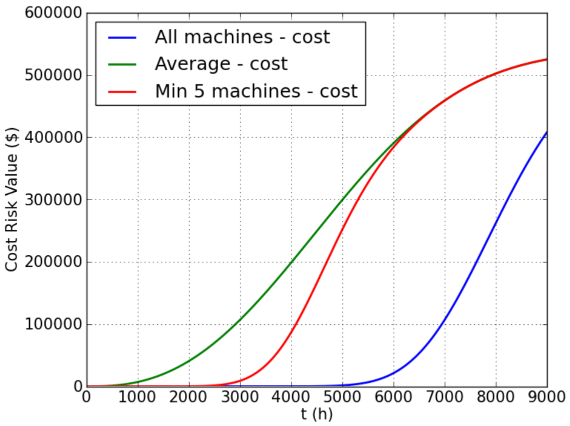


Figure 7-72. Cost risk value of machine failures (Weibull distribution)

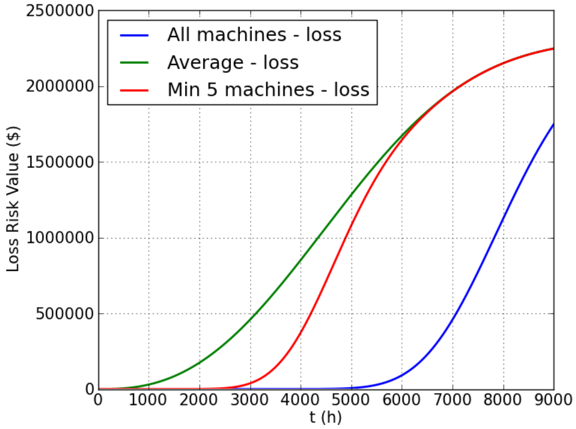


Figure 7-73. Loss risk value of machine failures (Weibull distribution)

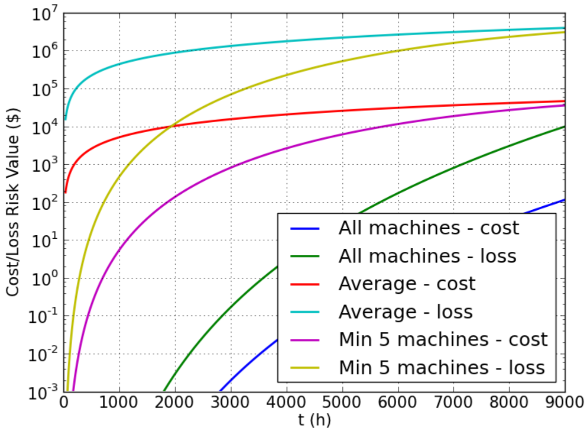


Figure 7-74. Risk value of machine environmental incidents for different risk situations

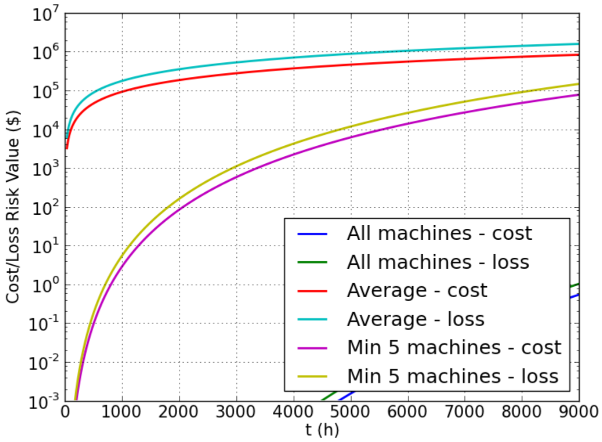


Figure 7-75. Risk value of machine safety incidents for different risk situations

7.1.4.5 PM-DES Results

Figure 7-76 to Figure 7-81 show the simulation histograms of the output variables for 400,000 real-time scenario simulations. Also for this scenario, the three different input distributions for machine failures all result in similar distributions for the output variables.

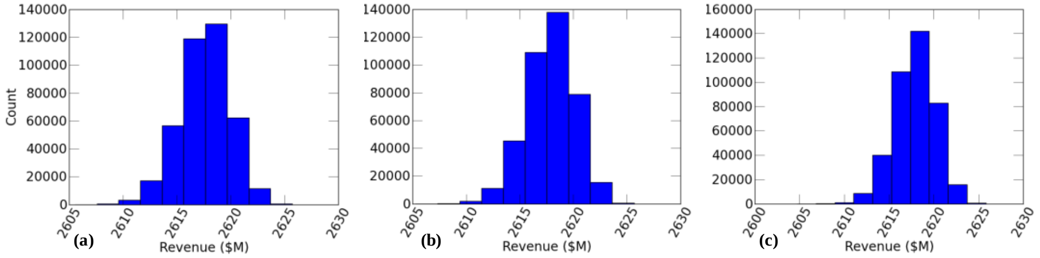


Figure 7-76. Histogram of revenue outcomes for the real-time system simulations based on three different distributions for machine failures, (a) uniform, (b) normal, and (c) Weibull

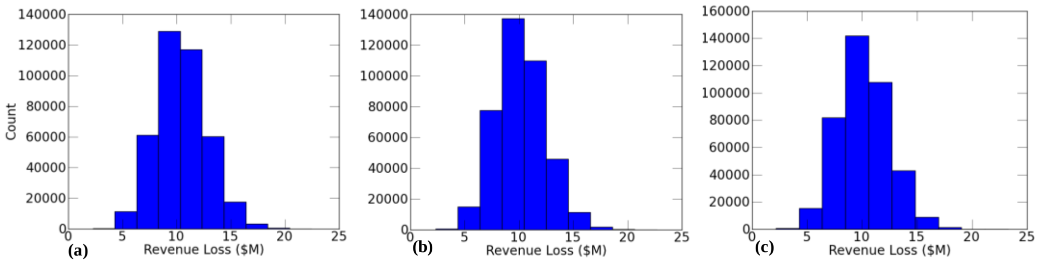


Figure 7-77. Histogram of revenue loss outcomes for the real-time system simulations based on three different distributions for machine failures, (a) uniform, (b) normal, and (c) Weibull

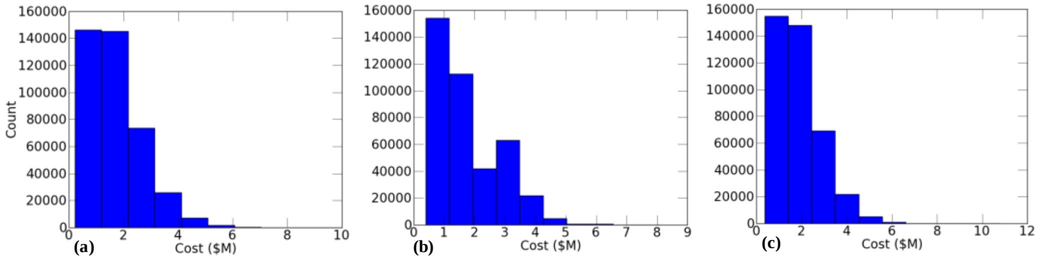


Figure 7-78. Histogram of cost outcomes for the real-time system simulations based on three different distributions for machine failures, (a) uniform, (b) normal, and (c) Weibull

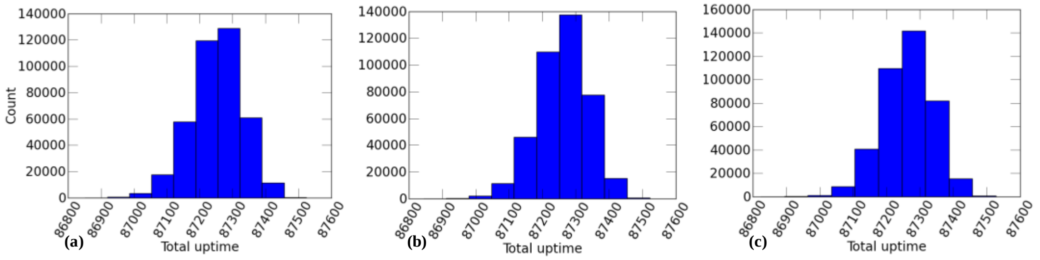


Figure 7-79. Histogram of total availability outcomes for the real-time system simulations based on three different distributions for machine failures, (a) uniform, (b) normal, and (c) Weibull

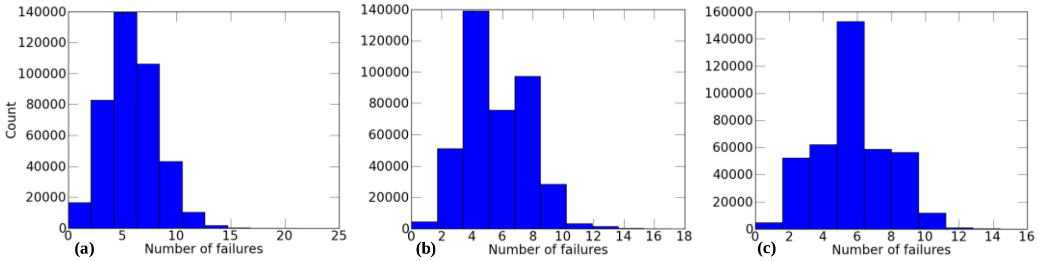


Figure 7-80. Histogram of the number of failure that occurred on the field for the real-time simulations based on three different distributions for machine failures, (a) uniform, (b) normal, and (c) Weibull

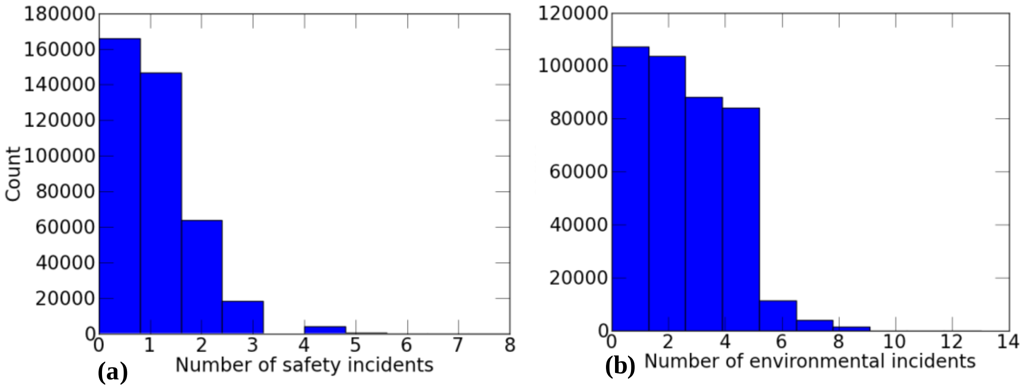


Figure 7-81. Histogram of the number of, (a) safety incidents and (b) environmental incidents that occurred on the field for the real-time system simulations based on uniform distribution for safety and environmental events

7.1.5 Model 1: Value Analysis and Choice Selection using the TERT Results

Once risk values and system performance based on the metrics of interest are calculated or estimated, the alternative systems and scenarios can be compared. The AHP multi-criteria decision making method is used in this case to select the best system that would achieve the hypothetical organization's objectives set for the system.

The performance criteria and the metrics to be used with the TERT method, for each criterion, are shown by amber ovals and yellow rectangles in Figure 7-82.

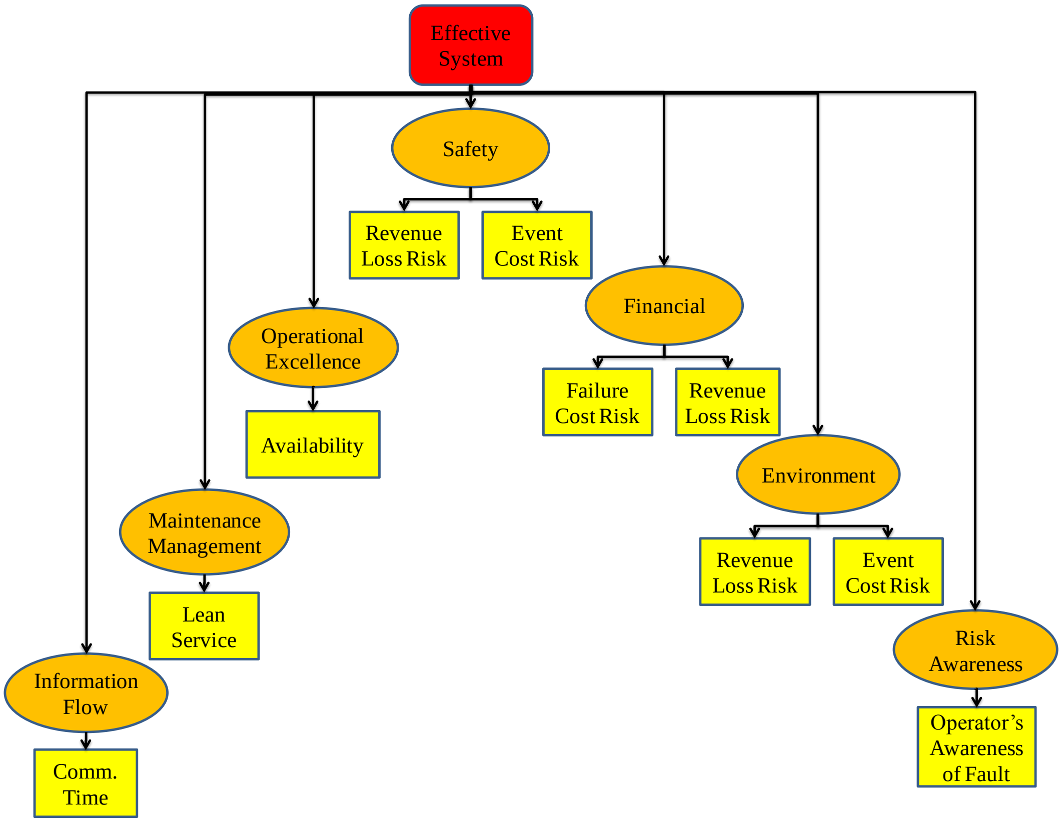


Figure 7-82. Hierarchy of first-level and second-level decision criteria used with the TERT method

The performance criteria form the first-level decision criteria, and the metrics constitute the second-level decision criteria in the context of this AHP decision method. The decision objective is to select the most effective system. The decision alternatives are the different system scenarios, i.e., the base scenario, existing scenario, offline CMMIS system, and the real-time CMMIS system. The hierarchy in Figure 7-82 shows the organization's ranking of the performance criteria. The procedure for calculating the criteria ranks and the alternatives' ranks within each criterion is as follows:

1. The matrix of first-level criteria, i.e. performance criteria, is constructed for pair-wise comparisons;
2. The eigenvector of the first-level criteria matrix is calculated which results in the relative ranking of the criteria;
3. For each first-level criteria that has more than one metric, a second-level criteria matrix is constructed, for which eigenvectors are calculated, resulting in the relative ranking of all second-level criteria;

4. The total criteria rank vector, i.e. relative ranking of all the metrics, is calculated by multiplying first-level criteria ranks by their respective second-level criteria ranks. A top level criterion's rank is transferred to the total rank vector entirely if that criterion has only one associated metric;
5. For each metric criterion in the total criteria rank vector, a pair-wise comparison matrix consisting of the alternatives is formed, and the eigenvectors of that matrix are calculated to obtain the ranks of the alternatives based on the criterion; and
6. The ranks of alternatives are then calculated by multiplying the alternatives-criteria matrix by the total criteria rank vector. The highest ranked alternative is the best alternative choice.

It is assumed for the hypothetical case that the first-level criteria, i.e. the performance criteria, are subjectively ranked by the organization, based on the 1-9 described in Section 6.4 with the relative importance weights outlined in the first-level criteria pair-wise matrix below:

	Safety	Financial	Operational Excellence	Environment	Maintenance Management	Risk Awareness	Information Flow
Safety	1	5	7	9	9	9	9
Financial	1/5	1	5	3	9	9	9
Operational Excellence	1/7	1/5	1	3	5	7	7
Environment	1/9	1/3	1/3	1	5	3	3
Maintenance Management	1/9	1/9	1/5	1/5	1	3	3
Risk Awareness	1/9	1/9	1/7	1/3	1/3	1	1
Information Flow	1/9	1/9	1/7	1/3	1/3	1	1

and the ranking matrix for the first-level criteria becomes:

Safety	0.489
Financial	0.237
Operational Excellence	0.120
Environment	0.071
Maintenance Management	0.037
Risk Awareness	0.025
Information Flow	0.021

It is assumed that the second-level criteria rankings are also roughly estimated based on their importance to the organization. Relative weights of pair-wise comparisons are based on the organization’s objective for the system, and emphasize the desire to decrease incident costs and revenue losses associated with safety and environmental incidents, and to increase machine availability for production. It is assumed that for failures and environmental incidents, the organization generally weighs the risk of revenue losses higher than the risk of direct costs associated with an incident because of the strategic emphasis of the organization on revenue expansion. For safety incidents, direct costs are deemed more important both because they are higher than revenue losses in case of incidents, and also because of a variety of other expenses and issues that are correlated with safety incidents and are undesirable (but difficult to quantify). Therefore the pair-wise comparisons of the risk of revenue losses versus direct costs for failures and incidents, and their corresponding eigenvectors (which results in the relative ranking of these second-level criteria), based on the 1-9 scale described in Section 6.4, are as follows.

Revenue losses due to failure are very strongly (a weight of 7) more important than direct failure costs:

$$\begin{array}{r|cc|}
 & \text{Failure Cost} & \text{Revenue Loss} \\
\text{Failure Cost} & 1 & 1/7 \\
\text{Revenue Loss} & 7 & 1
\end{array}$$

$$\begin{array}{r|c|}
\text{Failure Cost} & 0.125 \\
\text{Revenue Loss} & 0.875
\end{array}$$

Revenue losses due to environmental incidents are strongly (a weight of 5) more important than direct incident costs:

$$\begin{array}{r|cc|}
 & \text{Event Cost} & \text{Revenue Loss} \\
\text{Event Cost} & 1 & 1/5 \\
\text{Revenue Loss} & 5 & 1
\end{array}$$

$$\begin{array}{r|c|}
\text{Event Cost} & 0.167 \\
\text{Revenue Loss} & 0.833
\end{array}$$

Direct incident costs due to safety incidents are strongly (a weight of 5) more important than revenue losses due to safety incidents:

$$\begin{array}{r|cc|} & \text{Event Cost} & \text{Revenue Loss} \\ \text{Event Cost} & 1 & 5 \\ \text{Revenue Loss} & 1/5 & 1 \end{array}$$

$$\begin{array}{r|c|} \text{Event Cost} & 0.833 \\ \text{Revenue Loss} & 0.167 \end{array}$$

The total ranking matrix of the first-level and second-level criteria (global ranking) becomes:

Criteria	Metrics	Rank
Safety	Revenue Loss	0.082
	Event Cost	0.407
Financial	Revenue Loss	0.207
	Failure Cost	0.030
Operational Excellence	Availability	0.120
Environment	Revenue Loss	0.059
	Event Cost	0.012
Maintenance Management	Lean Service	0.037
Risk Awareness	Operator’s Awareness	0.025
Information Flow	Comm. Time	0.021

Once the ranking of all first-level and second-level criteria is completed, for each criterion (each metric), the alternatives must be ranked in the same fashion. This ranking can be done by relative weight estimation using the pair-wise matrix (as done for the criteria) and using the 1-9 relative strength scale. Or if the relative strength of an item is known over another based on calculated numerical values, then ranking can be done directly by calculating the normalized relative strength of the items. The ranking of alternatives for each criterion is discussed in the following.

The only alternative that provides risk awareness for a machine operator, by indicating if the machine is faulty, is the real-time CMMIS system. Therefore, it is assumed that the organization rates the real-time system to have the maximum advantage over all of the other alternatives while judging that the rest do not carry any significant weight over one another:

$$\begin{array}{c|cccc|}
\text{Scenarios} & \text{Base} & \text{Existing} & \text{Off-line} & \text{Real-time} \\
\text{Base} & 1 & 1 & 1 & 1/9 \\
\text{Existing} & 1 & 1 & 1 & 1/9 \\
\text{Off-line} & 1 & 1 & 1 & 1/9 \\
\text{Real-time} & 9 & 9 & 9 & 1
\end{array}$$

It is assumed that the only metric related to information flow which the organization determined to rank the alternatives with is communication time. In the case's context, it is assumed that the real-time CMMIS alerts the base and schedules maintenance immediately after a fault is detected, hence leaving no need for the operator to attempt contacting another party. It is assumed that the offline CMMIS does not possess this feature, however, its scheduling system still allows for coordination of tasks and required resources for maintenance. The existing and base scenarios lack such automated communications and coordination features. Therefore the organization designates the real-time CMMIS to be very strongly better (shorter time) than the offline CMMIS and extremely better than both the base and existing scenarios. The offline CMMIS is in turn deemed to be strongly better than both the base and existing scenarios. The existing scenario is assessed to not have any communication time advantages over the base scenario:

$$\begin{array}{c|cccc|}
\text{Scenarios} & \text{Base} & \text{Existing} & \text{Off-line} & \text{Real-time} \\
\text{Base} & 1 & 1 & 1/5 & 1/9 \\
\text{Existing} & 1 & 1 & 1/5 & 1/9 \\
\text{Off-line} & 5 & 5 & 1 & 1/7 \\
\text{Real-time} & 9 & 9 & 7 & 1
\end{array}$$

It is assumed that the organization assesses its success in achieving operational excellence by the degree of lean service for machines. Measuring the degree of lean service can have numerous specific and concrete metrics involved. It is assumed that the organization bundles all such metrics in the performance criterion category, designated from the application of the framework, in a single, relative measure of lean service. In this sense, the real-time CMMIS is deemed by the organization to have the highest advantage because it automatically coordinates and schedules service activity only when a fault is detected, hence eliminating the unnecessary use of time and resources. The offline CMMIS has advantage over the base and existing scenario because it reduces service time by using the fault detection application, and allows for the coordination of resources and optimization of service time. The existing scenario is in turn superior to the base scenario, since it prevents unplanned queues, uncoordinated service activities, and inefficient use of resources if several machines simultaneously require service. Based on these assumptions, the pair-wise relative comparisons of the alternative choices by the organization based on lean service are provided in the pair-wise matrix:

$$\begin{array}{c|cccc|}
\text{Scenarios} & \text{Base} & \text{Existing} & \text{Off-line} & \text{Real-time} \\
\text{Base} & 1 & 1/5 & 1/9 & 1/9 \\
\text{Existing} & 5 & 1 & 1/7 & 1/7 \\
\text{Off-line} & 9 & 7 & 1 & 1/5 \\
\text{Real-time} & 9 & 7 & 5 & 1
\end{array}$$

The one metric used for the maintenance management performance criterion is availability, also known as “uptime”, i.e. the duration which a machine is not inactive due to failures, incidents, and service. Pair-wise comparison of alternatives with respect to availability can be performed if calculated availability values for each alternative, such as averages, exist. Comparisons can be done based on judgmental estimation of performance expressed on the 1-9 scale as well. Since TERT analysis does not provide values for availability for the alternatives, the judgmental estimation approach is taken here. Hence, it is assumed that the organization assesses that the real-time CMMIS results in the highest availability because it eliminates both the need for routine inspections and queue times. It also deems the offline CMMIS is slightly better than the base scenario because it decreases the risk of failures, hence the risk of multiple machines failing at the same time and queuing for resources. The organization also deems the offline system to be much better than the existing system because it decreases downtime during fault detection by using the faster fault detection application of the system instead of an expert’s fault detection routine. However, the organization determines the base system to be much better than the existing system based on the machine availability metric because it does not impose long machine downtimes due to the routine inspection and planned service procedures. These pair-wise relative comparisons of these facts and judgments by the organization are expressed in the availability metric’s respective pair-wise matrix:

$$\begin{array}{c|cccc|}
\text{Scenarios} & \text{Base} & \text{Existing} & \text{Off-line} & \text{Real-time} \\
\text{Base} & 1 & 5 & 1/3 & 1/5 \\
\text{Existing} & 1/5 & 1 & 1/5 & 1/9 \\
\text{Off-line} & 3 & 5 & 1 & 1/5 \\
\text{Real-time} & 5 & 9 & 5 & 1
\end{array}$$

In the case of the TERT analysis, for each of the safety, financial, and environment criteria, there are two metrics that serve as decision criteria, i.e. revenue loss risk and event cost risk. Since for each decision alternative (scenario), these risk values for various risk event situations were calculated over time, the advantage of each alternative over the others can be directly calculated. Since the risk values at each point in time are different, it is assumed that the organization selects a certain period of interest which it calculates the arithmetic average of risk values for comparisons. Firstly, the Weibull distribution is selected for the calculations. Secondly, the period selected for the arithmetic average risk calculations is selected to start at 6,000 h for the duration of one week. It is assumed that the organization is interested in this time period for observing the risk values based on determined risk thresholds. Finally the averages are based on the risk curve representing the event situation that at least five machines fail simultaneously. The calculated arithmetic averages are shown in Table 7-1. The relative rank of alternatives is then calculated based on normalizing the inversed normalized average risk, i.e. the higher the average risk of an alternative, the lower its rank relative to other, e.g. the rank vector of the alternatives based on the direct cost risk of failures (Weibull failure distribution):

Scenarios	Rank
Base	0.234
Existing	0.257
Off-line	0.249
Real-time	0.260

	Financial		Environment		Safety	
	Failure Cost ($k)	Revenue Loss ($k)	Event Cost ($k)	Revenue Loss ($k)	Event Cost ($k)	Revenue Loss ($k)
Base	435.6	2232.5	20.0	1130.1	36.6	30.8
Existing	397.5	1746.5	13.1	1041.8	17.8	28.4
Offline	410.2	1908.5	15.4	1071.2	24.0	29.2
Real-time	392.0	1677.1	12.0	1028.1	14.8	28.0

Table 7-1. Risk values averaged over one week starting at 6,000 h of machine operations using the "Weibull" failure distribution

Once the alternatives are ranked based on all of the metrics, the alternatives-criteria matrix can be completed:

	Safety		Financial		Operational Excellence	Environment		Maintenance Management	Risk Awareness	Information Flow
Scenarios	Revenue Loss	Event Cost	Revenue Loss	Failure Cost	Availability	Revenue Loss	Event Cost	Lean Service	Operator's Awareness	Comm. Time
Base	0.236	0.142	0.209	0.234	0.123	0.236	0.182	0.032	0.080	0.052
Existing	0.256	0.291	0.267	0.257	0.041	0.256	0.278	0.080	0.080	0.052
Off-line	0.249	0.215	0.245	0.249	0.213	0.249	0.236	0.272	0.080	0.192
Real-time	0.259	0.352	0.278	0.260	0.623	0.259	0.303	0.616	0.760	0.704

When the alternatives-criteria matrix is multiplied by the total criteria rank matrix, the alternatives rank matrix is obtained:

	Safety (0.489)		Financial (0.237)		Operational Excellence (0.120)	Environment (0.071)		Maintenance Management (0.037)	Risk Awareness (0.025)	Information Flow (0.021)	
Scenarios	Revenue Loss (0.167)	Event Cost (0.833)	Revenue Loss (0.875)	Event Cost (0.125)	Availability (1.000)	Revenue Loss (0.833)	Event Cost (0.167)	Lean Service (1.000)	Operator Awareness (1.000)	Comm. Time (1.000)	Total Rank
Base	0.236	0.142	0.209	0.234	0.123	0.236	0.182	0.032	0.080	0.052	0.163
Existing	0.256	0.291	0.267	0.257	0.041	0.256	0.278	0.080	0.080	0.052	0.232
Off-line	0.249	0.215	0.245	0.249	0.213	0.249	0.236	0.272	0.080	0.192	0.225
Real-time	0.259	0.352	0.278	0.260	0.623	0.259	0.303	0.616	0.760	0.704	0.380

The final results are obtained based on the Weibull distribution assumption for calculating failure risks. When the final ranks are calculated based on the normal and uniform failure distribution assumptions, it can be seen that the failure risk rankings are the same as the ones based on the Weibull assumption at least to the two decimal points shown. Therefore from the perspective of this relative comparative analysis of alternatives for system selection, the choice of failure distribution does not make a difference.

Thus so far, the alternatives, including the framework deduced system choices, were ranked to yield the system that is the best (most effective) based on the selected metrics. This addresses two of the three characteristics of an effective system, i.e. the system being fit-for-purpose and holistic. However, to obtain the best performance-based system, total costs associated with the system should be considered for making the final system selection. One method in incorporating costs is to tabulate the alternative's relative value, its TCO, and the financial opportunity loss related to each alternative together. The TCO values include the cost of planned inspection plus the cost of the CMMIS (SC_x). For the offline CMMIS, this means \$26,000 cost for the weekly inspection program for 10 machines over a year in addition to the CMMIS purchase/development/maintenance cost. Opportunity loss is the production loss due to planned weekly inspection downtimes, which for the offline CMMIS, is \$7,800,000 for 10 machines over a year.

The relative values for the alternatives can be calculated as the ratio of the alternative's rank to the base scenario's rank in the AHP ranking results (Table 7-2). The value ratios indicate the superiority of the existing system over the base system. Since these values stem from the holistic performance criteria of the framework, a scenario with a value less than unity is not acceptable. However, to compare the value of the existing system, offline CMMIS, and real-time CMMIS against one another under a performance-based strategy, the costs associated with the system must also be considered. In this case, although the value ratio of the existing system is slightly higher than the offline CMMIS, the TCO and opportunity loss values associated with the existing system's inspection and maintenance practice are much higher than the offline CMMIS, hence overall a less effective system than the offline CMMIS. The real-time CMMIS scenario is both superior in value and lower acquisition costs as compared to other alternatives, hence it is the most effective system for the studied case organization.

	Value Ratio	TCO	Opportunity Loss (Production Loss $M)
Base	1	0	0
Existing	1.42	1,040,000	78
Offline CMMIS	1.38	26,000 + SC_1	7.8
Real-time CMMIS	2.33	SC_2	0

Table 7-2. The value/cost table of the alternatives

Table 7-3 shows the risk values averaged over one week starting at the 6,000th hour using the "uniform" distribution. The ranking matrix of alternatives with respect to "direct failure costs" and "revenue loss" using the "uniform" failure distribution are equal to that of the Weibull distribution (calculated using the normalized values of inversed normalized average risk values). The ranking matrix of alternatives with respect to "failure cost" is shown below, which indicates the same relative ranking as the Weibull distribution:

$$\begin{array}{c c} \underline{\text{Scenarios}} & \text{Rank} \\ \begin{array}{c} \text{Base} \\ \text{Existing} \\ \text{Off-line} \\ \text{Real-time} \end{array} & \left| \begin{array}{c} 0.234 \\ 0.257 \\ 0.249 \\ 0.260 \end{array} \right| \end{array}$$

Since the system's ranking based on all the other metrics are equal regardless of the failure distribution used, it can be stated that the same conclusion regarding the superiority of the real-time system and relative comparisons and ranking of other systems can be reached by using a simpler, uniform distribution assumption for failures. Hence in this case, even a uniform distribution for failures is sufficient for demonstrating the relative value of the systems, and decision making for system choice selection for implementation without the need for higher analytical accuracy.

	Financial		Environment		Safety	
	Failure Cost ($k)	Revenue Loss ($k)	Event Cost ($k)	Revenue Loss ($k)	Event Cost ($k)	Revenue Loss ($k)
Base	366.1	1876.4	20.0	1130.1	36.6	30.8
Existing	334.1	1460.0	13.1	1041.8	17.8	28.4
Offline	344.8	1604.2	15.4	1071.3	24.0	29.2
Real-time	329.5	1409.6	12.0	1028.1	14.7	28.0

Table 7-3. Risk values averaged over one week starting at 6,000 h of machine operations using the "uniform" failure distribution

7.1.6 Model 1: Value Analysis and Choice Selection using the PM-DES Results

7.1.6.1 Comparison of Averages and the Effect of Input Distributions

Results of the four simulated scenarios were shown in the previous four sections in the form of distributions of the output variables. In this section, these results are compared for the scenarios including the alternative systems as part of the value analysis and choice selection phase of the framework.

To compare the cases, average values of the output metrics can be used that are calculated from all the simulations. These values are shown in Tables 7-4 and 7-6 for all the four scenarios and the three different machine failure distributions for each scenario. These values are shown as bar charts in Figure 7-83 to Figure 7-87. Tables 7-5 and 7-7 show the variation of the average values of the uniform and normal distribution assumption for machine failures from the Weibull model. It can be seen from these tables that the percent variation in the number of field failures is around 8% for the uniform distribution assumption and less than 0.5% for the normal distribution for all the system scenarios.

When comparing the existing versus the base system scenarios, the distribution plots and the average value bar charts show a general decrease of field events as compared to the base scenario, however, the operation incurs a cost of $500 and $60,000 in revenue loss per machine per week due to scheduled inspection downtime.

For the offline system scenario, similar to the existing system scenario, the graphs generally show a slight decrease in cost, but a significant increase in revenue loss, albeit much lower revenue loss than the existing system scenario. Since it is assumed that the accuracy of the fault detection application of the offline system is much lower than that of an expert's, the number of field failures and events are higher compared to the existing system scenario. However, the considerably lower cost of inspection and revenue loss, i.e. $50 and.$15,000 per machine per week, respectively, and the much shorter inspection times should also be taken into account when comparing system values. Hence for these two systems, it can be seen that the main advantage of the offline system over the existing one is that it significantly increases availability, and as a result, overall revenue.

In both the existing system and the offline CMMIS, the risk of failures and incidents occurring on the field, decrease within two days before and after inspection time. However, for three days in a week, the machine is susceptible to becoming faulty and failing or producing an incident in the field. This matter is indirectly reflected in the output distributions and the metrics that measure the field failures and incidents.

On all accounts, it can be seen from the bar charts that the real-time system is superior compared to all of the other scenarios. In other words, despite the lower accuracy of its fault detection system, performance of the real-time system is higher on all the output metrics. Unlike the existing system and the offline CMMIS scenarios, the reduction in field failure and incident risks exists at all times throughout the machine's operation, and not just within a specific time range around an inspection instance in the case of the existing system. This is because the machines are under continuous, real-time condition monitoring by the real-time CMMIS. Moreover, unlike the existing system and the offline CMMIS scenarios, there are no inspection costs associated with this system. The real-time system provides slightly higher availability than the base scenario and significantly higher than the existing and offline system scenarios, therefore the overall revenue of the operations is also higher for the real-time system. On the other hand, operations cost is significantly lower for the real-time system as compared to the other scenarios, firstly because the real-time CMMS results in fewer failures and incidents in the field, and secondly because the high cost of routine, periodical service for preventive maintenance is eliminated.

Scenario	**Distribution**	**Revenue ($)**	**Lost Revenue ($)**	**Cost ($)**	**Total Availability (h)**	**Average Availability (h)**
Base	Uniform	2,616,086,572	11,950,567	3,188,206	87201.6	8720.2
	Normal	2,616,398,824	11,636,063	3,128,531	87212.1	8721.2
	Weibull	2,616,412,962	11,622,244	3,124,672	87212.6	8721.3
Existing	Uniform	2,541,208,303	86,828,994	3,787,770	84705.7	8470.6
	Normal	2,541,503,612	86,531,895	3,735,449	84715.6	8471.6
	Weibull	2,541,523,335	86,512,058	3,727,483	84716.3	8471.6
Offline	Uniform	2,608,760,096	19,277,428	2,996,070	86957.4	8695.7
	Normal	2,609,057,383	18,977,346	2,939,436	86967.4	8696.7
	Weibull	2,609,070,771	18,964,120	2,937,815	86967.9	8696.8
Real-time	Uniform	2,617,590,392	10,441,005	1,863,646	87,252	8,725
	Normal	2,617,890,896	10,138,926	1,801,508	87,262	8,726
	Weibull	2,617,904,272	10,125,940	1,798,512	87,262	8,726

Table 7-4. Average values of all simulations of revenue, lost revenue, cost, total availability, and per machine average availability values for the four simulated scenarios of Case Model 1 based on three different machine failure distributions

Scenario	Distribution	Revenue (Δ%)	Lost Revenue (Δ%)	Cost (Δ%)	Total Availability (Δ%)	Average Availability (Δ%)
Base	Uniform	0.012	2.825	2.033	0.013	0.013
	Normal	0.001	0.119	0.124	0.001	0.001
Existing	Uniform	0.012	0.366	1.617	0.012	0.012
	Normal	0.001	0.023	0.214	0.001	0.001
Offline	Uniform	0.012	1.652	1.983	0.012	0.012
	Normal	0.001	0.070	0.055	0.001	0.001
Real-time	Uniform	0.012	3.111	3.622	0.012	0.012
	Normal	0.001	0.128	0.167	0.000	0.000

Table 7-5. Distribution variations from the associated Weibull distribution values, based on the average values of all simulations for the output metric variables: revenue, lost revenue, cost, total availability, and per machine average availability values for the four simulated scenarios of Case-Model 1

Scenario	Distribution	Detected Faults	Failures	Safety Incidents	Environmental Incidents
Base	Uniform	0.1	15.1	2.2	6.4
	Normal	0.1	14.1	2.2	6.4
	Weibull	0.1	14.0	2.2	6.4
Existing	Uniform	11.8	12.6	1.8	5.3
	Normal	11.4	11.7	1.8	5.3
	Weibull	11.4	11.7	1.8	5.3
Offline	Uniform	4.3	13.8	2.0	5.8
	Normal	4.1	12.8	2.0	5.8
	Weibull	4.1	12.8	2.0	5.8
Real-time	Uniform	14.4	6.1	0.9	2.6
	Normal	13.7	5.7	0.9	2.6
	Weibull	13.7	5.6	0.9	2.6

Table 7-6. Average values of all simulations of detected faults, field failures, field safety incidents, and field environmental incident values for the four simulated scenarios of Case Model 1 based on three different machine failure distributions

Scenario	Distribution	Detected Faults (Δ%)	Failures (Δ%)	Safety Incidents (Δ%)	Environmental Incidents (Δ%)
Base	Uniform	4.18	7.72	0.04	0.10
	Normal	0.84	0.38	0.04	0.05
Existing	Uniform	4.20	7.35	0.14	0.20
	Normal	0.16	0.35	0.29	0.02
Offline	Uniform	4.17	7.82	0.27	0.09
	Normal	0.20	0.37	0.08	0.01
Real-time	Uniform	4.80	7.88	0.13	0.12
	Normal	0.18	0.49	0.03	0.01

Table 7-7. Distribution variations from the associated Weibull distribution values, based on the average values of all simulations for the output metric variables: detected faults, field failures, field safety incidents, and field environmental incident values for the four simulated scenarios of Case Model 1

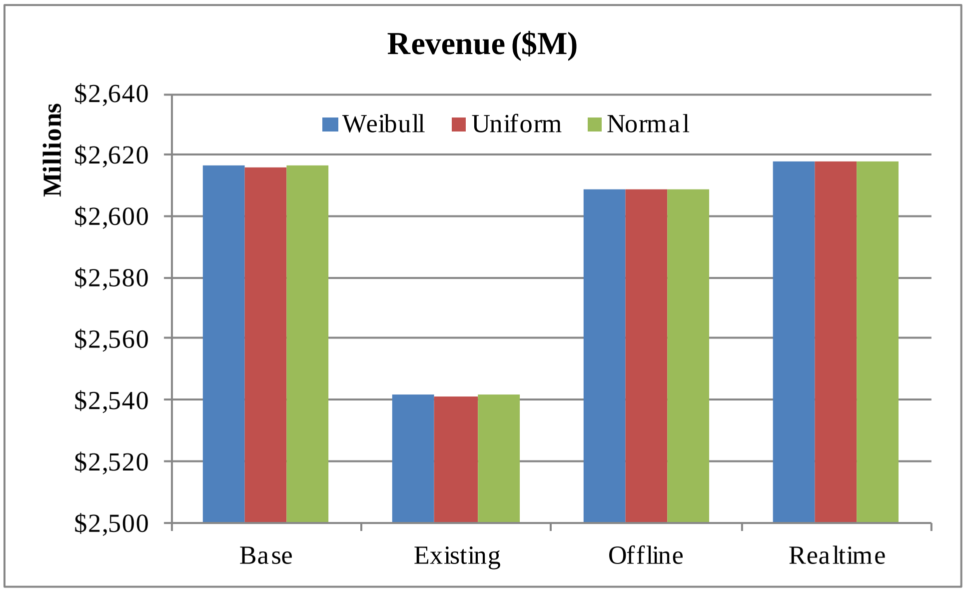


Figure 7-83. Output revenue average values of 400,000 simulations for the four simulated scenarios based on the Weibull distribution for machine failures of Case Model 1

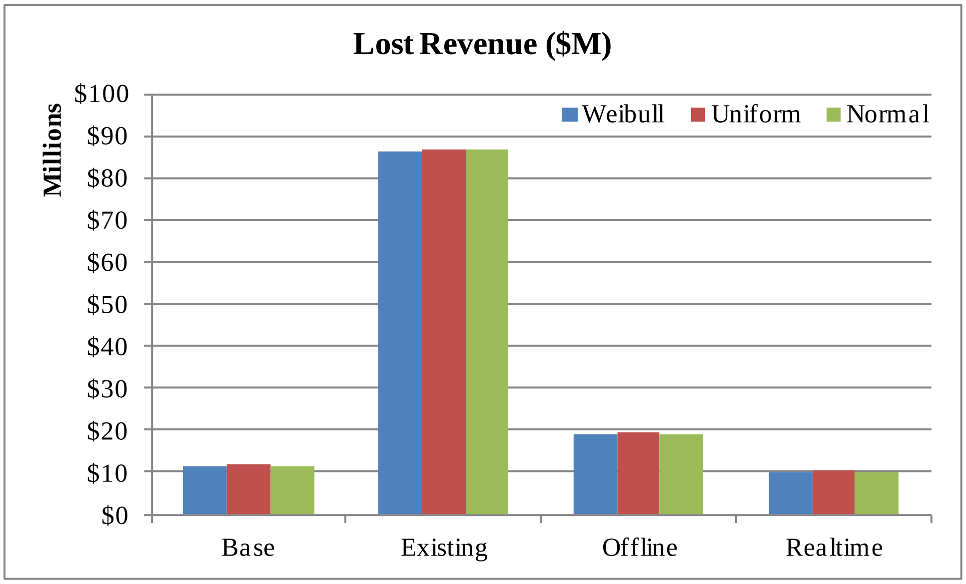


Figure 7-84. Output lost revenue average values of 400,000 simulations for the four simulated scenarios based on the Weibull distribution for machine failures of Case Model 1

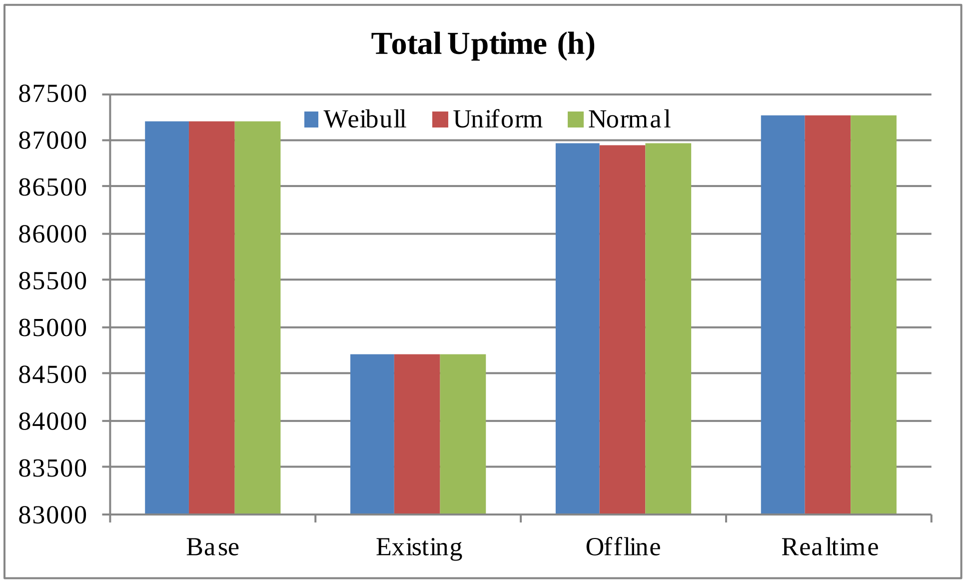


Figure 7-85. Output total availability (uptime) average values of 400,000 simulations for the four simulated scenarios based on the Weibull distribution for machine failures of Case Model 1

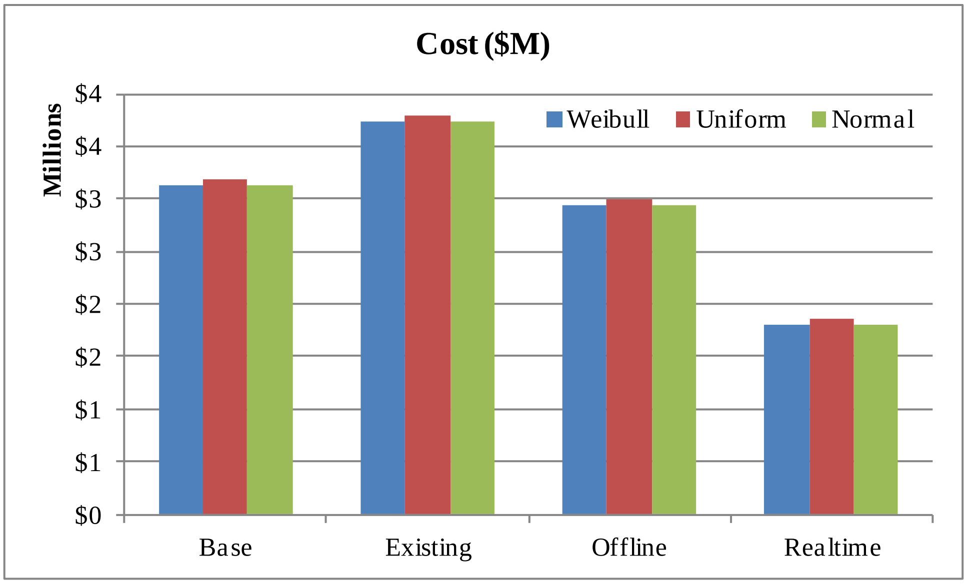


Figure 7-86. Output cost average values of 400,000 simulations for the four simulated scenarios based on the Weibull distribution for machine failures of Case Model 1

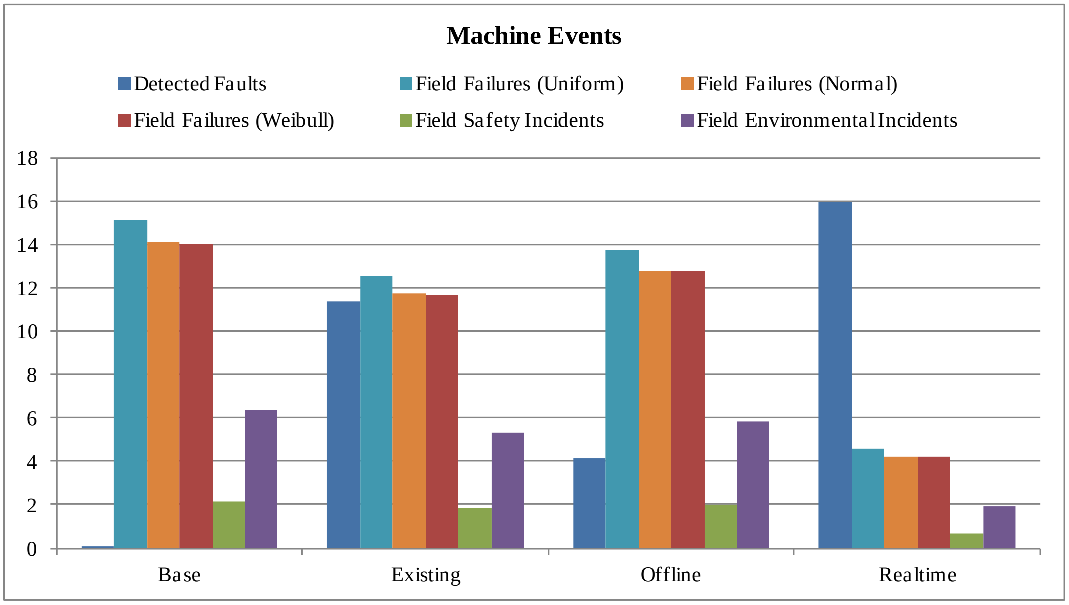


Figure 7-87. Output average values of detected faults, field failures, field safety incidents, field environmental incidents for 400,000 simulations for the four simulated scenarios based on the Weibull distribution for machine failures of Case Model 1

7.1.6.2 AHP Analysis for System Choice Selection

Similar to the system choice selection exercise from the TERT calculation results, once system performance based on the metrics of interest are calculated or estimated, the alternative systems and scenarios can be compared using the AHP method.

The performance criteria and metrics for each criterion used with PM-DES evaluation method are shown by amber ovals and yellow rectangles in Figure 7-88. The performance criteria form the first-level decision criteria, and the metrics constitute the second-level decision criteria in this AHP decision method context. The decision objective is to select the most effective system.

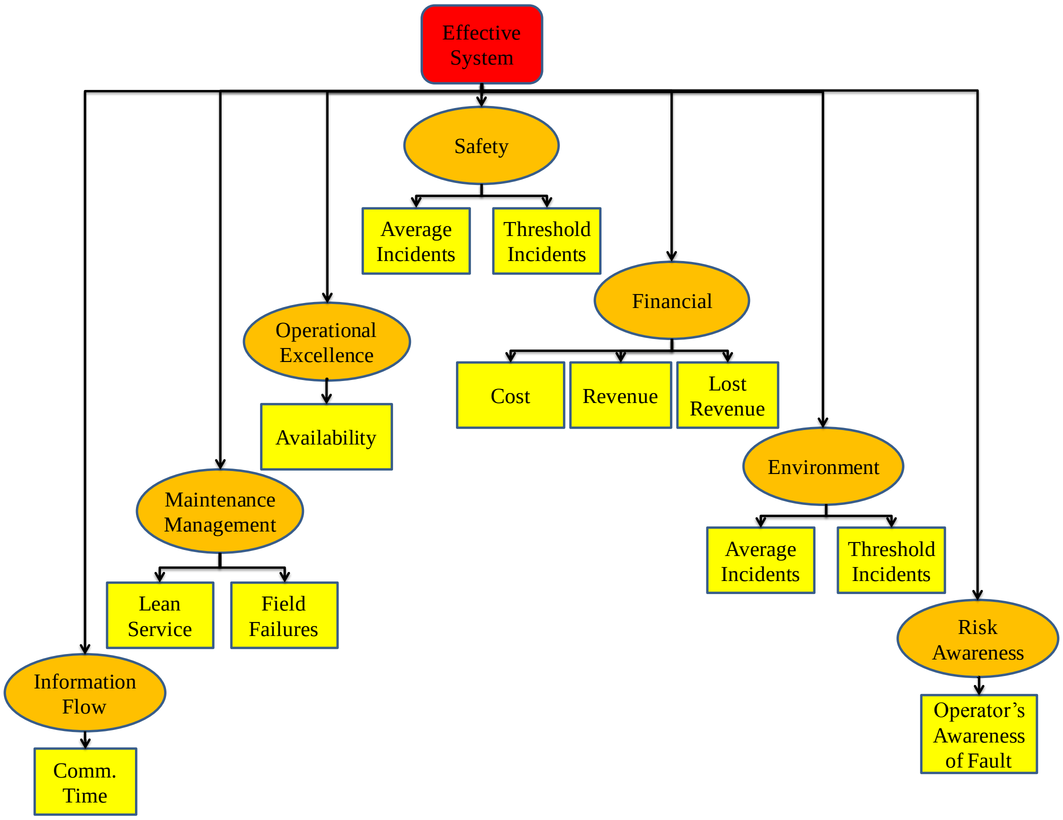


Figure 7-88. Hierarchy of first-level and second-level decision criteria used with PM-DES method

The procedure for calculating the ranking of performance criteria (first-level) and metrics (second-level) within each criterion was discussed in Subsection 7.1.5. It is assumed that the first-level criteria, i.e. the performance criteria, are subjectively ranked by the organization, with the relative importance weights outlined in the first-level criteria pair-wise matrix in Figure 7-88. The eigenvector calculation of the pair-wise comparison matrix of the first-level decision criteria and the resulting ranks are the same as for the TERT analysis, in the previous subsection, i.e.:

$$\begin{array}{c|c|}
\text{Safety} & 0.489 \\
\text{Financial} & 0.237 \\
\text{Operational Excellence} & 0.120 \\
\text{Environment} & 0.071 \\
\text{Maintenance Management} & 0.037 \\
\text{Risk Awareness} & 0.025 \\
\text{Information Flow} & 0.021
\end{array}$$

Similar to the AHP based on the TERT calculations, it is assumed that the second-level criteria rankings are also roughly estimated based on their importance to the organization. Relative weights of pair-wise comparisons are based on the organization's objective for the system, and emphasize the desire to decrease field incidents associated with safety and environmental incidents, overall decrease in cost, increase in revenue, and increase in machine availability for production. Based on this desire, the pair-wise comparisons of revenue, revenue losses and overall operations costs are described below.

It is assumed that the case organization rates the overall revenue and revenue loss to both be of equal importance with respect to each other, and both strongly (a weight of 5) more important than the overall cost, resulting in the pair-wise comparison matrix of the second-level decision criteria for the "financial" first-level criteria:

$$\begin{array}{c|ccc|}
 & \text{Revenue} & \text{Lost Revenue} & \text{Cost} \\
\text{Revenue} & 1 & 1 & 5 \\
\text{Lost Revenue} & 1 & 1 & 5 \\
\text{Cost} & 1/5 & 1/5 & 1
\end{array}$$

Ranking matrix of the second-level decision criteria for the "financial" first-level criteria therefore is:

$$\begin{array}{c|c|}
\text{Revenue} & 0.454 \\
\text{Lost Revenue} & 0.454 \\
\text{Cost} & 0.092
\end{array}$$

It is also assumed that the organization rates the average number of incidents for both environmental and safety incidents to be of equal (a weight of 1) importance compared to the probability of incidents being higher than a certain number, the latter metric named "threshold incident" metric. This results in the pair-wise comparison matrix of the second-level decision criteria for the "environment" and "safety" first-level criteria:

$$\begin{array}{c|cc|} & \text{Average Incident} & \text{Threshold Incident} \\ \text{Average Incident} & 1 & 1 \\ \text{Threshold Incident} & 1 & 1 \end{array}$$

therefore, ranking comparison matrix of the second-level decision criteria for the "environment" and "safety" first-level criteria is then:

$$\begin{array}{c|c|} \text{Average Incident} & 0.5 \\ \text{Threshold Incident} & 0.5 \end{array}$$

The first-level maintenance management criterion includes two second-level criteria (metrics), the number of field failures, and the capability of the system to provide "lean service". It is assumed that the organization deems the number of field failures to be strongly more important than lean service. Pair-wise comparison matrix of the "lean service" second-level decision criterion for the "maintenance management" first-level criterion then is:

$$\begin{array}{c|cc|} & \text{Field Failures} & \text{Lean Service} \\ \text{Field Failures} & 1 & 5 \\ \text{Lean Service} & 1/5 & 1 \end{array}$$

Ranking comparison matrix of the "lean service" second-level decision criterion for the "maintenance management" first-level criterion:

$$\begin{array}{c|c|} \text{Field Failures} & 0.833 \\ \text{Lean Service} & 0.167 \end{array}$$

The global, relative ranking matrix then becomes:

Criteria	**Metrics**	**Rank**
Safety	Average Incident	0.245
	Threshold Incident	0.245
Financial	Revenue	0.107
	Revenue Loss	0.107
	Cost	0.023
Operational Excellence	Availability	0.120
Environment	Average Incident	0.035
	Threshold Incident	0.035
Maintenance Management	Field Failures	0.031
	Lean Service	0.006
Risk Awareness	Operator's Awareness	0.025
Information Flow	Comm. Time	0.021

Once the ranking of all first-level and second-level criteria are completed, for each criterion (each metric), the alternatives must be ranked, similar to the procedure in Subsection 7.1.5.

Similar to the choice selection exercise based on the TERT analysis, the one metric used for the “operational excellence” performance criterion is availability, i.e. the duration which a machine is not inactive due to failures, incidents, and service. However, instead of judgmental assessment of availability performance used in the previous section, performance of the scenarios based on the availability metric is calculated from normalized values of total operations availability for each scenario with the total availability values tabulated in Table 7-4.

With regards to the safety, financial, and environment criteria, average values for field failures and incidents as metrics, based on all the simulations, were calculated in the previous section in Tables 7-4 and 7-6. Hence the advantage of each alternative over the others based on these average values, as normalized rank vectors, can be directly calculated. For the calculations, the Weibull distribution is selected. For example the ranking matrix of alternatives with respect to “costs” is:

$$\begin{array}{c|c|}
\underline{\text{Scenarios}} & \multicolumn{1}{c}{\text{Rank}} \\
\text{Base} & 0.216 \\
\text{Existing} & 0.181 \\
\text{Off-line} & 0.229 \\
\text{Real-time} & 0.374
\end{array}$$

The maintenance management, safety, and environment first-level criteria also include “threshold field failures” and “threshold incidents” as metrics (second-level criteria), which are calculated as normalized rank vectors and provided as the rows of Table 7-8. It is assumed that the hypothetical organization has specifically defined these metrics, i.e. in Table 7-8, the first row represents the “field failure” metric, i.e. normalized number of equal or less than 10 failures on the field for each scenario. The second row represents the safety “threshold incident” metric, i.e. normalized number of equal or less than 2 safety incidents on the field for each scenario. And the third row represents the environment “threshold incident” metric, i.e. normalized number of equal or less than 3 environmental incidents on the field for each scenario.

Event Type / Scenario	Base	Existing	Offline	Real-time
Failure (≤10)	0.035	0.298	0.145	0.989
Safety (≤2)	0.627	0.722	0.679	0.942
Environment (≤3)	0.104	0.206	0.152	0.747

Table 7-8. The incident threshold metric for safety and environmental incidents defined as the normalized count of equal or less than 10 field failures, equal or less than 2 field safety incidents, and equal or less than 3 field environmental incidents.

Once the alternatives are ranked based on all of the metrics, the alternatives-criteria matrix can be completed:

	Safety (0.489)		Financial (0.237)			Operational Excellence (0.120)	Environment (0.071)		Maintenance Management (0.037)		Risk Awareness (0.025)	Information Flow (0.021)
Scenarios	Average Incident (0.500)	Threshold Incident (0.500)	Revenue (0.454)	Revenue Loss (0.454)	Cost (0.092)	Availability (1.000)	Average Incident (0.500)	Threshold Incident (0.500)	Lean Service (0.167)	Field Failures (0.833)	Operator’s Awareness (1.000)	Comm. Time (1.000)
Base	0.173	0.211	0.252	0.345	0.216	0.252	0.173	0.086	0.030	0.151	0.080	0.050
Existing	0.206	0.243	0.245	0.046	0.181	0.245	0.206	0.170	0.080	0.181	0.080	0.050
Off-line	0.190	0.229	0.251	0.212	0.229	0.251	0.190	0.126	0.270	0.166	0.080	0.190
Real-time	0.432	0.317	0.252	0.396	0.374	0.252	0.431	0.618	0.620	0.502	0.760	0.710

When the alternatives-criteria matrix is multiplied by the total criteria rank matrix, the alternatives rank matrix is obtained:

	Safety (0.489)		Financial (0.237)			Operational Excellence (0.120)	Environment (0.071)		Maintenance Management (0.037)		Risk Awareness (0.025)	Information Flow (0.021)	
Scenarios	Average Incident (0.500)	Threshold Incident (0.500)	Revenue (0.454)	Revenue Loss (0.454)	Cost (0.092)	Availability (1.000)	Average Incident (0.500)	Threshold Incident (0.500)	Lean Service (0.167)	Field Failures (0.833)	Operator’s Awareness (1.000)	Comm. Time (1.000)	Total Rank
Base	0.173	0.211	0.252	0.345	0.216	0.252	0.173	0.086	0.030	0.151	0.080	0.050	0.210
Existing	0.206	0.243	0.245	0.046	0.181	0.245	0.206	0.170	0.080	0.181	0.080	0.050	0.197
Off-line	0.190	0.229	0.251	0.212	0.229	0.251	0.190	0.126	0.270	0.166	0.080	0.190	0.211
Real-time	0.432	0.317	0.252	0.396	0.374	0.252	0.431	0.618	0.620	0.502	0.760	0.710	0.382

The final results here are obtained based on the Weibull distribution assumption for calculating tire faults. It should be noted that, when the final ranks were calculated based on the normal and uniform distribution assumptions, the “field failure” metric rankings were the same as the ones based on the Weibull assumption at least to the two decimal points shown. Therefore from the perspective of this relative comparative analysis of alternatives for system selection, the choice of fault distribution does not make a significant difference.

Similar to the calculated value ratios based on the TERT analysis in Subsection 7.1.5, the value ratios for this analysis is shown in Table 7-9. It can be seen from this table that the existing system has a slightly lower value ratio than the base scenario, with the offline system having the same value. However, when TCO is considered, similar to the results obtained from TERT calculations, the advantage of the offline system is evident. Above that, the advantages of the real-time system both in terms of value and TCO are evidently superior from this analysis.

	Value Ratio	TCO ($)	Opportunity Loss (Production Loss $M)
Base	1.00	0	0
Existing	0.94	1,040,000	78
Offline CMMIS	1.00	26,000+SC_1	7.8
Real-time CMMIS	1.82	SC_2	0

Table 7-9. The value/cost table of the alternatives

7.2 Case Model 2: Multiple Events and Event Modes

The second case model (Case Model 2) of the studied application is that of a more elaborate operation than the first case (Case Model 1). All of the scenarios analyzed for this case model are similar to the first case model, i.e.:

1. Base scenario: the machines operate until a failure or incident occurs when at that time they receive maintenance service;
2. Existing system scenario: the machine are routinely inspected for faults as part of a preventive maintenance strategy;
3. Offline CMMIS: the machines are equipped with fault detection systems, where the machine condition data is retrieved for machine health prognosis at the routine inspection intervals instead of expert inspection; and
4. Real-time CMMIS: the machines are equipped with online fault detection systems for real-time monitoring and prognostics of machine condition, replacing the routine inspection process.

The focus of the second case model is to involve scenario parameters that can be studied using the simulation method, and that are difficult to study using the analytical methods such as the transient event-risk tree method.

When the number of stochastic events increases, it becomes very difficult to analytically calculate outcomes for a complex system. The second case assumes 100 machines operating simultaneously in the operations. It is also assumed that each machine can have multiple event types and fault event modes. Two additional fault modes are assumed for the second case, i.e. machine engine and strut failures with uniform and normal failure distributions, respectively. The event distributions for this case are described below.

Similar to Case Model 1, these distributions represent the time that the machine becomes faulty, and that after the machine becomes faulty, it leads to a random failure within a specific period of time based on a uniform distribution. It is assumed that for tire, environmental, and safety faults, the associated failure or incident randomly occur within 48 hours from the time the machine becomes faulty. For strut and engine faults, a failure randomly occurs within 96 and 72 hours, respectively.

$$F_{engine}(t) = \begin{cases} 0\,, & t < 5000 \\ \dfrac{t-5000}{5000}\,, & 5000 < t \leq 10000 \\ 1\,, & t > 10000 \end{cases}$$

$$F_{strut}(t) \;=\; \int_{-\infty}^{\frac{t-6000}{1000}} \frac{1}{\sqrt{2\pi}} e^{-\frac{\tau^2}{2}}\, d\tau$$

$$F_{tire}(t) = \; 1 - \; e^{-(\frac{t-35}{5399})^{2.5}}$$

$$F_{safety}(t) = \begin{cases} \dfrac{t}{87600}\,, & t \leq 87600 \\ 1\,, & t > 87600 \end{cases}$$

$$F_{environmental}(t) = \begin{cases} \dfrac{t}{35040}\,, & t \leq 35040 \\ 1\,, & t > 35040 \end{cases}$$

Case Model 2 also involves queuing for service and resources. In real world operations, resources for servicing machines are often limited. This limitation can exist for both routine service instants, and when several machines become eventful and require service at the same time. It is assumed for the second case that the machines are serviced on a first-in-first-out (FIFO) basis, i.e., when a machine requires service, if inspectors, maintenance technicians, and inspection/maintenance tools are available, the machine receives service, otherwise it is queued until resources become available after all the other machines in the queue. The case also involves priority assignment in queuing, i.e., machines are serviced with the highest priority from left to right: field incidents, field failures, flagged for maintenance by operator, and routine service. It is assumed that if two or more machines have the same priority, they are serviced on a FIFO basis.

Except for highly deterministic and structured processes, stochastic decision making exists in operations. Decisions of different parties, such as machine operators, technicians, and managers involved in an operation affect the system and the outcome variables. Stochastic decision making is difficult to include in analytical methods of modeling complex systems. It requires, first, modeling the decision making process and then including the model in the overall system model. The second case involves a model for the machine operator's decision making. It is assumed that the operator possesses an intuitive sense (based on either his intuition or informal observations) of when an asset might become faulty, which is represented in his decision making model.

For the second case, the stochastic decision making process of an operator is simulated. The operator can decide to get inspection, get maintenance, or continue operating at any moment while his machine is operating. The operator's decision moment can be calculated from a decision moment model assigned to him. The model can be a distribution that has been calculated from his past decision making behavior. The decision action after the decision moment is to get maintenance, get inspection, or continue operating (MIC) and is modeled based on the following assumed premises (Figure 7-89):

1. The operator checks the known condition of the machine. The known condition of the machine can be determined by an inspector, maintenance technician, or a condition monitoring system;
2. The machine's known condition can be faulty or healthy. If healthy, the time that has passed from when the machine was deemed healthy is a factor for the operator's decision. The longer this time (condition label time) the less confident the operator is that the machine's true condition is still healthy. The decision outcome path depends on whether the machine is faulty, or if it's healthy and condition label time is less than 48 h, or if it's healthy and condition label time is greater than 48 h;
3. The decision outcome also depends on whether the machine is under a CMMS. This fact also affects the operator's judgement on which action to take; and
4. Finally, when all the facts are checked by the operator, his decision outcome is random with probabilities shown in Figure 7-89.

After an inspector determines and reports the known condition of a machine, or when its CMMS detects a fault, the operator must make the decision to get maintenance or continue operating based on the MC model (Figure 7-90). This decision model is similar to the MIC model previously discussed, however, it takes place after the known condition of the machine is reported to the operator, hence, it does not include decision moment modeling.

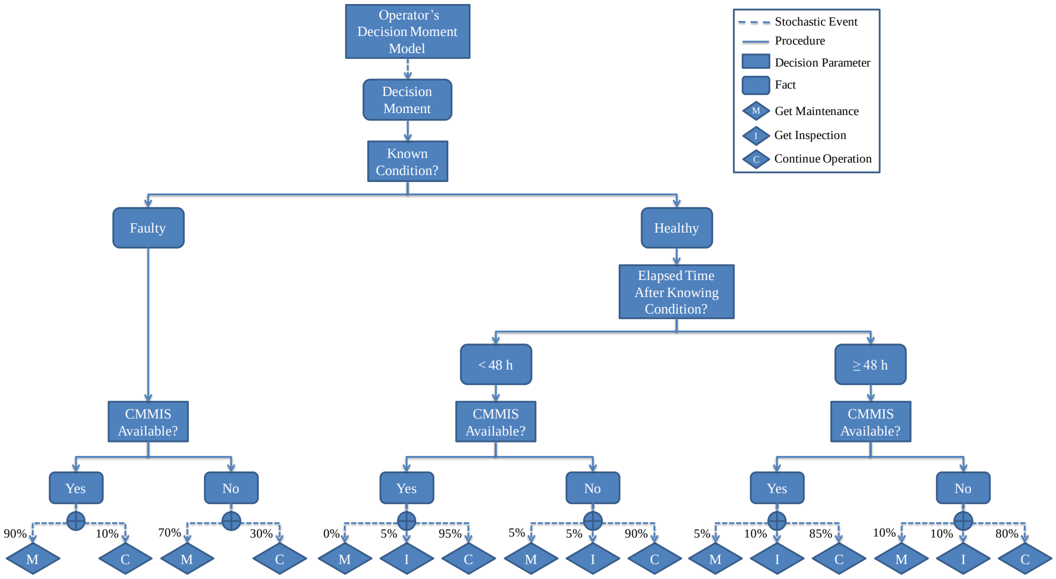


Figure 7-89. Operator's MIC decision model

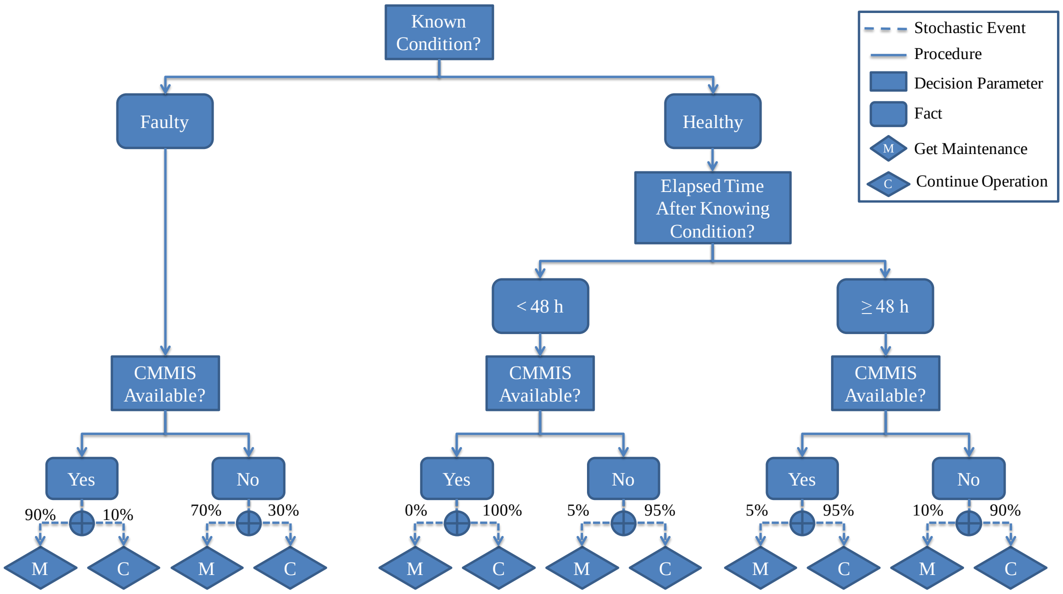


Figure 7-90. Operator's MC decision model

7.2.1 Case Model 2: Base Scenario (Run-to-Failure)

Similar to Case Model 1, it is assumed that the machines haul oil sands ore at a value rate of $30,000/h. The machines may fail or cause an incident while operating, which will result in penalty and transfer costs and downtime in addition to the standard maintenance cost associated with the failure or incident mode.

Similar to the base scenario of the Case Model 1, it is assumed that the machines operate in the field according to the operations schedule where no CMMIS for machines exist. The machines operate indefinitely until they fail or cause an incident, after which they are forwarded for maintenance. It is further assumed that when a machine fails or causes an incident on the field, the operator contacts the base via a radio phone to report the event, which takes 15 minutes. The machine is then taken off the field for maintenance where it requires to be queued until maintenance technicians and resources become available.

The maintenance costs and downtimes associated with each fault event used for the simulations are based on Table 7-10, which are related to when a machine is serviced at a designated service location. If a machine fails or causes an incident on the field, it is assumed that additional costs associated with responding to failures and incidents, including the cost and time to transfer to the service location exist. It is assumed that if a machine fails or causes an incident on the field, the extra downtime is 4 h. If a machine fails, the field response cost is $5,000. If a machine causes an incident, the response cost for safety and environmental incidents are $1,000,000 and $100,000, respectively. Since the severity and urgency of field incidents are typically higher than failures, such incidents are regarded as high priority events, hence the response procedure to incidents and repair of the machines are immediately performed.

Case Model 2 involves operator decision making. At any given time, the operator can request inspection to check the machine for faults or to request maintenance based on his decision moment model described in the previous section. The machine processes for the base scenario are shown in Figure 7-91 and Figure 7-92. The operator’s decision model is based on a uniform distribution of one decision in three days (72 hours of operation).

It is assumed that if the operator requests inspection, the machine is queued for inspection. Once resources become available, the inspector determines the condition of the machine based on the following conditional probabilities (in detecting or missing a fault given that the machine is truly faulty):

$$P(inspector\ detects\ fault \mid machine\ is\ faulty) = \frac{9}{10}$$

$$P(inspector\ misses\ fault \mid machine\ is\ faulty) = \frac{1}{10}$$

$$P(inspector\ deems\ healthy \mid machine\ is\ healthy) = 1$$

$$P(inspector\ deems\ faulty \mid machine\ is\ healthy) = 0$$

The operator then makes the decision to continue operating the machine or request maintenance based on his MC decision model described in the previous section.

It is assumed that the cost for each inspection is \$500 and takes 2 h downtime, and the base cost for requested maintenance is \$1000 and 5 h downtime. It is also assumed that maintenance technician assesses the condition of the machines during a maintenance job with the same conditionals as an inspector.

For Case Model 2, it is also assumed that the maintenance technicians also have the ability to diagnose any existing machine faults while servicing or repairing a machine, based on the same fault detection probability conditionals as the inspectors.

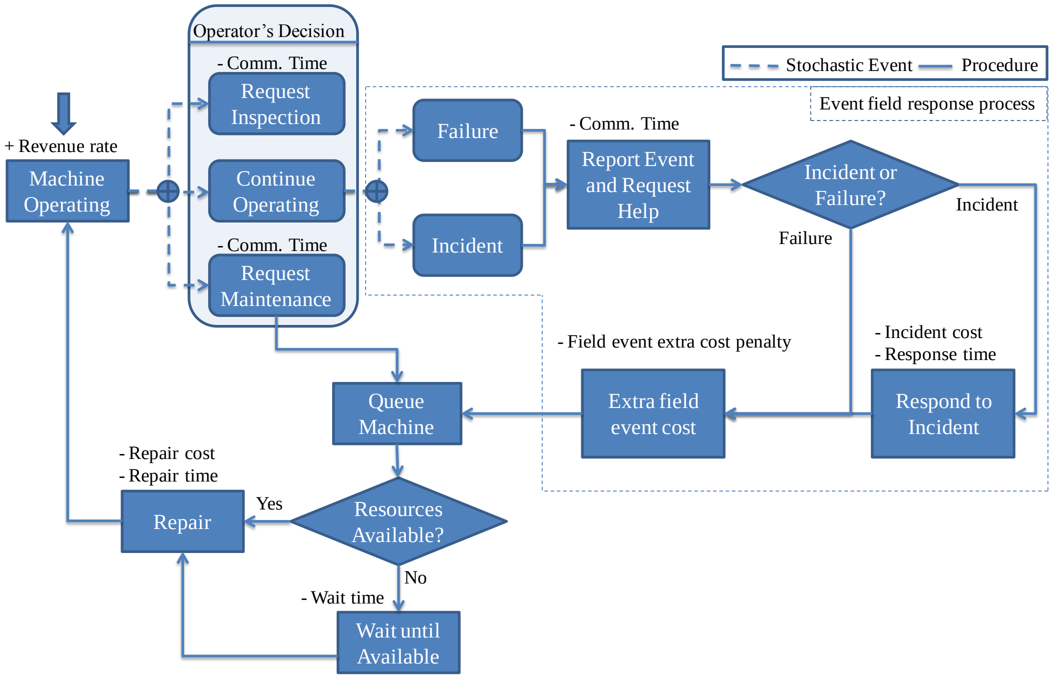


Figure 7-91. Machine operation process for the base scenario

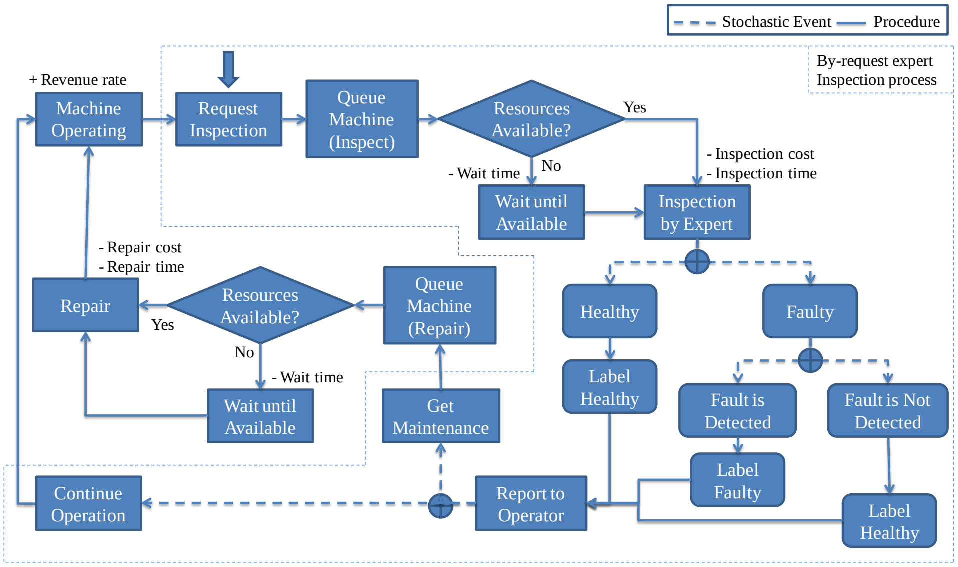


Figure 7-92. Machine inspection diagram for the base scenario

Event Type	Distribution	Maintenance Cost ($)	Maintenance Downtime (h)
Tire failure	Weibull	1000	5
Strut failure	Normal	5000	8
Engine failure	Uniform	20000	16
Safety incident	Uniform	5000	5
Environmental incident	Uniform	5000	5

Table 7-10. Assumed parameters for the "base" scenario.

7.2.2 Case Model 2: Existing System (Routine Major Prevention Service)

Similar to the existing scenario of Case Model 1, as the existing operations state of the case organization, machines are routinely inspected for faults at regular intervals (Figure 7-93). It is assumed that the machines are inspected weekly with the total number of machines spread over the inspection period so that at each inspection job, the number of machines queued is minimized. Each inspection job is assumed to have a duration of 5 h. It is assumed that over a period of one week, 3 machines enter an inspection job so that all the 100 machines can be inspected with an even spread over a week. It is also assumed that every inspection procedure costs $500 and 2 h to complete regardless of the machine condition and faults. The inspection is to determine whether a machine is faulty or healthy, which is then reported to the driver for him to decide whether to continue operations, or request maintenance. If maintenance is requested, the machine is queued to receive service once resources become available, which then machines are restored to their original condition as when they started operating.

Similar to the first case (Case Model 1), it is assumed that once a machine becomes faulty, the fault progresses towards failure or incident in a certain amount of time (mentioned in Section 7.2), hence if a fault is detected during inspection within this time period, the machine's failure on the field will be prevented, otherwise, a fault will occur and result in a failure or incident without the machine being inspected. The accuracy of the inspector's examination outcome is based on the conditional probabilities described in the previous section.

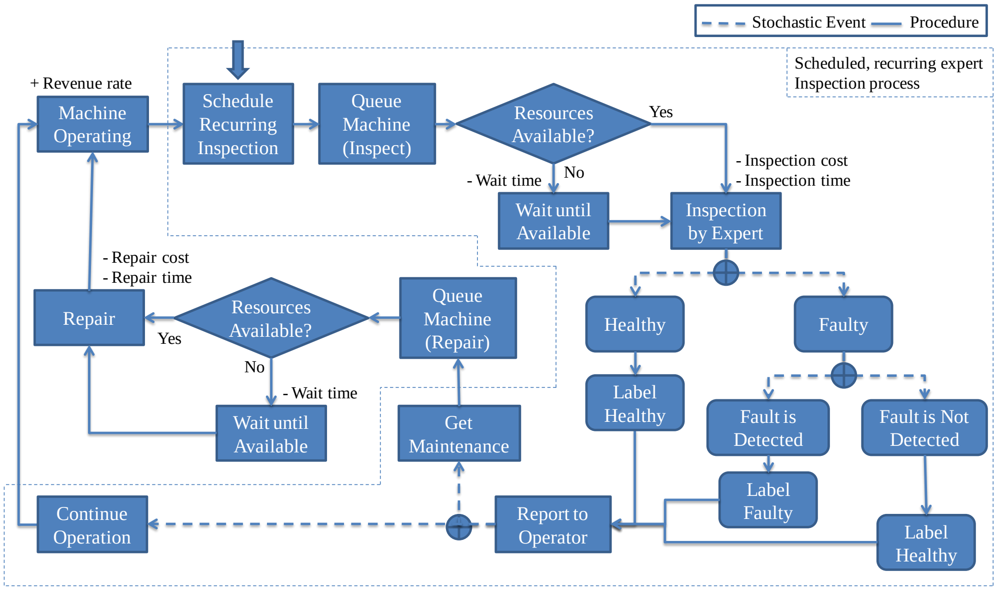


Figure 7-93. Machine operation process for the existing system scenario

7.2.3 Case Model 2: Offline System (Offline CMMIS with Routine Minor Prevention Service)

Similar to the Case Model 1, it is assumed that the machines in the offline system scenario are equipped with an on-board, non-networked, CMS. Instead of visual inspection by experts, the CMMIS's fault detection application is used by a technician to determine machine condition using machine condition data that has been manually downloaded from machines and loaded into the CMMIS fault detection application (Figure 7-94). It is assumed that this procedure costs \$50 and 0.5 h for each machine, much lower compared to complete inspection by an expert. Also similar to the existing system scenario, if a fault is not detected during the assumed two day period that takes for it to progress into a failure, the machine may become faulty and fail in the field without reaching its scheduled inspection time. One difference between this scenario and the base and existing scenarios is the communication time between the operator and the base when a machine fails or causes an incident in the field. It is assumed that when an event occurs in the field, the CMMIS alerts the base for the machine to receive an appropriate response, eliminating the need for the operator to call the base, saving 0.25 h in communication time.

Similar to the Case Model 1, it is assumed that the application has a far lower accuracy in correctly determining the condition of a machine when it is truly faulty:

$$P(application\ detects\ fault \mid machine\ is\ faulty) = \frac{6}{10}$$

$$P(application\ misses\ fault \mid machine\ is\ faulty) = \frac{4}{10}$$

$$P(application\ deems\ healthy \mid machine\ is\ healthy) = 1$$

$$P(application\ deems\ faulty \mid machine\ is\ healthy) = 0$$

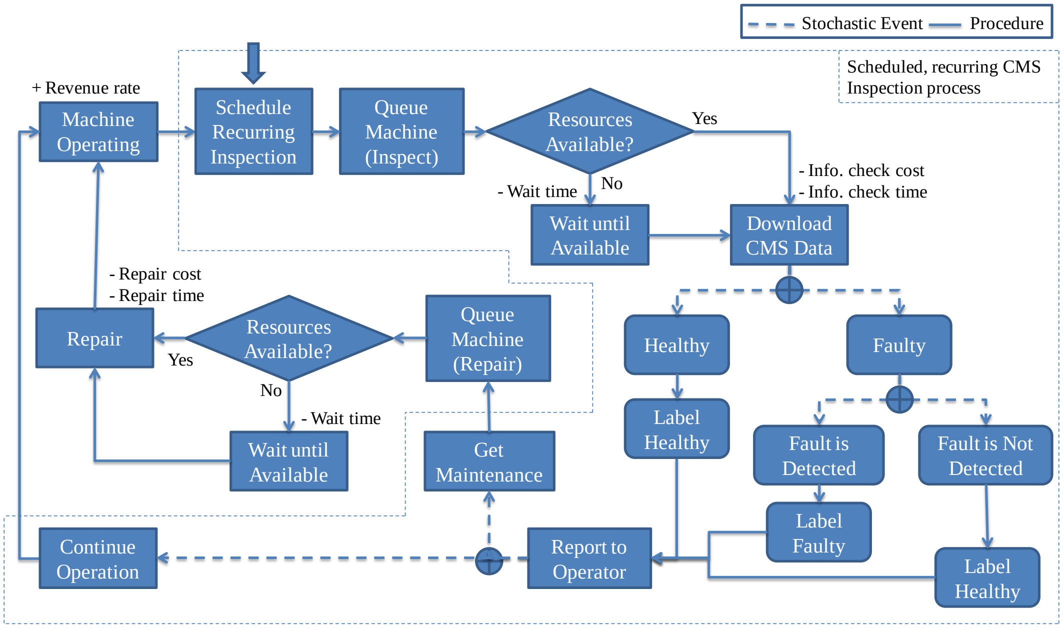


Figure 7-94. Machine operation process for the offline system scenario

7.2.4 Case Model 2: Real-Time CMMIS (With No Routine Prevention Service)

In this scenario the operation is equipped with the real-time CMMIS alternative for real-time condition monitoring of machines, and management of maintenance activities (Figure 7-95).

The conditional probabilities associated with detection errors when the machine is truly faulty are assumed to be equal to that of the offline CMMIS scenario, however, the conditional probabilities when the true condition of the machine is healthy is assumed to be less accurate, i.e.:

$$P(application\ detects\ fault \mid machine\ is\ faulty) = \frac{6}{10}$$

$$P(application\ misses\ fault \mid machine\ is\ faulty) = \frac{4}{10}$$

$$P(application\ deems\ healthy \mid machine\ is\ healthy) = \frac{7}{10}$$

$$P(application\ deems\ faulty \mid machine\ is\ healthy) = \frac{3}{10}$$

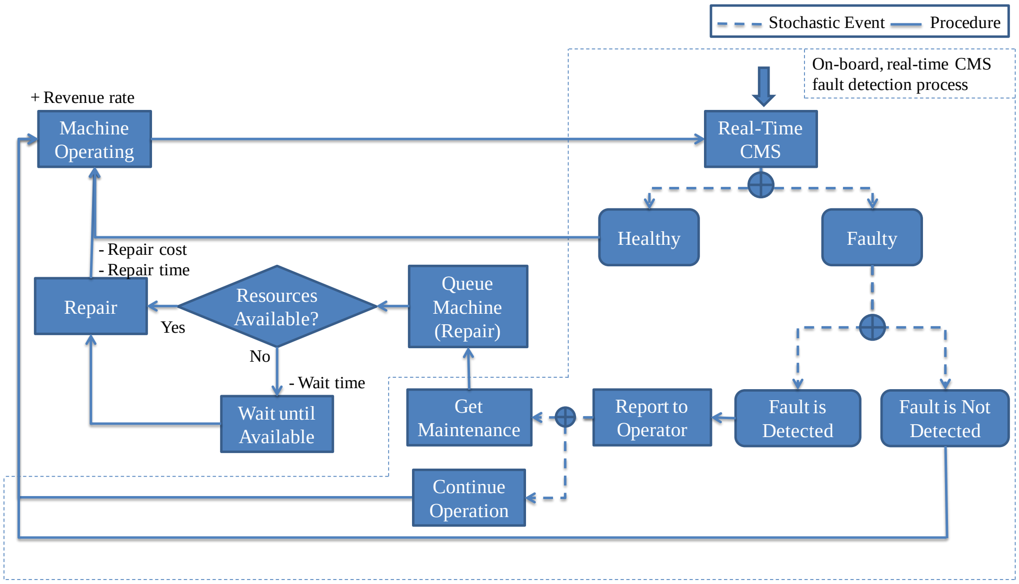


Figure 7-95. Machine operation process for the real-time system scenario

7.2.5 Case Model 2 Comparative Value Analysis and Choice Selection

7.2.5.1 Analysis of Output Metrics Distributions and Averages

Histogram results of the four simulated scenarios of Case Model 2 are shown in Figure 7-97 to Figure 7-102. As part of the value analysis and choice selection phase of the framework, these results are compared.

Similar to Case Model 1, average values of the output metrics can be used that are calculated from all the simulations. These values are shown in Tables 7-10 and 7-12, and illustrated by bar charts in Figure 7-103 to Figure 7-107.

As was with Model 1, field events are generally lower for the existing system as compared to the base scenario, however, the operation incurs a cost of $500 and $60,000 in revenue loss per machine per week due to scheduled inspection downtime.

The overall operations costs decreases for the offline system scenario, as well as the existing system scenario, when compared to the base system, but a significant increase in revenue loss is observed, albeit much lower revenue loss than the existing system scenario. This is expected because of the assumption of lower fault detection accuracy of the onboard fault detection system as compared to the expert's. As was with Model 1, the considerably lower cost of inspection ($50) and revenue loss ($15,000) per machine per week and the much shorter inspection time should also be taken into account when comparing system values. And the main advantage of the offline system over the existing one is that it significantly increases availability, and as a result, overall revenue.

For Case Model 2 also, based on all metrics, the real-time system is superior compared to all of the other scenarios, with much lower system cost. The real-time system provides slightly higher availability than the base scenario and significantly higher than the existing and offline system scenarios, resulting in higher total operations revenue. The real-time system results in significantly lower operations costs as compared to the other scenarios because fewer failures and incidents occur in the field, and because the high cost of routine, periodical service for preventive maintenance is eliminated.

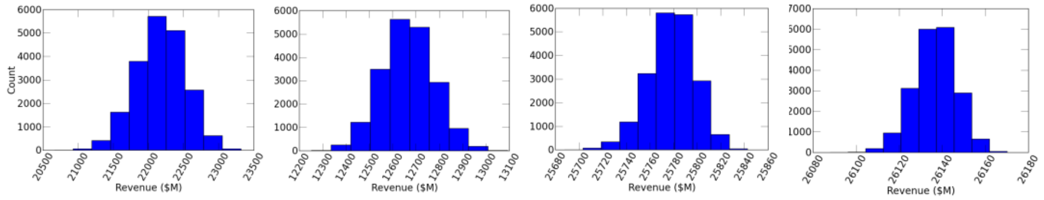


Figure 7-96. Histograms of revenue outcomes for the base, existing, offline, and real-time system simulations (left to right)

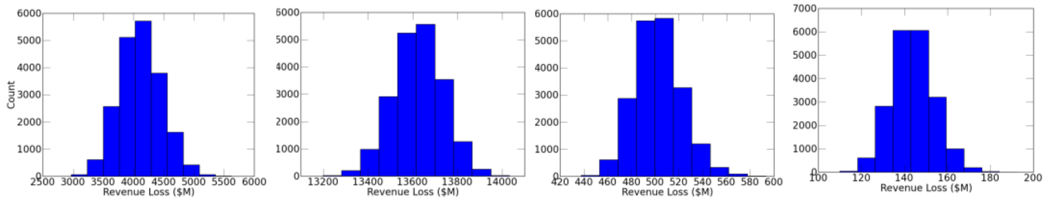


Figure 7-97. Histograms of lost revenue outcomes for the base, existing, offline, and real-time system simulations (left to right)

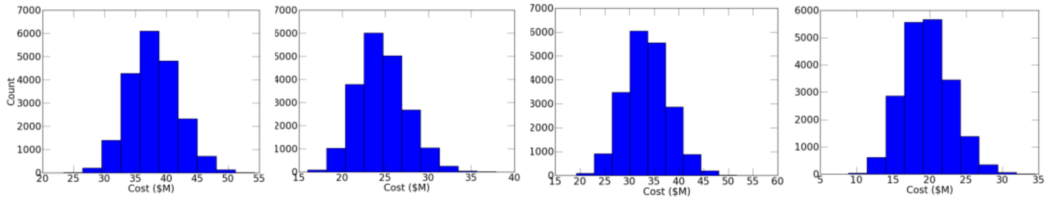


Figure 7-98. Histograms of cost outcomes for the base, existing, offline, and real-time system simulations (left to right)

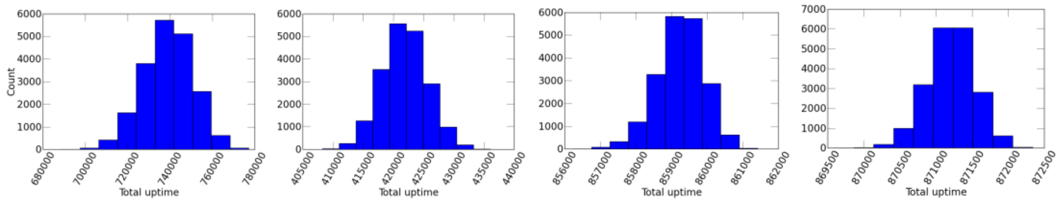


Figure 7-99. Histograms of total availability outcomes for the base, existing, offline, and real-time system simulations (left to right)

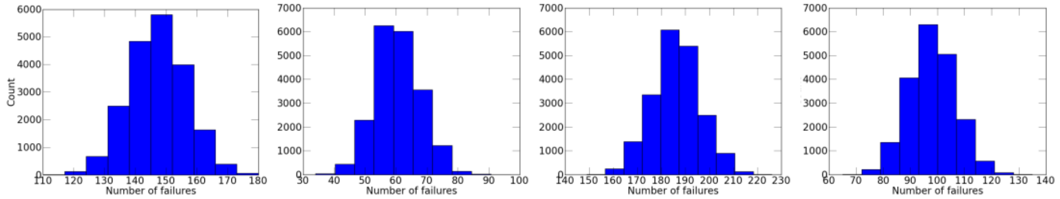


Figure 7-100. Histograms of field failure outcomes for the base, existing, offline, and real-time system simulations (left to right)

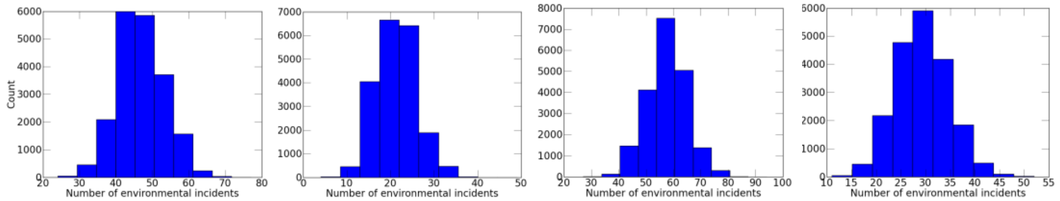


Figure 7-101. Histograms of field environmental incident outcomes for the base, existing, offline, and real-time system simulations (left to right)

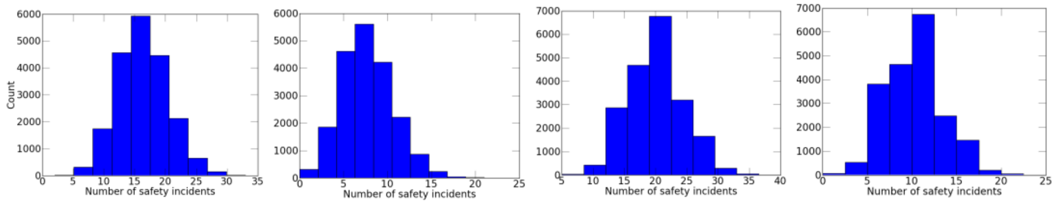


Figure 7-102. Histograms of field safety incident outcomes for the base, existing, offline, and real-time system simulations (left to right)

Scenario	Revenue ($)	Lost Revenue ($)	Cost ($)	Total Availability (h)
Base	22,173,902,530	4,109,934,001	37,971,210	739,002
Existing	12,663,966,180	13,623,834,967	24,590,667	421,872
Offline	25,779,507,531	501,000,331	32,763,244	859,300
Real-time	26,136,503,882	143,902,789	19,636,608	871,203

Table 7-11. Average values of all simulations of revenue, lost revenue, cost, total availability, and per machine average availability values for the four simulated scenarios of Case Model 2

Scenario	Detected Faults	Failures	Safety Incidents	Environmental Incidents
Base	48.6	146.7	16.3	46.7
Existing	59.9	60.5	7.8	21.0
Offline	87.0	176.8	19.0	55.6
Real-time	181.0	97.6	10.0	29.3

Table 7-12. Average values of all simulations of detected faults, field failures, field safety incidents, and field environmental incident values for the four simulated scenarios of Case Model 2

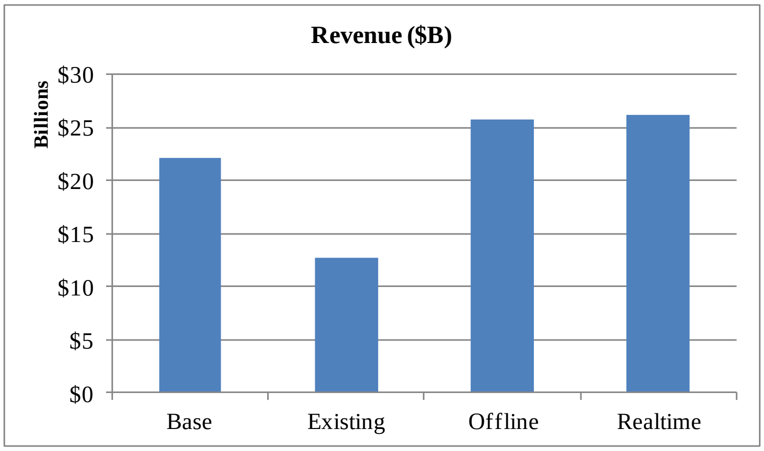


Figure 7-103. Output average revenue values of all simulations for the four simulated scenarios of Case Model 2

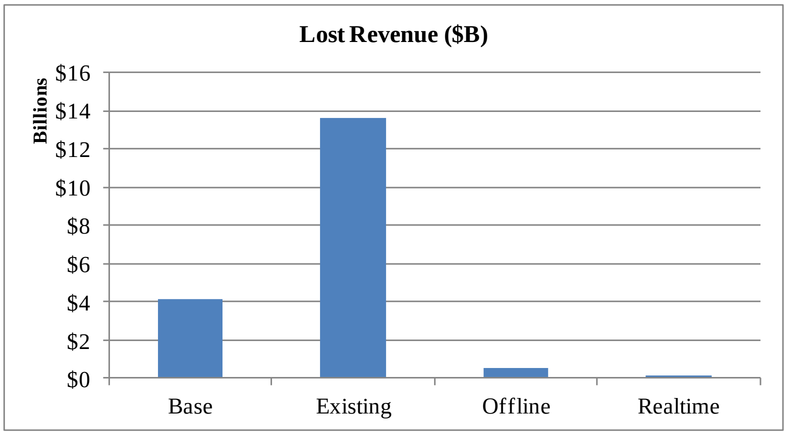


Figure 7-104. Output average lost revenue values of all simulations for the four simulated scenarios of Case Model 2

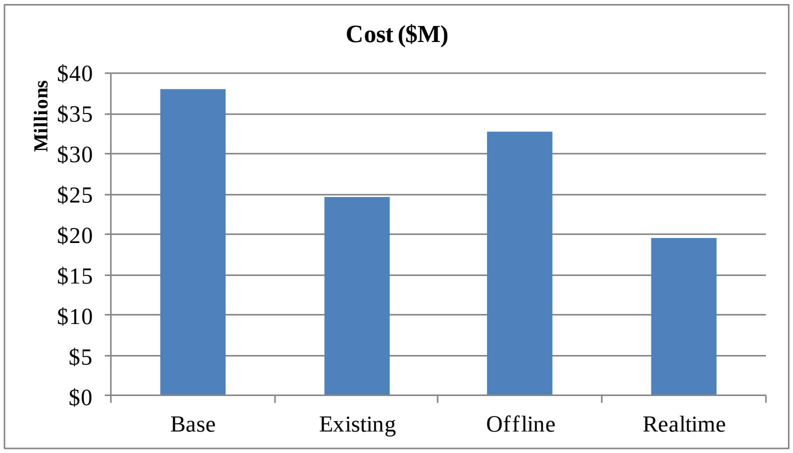


Figure 7-105. Output average cost values of all simulations for the four simulated scenarios of Case Model 2

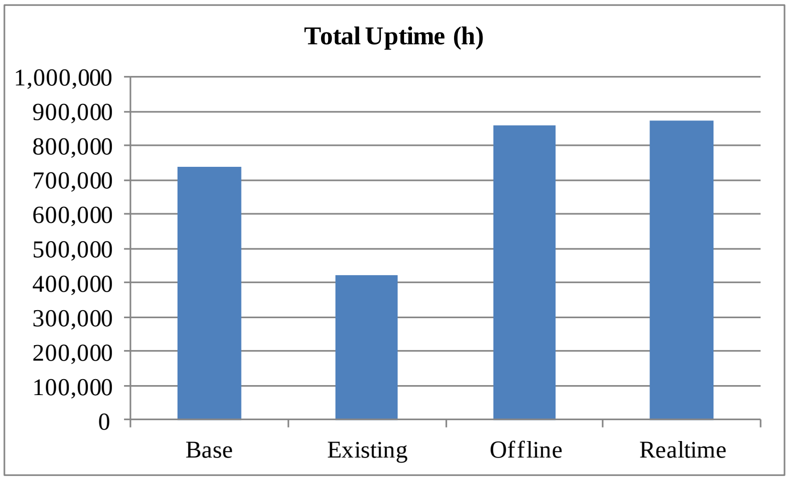


Figure 7-106. Output average total availability (uptime) values of all simulations for the four simulated scenarios of Case Model 2

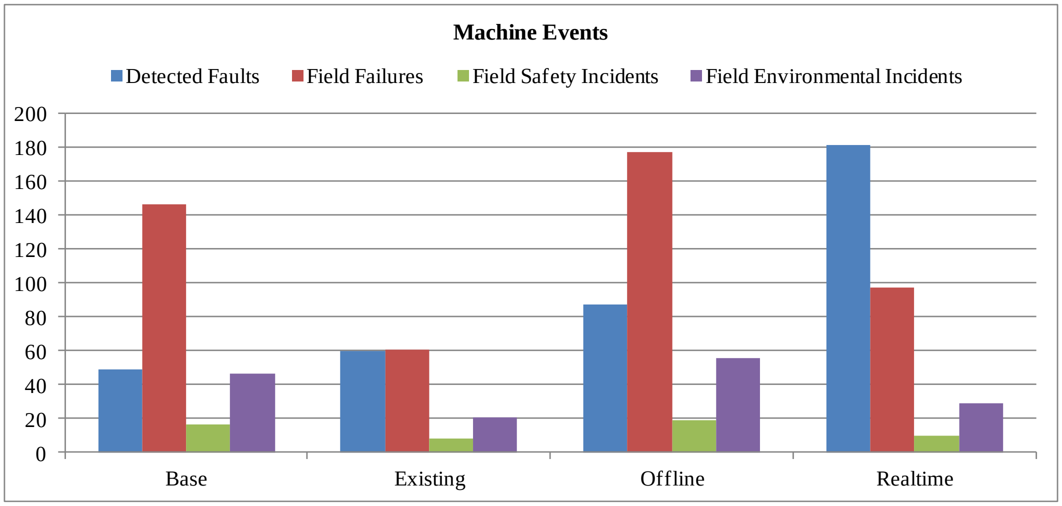


Figure 7-107. Output average values of detected faults, field failures, field safety incidents, field environmental incidents of all simulations for the four simulated scenarios of Case Model 2

7.2.5.2 AHP Analysis for System Choice Selection

The choice selection exercise of Case Model 1 in Subsection 7.1.67.1 can also be applied for Case Model 2, yielding similar results and findings.

Similar to Case Model 1, the alternatives-criteria matrix is multiplied by the total criteria rank matrix, the alternatives rank matrix is obtained (based on the Weibull distribution for tire faults):

	Safety (0.489)	Financial (0.237)			Operational Excellence (0.120)	Environment (0.071)	Maintenance Management (0.037)		Risk Awareness (0.025)	Information Flow (0.021)	
Scenarios	Average Incident (1.000)	Revenue (0.454)	Revenue Loss (0.454)	Cost (0.092)	Availability (1.000)	Average Incident (1.000)	Lean Service (0.167)	Field Failures (0.833)	Operator's Awareness (1.000)	Comm. Time (1.000)	Total Rank
Base	0.179	0.256	0.026	0.177	0.252	0.177	0.030	0.174	0.080	0.050	0.173
Existing	0.374	0.146	0.008	0.274	0.245	0.393	0.080	0.421	0.080	0.050	0.279
Off-line	0.154	0.297	0.216	0.206	0.251	0.149	0.270	0.144	0.080	0.190	0.188
Real-time	0.293	0.301	0.750	0.343	0.252	0.282	0.620	0.261	0.760	0.710	0.360

Also similar to the calculated value ratios in Subsection 7.1.6 for Case Model 1, the value ratios for the second model are shown in Table 7-13. It can be seen from this table that for this case, the existing system has a higher value than both the base scenario and the offline system in terms of their value ratios. Therefore, if the organization makes new system implementation decisions first based on system value, then it will not prefer the offline system to the existing system. However, if the organization also considers costs for system implementation decision making in equal regards to value, then since the TCO of the offline system is significantly lower than the existing system, it must decide whether it can afford losing % 34in system value to implement a lower cost system. The offline system itself shows similar value to the base scenario, however, when the TCO for systems are considered, the advantage of the offline system is evident. Above that, the advantages of the real-time system both in terms of value and TCO are evident, as was the case for Model 1.

	Value Ratio	TCO ($)	Opportunity Loss (Production Loss $M)
Base	1.00	0	0
Existing	1.63	10,400,000	780
Offline CMMIS	1.08	260,000+SC_1	78
Real-time CMMIS	2.08	SC_2	0

Table 7-13. The value/cost table of the alternatives

7.3 Other Considerations

7.3.1 Performance Visualization

When performing the comparative value analysis, performance of the system alternatives was evaluated based on the selected performance criteria and metrics using risk graphs in the case TERT analysis, or the distribution charts and values for specific output variables in the case of PM-DES analysis. Although these graphs, charts and values were sufficient for the performed analysis methods, it can be useful to visualize the relative performance of the alternative systems for human decision makers. Following the definition of the framework for an effective system, a visualization concept that shows how the systems are fit-for-purpose, performance-based, and holistic can be used to demonstrate the performance level of the systems. An example of such a concept is shown below in Figure 7-108.

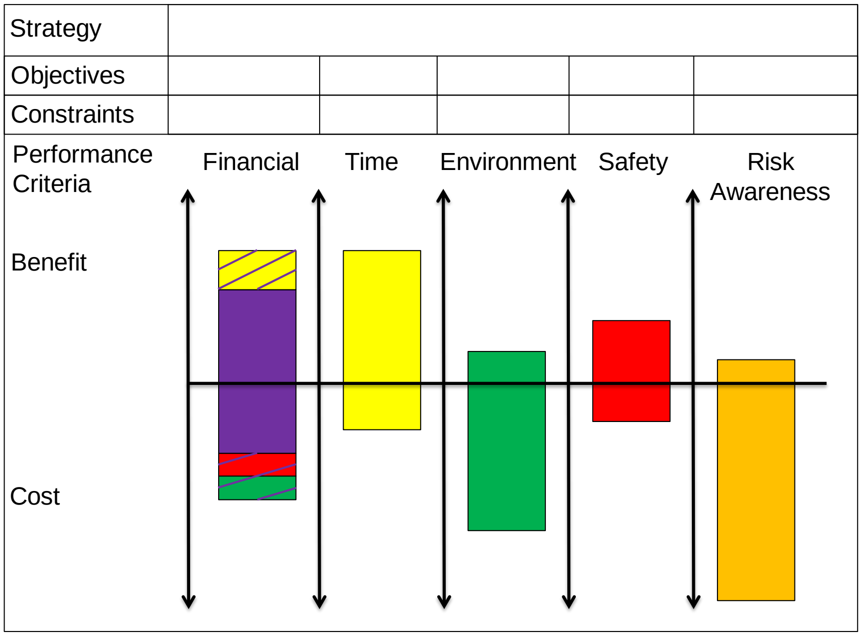


Figure 7-108. Example of a chart for visualizing the results of system comparative analysis

This example of a chart attempts to visualize the results of system comparative analysis with respect to a candidate system being fit-for-purpose, performance based, and holistic, as the three main aspects of an effective system. Specifically for this visualization paradigm, these aspects are included as:

1. fit-for-purpose: a summary of the strategy, objectives, and constraints deduced from the framework are required at the top to the attention of a decision maker;
2. holistic: the chart represents various performance criteria (specific metrics must be included in their respective performance criterion column); and
3. performance based: both the benefit and costs associated with the system related to each performance criterion is displayed.

The color scheme is to distinguish various performance criteria. If any criterion can be quantified in terms of another, then it can be illustrated at the section of that criterion with mixed colors, e.g. if operational savings in time can be measured in terms of monetary figures, them the value of the time saved can be indicated as the purple hatched yellow section of the financial criteria bar.

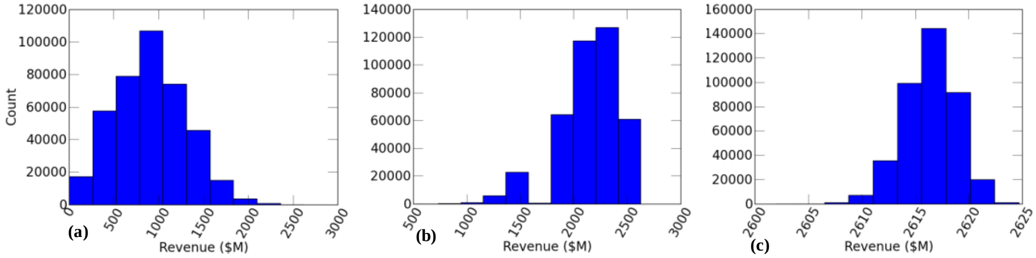
Such visualization concepts can be especially helpful for fast decision making and system evaluation especially if it is a feature of the CMMIS software application and that can be shown on mobile computer devices such as tablets and smart phones.

7.3.2 Transient Risk Progression Calculation for the PM-DES Method

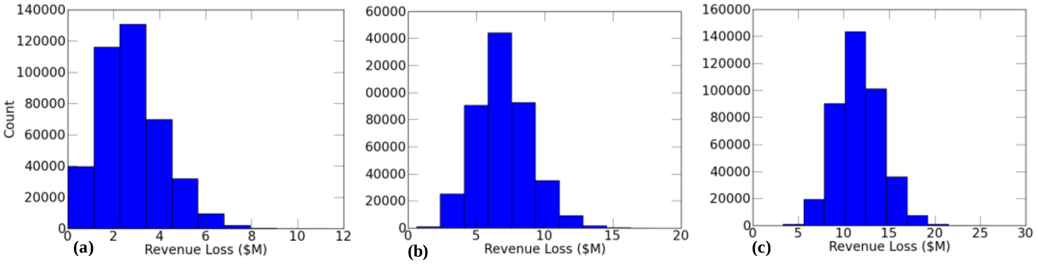
The simulation results shown in relation to the PM-DES method includes the distribution of outcomes at the end of the operation time, i.e. at the end of the total operating time of the machines. In this work, this was sufficient for the purpose of demonstrating the application of the framework to the case, and selecting the most suitable system alternative. These distributions can be used to calculate risk values for each outcome, e.g. similar to calculating the “threshold incidents” and “threshold failures” that was demonstrated in the previous sections. However, it may also be desirable to study the alternative systems based on the progression of risk throughout the total time of the operations at any given point in time.

Transient progression of risk can be visualized by plotting the distributions of an outcome of interest at specific time intervals. Once a certain outcome risk value based on a given distribution is defined, e.g. “threshold failure” or “threshold incidents” used in the previous chapter, the time-based risk values, which can be quantitatively calculated from the simulations, can be plotted as well and used for comparative analysis for more concrete evaluation.

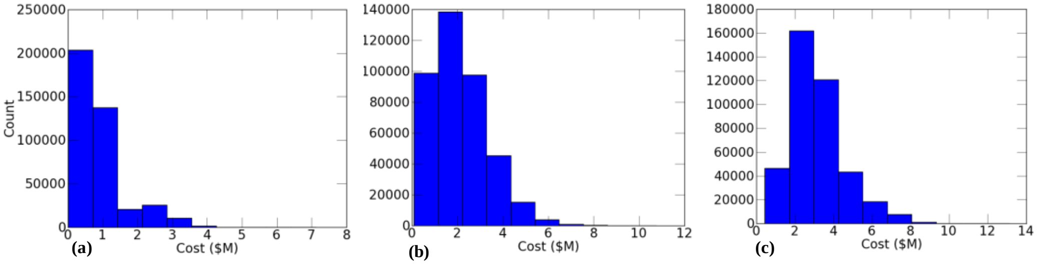
Transient risk plots and values may be very useful for system selection or other decision making reasons related to the operations, as they show the change of risk in time related to some outcome of interest. For example, Figures 5-67, 5-68, and 5-69 show the output histograms for total revenue, total cost, and average availability, respectively. Each plot shows time snapshots of the histograms at 2920 h, 5840 h, and 8760 h of operations. The simulation averages of total revenue, total cost, and average availability outputs over time are also shown in Figures 5-70, 5-71, and 5-72., which show how these values change in time which can be expressed in terms of risk.



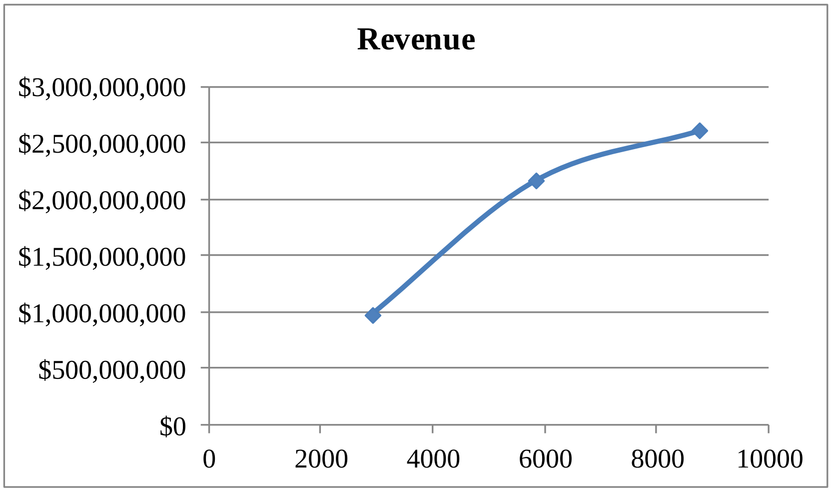
7-109. Histogram of revenue outcomes for the real-time system simulations at three points in time, (a) 2920 h, (b) 5840, and (c) 8760



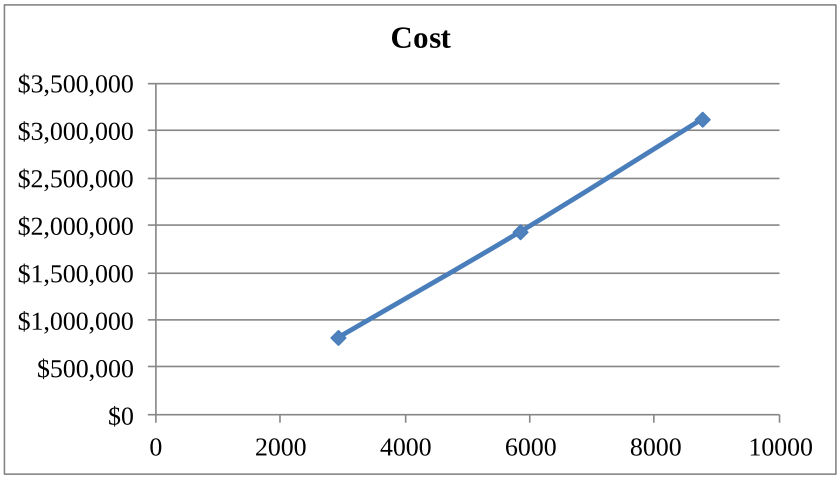
7-110. Histogram of cost outcomes for the real-time system simulations at three points in time, (a) 2920 h, (b) 5840, and (c) 8760



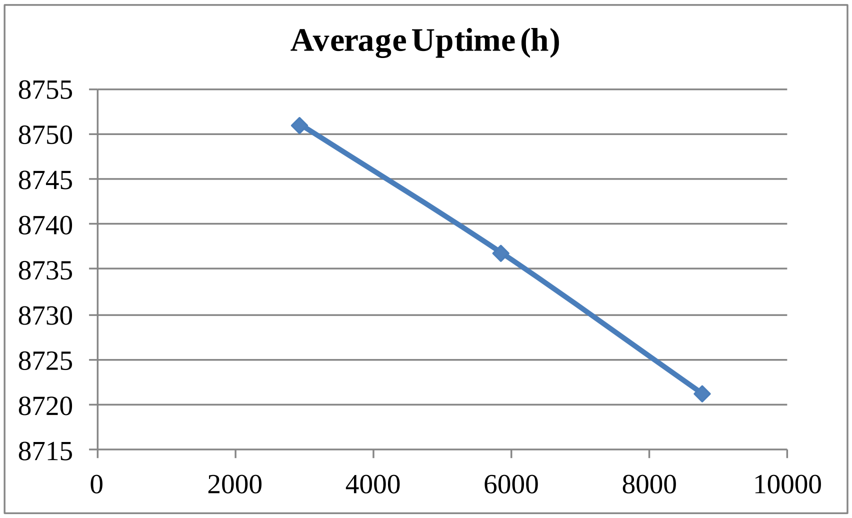
7-111. Histogram of average availability outcomes for the real-time system simulations at three points in time, (a) 2920 h, (b) 5840, (c) 8760



7-112. Simulation average of revenue outcomes for the real-time system simulations at three points in time



7-113. Simulation average of cost outcomes for the real-time system simulations at three points in time



7-114. Simulation average of average availability (uptime) outcomes for the real-time system simulations at three points in time

8. Expert Verification

To increase confidence in the framework verification process using the hypothetical case, it should be verified that the case description represents, at a high-level, a real industrial operation (Shannon, 1975; Knepell and Arangno, 1993; Robinson, 2004; Murray-Smith, 2012). The methods for evaluating system performance, i.e. the analytical risk assessment and the simulation methods should also be verified that they are based on models that represent the case operations with the objective of achieving meaningful comparative analysis. This includes verification of the consistency and plausibility of the values that were assumed for the parameters involved in the models according to real operations.

For this purpose, verification of the case description, models, and the assumed parameter values are achieved by subjecting them to the review of a subject matter expert that is acquainted with the type of operations which the hypothetical case is based on (Carroll, 2013). At the time when the expert review work was performed, the expert held the position of maintenance manager of mobile mine operations at a large Canadian oil sands production company. He held a Master of Science degree in engineering, and had adequate technical knowledge to comprehend the technical methods used in this work such as the simulation and risk analysis evaluation methods, and the AHP decision making method. He also had several years of operational experience related to the engineering and business topics and challenges of mobile mining machinery maintenance.

The expert was provided the content of Chapters 2, 4, 5, 6, and 7 of this thesis. He was asked to provide his opinion on the assumptions and parameters used for the organization’s case description, the case models, and the evaluation methods. His opinion was also queried about the application and results of the evaluation and decision making methods. He was requested to provide his opinion based on structured responses with four options for each topic of query.

As a result, in summary, the expert confirmed that the case description of the operations represents the real industry operations of the considered hypothetical organization. Moreover, it was confirmed that the values assumed for the used parameters in the models represent real operations at the intended approximate level (Carroll, 2013). The expert's detailed responses are provided in the following subsections.

8.1 Expert Review Related to the Case Description and Case Models

Related to description of the case operations, the expert was asked to frame his opinion under one of the following options, i.e. the case description:

1. describes, with close approximation, part of the operations of my organization or other organizations that I know of;
2. describes, with reasonable approximation, part of the operations of my organization or other organizations that I know of;
3. describes what may be a part of the operations of some organization in my industry; and
4. there are aspects of the case or approximations that are inconceivable to represent a part of the operations of some organization in my industry.

For which the expert responded that the case describes, with reasonable approximation, part of the operations of his organization or other organization's that he knew of.

Related to the two case models based on the case description, the expert was also asked to frame his response based on the same options mentioned above for the case description.

For Case Model 1, he responded that the high-level description of the model, relevant to this study, describes with reasonable approximation, part of the operations of his organization or other organization's that he knew of.

And for Case Model 2, he responded that the high-level description of the model, relevant to this study, describes with close approximation, part of the operations of his organization or other organization's that he knew of.

8.2 Expert Review Related to the Existing System of the Case and the Hypothetically Designed Alternative Systems

The expert was asked to provide his opinion on the existing system description based on the case, which was used in alternative system evaluations. He was asked to respond based the following option formats, i.e. the system description:

1. describes, with close approximation, the existing system of my organization or other organizations that I know of;
2. describes, with reasonable approximation, the existing system of my organization or other organizations that I know of;
3. describes what may be the existing system of some organization in my industry; and
4. there are aspects of the case or approximations that are inconceivable to represent the existing system of some organization in my industry.

The expert responded that the existing system description of the existing system describes, with reasonable approximation, the existing system of his organization or other organizations that he knew of.

The expert was also asked to provide his opinion on the hypothetical offline CMMIS and real-time CMMIS alternatives based on the following option formats:

1. the system design may be used in some part of the operations of my organization, other organizations that I know of, or some organization in my industry;
2. the system design may be used, with some modification, in some part of the operations of my organization, other organizations that I know of, or some organization in my industry; and
3. the system design cannot be used, in no part of the operations of my organization, other organizations that I know of, or any organization in my industry.

He responded that both the offline and real-time CMMIS may be used in some part of the operations of his organization, other organizations that he knew of, or some organization in his industry.

8.3 Expert Review Related to the TERT Evaluation Method

The expert's opinion was queried regarding the metrics selected to be used with the TERT evaluation method. He was asked to respond based on the format below, that the metrics:

1. are all relevant for system performance measurement from the perspective of my organization or other organizations that I know of;
2. are mostly relevant for system performance measurement from the perspective of my organization or other organizations that I know of;
3. may be relevant for system performance measurement from the perspective of some organization in my industry; and
4. are all irrelevant to any organization in my industry.

The expert responded that the metrics selected to be used with the TERT evaluation method are mostly relevant for system performance measurement from the perspective of his organization or other organizations that he knew of.

Furthermore, for each "base", "existing", "offline CMMIS", and "real-time CMMIS" alternative systems that were evaluated using the TERT method based on Case Model 1, the expert was asked to provide his response based on the following format:

A. The high-level description of the alternative systems based on Case Model 1 and the values assumed for the parameters, relevant to the study:
    1. describe, with close approximation, part of the operations of my organization or other organizations that I know of;
    2. describe, with reasonable approximation, part of the operations of my organization or other organizations that I know of;
    3. describe what may be a part of the operations of some organization in my industry;
    4. there are aspects of the case description, approximations, or assumptions that are inconceivable to be applicable to any organization in my industry.

B. The analysis results using the risk assessment (TERT) method were:
    1. Expected

2. Interesting
3. Plausible
4. Useful for decision making
5. Not expected
6. Does not make sense

The expert's responses related to each alternative system are summarized in Table 8-1.

System Alternatives	Response to part A	Response to part B
Base	3	1
Existing	2	2 and 3
Offline	1	2
Real-time	2	2, 3 and 4

Table 8-1. Expert's response related to the system alternative evaluations using the TERT method

8.4 Expert Review Related to the PM-DES Evaluation Method

The expert's opinion was also queried regarding the metrics selected to be used with the PM-DES evaluation method. He was asked to respond based on the same format related to the TERT evaluation method metrics mentioned in the previous subsection. The expert responded that the metrics selected to be used with the PM-DES evaluation method are mostly relevant for system performance measurement from the perspective of his organization or other organizations that he knew of.

The expert was asked to also provide his opinion on the high-level description of the model components used for the PM-DES evaluation method on the case, according to following response formats:

1. represents with close approximation part of the operations of my organization or other organizations that I know of;
2. represents with reasonable approximation part of the operations of my organization or other organizations that I know of;

3. represents what may be a part of the operations of some organization in my industry; and
4. there are aspects of the model that are inconceivable to represent a part of the operations of some organization in my industry.

The expert responded that the PM-DES model components represented with reasonable approximation part of the operations of his organization or other organizations that he knew of.

Furthermore, for both Case Model 1 and Case Model 2, for each "base", "existing", "offline CMMIS", and "real-time CMMIS" alternative systems evaluated using the PM-DES method, the expert was asked to provide his response based on the following format:

A. The high-level description of the alternative systems based on the Case Model 2 and the values assumed for the parameters, relevant to the study:
    1. describe, with close approximation, part of the operations of my organization or other organizations that I know of;
    2. describe, with reasonable approximation, part of the operations of my organization or other organizations that I know of;
    3. describe what may be a part of the operations of some organization in my industry; and
    4. there are aspects of the case description, approximations, or assumptions that are inconceivable to be applicable to any organization in my industry.

B. The analysis results using the PM-DES method were:
    1. Expected
    2. Interesting
    3. Plausible
    4. Useful for decision making
    5. Not expected
    6. Does not make sense

The expert's responses related to each alternative system are summarized in Table 8-2.

System Alternatives	Response to part A	Response to part B
Model 1: Base	3	1
Model 1: Existing	2	2 and 3
Model 1: Offline	1	2
Model 1: Real-time	2	2, 3 and 4
Model 2: Base	2	2
Model 2: Existing	2	2
Model 2: Offline	2	2 and 4
Model 2: Real-time	2	2 and 4

Table 8-2. Expert's response related to the system alternative evaluations using the PM-DES method for both Case Model 1 and Case Model 2

8.5 Expert Review Related to the System Choice Selection Procedure

Finally, related to the value analysis and choice selection exercise the expert was asked to provide his opinion related to the AHP method on the values assumed for the parameters, and the relative preference assumptions relevant to the study, based on the following format, i.e. the approximations made are:

1. are close approximations applicable to my organization or other organizations that I know of;
2. are reasonable approximations applicable to my organization or other organizations that I know of;
3. may be applicable to some organization in my industry; and
4. there are aspects of the case description, approximations, or assumptions that are inconceivable to be applicable to any organization in my industry.

The expert's response was that the values assumed for the parameters and the relative preference assumptions used in for the AHP choice selection method were reasonable approximations applicable to his organization or other organizations that he knew of.

The expert was also asked his general opinion on the analysis results using the AHP choice selection method, and it was suggested to him to respond using the words:

1. Expected
2. Interesting
3. Plausible
4. Useful for decision making
5. Not expected
6. Does not make sense

Regarding the AHP analysis exercise in conjunction with the TERT evaluation analysis, and the PM-DES analysis for both case models, the expert responded that the results from the AHP choice selection method were "interesting" and "useful for decision making".

9. Summary and Discussion

In this work, a framework was developed for the design and performance evaluation of effective IIS, i.e.by providing a structured method for guiding the design, development and performance evaluation of a system that is fit-for-purpose, performance-based and holistic, resulting in an effective system from the view point of the framework. The notion of a performance-based system emphasizes the importance of value trade-off. A fit-for-purpose system emphasizes the requirement for a system that is expected to achieve clear organizational business objectives. A holistic framework addresses various performance criteria for the system that are critical to the organization.

The research objectives for this work were to explore the need for effective IIS and what constitutes an effective system, and then to develop a framework that can be used for designing, selecting, and evaluating the performance of such a system. Furthermore the thesis described the application of the framework and verifies it as a hypothesis using a case study. The framework has been proposed and developed in this research as a method for designing and evaluating effective IIS. Based on this intention, the main hypothesis of the research was that the developed framework and its methods are effective in designing and evaluating the performance of industrial information systems that are fit-for-purpose, performance-based, and holistic. This section summarizes the work that was performed and described in this thesis to achieve the mentioned research objectives and verify the stated hypothesis.

The importance of the information system aspect of a CMMIS was mentioned. It was emphasized that the framework takes an information system centric view for the design of an IIS such as CMMIS, and has been developed considering an organization’s enterprise system.

In order to achieve effective systems, performance criteria for holistic performance assessment of IIS were specifically mentioned in Chapter 2. These metrics were related to the specific IIS domain, financial performance, safety and environmental performance and impact, the system capability in providing risk awareness, information flow in the system, and operational excellence, among others. Furthermore, for each criterion, sample metrics were mentioned that could be used for specific performance measurement. The need for prioritizing the performance criteria and their relative metrics, including a simple and visual criteria ranking method, were also briefly discussed.

The three main phases of the framework were described, two of which are pre-design and development activities. The needs assessment phase provides a systematic means in defining the current state of the industrial application (the organization), the requirements for implementing the intended IIS, the resources and methods for design and development, and the system performance measurement criteria. The performance criteria development phase involves activities that are related to designing performance evaluation methods, metrics, or key performance indicators for pre-evaluating potential system performance and gauging performance after implementation. The pre-evaluation of alternatives and choice selection phase is on assessing the performance of designed system alternatives based on the performance criteria and metrics developed during the first two phases, by means of relevant, comparative, analytical or simulation methods.A significant portion of this work was dedicated to testing the effective application of the framework as the hypothesis. For this purpose, a hypothetical industrial case was selected to demonstrate the application of the framework, and to verify its effectiveness. Ideally, validation of this hypothesis can be achieved by applying the framework to a large set of application cases, to statistically conclude whether the hypothesis stands or can be rejected. Such complete validation of the framework hypothesis involves design, development, implementation, and performance evaluation of large, complex, human-computer systems in real-world industrial operations settings. This approach of hypothesis testing was beyond the time-frame and limitations of this work. Therefore, the case study approach towards research hypothesis testing was taken resulting in a more feasible way to examine and verify the hypothesis within the scope and parameters of a relevant case.

The case was selected and structured to contain sufficient information on an organization that has the objective of implementing some form of an IIS. In this work, the specific IIS domain for the studied case was a CMMIS, where it was to be used for maintenance management of mining truck operations in the resource production industry for a hypothetical organization that had the objective of implementing an effective CMMIS. Since the framework has been developed to be flexible and general enough to be applicable to a wide range of IIS, other types of IIS and industrial operations can be used as cases as well. The case of a CMMIS used for mining truck machine management has the advantage of being relatively straightforward for general comprehension and model development, while it contains many aspects that provide the opportunity for generalization.

The case was used to design two hypothetical CMMIS using the framework at a high level. The functionality and the potential performance of the designed hypothetical systems were evaluated using the developed evaluation methods as part of the framework. The hypothetical CMMIS alternatives were compared to the existing practice of the case organization. These comparisons were conducted according to the performance criteria and metrics that were selected according to the case. The comparisons were performed to measure the degree to which the framework resulted in a better system than the existing practice, and to measure its effectiveness in resulting in a fit-for-purpose, holistic, and performance-based system. This analysis was the basis of the hypothesis verification work.

Two different CMMIS were designed using the framework. One system involved a real-time CMS, and the other represented an offline CMS. These two systems, along with the existing practice of the case organization and a base scenario for analysis control constituted four scenarios for the comparative evaluation and choice selection analysis part of the framework. Many systems with infinite combinations of processes and features could be designed using the framework, however, following the Occam's razor principle, generation of alternatives should be limited so it may result in the fewest and simplest set of alternatives possible.

Two evaluation methods were developed and used. The first method was a risk assessment method for analytical evaluation of system performance using a transient event-risk tree model, discussed in Section 6.1. The second method involved simulations for evaluating system performance based on a developed stochastic discrete event simulation method based on a stochastic model of the case operations, discussed in Section 6.2.

This transient event-risk tree (TERT) approach was developed to show how analytical probability methods can be used to assess system performance using the concept of risk, and progression of risk over time. The stochastic simulation method was developed to perform more elaborate assessments of the application of the system within the case operations, to include the simulation of case operations, production, occurrence of fault and failure events, fault detection and prediction, maintenance activities, human and system decisions, task scheduling, and other discrete events. The system performance evaluation analysis described in Chapter 7 involved two case models, both based on the case description in Section 5.3. One model, Case Model 1, was a relatively simplified model of the case operations. The other model, Case Model 2, was a more elaborate case based on the same case operations. The simpler Case Model 1 was used in conjunction with both of the TERT and PM-DES evaluation methods, to study the kind of meaningful conclusions that could be made for effective choice selection, and to observe if both evaluation methods can result in the same or similar conclusions. Indeed, both methods resulted in similar conclusions. The more elaborate case study was used to show the limitations of analytical methods and the type of complex features that can be studied using the simulation method.

The studied case involved stochastic events, including ones with undesirable outcomes such as machine faults, failures, and safety and environmental incidents. Tire maintenance data existed for the case, which allowed for using reliability models to generate simulated stochastic faults and failures. The specific tire maintenance data more accurately represented tire faults. The tire reliability models used for the risk assessment method in Chapter 7, however, was assumed to represent immediate tire failures. This assumption was used so that the analytical probability models of the transient event-risk tree method could be simplified while still achieving consistent and logical comparative results. The reliability models used for the simulation method in Chapter 7 was assumed to represent tire faults that would result in tire failures based on a specific model. All other events were modeled based on assumptions that were verified by a subject matter expert.

To calculate the risk values of the TERT calculations, stochastic models were used for events such as failures and incidents based on both assumed parameters, and real machine tire failure data obtained from the operations of a similar organization to the case’s hypothetical organization within the same industry.

For each risk event, such as a failure or an incident, an event probability tree was drawn to show risk value outcomes of the selected risk situations, based on a specific distribution function for the risk event. Each branch of the risk tree represented an uncertain risk situation related to some machine event with an undesirable outcome. Four risk situations were defined and used for this purpose:

1. “good” situation, or the risk of none of the machines having a failure or incident event;
2. “bad” situation, or the risk of at least five of the machines having a failure or incident event;
3. “ugly” situation, or the risk of all of the machines having a failure or incident event; and
4. “expected” situation, or the total average risk of the machines having a failure or incident event.

Once risk values and system performance based on the metrics of interest were calculated or estimated, first, the alternative systems and scenarios were compared related to each performance criteria were risk values were calculated. Next, the AHP multi-criteria decision method was used to select the best system that would achieve the organization’s objectives set for the system.

In terms of performance based on the various selected performance criteria, it was found that both the existing system and offline CMMIS scenarios were superior to the base scenario. The offline CMMIS was ranked slightly lower than the existing system. However, the real-time CMMIS significantly outperformed the existing system and the offline CMMIS.

An effective system is also a performance-based one, were the total cost of ownership of a particular system must also be considered. When these costs were considered, the significantly lower cost of ownership of the real-time CMMIS and offline CMMIS, especially the real-time CMMIS, resulted in these two system being better performance-based systems. The real-time CMMIS was both superior to the existing system in terms of performance, and in terms of lower ownership costs.

The PM-DES simulation method involved simulations for evaluating system performance based on a developed stochastic discrete event simulation method that uses a stochastic model of the case operations. Simulations of machine operations involving machine events and system work flow, information flow and decision making were performed based on a code that was developed to simulate case operations, production, occurrence of fault and failure events, fault detection and prediction, maintenance activities, human and system decisions, task scheduling, and other discrete events. A range of distributions for the input variables were considered representing variable uncertainty, resulting in a monte carlo type simulation.

Simulation output was expressed based on assumed performance metrics based on the application of the framework to the case. Results of the four simulated scenarios were shown in the form of distributions of the output variables. These results were compared for the scenarios as part of the value analysis and choice selection phase of the framework.

On all accounts, it was evident that the real-time system was superior compared to all of the other scenarios. Unlike the existing system and the offline CMMIS scenarios, the reduction in field failure and incident risks exists at all times throughout the machine’s operation, not only within a specific time range around an inspection instance, because the machines were under continuous, real-time condition monitoring by the real-time CMMIS. Moreover, unlike the existing and the offline system scenarios, there were no inspection costs associated with this system.

For the PM-DES analysis also, when costs were considered, the significantly lower cost of ownership of the real-time CMMIS and offline CMMIS, especially the real-time CMMIS, resulted in these two system being better performance-based systems. The real-time CMMIS was both superior to the existing system in terms of performance, and in terms of lower ownership costs.

When assessing the system holistically, and relatively comparing system performance, some traditional metrics for assessing individual system domains might not be relevant anymore, because higher level organizational performance is what matters not the performance if individual domains. For example, by using the holistic metrics for the studied cases, the relative performance of the systems were analyzed to assess the total effectiveness of the systems, without the need to use a traditional metrics such as serviceability.

An interesting finding using both the TERT analysis and the simulation method was that, the different failure probability functions used to model the tire failure distribution, did not significantly affect the higher level outcomes of interest, i.e. the output metrics and the alternative selection result. Specifically, the same high-level conclusions in relatively evaluating the performance of the alternative systems were made using a simple, uniform failure function based on the tire failure distributions as compared to the more accurate normal and Weibull failure functions. This result implies that, for certain cases, higher-level, relative results for evaluating system performance, effective system selection, and studying the effect of various system features on the operations, can be obtained without investing in more accurately modeling lower-level uncertainties.

Although average values of simulation output distribution were used for several metrics, the simulation method allows for using different aspect of the entire distribution of an output variable as a metric, and thus preventing pitfalls associated with only considering average values (Savage, 2012), as was shown by using the “threshold event” metrics.

The goal of evaluation methods, the risk assessment and simulation method in this case, was to achieve a better high-level understanding of the sensitivities, uncertainties, risks, and opportunities related to system alternatives; i.e. to achieve a meaningful decision making by means of a method that is informative, and provides relative, comparative, evaluation process. The goal was not to perform accurate calculations, optimizations, and simulations that are based on precise and detailed models of the system application.

It was noted in Chapter 3 that there were four aspects to the verification work, i.e. verification that:

1. the application of the framework and its usefulness for designing and evaluating effective IIS;
2. the case description represents, at a high-level, a real industrial operation for which the application of the framework is demonstrated;
3. the methods for evaluating system performance, i.e. the analytical risk assessment and the simulation methods were based on models that represent the case operations with the objective of achieving meaningful comparative analysis; and
4. the assumed model parameters values were plausible in real operations.

The first aspect of the verification work was achieved by defining the case and demonstrating the application of the framework in the case. Verification of the case description, models, and the assumed parameter values were achieved by subjecting them to the review of a subject matter expert that was acquainted with the operations which the case was based on.

At a high level of abstraction, the developed framework was designed to address the design and performance assessment issues of IIS in general. However, it was also recognized that the specific problems, methods, processes, concepts, practices, issues, challenges, etc. are different from one business function to another. For example a CMMIS is different from a chemical material monitoring and process control system, a flow assurance system, or a supply chain management system in many ways. The differences also exist from one industry to another, where many industry specific considerations exist. These differences are acknowledged in this work, i.e. CMMIS is one class of IIS and the selected industrial case is representative of only one industry. However, the intention was not to fully validate the framework's ubiquitous effectiveness, rather it was to verify its potential for resulting in an effective system implementation that is holistic, fit-for-purpose, and performance-based, and to make generalizations where possible.

The framework has been developed with the purpose of demonstrating the value of various choices for IIS design and implementation investments for an organization. i.e. demonstration of the business value of various aspects of the system, and how each component or functionality of the system creates value, affects the organization, and potentially achieves business objectives.

10. Conclusions

In this work, a holistic framework has been developed for guiding design, development, and evaluation of an IIS, to facilitate the implementation of performance-based and fit-for-purpose systems with higher potential for maximizing production, minimizing economic losses, and environmental and safety risks.

In practice, often systems that typically have low TCO are advocated for implementation, however, many such implementations can fail to perform effectively and deliver functionalities that are critical to an organization's objectives, constraints, and strategies. The objective of this research was not to prescribe particular systems for a specific application; rather the intention was to develop a holistic framework that can increase the potential for effective system implementations. The developed framework was described in this thesis along with the proposed path and activities for verifying its effectiveness.

Although only the application of one instance of the framework was described and verified, i.e. for designing and evaluating a CMMIS, the general method can be applied to other IIS since the framework has been developed at a level of abstraction that allows this general application, and with the intention that could allow for many instantiations for designing specific IIS.

It was shown by the verification process involving the application of the framework to the hypothetical case, that the framework can be used to design effective systems, and to compare the performances of these alternative systems against an existing system for system choice selection prior to implementation, hence supporting the main hypothesis stated in this thesis.

10.1 Summary of Contributions and Significance of Work

The major contributions of this work were related to the development of the framework, and the methods for carrying out the verification work. In summary, the main contributions of this research are listed below:

1. development of the framework for performance-based, fit-for-purpose, and holistic design and performance evaluation of effective IIS, and specifically for CMMIS;

2. identification and elaboration of performance criteria and related metrics for a holistic system;
3. methods for analyzing information flow and decision making in a CMMIS;
4. analysis of uncertainty handling and risk in an IIS, and specifically for CMMIS, using the developed transient, event-risk tree method for multiple machines with multiple events;
5. probabilistic graph modeling of relationships and propagation of uncertainty from sensed equipment data and subjective input at the machine level on the field to high-level business performance indicators;
6. procedure and method for simulating an IIS, specifically a CMMIS including its functionalities, architecture and design using the developed PM-DES simulation method;
7. simulation of operational performance assessment of several fault detection and reliability estimation models related to large hauler truck maintenance; and
8. demonstration of mining truck maintenance management improvement due to wireless powered CMMIS.

10.2 **Recommendations for Future Work**

The framework was developed as a general tool for effective IIS design and evaluation. This work explored the constituent aspects of an effect system, how it can be applied to a specific IIS, such as a CMMIS based on an industrial case, and how the performance of the resulting system(s) can be evaluated for implementation. The work described in this thesis can be a foundation for future work on:

1. application of the framework to other specific IIS and industries;
2. validation of framework effectiveness as a hypothesis using extensive industrial case data, as a structured statistical research, over longer periods of implementation times in real world applications as part of a long-term research project;
3. using the developed simulation method and simulator to perform comprehensive sensitivity analysis on the many parameters than can be of interest within the described application and operations;

4. performing structured, systematic interviews with industry users and experts with the objective of analyzing their response to what they have learned from the application of framework and the evaluation methods; and
5. researching how the framework and the evaluation methods can improve the quality of decisions both at operational and overall business decisions within an organization.

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Appendix

A. Decision Making

A.1. Decision Analysis and Organizational Decision Making

An organization operates in an uncertain environment and requires many decisions in the path towards value creation while the decisions can have various risks.

Among various decisions that an organization is obliged to make, some of the most important ones are those related to capital investments. Such capital investments are made with the expectation that they will eventually create value for the organization. Value creation can be objectively measured by monetary instruments. Organizations in the form of modern corporations have been created with the mandate of increasing shareholder value. This has resulted in most investment decisions to be focused on the monetary return of an investment. Hence in the simpler environment of past organizations, the traditional valuation methods were developed to facilitate the understanding of the investment decision process, and results (returns) were developed with the sole objective of increasing monetary return under deterministic assumptions. These methods may be insufficient and incapable in handling the complex and uncertain conditions under which the modern organization is required to make decisions considering multiple objectives.

On the other hand, more than ever before, businesses are called to improve their activities to account for environmental and social impact of their operations. Environmental and social risks are also financially very expensive for companies with long lasting consequences. The prevalent capital budgeting decision methods are not capable of adequately modeling these risks, and hence may fail to account for them. However, models that do take into account such risks, quantify their uncertainty, and explicitly demonstrate their impacts in the context of decisions, and which at the same time, take into account for flexibility in the organization's actions can be effective in increasing the understanding the extent of environmental and social risks associated with decisions. The modern organization requires various decisions on matters that can be financially quantified, and some that cannot be readily valued in financial terms.

A highly representative example of this situation is an organization contemplating to implement a new technology product or project. In short, this is an organization that is required to invest (or not) in new uncertain technology in an uncertain environment. Given uncertainties with new technologies, how can a company asses investment opportunities in new technologies? How can a company continue to create value by making appropriate investment decisions, while understanding the risks in new technology investment?

Decision making is a process (however short) that, based on the goal of achieving a desirable outcome, alternative options are assessed and the ones deemed suitable are selected. Decision science is the formal field of study dedicated to understanding the decision making process. Studies in this field aim to answer questions such as: what makes a good decision? What makes a good decision making process? What are the barriers to making good decisions? How can the decision making process be formalized, quantified, and practiced with consistency? What is the proper way to define and frame a problem for decision making? How does decision making occur in an organization? How do individuals make decisions? What if the decision is to gain the maximum economic value? What if there are multiple, options, multiple objectives, and an uncertain environment? What are human psychological aspects of decision making? And so on...

Decision analysis is a process, by which unclear decision problems are formed into explicit sequential steps and paths (Howard 1988).

In general, study on decision making entails both the “soft” aspect of decision making, and the quantitative or “hard” aspect of decision making. In studying the “soft” aspects of decision making, the focus is on qualitatively understanding and improving the decision making process, such as:

- Defining, framing, and dissecting the decision problem
- Transforming or modeling the action of decision making into a process, procedure, or a system
- Studying behavioral and psychological issues with regards to decision making both from an individualistic and organizational perspectives

On the other hand, the quantitative studies on decision making are concerned with mathematically modeling decisions both for understanding what (and to what extent) affects decision outcomes and to improve the decision making process.

The basic premise of the economical or “rational” decision making models, also the normative or objective decision making approach, are that individuals make decisions based on the principles of self-interest and rationality for maximizing utility (Von Neumann and Morgenstern, 1947), where utility is judged in relative economics of the decision outcome, which is traditionally in monetary terms, but can be formulated in other terms such as happiness or power.

Qualitative decision analysis is the procedure where the problem is defined, the risk and uncertainties identified, and the objective of the analysis, decisions to be made, and the events that would occur described. This is to explain and frame the context of the problem that requires assessment. The two main questions that ultimately decision analysis aims to answer are:

- What is a good decision outcome?
- What is a good decision?

Both questions can be seen as philosophical questions, especially if the answer is not expressed in terms of concrete economic utility maximization terms. However, if the question is on finding the best decision-making process for a problem, such a question may be addressed more objectively, with the objectives of improving the decision making experience and the quality of the decision outcome.

A good decision making process may not always yield a good outcome. However, if the process allows for learning, understanding the uncertainties, and the role of parameters on the outcome, both what can be controlled and what is based on chance, then a decision making system is created which is progressively optimized for good outcomes in time.

Simon (1947) mentions that the decision process should be appropriate for the decision type, and that seeking optimality for every decision problem is not practical. He metaphorically describes the concept as a scissor with two blades, type and process, the satisficing scissor which is required to cut it. This has also been demonstrated empirically by Nutt (2001).

Many models have been proposed for an effective decision making process. The decision analysis cycle (Howard 1968) proposes the following elements:

1. Formulation: in identifying the decision objective, alternatives, constraints, and data and assumptions;
2. Deterministic analyses: the uncertainties are assessed at a high level and key uncertainties are determined using sensitivity analysis techniques e.g. multi-graph charts, tornado charts etc.;
3. Probabilistic analyses: uncertainties are assigned, risk attitude and risks are determined, alternatives are identified;
4. Appraisal: the sensitivity to probability is determined, to assess the sensitivity of the course of action to assessments. Value of information is also determined here;
5. Decision or iterate going to step 1: if further justifiable (e.g. would have value) information can be gathered that can affect the decision, otherwise decision should be made. Decision process is complete when more information cannot affect the decision.

A.2. **Psychological Aspects of Decision Making**

Three main heuristics in decision making psychology (Tversky and Kahneman, 1974) are:

- Representativeness
- Availability
- Adjustment and anchoring

From these heuristics, numerous human biases in decision making have been identified. When human decision making is involved, these heuristics must be accounted for. An example of models that are based on intuitive human decision making processes is the recognition primed decision model, a step wise decision making process from observing the decision making under uncertainty behavior of firefighters by Klein (1998).

A.3. **Decision Making under Uncertainty**

An important topic in decision analysis is decision making under uncertainty. It can be stated that most real application decisions are made under some degree of uncertainty.

In terms of common sense, reduction in uncertainty is only of value when a decision has not been made, when the uncertainties are related to the decision parameters, and when the price of reducing uncertainties is not higher than the value (or consequence) of the decision outcome.

The term “uncertainty” is sometimes used interchangeably with “risk”. It is important to distinguish between the two. Uncertainty is related to chance, and related to our knowledge of the likelihood of some event happening or not happening, or the likelihood of some claim or information being true or false, or any other type of a statement which is under some degree of doubt. Uncertainty is a degree to which a statement is doubted, and can be expressed using the probability axioms. Risk on the other hand can also be expressed using probability axioms, however, it has a negative connotation. Risk is a subjective term, and is an expression of an undesirable outcome of an uncertain event. Formally, risk is the severity of the outcome of an uncertain event multiplied by the probability of the occurrence of the event.

As previously mentioned, decision making in real life scenarios typically occurs under uncertain circumstances. Hence it is important to understand uncertainties related to a decision process to improve the decision outcome. It is also important to consider risks in the decision making process, to understand the possibly negative effects of the decision process and the decision outcome.

To quantify or reduce uncertainty, further information needs to be obtained or analysis needs to be performed. Information is only pertinent to a decision if it can affect the decision outcome (Savage, 2012). Furthermore, obtaining the information is justified if the incremental outcome of a decision is more beneficial than the cost of acquiring the information. Especially, when new information itself is uncertain and if it will not eliminate uncertainty.

A note should be made on the difference between uncertainty modeling and uncertainty reduction. Modeling uncertainty does not reduce or eliminate it. It frames and clarifies the uncertainty for aiding decision making. The uncertainty had existed and will exist with or without uncertainty quantification. Uncertainty is reduced by obtaining more accurate information on the subject of uncertainty.

A.4. **Benefits of Using Decision Making Methods and Decision Analysis**

Oil & gas industry projects have high degrees of uncertainty (Peterson et. al. 2005). Problems are complex, with high inter-correlated uncertainties, long time spans, and conflicting objectives.

The common problems in the industry are characterized by being highly complex, workflows requiring several stages with high uncertain input and output parameters, interdependency and cross correlation of uncertainties, requirement of various decision and risk analysis methods to a particular problem (Virine and Rapley 2003). The complexity arises from the numerous decisions involved, the risk associated with decisions, the pressure and effort required to estimate production with high accuracy, and the production methods depending on the uncertainties (Suslick et. al. 2009). In general, investments in the industry are costly with high risks which result in uncertain revenue, and it is not uncommon for investments to just break even (Brashear 1999, Brashear 2000, Goode 2002, Cottrill 2003, Rose 2003, Durham 2004, Bratvold 2007).

Hence methods that identify uncertainties, and provide decision options based on uncertain parameters have very high potential in improving business performance by showing the risks and opportunities represented in probability values. Decision methods combined with advanced risk analysis and valuation methods allows for formulating complex problems, with high uncertainties, and multiple inter-related decision making steps. Thus formal use of decision and risk analysis methods integrated in company workflows may have the potential to improve the financial bottom-line of the company.

Decision and risk analysis allows for resolving competing interests of objectives and multiple parties in a project. Decision methods provide a formalized means for framing relevant parameters that affect decision along with the associated uncertainties. For example, the performed Monte Carlo simulations allowed Gray (2007) to understand the project economic sensitivity to cost parameters, hence providing an opportunity to optimize costs associated with activity that have the highest impact.

A.5. **Barriers to Effective Use of Decision Making Methods in Industry**

Although decision analysis methods are used in many industries, and there are numerous publications demonstrating their efficacy in solving different problems, they are not widely implemented. There are still many barriers to adapting formal decision making methods in solving problems. Some of these challenges have been noted as lacking formal decision making methods education in engineering curricula (Rugarcia et. al., 2000), complexity of methods which requires education in decision theory, risk analysis (Virine and Rapley 2003), probability and computational statistics, and advanced financial valuation methods. There other many other factors acting as barriers which some important ones are mentioned in this section.

One misunderstanding in using decision methods is that they can reduce risk. As stated by Suslick et. al. (2008) quoting Newendorp and Duggan (2000), risk is not reduced or eliminated by employing decision analysis methods, and the judgment of professional would still be the key factor in determining the outcome of the decision. The decision analysis methods, however, would serve to illustrate and frame the uncertainties for the decision maker.

Limitations in using decision methods are sometimes due to the improper application to a specific problem (Peterson et. al. 2005, suslick et. al. 2009). Several significant and common misunderstandings in the petroleum industry have been pointed out by Peterson et. al. (2005):

- overconfidence in using uncertainty assessment and decision tools, which can prove to be costly for companies in the long run and results in negative experiences in using the methods;
- Enough information can be obtained to perform deterministic analysis, but not uncertainty analysis;
- Deterministic estimates should be available prior to uncertainty analysis, and the statistical relevance of the deterministic estimates are acknowledged;
- Uncertainty analysis are beneficial during the course of a project;
- Accuracy of estimates is enhanced by uncertainty analysis;

- All risks should be recorded; and
- With progression of the project, uncertainty is reduced.

Peterson et. al. (2005) also mentions some misapplications in uncertainty analysis, such as separation of cost analysis from market and financial uncertainty assessment, or marginalizing uncertainty assessment because a widely agreed upon deterministic assessment is located at an unattractive probability point of the calculated probability distribution. Another set of problem according to Peterson et. al. (2005) is that uncertainties are not correctly assigned due to an over optimistic viewpoint, central limit theorem effects not understood and accounted for, risk events and their probabilities are not properly determined, and correlations between uncertainties not accounted for.

A.6. **Select Decision Methods Used in the Petroleum Industry**

A.6.1. **Discounted Cash Flow Valuation**

A main assumption in using DCF methods is that the project will continue once it starts with no further interruptions or changes. This is in the case in practice, where due to various conditions changing at the firm level and market level, the decision makers can adjust the path of the project or even stop it.

A.6.2. **Decision Analysis with Decision Trees**

Typically decision trees are constructed by identifying the decisions to be made, including development, information gathering, flexibility inclusion, and tactical operations decisions, along with their uncertainties, under high-level company objectives or value drivers. For each option, single discrete probabilities are applied to the tree branches which then allow calculation of the probability adjusted NPV for each decision. This method can be used for projects with one starting decision point, however, unsuitable for projects for which future decisions require assessment.

The tree demonstrates flexibility in the decision process, where at each node, the decision maker has the option (path) for a particular choice with outcomes that “branch” out resulting with further or final outcomes. The branching occurs at a “node” which is the parent location of the child branches. The selection of the proper path (decision) is based on certain defined logic, e.g. highest NPV associated with a decision trumps other decisions in sibling branches. Decisions at child branches usually depend on uncertainty reduction, or characterization of the parent decisions.

A.6.3. **Real Options**

The real options method includes multiple decision stages, which can have uncertainties associated with decision input parameters and decision outcomes. The real option method is extensively used in the bio-medical and pharmaceutical industries due to clear and discrete regulatory stages of product development.

For example among the notorious types of options that can be used in the petroleum industry are upgrading, abandonment, delaying, and accelerating/decelerating/halting production (Myers 1987, Merton 1985).

A.6.4. **Portfolio Management**

The objective is to maintain an optimum portfolio of projects with diversified risk, with maximum value and lowest risk. This is based on the modern portfolio theory of Markowitz (1952), which is currently widely used in the finance industry for setting up investment portfolios.

An optimal portfolio is one that has lower or the same level of risk as other portfolios with the same value and higher or the same value than other portfolios with the same level of risk. In portfolio theory, interplay among projects is a key factor in achieving the optimal portfolio (Savage, 2012)

The objective in assembling an optimal portfolio is to arrive at a balance in risk and value, as there is no one optimum portfolio.

An optimal portfolio requires the risk taking strategy of the firm to be defined, which serves with the objective of increasing company value (walls 2004). In the oil and gas production industry, comprehensive description of oil and gas venture portfolios have been provided by Ross (2004) which looks at risk and uncertainty associated with projects, resources, and volumetric uncertainties.

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B. Conceptual High-Level CMMIS Architecture

Figure B-1 illustrates a conceptual, high-level architecture of a CMMIS for mining haul truck maintenance operations that employs field wireless sensors and an n-tier internet client-server application. Information flow in this architecture can be described as:

Part [1], wireless field data collection: data from the truck motes are transmitted to a sink node, which collects and sends data to a local data center [3];

Part [2], data collection in the maintenance depot: data collected from digital imagery equipment and other external (off-board) sensors are collected by technicians and sent to the local data center [3];

Part [3], local data center: field data is collected, conditioned, and pre-processed by the local application server as required by the system. This data is stored in a local data base, and also uploaded to the internet server-application tier and stored in the cloud persistence tier;

Part [4], the external CMMIS application: the CMMIS internet server, database, and application server are hosted in the cloud. This part contains, pre-processed data; the application model including (a) maintenance management rules and logic, and (b) reliability, fault detection, and condition prediction models and algorithms; data and requests control, and the application views presented to the application clients;

Part [5], maintenance technicians: as the CMMIS application clients, maintenance technicians interact with the system by requesting information on machine condition and their work processes, and inputting their observations, decisions, and action results; and

Part [6], control center: the control center’s role is to access relevant information from the CMMIS cloud application and send this information along with any other ancillary instructions to the stakeholders who do not have direct access to the application. e.g. when a fault is detected on a truck, or when a maintenance call is requested for it, the truck driver is notified to proceed to the maintenance depot.

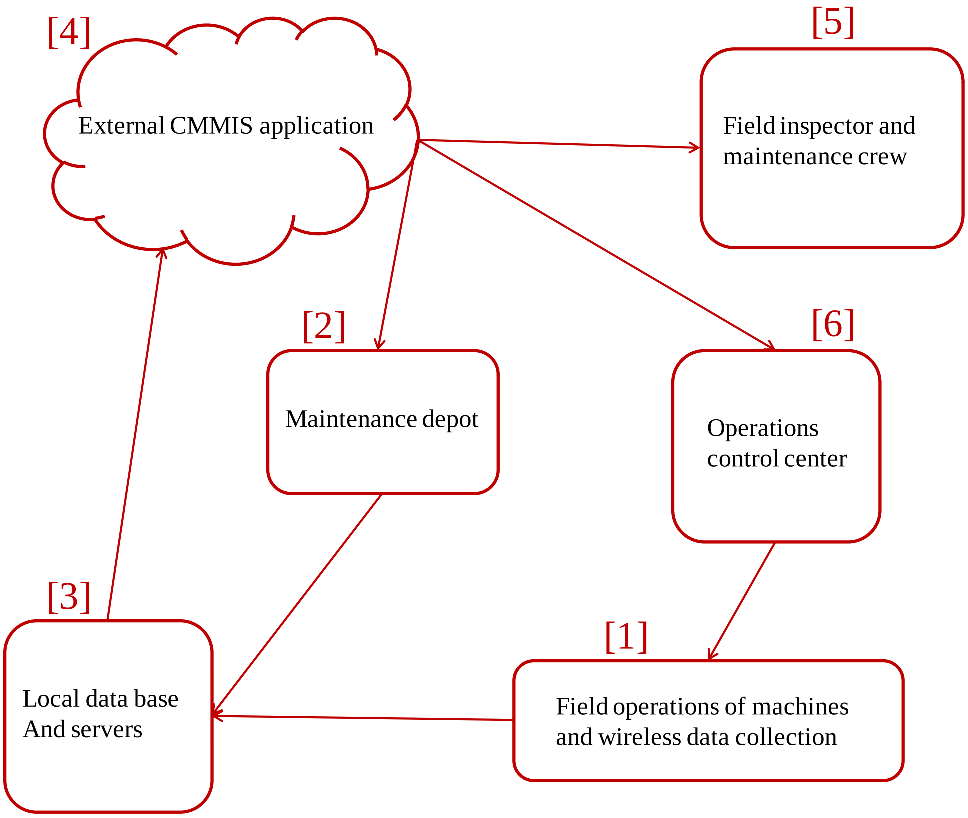

Figure B-1. Schematic of a conceptual, high-level architecture of a CMMIS using wireless sensors and the internet

C. Simulation Method

This appendix describes matters related to the programming details of the simulation method discussed in Chapter 5. The simulation method is based on the discrete event simulation method that includes stochastic events and is linked to a probability model that represents the inter-relationships, dependencies, and mutual influences of the stochastic parameters and events through graph models of prior, conditional, and posterior probabilities. This method is introduced in this thesis as Probability Model Linked, Discrete Event Simulation (PM-DES).

C.1. Algorithm

The underlying algorithm for the simulation code, based on the PM-DES method is provided below. The names in double quotation marks are simulation objects including processes, resources, signals, and interruptions. The names prefixed with ‘var’ are variables names used in the code.

I. For the number of simulations:

A. Initialize operations variables

B. Run operations simulation:

1. Create the simulation resource “maintenance technicians” and assign to it the total number of maintenance staff
2. Create the simulation resource “inspector” and assign to it the total number of inspection staff
3. If the resource “maintenance tools” is finite, create a simulation resource “maintenance tools” and assign to it the total maintenance tools quantity
4. If the resource “inspection tools” is finite, create a simulation resource “inspection tools” and assign to it the total maintenance tools quantity
5. For each machine in the operation’s machine list:

5.1. Create an “operator” process and initialize it with the operator’s name, and the operator’s decision making model

5.2. Start the operator process

5.3. Create an “machine” process and initialize it with the machine’s name, profit rate, cost rate, scheduled operating time, and its operator process name

5.4. **Start the “machine” process**

5.5. If the simulation is set to have routine maintenance:

    5.5.1. Create a “maintenance procedure” process for the machine, and assign to it the machine’s maintenance interval, maintenance time and cost for different maintenance routines

    5.5.2. Start the “maintenance procedure” process

5.6. If the simulation is set to have routine inspection:

    5.6.1. Create an “inspection procedure” process for the machine and assign to it the machine’s inspection interval, inspection time and cost for different inspection routines

    5.6.2. Start the “inspection procedure” process

5.7. For each failure in the list of the machine’s failures data:

    5.7.1. Create a “failure” process and assign to it the failure mode, the failure time distribution of this mode, and the duration and cost to repair the machine in this failure mode

    5.7.2. Start the “failure” process

    5.7.3. Add the “failure” process to the machine’s events list

5.8. For each incident in the list of the machine’s incident data:

        5.8.1. Create an “incident” process and assign to it the incident mode, the incident time distribution of this mode, and the duration and cost to the operation due to this incident mode
        5.8.2. Start the “incident” process
        5.8.3. Add the “incident” process to the machine’s events list
    5.9. For each fault in the list of the machine’s faults data:
    5.10. Create a “fault” process and assign to it the fault mode, the fault time distribution of this mode, and the duration and cost to repair the machine in this fault mode
    5.11. Start the “fault” process
    5.12. Add the “fault” process to the machine’s events list
  C. Calculate metrics for the operation (aggregate of all the metrics for the machines and those specifically for the operation)
  D. Output results
II. Calculate metrics for all the simulations (averages and aggregates of all the metrics for the operation simulations and those specifically for the entire set of simulations)
III. Output results

Run the “machine” process:

1. Set the total simulated operating time of the machine (var time_operating) to its scheduled maximum operating time (value of var optime_scheduled)
2. While the machine’s remaining operating time (var optime_remaining) is greater than zero and the current simulation time is less than the scheduled maximum operating time (var optime_scheduled):
    2.1. Advance simulation time to the value of var optime_remaining (initialized to the value of optime_scheduled when the process was created)

2.2. Check if the “machine” process has been interrupted by some other process

2.3. If interrupted:

2.3.1. Reset the machine’s interruption state (to non-interrupted state)

2.3.2. Add the event that caused interruption and the time that interruption occurred to the machine’s list of occurred events

2.3.3. If the interruption cause was a failure, incident, maintenance, or inspection; or if the machine was flagged for maintenance or inspection:

2.3.3.1. Set the machine’s state to inspection

2.3.3.2. If the machine is flagged for inspection or the interruption is due to a routine inspection service:

2.3.3.2.1. If inspection is due to operator request, set the priority of the machine in receiving resources to “1”, else if inspection due to routine maintenance, set the priority to “0”

2.3.3.2.2. Request a unit of “inspector” resource: if inspector available, proceed to inspection process, else wait until an inspector becomes available

2.3.3.2.3. Request a unit of “inspection tools” resource: if tools available, proceed to inspection process, else wait until inspection tools become available

2.3.3.2.4. Calculate how much time took to wait for resources and calculate the total downtime which includes the inspection time

2.3.3.2.5. Inspection process: the inspector inspects the machine and determines its condition based on the inspector’s decision model and the machine’s true condition (var condition_true), and reports the result (var condition_known time stamped) to the operator

- 2.3.3.2.6. Based on the known condition of the machine (var condition_known), and the operator's decision model, operator makes decision to either continue operating the machine or send it for maintenance: If the operator decision is to get maintenance, flag the asset for maintenance and start an interruption process so that the machine's process gets interrupted and the next simulation time
- 2.3.3.2.7. Calculate time and cost due to the process and adjust var optime_remaining by subtracting downtime
- 2.3.3.2.8. Set the state name to "production" and remove the machine's inspection flag
- 2.3.3.2.9. If the inspection process was due to regular inspection intervals, set the next scheduled inspection time
- 2.3.3.2.10. Add the event to the list of events that occurred
- 2.3.3.2.11. Advance the simulation time by an amount equal to the downtime
- 2.3.3.2.12. Release the resources "inspection tools" and "inspector" that were occupied

2.3.3.3. Otherwise (implicit condition, i.e. if the machine is flagged for maintenance, or the interruption is due to routine maintenance, or the machine has failed or caused an incident):

- 2.3.3.3.1. Set the machine priority to receive maintenance resources:
  - 2.3.3.3.1.1. If maintenance is due to incident, set the priority of the machine in receiving resources to "3"
  - 2.3.3.3.1.2. else if due to failure, set the priority of the machine in receiving resources to "2"

        - 2.3.3.3.1.3. else if due to operator request, set the priority of the machine in receiving resources to “1”
        - 2.3.3.3.1.4. else if inspection due to routine maintenance, set the priority to “0”
    - 2.3.3.3.2. Request a unit of “maintenance technician” resource: if available, proceed to maintenance process, else wait until resource becomes available
    - 2.3.3.3.3. Request a unit of “maintenance tools”: if tools available, proceed to maintenance process, else wait until maintenance tools become available
    - 2.3.3.3.4. Calculate the time that took to wait for resources and calculate total downtime which includes the maintenance time
    - 2.3.3.3.5. If interruption was due to failure or incident:
        - 2.3.3.3.5.1. Add to event count
        - 2.3.3.3.5.2. Calculate downtime including maintenance time for the failure or incident
        - 2.3.3.3.5.3. Start a new “fault”, “failure” or “incident” process with the same mode and the appropriate distribution
        - 2.3.3.3.5.4. Cancel the old (detected) event and remove from it the machine’s events list
        - 2.3.3.3.5.5. For each true fault (if var condition_true equals “faulty”) in the machine’s existing fault list, the maintenance technician makes a diagnosis based on his fault diagnosis and detection decision model: if he determines faulty, remove the fault from the fault list, and calculate the cost

and time for eliminating the fault (performing maintenance) and restart a same “fault” process, else if he fails to detect the fault, continue

2.3.3.3.6. Else (implicit condition, i.e. if interruption was due to routine maintenance or if the machine was flagged for maintenance):

2.3.3.3.6.1. Calculate downtime (general maintenance + specific event)

2.3.3.3.6.2. If the maintenance process was due to regular maintenance: set the next scheduled maintenance time

2.3.3.3.6.3. For each true fault (if var condition_true equals “faulty”) in the machine’s existing fault list, if the machine has a condition monitoring system (var cms = True) or the maintenance technician makes a diagnosis based on his fault diagnosis and detection decision model and determines faulty, remove the fault from the fault list, and calculate the cost and time for eliminating the fault (performing maintenance) and restart a same “fault” process, else if he fails to detect the fault, continue

2.3.3.3.6.4. Start all detected and fixed failure, fault, and incident events with the appropriate distribution

2.3.3.3.6.5. Cancel the old events and remove them from the events list

2.3.3.4. Set the machine state to production, set var condition_known to “healthy” with time stamp, and remove the machine’s maintenance flag

2.3.3.5. Advance the simulation time by an amount equal to the downtime

2.3.3.6. Release the resources “maintenance tools” and “maintenance technicians” that were occupied

2.3.4. If the interruption was caused by an operator’s decision moment:

2.3.4.1. Obtain decision based on the operator’s decision model

2.3.4.2. If decision is to do maintenance or do inspection: flag the machine for maintenance or inspection, start a “flag” interruption process and flag machine for maintenance to be serviced at the next simulation time , else remove any flag and continue

2.3.5. If the interruption was caused by a “fault” process:

2.3.5.1. Set the true condition (var condition_true) of the machine to “faulty”

2.3.5.2. Add the fault to the machine’s existing fault list (var faults_existing)

2.3.5.3. If the machine has a condition monitoring system (var cms = True):

2.3.5.3.1. the condition monitoring system makes a diagnosis based on its fault detection model, if fault is detected:

2.3.5.3.1.1. the operator makes a decision based on his decision model: if decision is to get maintenance, start a “flag” interruption process and flag machine for maintenance to be serviced at the next simulation time, else continue

2.3.5.4. Find failures and incidents in the machine’s events list affected by this fault mode

2.3.5.4.1. If such failures and incidents exist:

2.3.5.4.1.1. Start new “failure” and “fault” processes with the same fault mode based on the adjusted event probabilities conditioned on the fault that occurred

            2.3.5.4.1.2. Cancel the old events (related to the fault) and remove them from the event list
        2.3.5.4.2. Else (this means the fault can result to a new failure or incident): start new “failure” or “fault” process, based on the appropriate probability in the fault data
        2.3.5.4.3. Add new event to the machine’s event list

3. Calculate metrics for the machine

C.2. **Code Verification and Testing**

Code testing greatly enhances the quality of software by reducing bugs that can cause various defects and erroneous results. The testing strategy that was used for the development of the simulator code included:

1. Unit testing of individual functions, methods, and sub-routines;
2. Use of “assert” statements throughout the code;
3. Testing the entire simulator code using a test suite with known outputs for specific input variable values.

C.2.1. **Unit Testing**

Unit testing is generally performed to test specific functions, methods, and sub-routines to observe their individual performance independent from the whole software.

These units may take input parameters, use global and local variables, produce output variables, and have a certain utility for the software system which it serves. Unit tests are performed by running the unit and checking the results or effects of the executed unit against results that are previously known. Unit tests are typically written as part of the subroutine and executed by a separate script while debugging or compiling, or be the IDE (integrated development environment).

C.2.2. **Assert Statements**

Assert statements are typically used to test the validity of a statement. If the statement is true, the execution of code continues, if false however, the assert statement raises an exception and the execution of code is halted.

The assert statement is typically used to test the validity of input and output variables within functions and various other parts of the software. They are used to reduce the input space and check the valid output range of functions or methods before continuing to other parts of the code and potentially spreading an infection throughout the software. For example, if a function is not meant to accept negative numbers, or if the function output should be an integer between 0 and 1000, then an assert statement checks for the validity of these statements, with the former statement used at the beginning of the function body and the latter at the end of it. If any of the conditions of the assert statement is violated, an exception is raised and the code execution is halted.

C.2.3. **Test Suite**

Test suites are typically used to test the validity of a body of code, specifically, the entirety of the software system. For this purpose, cases are created were based on specific variable values, the performance of the software is monitored to match an outcome that is known. Test suites are very useful when developed and used during both early software development stages and later revisions and updates to the code. It is used to ensure that given changes in the code, the functionality of the software remains valid.

For the simulator code, a test suite was developed that according to known outcomes based on specific sets of variables, checked the validity of the code throughout development.

C.3. **Convergence**

The PM-DES method is a monte carlo type simulation method where given probability distributions for input variables, numerous simulations are performed, with each simulation based on one set of variables that are randomly assigned with their probability of occurrence being based on the probability distribution of the variable.

Hence the output variables, i.e. the simulation result variables of interest can also be distributions, created from running many simulations. Some output variables such as averages, maximums, minimums, and counts are single value outputs that are calculated from numerous simulations.

It is important to achieve convergence in the output variables (result variables) to a point where a change in results due to an additional simulation is not significant. Testing for convergence provides the assurance that a certain level of accuracy has been reached for the numerical results, without requiring further simulations that consume computational resources.

For example the histograms of the output result variables “revenue” and “number of environmental incidents in the field” are shown in Figures C-1 and C-2. The histograms are for the “base” scenario for Case 1 of Chapter 5 for 1000, 10000, 100000, 200000, 300000, and 400000 simulations. It can be seen from these figures that the shape of the histograms become closer in shape as the number of simulations increases. However, this resemblance is not a quantitative measure.

The basis of convergence can be any output variables, or a set of variables meeting a certain criteria. For example the average value for a certain value, root mean square of several variables, or where distributions exist, geographic means of a histogram can be used to approve convergence once such convergence variables are deemed smaller than a selected small number. This small number is typically called convergence error of the simulations.

Figures C-3 and C-4 show logarithmic charts of relative convergence errors of the output variables “average revenue” and “average number of environmental incidents in the field” of the “base” scenario for Case 1 of Chapter 5 for 10000, 100000, 200000, 300000, and 400000 simulations. Relative error for each simulation level is calculated based on the previous error level, i.e.:

$$\varepsilon = \frac{|X_n - X_{n-1}|}{X_{n-1}}$$

Figures C-3 and C-4 show that the relative errors decrease as the number of simulations increases. The errors decrease to less than 1E-6 for the “average revenue” and 1E-4 for the “average number of environmental incidents in the field” output result variables, respectively. In practice, this level of error is sufficient to claim that an acceptable level of convergence has been achieved.

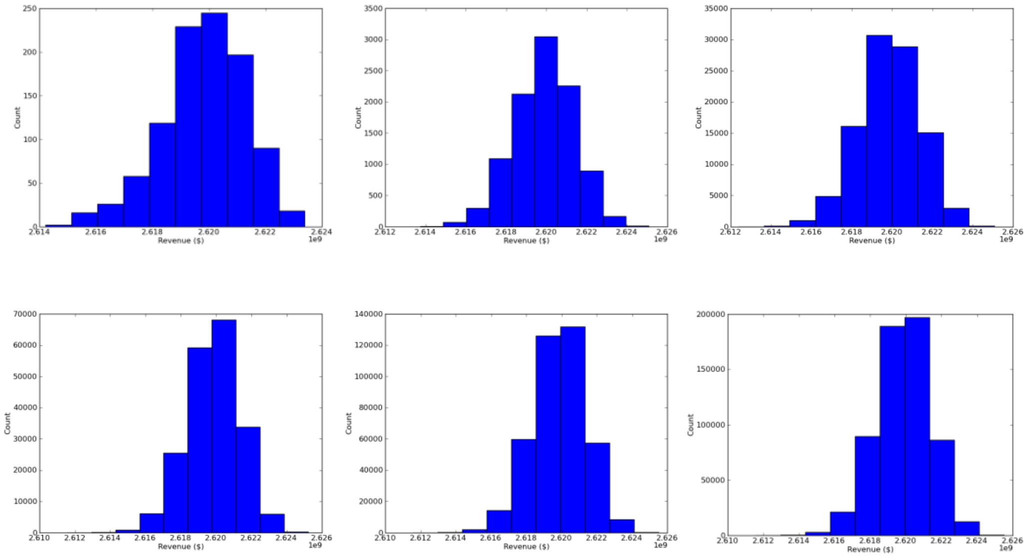

Figure C-1. Revenue histograms of the "base" scenario for Case Model 1 of Chapter 5 for 1000, 10000, 100000, 200000, 300000, and 400000 simulations (order left to right then top to bottom)

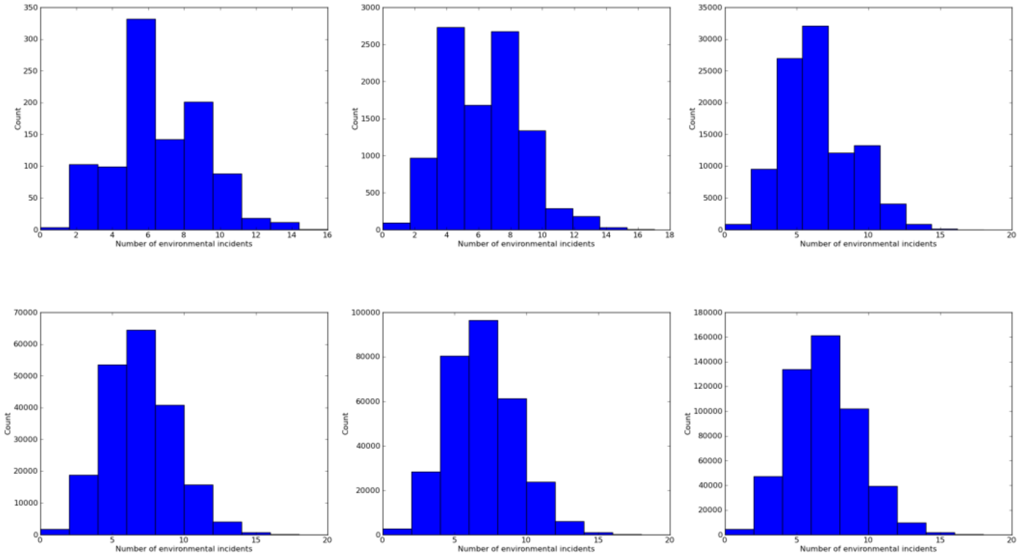

Figure C-2. Histograms of the number of environmental incidents occurred in the field for the "base" scenario for Case Model 1 of Chapter 5 for 1000, 10000, 100000, 200000, 300000, and 400000 simulations (in the order of left to right then top to bottom)

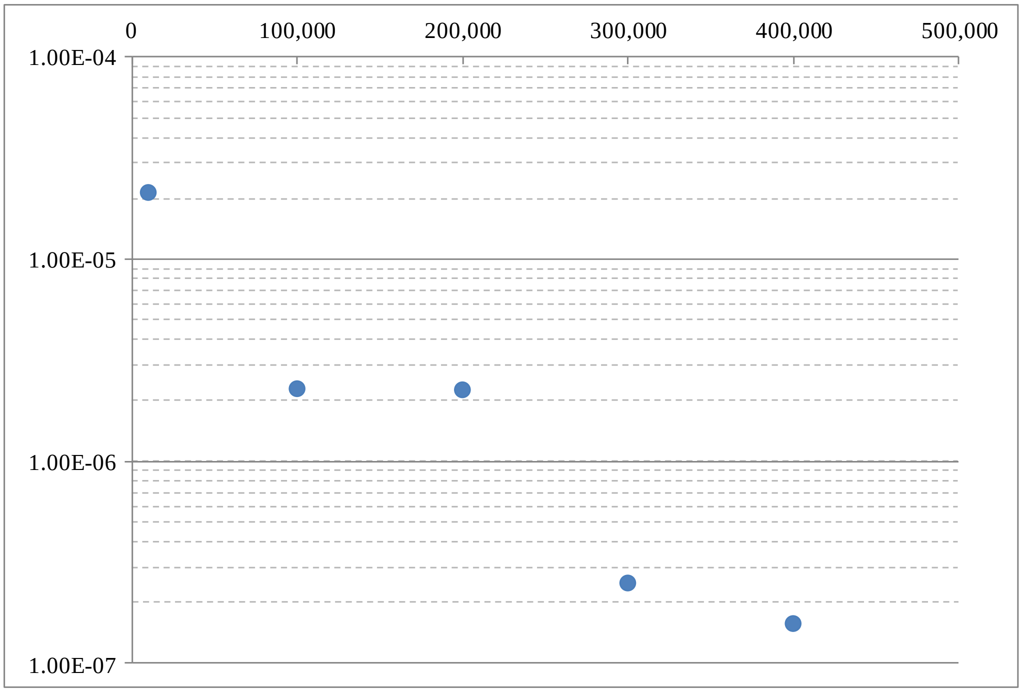

Figure C-3. Logarithmic chart of relative (to previous number of simulations) convergence errors of the average revenue output variable of the "base" scenario for Case Model 1 of Chapter 5 for 10000, 100000, 200000, 300000, and 400000 simulations

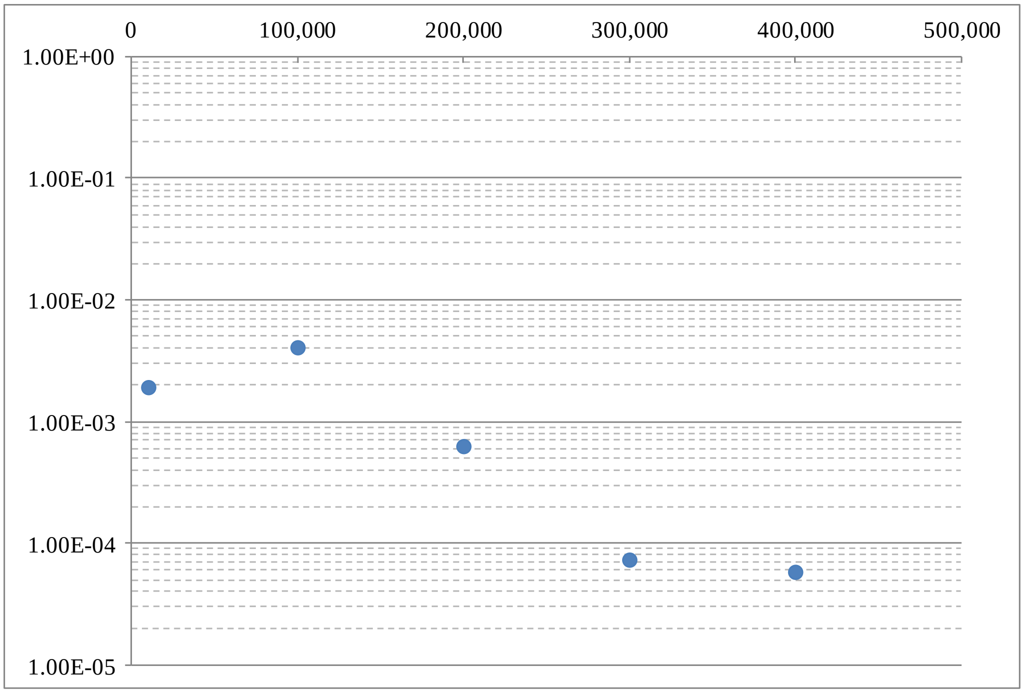

Figure C-4. Logarithmic chart of relative (to previous number of simulations) convergence errors of the average number of environmental incidents occurred in the field output variable of the "base" scenario for Case Model 1 of Chapter 5 for 10000, 100000, 200000, 300000, and 400000 simulations