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APPROACH TO ACHIEVE HIGH AVAILABILITY IN CRITICAL INFRASTRUCTURE

by

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September 2015

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The requirement for high availability of critical infrastructure necessitates the use of correct maintenance approaches for each system that supports the DOD missions. This thesis used a risk-adjusted cost method as the means to analyze the suitability of maintenance approaches, namely the no-preventive maintenance approach, the time-based maintenance approach, and the condition-based maintenance approach for different critical infrastructure. These three maintenance strategies were implemented using appropriate types of contracts and proper configuration management for the critical infrastructure. A sensitivity analysis was conducted, which validated Koeneman's 2009 findings for ships that condition-based maintenance can result in a significant increase in operational availability as compared to the no-preventive maintenance approach, and a larger increase as compared to the time-based maintenance approach. This validation of the sensitivity analysis performed for critical infrastructure shows that the use of condition-based maintenance results in higher availability than either the time-based or no maintenance-based strategies.

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APPROACH TO ACHIEVE HIGH AVAILABILITY IN CRITICAL INFRASTRUCTURE

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ABSTRACT

The requirement for high availability of critical infrastructure necessitates the use of correct maintenance approaches for each system that supports the DOD missions. This thesis used a risk-adjusted cost method as the means to analyze the suitability of maintenance approaches, namely the no-preventive maintenance approach, the time-based maintenance approach, and the condition-based maintenance approach for different critical infrastructure. These three maintenance strategies were implemented using appropriate types of contracts and proper configuration management for the critical infrastructure. A sensitivity analysis was conducted, which validated Koeneman's 2009 findings for ships that condition-based maintenance can result in a significant increase in operational availability as compared to the no-preventive maintenance approach, and a larger increase as compared to the time-based maintenance approach. This validation of the sensitivity analysis performed for critical infrastructure shows that the use of condition-based maintenance results in higher availability than either the time-based or no maintenance-based strategies.

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LIST OF ACRONYMS AND ABBREVIATIONS

A&A	Addition and Alteration
AFCEC	Air Force Civil Engineering Center
B&I	Building & Infrastructure
BAS	Building Automation System
C3I	Command, Control, Communication and Intelligence
CBM+	Condition-based Maintenance plus
CEOF	Civil Engineer Operations, Facility System
CEOHS	Civil Engineer Operations, Heavy Repair, Structures Element
CEOHP	Civil Engineer Operations, Heavy Repair, Pavement
CEOIH	Civil Engineer Operations, Infrastructure Systems, HVAC (Heating, Ventilation and Air Conditioning)
CEOIU	Civil Engineer Operations, Infrastructure Systems, Water and Fuel Systems Maintenance
CM	Corrective Maintenance
CMMS	Computerized Maintenance Management System
COTS	Commercially Off the Shelf
DCA	Defense Critical Assets
DCI	Defense Critical Infrastructure
DISLA	Defense Infrastructure Sector Lead Agent
DOD	Department of Defense
FAR	Federal Acquisition Regulation
HQUSAE	United States Army Corp of Engineers
ID/IQ	Indefinite Delivery/ Indefinite Quantity
KPI	Key Performance Indicator
LORA	Level of Repair Analysis
M&E	Mechanical and Electrical
MAC	Multiple Award Contracts
MTBF	Mean Time Between Failure
MTTF	Mean Time to Repair
NAVFAC	Naval Facilities Engineering Command

O&M	Operations and Maintenance
RFID	Radio Frequency Identification Device
ROI	Return on Investment
PM	Preventive Maintenance
PBL	Performance Based Logistics
PBMC	Performance-Based Maintenance Contracts
PWD	Public Works Department
QDR	Quadrennial Defense Review
RCM	Reliability Centered Maintenance
RTF	Run to Failure
TBM	Time-Based Maintenance
TCA	Task Critical Assets
UAV	Unmanned Aerial Vehicle
VRV	Variable Refrigerant Volume

EXECUTIVE SUMMARY

DOD Directive Number 3020.40 defines defense critical assets "as an asset of such extraordinary importance to operations in peace, crisis, and war that its incapacitation or destruction would have a very serious, debilitating effect on the ability of the Department of Defense to fulfill its missions." As such, the high availability of critical infrastructure such as fuel, airfield, power, water, cooling, blast protection, and fire protection must be achieved.

Three maintenance approaches commonly used to perform operations and maintenance are compared, namely the no-preventive maintenance (corrective maintenance (CM) performed upon failure), time-based maintenance (maintenance performed according to time norm) and condition-based maintenance (maintenance performed based on feedback from sensors) approaches. The comparison, based on cost and availability, suggests a possible approach and the implementation means to ensure high availability of critical infrastructure in the support of key military operations In general, this research indicates that cost increases and availability declines with increasing maintenance; and further that a suitable maintenance approach should be chosen for each DOD system.

Koeneman, in his 2009 master's thesis, "An Analysis of Sensor Effectiveness to Inform a Predictive Maintenance Policy," found that the use of effective sensors used on ships could increase operational availability significantly for systems with unobservable failure on ships, but only a smaller increase in availability for systems with observable failure on ships.

A sensitivity analysis was conducted which validated Koeneman's (2009) findings for ships that condition-based maintenance can result in a significant increase in operational availability as compared to the no-preventive maintenance approach, and a larger increase as compared to the time-based maintenance approach. This validation of the sensitivity analysis performed for critical infrastructure shows that the use of condition-based maintenance results in higher availability than either the time based or no maintenance-based strategies.

Further, the analysis show that a reduction in logistics delay time and administrative delay time can result in an increase of the operational availability that is significant to critical infrastructure as it can impact the operations of system using the critical infrastructure as a key resource.

While Koeneman suggested the use of condition-based maintenance for systems with unobservable failure, where a consistently accurate sensor could be identified and integrated, this thesis suggests incorporating a risk-adjusted cost analysis based on Langford in his 2012 book *Engineering System Integration, Theory, Metrics and Methods* in which he used loss functions to quantify the risk due to failure of systems (Appendix A).

From the perspective of risk-adjusted cost analysis vs. the cost of implementation, the cost of failure for the condition-based maintenance approach is compared with that of the time-based maintenance approach (Appendix C). The same risk-adjusted cost analysis perspective is also recommended for the condition-based maintenance for systems with observable failure vice the no-preventive maintenance approach. Hence, systems with observable failure can be maintained using the no-preventive maintenance approach, while the condition-based maintenance approach could also be adopted if the risk of failure is high.

Further, systems with unobservable failure can be maintained using the time-based maintenance approach, while the condition-based maintenance approach could also be adopted if the risk of failure is high. Regular inspections should be scheduled and performed on all systems. Specifically, the use of the no-preventive maintenance approach for the power distribution system is recommended unless the risk due to failure of the system outweighs the cost to perform condition-based maintenance in which case the condition-based maintenance approach should be chosen for the power distribution system. Condition-based maintenance approach is recommended for cooling systems, unless the risk due to failure of the system outweighs the cost to perform condition-based maintenance in which case the condition-based maintenance approach should be chosen for cooling systems. Blast doors, fire protection systems, water distribution systems, fuel distribution systems and airfield pavements should still be maintained using the time-based maintenance approach.

Finally, steps must be taken to reduce the mean down time for all systems to optimize the operational availability, particularly in the reduction of logistics delay time and administrative delay time.

The no-preventive maintenance approach requires the use of inspection and CM contracts, which can be contracted using the performance-based contract and the prescriptive contract, respectively. The time-based maintenance should comprise of the use of inspection, preventive maintenance (PM) and CM contracts, which can be contracted together as a single performance-based package. Condition-based maintenance should comprise the use of inspection, PM and CM contracts as a single package, of which the first two could be implemented using a performance-based contract and the latter a prescriptive contract.

The organization should be careful to reduce interdependent performance indicators across different contracts in the implementation of the performance-based contracts, as these are the key areas of conflict.

A proper configuration management scheme approved by a single approval agency is recommended for critical infrastructure, particularly for fuel, airfield, power, water cooling, blast protection and fire protection to prevent impacts on other systems. In particular, configuration management should be performed for both the acquisition of new systems and the implementation of system upgrades. At the same time, there should be a single approving party as a gatekeeper for authorizing the use of the critical infrastructure. However, in the event the existing critical infrastructure is insufficient to support the new system, the critical infrastructure should be upgraded before the implementation of the new system. However, the cost of the critical infrastructure upgrade may be significantly more than that of the new acquisition project. Hence, it is recommended to have a separate fund for the purpose of an upgrade to the critical infrastructure.

Management approaches to increasing availability and types of outsourcing contracts are also found to be important (Appendix B). A computerized maintenance management system can be an important tool for the maintenance approach and the contract management. It should be used as a process management system that enforces the use of the system over the entire process, and enforce updates to a system record during the process of CM, PM and inspections to maintain an accurate inventory.

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I. INTRODUCTION

DOD Directive Number 3020.40 defines Defense Critical Assets "as an asset of such extraordinary importance to operations in peace, crisis, and war that its incapacitation or destruction would have a very serious, debilitating effect on the ability of the Department of Defense (DOD) to fulfill its missions." As such, the high availability of critical infrastructures such as fuel, airfield, power, water, cooling, blast protection, and fire protection systems must be achieved.

DOD Instruction Number 4151.22 mandated the use of Condition-Based Maintenance Plus (CBM+) as a principal consideration "in the selection of maintenance concepts, technologies and processes for all new weapon systems, equipment and materiel programs based on readiness requirements, life cycle cost goals, and Reliability Centered Maintenance (RCM) based functional analysis" formulated in a comprehensive reliability and maintainability engineering program.

In optimizing the frequency of maintenance, condition-based maintenance identifies where a need for maintenance of a system arises, thereby reducing the cost compared to properly timed but not truly needed maintenance. Since unneeded maintenance is eliminated, there is a reduction in downtime of a system; the availability of the system is increased.

However, condition-based maintenance may not be the single best maintenance approach to achieving high availability for a particular system. This thesis discusses the relevance of three maintenance approaches for critical infrastructure for high availability and to propose the methods for their implementation.

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II. LITERATURE REVIEW

A. AVAILABILITY

High availability is achieved by minimizing downtime. This availability could be done through design, configuration management and maintenance management.

Blanchard (2008) gave three definitions for the availability of a system, namely inherent availability, achieved availability and operational availability.

Inherent availability is impacted primarily by the system design and the repair time. Blanchard defined inherent availability as:

$$A_i = \frac{MTBF}{MTBF + \bar{M}_{ct}} \tag{1.1}$$

where A_i represents inherent availability, *MTBF* represents the mean time between failure, and indicates reliability, and $\bar{M}_{ct}$ represents the mean corrective maintenance (CM) time or the mean time to repair. Blanchard (2008) also cautioned that the inherent availability may not be as relevant as operational availability. This is because operational availability includes downtime associated with preventive maintenance (PM) and the associated administrative and logistics downtime.

The *MTBF* is primarily determined during the design and development stage and could not be impacted easily downstream. However, an increase to the load of the system or a deterioration of system effectiveness during the operations and maintenance stage could lead to a decrease in *MTBF*. For example, a household circuit breaker may be designed to withstand the power requirement of a refrigerator. When a kettle and a toaster oven are added to the circuit breaker, the overall load may exceed the capability of the circuit breaker, and lead to a decrease in *MTBF*. The design is assumed to be robust, so in the example above, the circuit breaker is designed to meet the requirements for the simultaneous operations of the refrigerator, toaster and kettle. Hence, configuration management principles should be applied in the operations and maintenance phase to prevent future overload, i.e., operating more systems than the refrigerator, toaster and kettle at the same time.

This thesis notes that the $\bar{M}_{ct}$ should be kept low to achieve the highest A_i. However, $\bar{M}_{ct}$ is highly dependent on systems, training, organizations and policies. Hence, $\bar{M}_{ct}$ is assumed to be fixed. The influence of $\bar{M}_{ct}$ on availability is a recommended topic for future exploration.

To take into consideration system deterioration, Blanchard's (2008) view is adopted that achieved availability would be a better indicator than inherent availability. Achieved availability is impacted primarily by corrective and PM. Blanchard defined achieved availability as:

$$A_a = \frac{MTBM}{MTBM + \bar{M}} \tag{1.2}$$

where A_a represents achieved availability, $MTBM$ represents the mean time between maintenance and $\bar{M}$ represents the mean active maintenance time. Again, Blanchard (2008) cautioned that the achieved availability may not be as relevant as operational availability. However, A_a is important from an Operations and Maintenance (O&M) point of view as the O&M community's influence on logistics delay time and administrative delay time.

Both $MTBM$ and $\bar{M}$ are influenced by corrective and PM. Platis et al. (2014) propose a two tiered PM model to achieve the best cost effectiveness and availability and Eti et al. (2006) recommends for good maintenance management for the Nigerian industries, showing the importance of PM in maintaining reliability and achieving high availability. The importance of PM in achieving high availability is recognized and will discuss the different maintenance approaches, namely the no-preventive maintenance approach, the time-based maintenance approach and the condition-based maintenance approach in detail.

The other factor that impacts A_a is maintainability. United States (U.S.) Army Materiel Command defines maintainability as "a characteristic of design and installation which imparts to a system or end item a greater inherent ability to be maintained, so as to lower the required maintenance man-hours, skill levels, tools, facilities, and logistics costs, and to achieve greater mission availability" (1976, 1–1). A robust design with maintainability built into the systems is assumed and this thesis will not be discussing maintainability in detail.

Further, the Department of Defense Handbook – Level of Repair Analysis (LORA) (2015) states that if LORA “analysis recommends a repair decision, the LORA process continues to the optimum repair level (i.e., depot, intermediate, organizational) according to the service repair requirements.” Hence, competency of staff performing the O-level, I-level, D-level maintenance would greatly impact both A_a and A_i. However, competency issues that are sometimes a major factor in carrying out maintenance will not be discussed in detail as it assumes the use of contracting mechanisms to implement the maintenance activities, where competency requirements are built into the contract specifications.

While PM can be performed through outsourcing or with in-house capabilities, the focus of this thesis is the outsourced mode, which the author recognizes from his personal experience is the general direction building maintenance is moving to. As such, the different types of outsourcing available in the Building and Infrastructure (B&I) market will be discussed.

Operational availability is impacted not only by corrective and PM but also by logistics delay time and administrative time. Blanchard (2008) defined operational availability as:

$$A_o = \frac{MTBM}{MTBM + MDT} \tag{1.3}$$

$$A_o = \frac{Uptime}{Uptime + Downtime} \tag{1.4}$$

where A_o represents operational availability, $MTBM$ represents the mean time between maintenance and MDT represents the mean down time. A_o offers the most representative view of the situation, and includes all downtime. However, the key difference between A_o and A_a is logistics delay time and administrative time. Logistics delay time and administrative time are highly dependent on systems, training, organizations and countries. Hence, logistics delay time and administrative down time is assumed to be fixed.

B. CRITICAL INFRASTRUCTURE

Different organizations define critical infrastructure differently, and manage them differently. In the area of defense, they are managed via the services which require them.

DOD Directive Number 3020.40, *Policy and Responsibilities for Critical Infrastructure*, (2010) defines the "framework of interdependent physical and cyber-based systems comprising identifiable industries, institutions (including people and procedures), and distribution capabilities that provide a reliable flow of products and services essential to the defense and economic security of the U.S., to the smooth functioning of government at all levels, and to society as a whole."

Defense Critical Assets – DOD Directive Number 3020.40 (2010) defines "defense critical assets (DCA) as an asset of such extraordinary importance to operations in peace, crisis, and war that its incapacitation or destruction would have a very serious, debilitating effect on the ability of the Department of Defense to fulfill its missions."

Task Critical Assets – DOD Directive Number 3020.40 (2010) defines task critical asset (TCA) as "an asset that is of such extraordinary importance that its incapacitation or destruction would have a serious, debilitating effect on the ability of one or more DOD Components or DISLA organizations to execute the task or mission-essential task it supports. Task critical assets are used to identify defense critical assets."

Critical Infrastructure – section 1016(e) of the USA Patriot Act of 2001 (42 U.S.C. 5195c(e)), identifies critical infrastructure "as systems and assets, whether physical or virtual, so vital to the U.S. that the incapacity or destruction of such systems and assets would have a debilitating impact on security, national economic security, national public health or safety, or any combination of those matters;" Executive Order EO 13010, 1996 "*Critical Infrastructure Protection"* lists "telecommunications, electrical power systems, gas and oil storage and transportation, banking and finance, transportation, water supply systems, emergency services" as critical infrastructure.

DOD Directive Number 3020.40 (2010) defines "Defense Critical Infrastructure (DCI) as the composite of DOD and non-DOD assets essential to project, support, and sustain military forces and operations worldwide. DCI is a combination of task critical assets and defense critical assets."

The type of critical infrastructure differs greatly amongst the different services. To limit the complexity of analysis, this thesis will concentrate on some of the common critical infrastructure: fuel, airfield, power, water, cooling, blast protection and fire protection systems.

The electrical power component of critical infrastructure generally consists of the power generation network and power distribution network. The power generation network and power distribution network were part of the B&I assets in a military base, which provided power for military platforms such as radar systems, Command, Control, Communications and Intelligence (C3I) and Unmanned Aerial Vehicle (UAV) control systems. Contingencies and backup power supplies for these platforms can include uninterrupted power supply by the platform, as well as backup fixed and mobile generators by B&I.

Further, C3I systems are heavy consumers of power and generate huge amount of heat. As overheating severely interferes with the performance of, or even cause damage to, the C3I system, cooling became critical to the continued good performance of the C3I system. Due to the large cooling load of these systems, chillers plants (large centralized air conditioning systems) and computer room air conditioning were required. The running of the chiller plants also requires the use of huge amounts of power and water, both of which are part of critical infrastructure and provided for by B&I.

Fire protection services are key safety requirements in any operations based in a building. Fire protection systems such as fire detection systems, inert gas fire suppression systems, sprinkler systems require use of power and/or water for the protection of lives and equipment. There are serious safety and risk implications in the event of the failure of the fire protection systems, which are dependent on critical infrastructure, namely power and water.

Fuel distribution networks provide jet fuel to aircraft and diesel to ships, and are also part of critical infrastructure provided for by B&I. While failure of fuel distribution networks could be mitigated with bowsers (tankers) and mobile fuel dispensers, these are temporary measures whose performance would not match that of the fuel distribution networks.

The importance of interoperability within and without B&I is even more pronounced when renovation and upgrades are constantly being performed over the lifespan of the B&I, and new technology interfaces with older technology. For example, the use of newer and higher capacity Variable Refrigerant Volume (VRV) air conditioning (or multi split units) to replace central air conditioning such as air/ water cooled packaged units and chiller plants often results in higher variation in loads and high power requirements which increases the load on the power distribution system. As the power distribution system also supplies power to other platforms beyond the control of B&I, there may be operational impacts requiring a system-of-systems analysis. On the other hand, an upgrade of the C3I design to create a new data center would require additional power, cooling or fire protection. The impact on other platforms and B&I must also be considered in such a scenario.

Further, while most systems require power to operate, the type of power can vary greatly across that of different systems. For example, a U.S. product generally uses the 110V power supply, while one in Singapore uses a 220V power supply. While this disparity could be fixed easily using a good power transformer, it should be taken care of during the design/ acquisition phase. Further, maritime platforms generally utilized a 60Hz frequency, while radar systems utilized a 400Hz frequency. The range of power frequencies required for the operations of systems using the standard 50Hz power supply from most power grids leads to the need for frequency convertors to be used to ensure the power provided to the platforms meet the intended requirements.

The configuration management of critical infrastructure must be holistic and comprehensive enough to ensure that the capacity of critical infrastructure is sufficient to contain the requirements of the various platforms integrating and interoperating with it and those that must take place throughout the life cycle of the critical infrastructure. The life cycle of critical infrastructure started at the design phase, which included integration and interoperability with existing systems, and takes into consideration redundancies required for future upgrades. The O&M of the critical infrastructure then comes into play to ensure good maintenance of the critical infrastructure and that future integration to the existing critical infrastructure remained within the ability of the critical infrastructure to maintain high availability. In the event the configuration management process determines that the critical infrastructure is unable to sustain future capabilities, the critical infrastructure could be retired or upgraded.

C. MAINTENANCE APPROACHES

Maintenance can be classified into two key types: CM and PM. However, maintenance approaches differ in two areas, namely how PM is done and how monitoring is done. With these two parameters, the following maintenance approaches are determined.

1. No-Preventive Maintenance Approach

Depending on the system and requirements for availability, PM may or may not be a necessity. Koeneman (2009) compared the “Run to Failure” (RTF) model, a traditional maintenance policy model where CM is the only maintenance done on a system, and only when it fails, and the condition-based maintenance model where maintenance is only performed when signals from sensors indicate the need. His study, which is based on the maintenance of ships suggested that the RTF approach could be used for systems where failure is observable resulting in a 94% operational availability, as opposed to a 97% operational availability from a condition-based maintenance approach assuming a good sensor is available. If a 3% increase in operational availability is insufficient to justify for the additional cost of implementing a condition-based maintenance approach, following an RTF approach for systems with observable failures may be a good choice. This type of RTF is classified here as a no-preventive maintenance approach, where a system is left to operate until failure. Then CM is performed on the system to restore the condition to normal. The CM performed here is generally replacement work, where components, subsystems or the entire system is immediately replaced to reduce the impact on availability. On site repair should not be considered for this case, as this would lead to additional downtime.

Koeneman (2009) also suggested that mean cost to repair a failed system from an RTF approach would incur up to three times the cost to repair a system which is predicted to fail. From experience in building systems, this outcome is heavily dependent on the frequency of failure versus the frequency of warning. It is also a function of the type of repairs being performed. For example, switch gears or air circuit breakers in a Low Tension (LT) switch room are generally very reliable and are seldom repaired because the cost of a replacement is low and results in a lower life cycle cost. Further, power distribution systems are generally modular in nature where switch gears and circuit breakers could be isolated and replaced within a short period of time, which makes the power distribution system a possible candidate for the no-preventive maintenance approach.

2. Time-Based Maintenance (TBM)

Time-based maintenance (TBM) could be grouped into two distinct types, namely time-based PM and time-based CM. Koeneman (2009) suggested that failures that are not observable could result in an 83% operational availability using inspections. This model of TBM is primarily time-based PM where inspections are scheduled and conducted on a regulated basis and CM performed as and when inspection determines the necessity.

The other type of time-based maintenance is time-based CM. Zhuang et al. (2011) suggested that TBM is done when each component is replaced after serving for a predetermined period. His idea of time-based maintenance is identified in this thesis as time-based CM. This type of time-based CM could again be divided into two categories, namely those requiring regular PM, and those that do not. For example, switch gears and air circuit breakers are those that do not require PM because they are designed in a modular black box, and are in continuous operations in an enclosed switchboard throughout their life.

The third type of time-based maintenance includes both PM and CM, which Koeneman (2009) referred to as proactive maintenance. This definition of proactive maintenance only targets one aspect of proactive maintenance. Swanson (2001, 238) defined proactive maintenance as “a strategy for maintenance whereby breakdowns are avoided through activities that monitor equipment deterioration and undertake minor repairs to restore equipment to proper condition.” Swanson (2001) further elaborated that “these activities, including preventive and predictive maintenance, reduce the probability of unexpected equipment failures.” As suggested by Swanson (2001), predictive maintenance is synonymous with condition-based maintenance. However, it is clear from her definition that time based maintenance that comprises both PM and CM is generally known as PM.

Many articles, including those by Koeneman (2009) and Swanson (2001), as well as books such as Blanchard and Fabrycky (2010) theorize that PM increases the life of a system. The premise that PM increases the life of a system is used as the basis of the argument for TBM as a maintenance strategy.

3. Condition-Based Maintenance (CBM)

Swanson (2001) defined condition-based maintenance as maintenance initiated in response to a specific equipment condition. Koeneman (2009) further suggested the use of sensors to determine the condition of the system. He gave examples of an increase in operational availability of up to 3% over the no-preventive maintenance approach for systems with observable failures, and up to 9% over the PM approach. Zhuang et al. (2011) also suggested that their simulation results based on their predefined parameter show that condition-based maintenance outperforms time based maintenance when diagnostic error of the sensor is low. Hence, the effectiveness of condition-based maintenance would only work as well as the sensor deployed. Swanson (2001) cited examples of physical parameters from Eade (1997) that could be measured by sensors under condition-based maintenance, namely heat, sound, vibration and corrosion. While some of these physical parameters such as temperature could be taken with hand-held devices (and hence tie in with PM), most of the sensors would be more effectively implemented as part of the design. As such, the enhanced design entails additional cost which must be considered over the life cycle of the system.

DOD Instruction Number 4151.22 mandated the use of CBM^+ as a principal consideration "in the selection of maintenance concepts, technologies and processes for all new weapon systems, equipment and materiel programs based on readiness requirements, life cycle cost goals, and" Reliability Centered Maintenance "(RCM) based functional analysis" formulated in a comprehensive reliability and maintainability engineering program.

4. Reliability Centered Maintenance

DOD Manual Number 4151.22-M defines RCM “as a logical, structured process to determine the optimal failure management strategies for any system, based on system reliability characteristics and the intended operating context.” It “is a continuous process that requires sustainment throughout the life cycle,” and “uses design, operations, maintenance, engineering, logistics, and cost data to improve operating capability, design and maintenance.” In essence, RCM is a concept to analyze a system to identify the best means to maintain, operate or modify it so that the functionality of the system is maintained. As such, RCM becomes an enabler to the use of CBM, and is not truly a maintenance approach. Hence, the focus will be on CBM instead of RCM.

D. MAINTENANCE CONTRACTS

Outsourced maintenance contracts can take many forms but are primarily divided into traditional (prescriptive) contracts and performance based (outcome based) contracts.

Straub and van Mossel (2005, 350) state that traditional maintenance contracts encompass “detailed description or specification of work to be performed, procurement by means of competitive tender, role of the maintenance contractor is limited to the actual work, and the objective is to achieve the lowest price or best price-quality ratio.”

In contrast, they state that performance based contracts encompass “performance agreement based on standard activities and unit prices, cooperation with a selected group of maintenance contractors, contracts valid for one or two maintenance intervals, the maintenance contractor contributes to the planning process, the objectives are improved quality, direct cost reductions, budgetary certainty and the development of sustainable relationships.”

Hyman (2009, 4) states that “performance-based maintenance contracting (PBMC) is a contracting method that provides incentives and/or disincentives to the contractor to achieve desired outcomes or results. In its purest form, PBMC does not detail how, when or where to do the work.” The *Performance Based Logistics (PBL) Guidebook* (2014) states that “PBL has been the preferred sustainment strategy since the 2001 Quadrennial Defense Review (QDR).” The *QDR* (2001) states that “DOD will implement PBL to compress the supply chain and improve readiness for major weapons systems and commodities. Since then, it has been both DOD policy and a strategic priority to increase the use of performance-based arrangements to deliver product support solutions that satisfy warfighter requirements." Kennedy and McClure (2005) further stated that a performance based contract should minimally comprise a performance work statement, performance measurement factors and standards, incentives, disincentives or penalties, and a quality assurance plan. Hence, a performance based contract would require things to measure, means to measure, a predefined "carrot and stick" and means to ensure quality.

The outcomes of traditional contracts and performance based contracts are similar, but the processes greatly differ. With traditional contracts, while work is implemented by contractors, responsibility for the availability of the systems remains with the owner. Hence, the owner would still be the decision maker regarding the work being performed. Performance based contracts, however, transfer responsibilities to the contractors, who will be the key decision makers about when and how work will be done to achieve the performance measures stated in the contract. Straub and van Mossel (2005, 348) argue that contractors "become active participants in the overall maintenance process and assume certain risks and responsibilities with regard to the quality and costs of maintenance activities, doing so for a long period" whenever possible. They cited examples such as contractors providing improvement in "performance and service and innovations in the whole maintenance process by having continuity in orders and cultivating sustainable relationships with clients." Both "have a common interest in developing performance based concepts and suitable instruments for performance measurement."

Kennedy and McClure (2005) offered examples of performance based contracts that could be implemented that are grouped either fixed-priced contracts or cost-reimbursement contracts, namely firm fixed priced contracts, fixed priced contracts with provisions for economic price adjustment, fixed price incentive fee contracts, cost-reimbursable contract, cost-plus-fixed-fee contract, cost-plus-incentive-fee contract, cost-plus-award-fee contract, cost-sharing contract, cost-without-fee contract, cost-plus-award-term contract, hybrid ID/IQ cost-plus-performance-fee task order contract, ID/IQ cost-plus-fixed-fee task/delivery order contract (non-performance-based contract), and hybrid ID/IQ multi-format task/delivery order contract. Each contracting mechanism has its own advantages and disadvantages, and detailed analysis should be done to ensure that the correct tool is used for maximum benefit to the organization.

E. DOD MAINTENANCE AGENCIES

B&I belonging to the U.S. DOD were managed by the United States Army Corp of Engineers (HQUSACE), Naval Facilities Engineering Command (NAVFAC) and the Air Force Civil Engineering Center (AFCEC) who were responsible for the B&I of the Army, the Navy and the Air Force, respectively.

Information from HQUSACE could not be found in open literature. Hence, analysis will be performed on the maintenance approaches adopted by NAVFAC and AFCEC.

NAVFAC utilized a condition-based maintenance approach for its B&I, primarily with outsourced contractors. NAVFAC states some of the product lines under the public works business line such as facilities management and sustainment – building and specialized infrastructure maintenance, energy management and sustainability, condition-based maintenance management and workforce efficiency initiative metrics, utilities and energy management - utility commodities and infrastructure, energy management and conservation, industrial control systems operations and maintenance, facility support contract management and facility services – base operations contracting, deliberate planning via regional acquisition strategies, standard contract templates. The NAVFAC Public Works Department (PWD) Management Guide states the need for work orders to be issued for work to be done, which is managed by the PWD. The work order can initiate from condition assessment by PWD, Architects-Engineers, or Naval Facilities Engineering Service Center; or from system failure reports from supported commands. Hence, there is a robust means of pre-emptive inspection to assess condition of B&I, as well as ongoing inputs from the supported commands.

Higdon (2007, 5) found that other real estate related work were primarily outsourced via facilities services contracts or base operations and support contracts, such as "emergency/service work reception desk, maintenance, repair, alteration and construction of real property, maintenance of grounds, grounds structures, surfaced areas and pest control, utilities systems operations and maintenance, transportation operations and maintenance, family housing maintenance, storage and warehousing, supply operations, environmental, refuse services, weight handling, custodial services and grounds maintenance.” In summary, NAVFAC generally outsources the maintenance activities of the B&I facilities within the naval bases.

Smith (2012) highlighted that NAVFAC follows the performance based contracting mechanisms, showing that NAVFAC focuses their attention on maintenance planning and management, as well as on inspections to take pre-emptive action to perform CM.

However, Smith also highlighted that need of a five-year limit on single award service contracts and multiple award contracts (MACs) that brings about increased work for the acquisition teams. The key problem the five year limit creates is the issue of continuity and knowledge management issues during contract renewal, which should be planned for and mitigated.

The AFCEC utilized a condition-based maintenance approach for its B&I with in-house engineers. Air Force Instruction 32–1001, *Operations Management* (2004) mandates the Operations Flight to assess the condition of all assets requiring PM. Air Force Instruction 32–1001 (2004, 5) also states that PM tasks must be “defined, standardized, balanced, scheduled, monitored, and measured addressing life-cycle management and ROI” the PM tasks as part of the PM program. Air Force Instruction 32–1001 (2004 pp.3) also mandates that “Staffing for the Operations Engineering element must include a civil, mechanical, and electrical engineer as well as technicians from CEOHS, CEOHP, CEOIU, CEOIH and CEOF.” Hence, the PM of most M&E equipment in the Air Force is performed in-house. With proper prioritization of works and sufficient well-trained manpower, all required PM tasks should be timely completed and maximum availability achieved, *ceteris paribus*.

AFCEC states that it is privatizing the operations and maintenance of utilities, namely water, wastewater, electric and natural gas utility systems, as opposed to being responsible for in-house utility operations. However, Air Force military civil engineers still receive training on the privatized system when training is included in the utility services contract, which makes sense as it allows redundancies in the event of emergency. The AFCEC also states that housing for the Air Force has been privatized.

The privatization creates partners for 50-year agreements, which should allow for continuity in the long run. However, during contract renewal, a loss in continuity can occur when trained workers with relevant experience and context in the system leave the service and new workers replace them. Continuity must hence be built into the system during the planning phase for such long term contracts.

III. CURRENT ISSUES FACED

Availability of systems can be impacted by the maintenance approach as well as the type of contract and its management approach. The maintenance approach is determined primarily by the maintenance approach adopted by the agency. The two approaches adopted by the NAVFAC and AFCEC, which were primarily the time-based maintenance and condition-based maintenance will be compared with the no-preventive maintenance approach.

B&I maintenance could be done in-house or through outsourced contractors. For example, NAVFAC works primarily through outsourced contractors, while AFCEC works primarily with in-house staff. With the growing dependence on outsourced contractors for maintenance activities, a key focus by the operational organizations is to manage contractors to ensure an acceptable quality of work. On the other hand, with the increasing shortage of manpower, in-house maintenance is increasingly overloaded and prioritization of tasks is required, which is clearly demonstrated by AFCEC's prioritization of PM assets, and to focus on PM and sustainment work before addressing enhancement work. The differences between the various types of contracting mechanisms and the means to ensure high availability of critical infrastructure is discussed (Appendix A).

Finally, a computerized maintenance management system suitable for military B&I is discussed in the context of providing an effective configuration management, maintenance management, and contracts management support. The requirements of the CMMS to enable high availability of critical infrastructure is also discussed (Appendix A).

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IV. PURPOSE

B&I is a complex domain to decipher and manage. The purpose of this research is to determine if there is a best maintenance approach coupled with the appropriate contract and management approach to ensure the high availability of critical infrastructure, through a sensitivity analysis on the operational availability to validate Koeneman (2009)'s findings that condition-based maintenance can increase availability as opposed to no-preventive maintenance and time-based maintenance. **

The three key maintenance approaches for performing operations and maintenance are analyzed based on the results of the sensitivity analysis for suitability for different critical infrastructure, namely fuel, airfield, power, water, cooling, blast protection and fire protection systems. In addition, the suitability of contracts for different maintenance approaches, as well as the use of computerized maintenance management systems and configuration management are discussed for a more holistic means of ensuring high availability of critical infrastructure in the support of key military operations.

Maintenance contracts and management approaches are discussed in Appendix B.

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V. COMPARISON OF CURRENT BUILDING MAINTENANCE APPROACH

This section defines the different types of building maintenance approaches and contracting mechanisms analyzed and makes a comparison of the types of approaches and contracts in general, and hence identifies the scope of analysis.

A. COMPARISON BETWEEN MAINTENANCE APPROACHES

Different maintenance approaches provide different results, and can be **viewed** from various aspects. The key aspects analyzed here are availability and cost.

1. Availability

The impact of maintenance approaches on availability is primarily focused on the downtime due to preventive and CM. Koeneman (2009) found CBM could increase the operational availability of a system with observable failure by 3% as compared to a no-preventive maintenance approach, and could also increase the operational availability of a system with unobservable failure by up to 25% as compared to TBM. This section takes the Koeneman study further by generating a sensitivity analysis of operational availability resulting from a change in parameters, namely the frequency of preventive and corrective maintenance and the time to perform the preventive and corrective maintenance.

The variables chosen for this sensitivity analysis are based on the formal definitions of availability from Blanchard and Fabrycky (2010). Alhouli (2011) suggested maintenance on ships to be performed daily for hours at a time. For example, when the corrective maintenance is performed daily, and the average time to perform corrective maintenance is reduced from 2 hours to 1.5 hours, the operational availability changes from 92% to 94%, which corroborates with Koeneman's data.

When condition-based maintenance approach is conducted in place of no-preventive maintenance approach, the expected change is a reduction in frequency of maintenance and a possible decrease in time to perform maintenance. Similarly, when condition-based maintenance approach is conducted in place of time-based maintenance approach, the expected change is also a reduction in frequency of maintenance and a possible decrease in time to perform maintenance. When time-based maintenance approach is conducted in place of no-preventive maintenance approach, the expected change would be a reduction in operational availability through the increase in downtime for preventive maintenance as well as a corresponding decrease in downtime through the decrease in frequency of corrective maintenance.

This study will be using values from maintenance data common in building and infrastructure to perform the sensitivity analysis. The results will then be matched in section-d with the adoption of the three maintenance approaches, namely the no-preventive maintenance approach, the time-based maintenance approach, the condition-based maintenance approach, to compare the impact of their implementation on operational availability.

One of the assumptions for the analysis is that the frequency of performing corrective maintenance is significantly less than the frequency of performing preventive maintenance. For example, preventive maintenance can be performed on monthly, two-monthly or quarterly, while corrective maintenance can be performed on annual, two-yearly or even longer periods. Further, preventive maintenance is assumed to be completed in hours, while corrective maintenance can take days to complete. A specific example of an air-conditioner with planning for 5 years of corrective maintenance, a quarterly preventive maintenance, one hour to perform preventive maintenance, and one day to perform corrective maintenance will be used in the analysis to simulate a typical building M&E system.

To take into consideration different complexity in both preventive and corrective maintenance, the time to perform preventive maintenance will be varied from one to five hours, and the time to perform corrective maintenance will be varied from one to 20 days. The lack of preventive maintenance is assumed to cause increased frequency of corrective maintenance, as well as time to perform corrective maintenance. It is also assumed that good sensors that are 100% effective in sensing impending failure are available for the implementation of condition-based maintenance for both preventive maintenance and corrective maintenance, which can reduce the frequency of preventive and corrective maintenance. As such, the mean time between corrective maintenance for the air conditioner is varied between two years and eight years, while the mean time between preventive maintenance is varied between one month and five months. Further, a good sensor can pre-empt failure of system, hence leading to the assumption that logistics delay time and administrative delay time is zero for systems with good sensors built in. These common inputs are used in the sensitivity analysis in the next section.

The frequency of CM and the time to perform CM could increase as a result of lack of PM, while the time to perform CM could also decrease as a result of the use of good sensors to implement a condition-based maintenance approach for system. Hence, the no-preventive maintenance approach is analyzed by assessing the change in availability due to the change in frequency of CM and time to perform the CM.

The frequency of PM and the time to perform PM could also result from a change in policy, or the implementation of good sensors to identify the time when PM is needed. Hence, the time-based maintenance approach is analyzed for changes to availability due to changes in the frequency of PM and time to perform the PM, keeping the frequency of CM and the time to perform CM constant.

The use of good sensors to implement a condition-based maintenance approach with both PM and CM can allow a decrease in frequency of CM and time to perform CM. Hence, the third case is analyzed for changes to availability due to changes in the frequency of CM and time to perform the CM, keeping the frequency of PM and the time to perform PM constant.

a. Sensitivity Analysis on Availability from changes to MDT and MTBM When No Preventive Maintenance is Done

From equation 1.3, Blanchard and Fabrycky (2010) define the total maintenance downtime (*MDT*) as

$$MDT = \bar{M} + LDT + ADT \tag{1.5}$$

The mean active maintenance time $\bar{M}$ is defined as

$$\bar{M} = \frac{\lambda\left(\bar{M}_{ct}\right) + fpt\left(\bar{M}_{pt}\right)}{\lambda + fpt} \tag{1.6}$$

where $\bar{M}_{ct}$ denotes the mean CM time and $\bar{M}_{pt}$ denotes the mean PM time, λ is the failure rate or $\frac{1}{MTBF}$, and *fpt* is the rate of PM. When $fpt = 0$,

$$\bar{M} = \bar{M}_{ct} \tag{1.7}$$

Boensel, in his 2015 NPS lecture notes on "SE 3302 System Suitability." calculates the logistics delay time as

$$LDT = \frac{\lambda\left(LDT_c\right) + fpt\left(LDT_s\right)}{\lambda + fpt} \tag{1.8}$$

where LDT_c denotes the mean corrective logistics delay time and LDT_s denotes the mean scheduled logistics delay time. When $fpt = 0$,

$$LDT = LDT_c \tag{1.9}$$

Boensel also calculates the administrative delay time as

$$ADT = \frac{\lambda\left(ADT_c\right) + fpt\left(ADT_s\right)}{\lambda + fpt} \tag{1.10}$$

where ADT_c denotes the mean corrective administrative delay time and ADT_s denotes the mean scheduled administrative delay time. When $fpt = 0$

$$ADT = ADT_c \tag{1.11}$$

Hence, this gives rise to the equation when no preventive maintenance is done

$$MDT = \bar{M}_{ct} + LDT_c + ADT_c \tag{1.12}$$

Hence, when no preventive maintenance is done, the mean PM time is zero. The key impact to the operational availability is CM. From equation 1.3, the lower the *MDT*, the higher the availability of the system. The Mean Time Between Maintenance (*MTBM*) is used in place of MTBF in this section due to the fact that no preventive maintenance is performed.

A sensitivity analysis was done on *MDT* and *MTBM* based on a simple example of a newly installed split unit air conditioning system in an office. For this example, we assume the basic parameters $\bar{M}_{ct}$ = 1 day, LDT_c = 1 day, ADT_c = 1 day and *MTBM* = 5 years, which is based on the typical warranty period of 5 years for the compressor of the split unit air conditioning system. From equation 1.12, *MDT* = three days and *Ao* is obtained from equation 1.3. Changes in *Ao* due to *MDT* denote the relative percentage change in *Ao* resulting from a change in *MDT*, and the changes in *Ao* due to *MTBM* denote the relative percentage change in *Ao* resulting from a change in *MTBM*.

However, as $\bar{M}_{ct}$, *LDTc* and *ADTc* could vary due to delays from implementation, logistics and administrative issues such as downstream problems e.g., power overload, possible increase in down time due to the lack of PM, inability to obtain access to site, approval, performance of feasibility studies, *MDT* is varied from one to 20 days. Further, as the system could fail at times different from the warranty period, perhaps a shorter period as a result from more frequent failure due to lack of PM, or a longer period due to the use of a good sensor to implement the condition-based maintenance approach, *MTBM* is varied from two to eight years (three years away from the typical warranty period of five years). The results are shown in Table 1.

Table 1 Summary Results of Sensitivity Analysis When No Preventive Maintenance is Done

MDT **(day)**	***MTBM*** **(year (day))**	**Availability (*Ao*)** $A_o = \frac{MTBM}{MTBM + MDT}$	**Changes in *Ao* due to changes in *MDT*** $\frac{\Delta Ao}{\Delta MDT} = \frac{Ao(\mathrm{MDT} = i) - Ao(\mathrm{MDT} = 3)}{i-3}$	**Changes in *Ao* due to changes in *MTBM*** $\frac{\Delta Ao}{\Delta MTBM} = \frac{Ao(\mathrm{MTBM} = i) - Ao(MTBM = 5)}{i-5}$
1	5 (1825)	0.9995	-0.05%	-
2	5 (1825)	0.9989	-0.05%	-
3	5 (1825)	0.9984		-
4	5 (1825)	0.9978	-0.05%	-
5	5 (1825)	0.9973	-0.05%	-
6	5 (1825)	0.9967	-0.05%	-
7	5 (1825)	0.9962	-0.05%	-
8	5 (1825)	0.9956	-0.05%	-
9	5 (1825)	0.9951	-0.05%	-
10	5 (1825)	0.9946	-0.05%	-
11	5 (1825)	0.9940	-0.05%	-
12	5 (1825)	0.9935	-0.05%	-
13	5 (1825)	0.9929	-0.05%	-
14	5 (1825)	0.9924	-0.05%	-
15	5 (1825)	0.9918	-0.05%	-
16	5 (1825)	0.9913	-0.05%	-
17	5 (1825)	0.9908	-0.05%	-
18	5 (1825)	0.9902	-0.05%	-
19	5 (1825)	0.9897	-0.05%	-
20	5 (1825)	0.9892	-0.05%	-
3	8(2920)	0.9990	-	0.02%
3	7(2555)	0.9988	-	0.02%
3	6(2190)	0.9986	-	0.03%
3	5 (1825)	0.9984	-	-
3	4 (1460)	0.9979	-	0.04%
3	3 (1095)	0.9973	-	0.05%
3	2 (730)	0.9959	-	0.08%

The first set of data in Table 1 shows the changes in availability as a result from changes to *MDT* from one day to 20 days, while the second set of data shows the changes in availability as a result from changes to *MTBM* from two to eight years. The change in *Ao* resulting from an increase in *MDT* from one day to 20 days is from 99.9% to 98.9%, and the change in *Ao* resulting from a decrease in *MTBM* from eight years to two years is less than 0.2% and hence is small. The availability in this case is hence insensitive to changes in frequency of maintenance but is more sensitive to time required to perform maintenance, and the delays due to administrative and logistical issues.

Table 2 shows the relationships between availability and both *MDT* and *MTBM*, which suggests that a significant impact to availability of 2.5% can occur when *MDT* is varied from one day to 20 days, keeping *MTBM* at two years; while the corresponding impact to availability by keeping *MTBM* at eight years is 0.6%. Table 2 also shows a significant impact to availability of 1.9% can occur when *MTBM* is varied from eight years to two year, keeping *MDT* constant at 20 days. However, when *MDT* is kept constant at one day, the impact to availability is lowered to 0.2%. This analysis further suggests *MDT* should be kept low as changes in *MDT* can lead to significant impact to availability, while *MTBM* can still contribute to a significant decrease in availability when *MDT* is high.

Table 2 Table Summarizing Changes in Availability Due to Changes in *MDT* and *MTBM*

MDT(day)\MTBM(yr)	**2**	**3**	**4**	**5**	**6**	**7**	**8**
1	99.9%	99.9%	99.9%	99.9%	100.0%	100.0%	100.0%
2	99.7%	99.8%	99.9%	99.9%	99.9%	99.9%	99.9%
3	99.6%	99.7%	99.8%	99.8%	99.9%	99.9%	99.9%
4	99.5%	99.6%	99.7%	99.8%	99.8%	99.8%	99.9%
5	99.3%	99.5%	99.7%	99.7%	99.8%	99.8%	99.8%
6	99.2%	99.5%	99.6%	99.7%	99.7%	99.8%	99.8%
7	99.1%	99.4%	99.5%	99.6%	99.7%	99.7%	99.8%
8	98.9%	99.3%	99.5%	99.6%	99.6%	99.7%	99.7%
9	98.8%	99.2%	99.4%	99.5%	99.6%	99.6%	99.7%
10	98.6%	99.1%	99.3%	99.5%	99.5%	99.6%	99.7%
11	98.5%	99.0%	99.3%	99.4%	99.5%	99.6%	99.6%
12	98.4%	98.9%	99.2%	99.3%	99.5%	99.5%	99.6%
13	98.3%	98.8%	99.1%	99.3%	99.4%	99.5%	99.6%
14	98.1%	98.7%	99.1%	99.2%	99.4%	99.5%	99.5%
15	98.0%	98.6%	99.0%	99.2%	99.3%	99.4%	99.5%
16	97.9%	98.6%	98.9%	99.1%	99.3%	99.4%	99.5%
17	97.7%	98.5%	98.8%	99.1%	99.2%	99.3%	99.4%
18	97.6%	98.4%	98.8%	99.0%	99.2%	99.3%	99.4%
19	97.5%	98.3%	98.7%	99.0%	99.1%	99.3%	99.4%
20	97.3%	98.2%	98.6%	98.9%	99.1%	99.2%	99.3%

b. *Sensitivity Analysis on Availability from changes to $\bar{M}_{pt}$ and MTBMs When Corrective Maintenance is Constant*

From section-a, availability is insensitive to frequency of CM, but is more sensitive to time required to perform CM, and the delays due to administrative and logistical issues. Hence, the sensitivity of the frequency of PM and time required to perform PM is discussed.

By combining equations (1.5), (1.6), (1.8) and (1.10), we obtain

$$MDT = \frac{\lambda\left(\bar{M}_{ct} + ADT_c + LDT_c\right) + fpt\left(\bar{M}_{pt} + ADT_s + LDT_s\right)}{\lambda + fpt} \tag{1.13}$$

Blanchard and Fabrycky (2010) define

$$MTBM = \frac{1}{\dfrac{1}{MTBMu} + \dfrac{1}{MTBMs}} \tag{1.14}$$

Where *MTBMu* denotes the mean time between unscheduled (corrective) maintenance and *MTBMs* denotes the mean time between scheduled (preventive) maintenance. Combining these with equation 1.3, we obtain

$$A_o = \frac{1}{1 + \lambda\left(\bar{M}_{ct} + ADT_c + LDT_c\right) + fpt\left(\bar{M}_{pt} + ADT_s + LDT_s\right)} \tag{1.15}$$

A sensitivity analysis using the same example used in section-a was done on $\bar{M}_{pt}$ and *MTBMs* assuming the following parameters. $\bar{M}_{ct}$ = 1 day, LDT_c = 1 day, ADT_c = 1 day. For the purpose of this analysis, we assume as the air conditioner is functioning until the point of PM. Hence, *ADTs* = *LDTs* = 0. Based on the author's personal experience, the basic $\bar{M}_{pt}$ is assumed to be one hour. Similar to section-a, $MTBM_u$ = 5 years = 1825 days and based on the typical norm for air conditioning servicing in Singapore, $MTBM_s$ = three months = 90 days.

Ao is obtained from equation 1.3, while the changes in *Ao* due to $\bar{M}_{pt}$ is the relative percentage change in *Ao* resulting from a change in $\bar{M}_{pt}$, and the changes in *Ao* due to *MTBMs* is the relative percentage change in *Ao* resulting from a change in *MTBMs*. However, as $\bar{M}_{pt}$ could vary due to maintainability issues such as accessibility, $\bar{M}_{pt}$ is varied from one to eight hours. Further, as the system could be maintained at different frequencies other than the typical norm, the *MTBMs* is varied from 30 days to 150 days, two months away from the typical norm of three months. The results are shown in Table 3.

Table 3 Summary Results of Sensitivity Analysis when Corrective Maintenance is Constant

$\bar{M}_{pt}$ **(hour)**	$MTBM_s$ **(day)**	**Availability** $A_o = \dfrac{1}{1+\lambda\left(\bar{M}_{ct}+ADT_c+LDT_c\right)+fpt\left(\bar{M}_{pt}+ADT_s+LDT_s\right)}$	**Changes in Ao due to changes in** $\bar{M}_{pt}$ **:** $\dfrac{\Delta Ao}{\Delta \bar{M}pt} = \dfrac{Ao(\bar{M}pt=i)-Ao(\bar{M}pt=1)}{i-1}$	**Changes in Ao due to changes in** $MTBM_s$ $\dfrac{\Delta Ao}{\Delta MTBMs} = \dfrac{Ao(MTBMs=i)-Ao(MTBMs=90)}{i-90}$
1	90	0.99790	-	-
2	90	0.99744	-0.046%	-
3	90	0.99698	-0.046%	-
4	90	0.99652	-0.046%	-
5	90	0.99606	-0.046%	-
1	150	0.99810		0.000%
1	120	0.99801		0.000%
1	90	0.99790		
1	60	0.99767		-0.001%
1	30	0.99698		-0.002%

The first set of data in Table 3 shows the changes in availability as a result from changes to $\bar{M}_{pt}$ from one day to five days, while the second set of data shows the changes in availability as a result from changes to *MTBMs* from 30 days to 150 days. The change in *Ao* resulting from a change in $\bar{M}_{pt}$ and *MTBMs* is less than 0.2% and hence is small. The availability in this case is hence insensitive to the frequency of and time needed to perform PM.

Table 4 shows the relationships between availability and both $\bar{M}_{pt}$ and *MTBMs*., which suggests that a significant impact to availability of 1.0% can occur when $\bar{M}_{pt}$ is varied from one hour to eight hours, keeping *MTBMs* at 30 days, while the corresponding impact to availability by keeping *MTBMs* at 150 days is 0.2%. Table 4 also shows a significant impact to availability of 0.9% can occur when *MTBMs* is varied from 150 days to 30 days, keeping $\bar{M}_{pt}$ constant at eight hours. However, when $\bar{M}_{pt}$ is kept constant at one hour, the impact to availability is lowered to 0.1%. This analysis further suggests $\bar{M}_{pt}$ should be kept low and/or *MTBMs* should be kept high as changes in $\bar{M}_{pt}$ or *MTBMs* can lead to significant impact to availability when *MTBMs* is low or $\bar{M}_{pt}$ is high, respectively. This could be achieved by using condition-based maintenance to delay *MTBMs*.

Table 4 Table Summarizing Changes in Availability Due to Changes in $\bar{M}_{pt}$ and *MTBMs*

$\bar{M}_{pt}$ **(hr)\\ *MTBMs(days)***	**30**	**60**	**90**	**120**	**150**
1	99.7%	99.8%	99.8%	99.8%	99.8%
2	99.6%	99.7%	99.7%	99.8%	99.8%
3	99.4%	99.6%	99.7%	99.7%	99.8%
4	99.3%	99.6%	99.7%	99.7%	99.7%
5	99.1%	99.5%	99.6%	99.7%	99.7%
6	99.0%	99.4%	99.6%	99.6%	99.7%
7	98.9%	99.4%	99.5%	99.6%	99.6%
8	98.7%	99.3%	99.5%	99.6%	99.6%

c. *Sensitivity Analysis on Availability from changes to RT and MTBMu When Preventive Maintenance is Constant*

From section-b, the availability is insensitive to the frequency of and time needed to perform PM unless *MTBMs* is low or $\bar{M}_{pt}$ is high. As such, the sensitivity of availability to the frequency and time needed to perform CM when PM is being done is discussed. Assuming good sensors are used in CBM to identify when maintenance is required for a system to maximize the $MTBM_{u}$, this would result in the lowest possible *failure rate* as compared to the time-based maintenance approach. Let Repair Time: $RT = \bar{M}_{ct} + LDTc + ADTc$. Using the same example as above, and assuming the availability of a good sensor which can detect impending failure, an analysis was performed on the impact of *MTBMu* and *RT* on the availability, as the use of sensors allow CBM to maximize *MTBMu* in Table 5.

Table 5 Summary Results of Sensitivity Analysis when Preventive Maintenance is Constant

$RT = \bar{M}_{ct} + LDTc + ADTc$ **(day)**	$MTBMu$ **(year)**	**Availability:** $A_o = \frac{1}{1+\lambda\left(RT\right)+fpt\left(\bar{M}_{pt}+ADT_s+LDT_s\right)}$	**Changes in Ao due to changes in** RT: $\frac{\Delta Ao}{\Delta(RT)} = \frac{Ao(RT=i)-Ao(RT=1)}{i-1}$	**Changes in Ao due to changes in** $MTBMu$: $\frac{\Delta Ao}{\Delta MTBMu} = \frac{Ao(MTBMu=i)-Ao(MTBMu=90)}{i-90}$
1	**5**	0.9979	-	-
2	**5**	0.9974	-0.055%	-
3	**5**	0.9968	-0.055%	-
4	**5**	0.9963	-0.054%	-
5	**5**	0.9957	-0.054%	-
6	**5**	0.9952	-0.054%	-
7	**5**	0.9946	-0.054%	-
8	**5**	0.9941	-0.054%	-
9	**5**	0.9936	-0.054%	-
10	**5**	0.9930	-0.054%	-
11	**5**	0.9925	-0.054%	-
12	**5**	0.9919	-0.054%	-
13	**5**	0.9914	-0.054%	-
14	**5**	0.9909	-0.054%	-
15	**5**	0.9903	-0.054%	-
16	**5**	0.9898	-0.054%	-
17	**5**	0.9892	-0.054%	-
18	**5**	0.9887	-0.054%	-
19	**5**	0.9882	-0.054%	-
20	**5**	0.9876	-0.054%	-
1	2	0.9954	-	0.082%
1	3	0.9968	-	0.055%
1	4	0.9975	-	0.041%
1	**5**	0.9979	-	-
1	**6**	0.9982	-	0.027%
1	**7**	0.9984	-	0.023%
1	**8**	0.9985	-	0.020%

As $\bar{M}_{ct}$, *LDTc* and *ADTc* could vary due to delays from implementation, logistics and administrative issues such as downstream problems e.g., power overload, possible increase in down time due to the lack of PM, inability to obtain access to site, approval, performance of feasibility studies, *RT* is varied from one to 20 days in the first data set. Further, as the system could fail at times different from the warranty period, perhaps as a result from more frequent failure due to lack of PM, *MTBMu* is varied from two to eight years (a random number of three years away from the typical warranty period of five years) in the second data set. For example, picking a random number for illustrative purposes, increasing the *MTBMu* from two years to eight years can result in an increase in operational availability from 99.5% to 99.9%, which is more significant than the difference between the no-preventive maintenance approach and the condition-based maintenance approach in Table 1. Hence, PM tasks increases the sensitivity of changes in availability due to changes in frequency of CM. On the other hand, increasing *RT* from one day to 20 days would lead to a decrease in operational availability from 99.8% to 98.8%, which has similar sensitivity to that in section-b. Hence, PM tasks may not have a large impact on the sensitivity of changes in availability due to changes in *RT*. The availability in this case is hence insensitive to changes in frequency of CM but is more sensitive to time required to perform CM, and the delays due to administrative and logistical issues.

Table 6 Table Summarizing Changes in Availability Due to Changes in *RT* and *MTBMu*

RT(day)/MTBMu(yr)	2	3	4	5	6	7	8
1	99.5%	99.7%	99.7%	99.8%	99.8%	99.8%	99.9%
2	99.4%	99.6%	99.7%	99.7%	99.8%	99.8%	99.8%
3	99.3%	99.5%	99.6%	99.7%	99.7%	99.8%	99.8%
4	99.1%	99.4%	99.5%	99.6%	99.7%	99.7%	99.7%
5	99.0%	99.3%	99.5%	99.6%	99.6%	99.7%	99.7%
6	98.9%	99.2%	99.4%	99.5%	99.6%	99.6%	99.7%
7	98.7%	99.1%	99.3%	99.5%	99.5%	99.6%	99.6%
8	98.6%	99.0%	99.3%	99.4%	99.5%	99.6%	99.6%
9	98.5%	99.0%	99.2%	99.4%	99.5%	99.5%	99.6%
10	98.3%	98.9%	99.1%	99.3%	99.4%	99.5%	99.5%
11	98.2%	98.8%	99.1%	99.2%	99.4%	99.4%	99.5%
12	98.1%	98.7%	99.0%	99.2%	99.3%	99.4%	99.5%
13	97.9%	98.6%	98.9%	99.1%	99.3%	99.4%	99.4%
14	97.8%	98.5%	98.9%	99.1%	99.2%	99.3%	99.4%
15	97.7%	98.4%	98.8%	99.0%	99.2%	99.3%	99.4%
16	97.5%	98.3%	98.7%	99.0%	99.1%	99.3%	99.3%
17	97.4%	98.2%	98.7%	98.9%	99.1%	99.2%	99.3%
18	97.3%	98.2%	98.6%	98.9%	99.0%	99.2%	99.3%
19	97.2%	98.1%	98.5%	98.8%	99.0%	99.1%	99.2%
20	97.0%	98.0%	98.5%	98.8%	99.0%	99.1%	99.2%

Table 6 shows the relationships between availability and both *RT* and *MTBMu*, which suggests that a significant impact to availability of 2.5% can occur when *RT* is varied from one day to 20 days, keeping *MTBMu* at two year, while the corresponding impact to availability by keeping *MTBMu* at eight years is 0.7%. Table 6 also shows a significant impact to availability of 2.2% can occur when *MTBMu* is varied from eight years to two year, keeping *RT* constant at 20 days. However, when *RT* is kept constant at one day, the impact to availability is lowered to 0.4%. This analysis further suggests *RT* should be kept low as changes in *RT* can lead to significant impact to availability, while *MTBMu* can still contribute to a significant decrease in availability when *RT* is high.

d. *Comparison of Availability Between No-Preventive Maintenance Approach, Time-Based Maintenance Approach and Condition-Based Maintenance Approach*

Sections a, b and c show the impact on availability as a result of changing the key factors of *MDT, MTBM,* $\bar{M}_{pt}$, *MTBMs, RT and MTBMu* for the three cases of having no preventive maintenance, having constant corrective maintenance and having constant preventive maintenance, respectively. This can show the impact on availability from the adoption of the three maintenance approaches, namely the no-preventive maintenance approach, the time-based maintenance approach and the condition-based maintenance approach, and the results are summarized in Table 7, and details discussed below.

Table 7 Side by Side Comparison between No-Preventive Maintenance Approach, Time-Based Maintenance Approach and Condition-Based Approach

Factor	**NPM**	**TBM**	**CBM**
Frequency of PM	NA	PM performed based on pre-determined schedule	PM performed when necessary, usually lower frequency than TBM
Changes to availability as a result from change in frequency of PM	NA	NA	Significant impact only when $\bar{M}_{pt}$ is high
Frequency of CM	CM performed during failure, can have higher frequency than TBM due to lack of PM	CM performed during failure	CM performed when sensors give warning. If good sensors used, can have lower frequency than TBM
Changes to availability as a result of change in frequency of CM	Significant impact only when *MDT* is high	NA	Significant impact only when *MDT* is high
Time to perform CM	Can result in longer time to perform CM than TBM	Include $\bar{M}_{ct}$, *LDTc* and *ADTc*	*LDTc* and *ADTc* can be reduced, as a result of early warning from sensors
Changes to availability as a result of change in time to perform CM	Compared to TBM - Significant impact when change in time to perform CM is large	NA	Compared to TBM - Significant impact when change in time to perform CM is large
	NA	NA	Compared to NPM – Significant impact when change in time to perform CM is large

Time-based maintenance approach versus no-preventive maintenance approach – The results of the sensitivity analysis performed in section-b suggests that frequency of PM has limited impact on operational availability provided the system remains operable before and after the active PM time. In contrast, section c suggests that the time taken to perform CM including logistics delay time and administrative delay time has an impact on operations, as a 1% reduction in availability can result in 18 days reduction in downtime over a period of five years, which can be significant as the loss of use of critical infrastructure can impact operational readiness for the different systems requiring the critical infrastructure (Appendix A).

This means that availability resulting from the use of time-based maintenance approach would not be significantly different from a system maintained using the PM approach if the frequency of CM and time to perform CM remains constant. In actual operations, the frequency of CM and time to perform CM can increase with the no-preventive maintenance approach. However, the results from section-a also suggest that the impact to availability for critical infrastructure from the increased frequency of CM is insignificant unless time to perform is large, while the impact to availability from increased time to perform CM can be significant. The choice between the no-preventive maintenance approach and the time-based maintenance approach should be made, which will be discussed in section VI.A.1.

Condition-based maintenance approach versus no-preventive maintenance approach – The results from section-a suggest that availability is insensitive to the frequency of CM unless time to perform CM is large, but is sensitive to time to perform CM. A good sensor can allow early detection of failure, which leads to reduced *ADT* and *LDT*. Time to perform CM is hence shorter, and hence, condition-based maintenance can be a good choice against the no-preventive maintenance approach.

Condition-based maintenance approach versus time-based maintenance approach – The results from section-b suggest that availability is insensitive to both the frequency of PM and the time to perform PM, while results from section-c suggests that the impact to availability for critical infrastructure from the increased frequency of CM and increased time to perform CM can be significant. As a good sensor can allow early detection of failure, and increase the frequency to perform CM, condition-based maintenance can be a good choice against the time-based maintenance approach.

The results of the sensitivity analysis validates Koeneman (2009)'s examples of increase in operational availability arising from adopting condition-based maintenance approach over the time-based maintenance approach and no-preventive maintenance approach. However, there are notable differences between Koeneman's work and this thesis which focused on infrastructure. The use of condition-based maintenance does not have as much impact as Koeneman's research indicated for ships, as maintenance of infrastructure such as air conditioning and fire protection is most likely performed less often than ship maintenance. For example, Alhouli (2011) developed a case study on oil tanker maintenance. The daily maintenance crew of 12 to 18 people spend between two to eight hours performing engineering, electrical, and mechanical maintenance. The ship would also undergo intermediate and major classification surveys every 2.5 years and five years, respectively at the shipyard. During these classification surveys the ship's machinery is overhauled. By percentage, 75% of these classifications are for routine maintenance and 25% is for major work to repair damage or to upgrade capability (Alhouli citing Mackenzie 2004)

This thesis corroborates the research by Koeneman when the models used in V are adjusted for a much longer $\bar{M}_{ct}$ and $\bar{M}_{pt}$, and a larger *fpt* to be consistent with ship maintenance. This validation of the infrastructure maintenance model for use with critical infrastructure confirms the functional approach, boundary conditions, and the availability assumptions used in the analysis in V.

Since the results show a slight improvement in operational availability when the *MTBM* is maximized, condition-based maintenance can be used when possible when a system is maintained under the time-based maintenance approach or the no-preventive maintenance approach if the cost of failure outweighs the cost of maintenance, which will be discussed further in section IX.B.a.

Further, in the examples above, the most influential factor to achieving high availability is the reduction of repair times which includes $\bar{M}_{ct}$, *ADT* and *LDT* for CM. However, $\bar{M}_{ct}$ is assumed to be fixed in this case as the maintainability is determined at the design phase. As such, steps taken to reduce the *ADT* and *LDT* is recommended to achieve the highest availability.

2. Cost

There are two aspects to analyze maintenance approaches with respect to cost, namely short-term and long-term cost. In general, it could be said that the fewer the PM activities, the lower the short-term cost, while the more the CM, the higher the long-term cost.

a. No-Preventive Maintenance Approach

Koeneman (2009) found that generally, the no-preventive maintenance approach is twice as expensive as CBM when the mean cost of repair when failure occurs is more than three times the mean cost of repair when warning occurs. However, for systems with observable failure, the use of CBM with poor quality sensors that detects failure too early or fails to detect failure could be significantly more costly than the no-preventive maintenance approach. Primarily, this shows that for systems where good sensors are difficult to implement, the no-preventive maintenance approach would have a lower short-term and long-term cost, particularly if the cost of repair is similar regardless of failure or not.

For example, the cost of replacement of switch gears would be similar whether it is due to failure or not. A possible sensor for ascertaining the condition of switch gears is the passive, real-time and low cost surface acoustic wave wireless sensor, which has been introduced by several manufacturers to monitor the temperature of switch gears. Further studies could be done to verify the effectiveness of the surface acoustic wave wireless sensor in reducing the cost of switchgear replacement. However, since the base load power generation system is generally built in redundancy to the power grid supply, there is no significant improvement in availability of power or lifespan due to failure. With similar impacts to operations, based on Koeneman's (2009) methodology, the long-term cost would be similar while payment for PM and/or sensors would prove more expensive than that of the no-preventive maintenance approach. Hence, the no-preventive maintenance approach should be more cost effective for systems without life-extending PM tasks such as the power distribution system.

On the other hand, mechanical systems generally have a long service life, and require PM tasks such as lubrication, filter cleaning and changing, and the changing of worn-out gears and valves that would significantly prolong the life of a system. While the short-term cost for such systems would increase, there could be long-term cost savings in terms of operational availability and replacement cost. Hence, for mechanical systems where replacement cost is significantly higher than preventive and CM cost, where PM significantly prolongs the life of the system, or where there is no built-in redundancy to the system, the no-preventive maintenance approach would not be cost effective.

b. Time-Based Maintenance Approach

Blanchard and Fabrycky (2010) suggested an increase in lifespan through the performance of time-based maintenance. The actual cost impact would be from both the short-term and long-term perspective, and has to be explored further. Basically, the more PM is performed on a system, the higher the short-term cost, but due to increased lifespan, it could also lead to a lower long-term cost.

For example, the replacement cost of a centralized air conditioner for home usage is in the lower thousands in 2015, while the PM could cost about $100 a year. Given that the life of a centralized air conditioner can be up to 20 years, the relative cost of PM is low as compared to the replacement cost. Further, PM such as cleaning or replacement of filter and charging of refrigerant would allow the system to maintain optimal efficiency, which would lead to lowered energy costs in the long run.

In general, most mechanical systems would have a similar profile, and lead to a lower life-cycle cost with PM than without PM.

However, the other aspect of time-based maintenance is the use of time-based CM, which would involve doing repairs and even replacement on a scheduled basis. For example, companies would normally give a five-year warranty for a compressor used in a three-phased power supply. One can postulate that while the compressor may not fail even if the age crosses five years, the probability of failure over a large number of systems would be higher and hence unprofitable for the company once the life of the compressor exceeds five years. Hence, while filters could be cleaned once a quarter, the compressor would be replaced every five years in this instance. Further, as the life of the centralized air conditioner can be up to twenty years, the replacement of the entire system would be scheduled for 20 years. This method would prove uneconomical if the system could have been used until just before failure.

As such, while time-based PM would generally reduce the overall life-cycle cost, time-based CM may instead increase the long-term cost of a system.

c. Condition-Based Maintenance Approach

The difference between CBM and time-based maintenance is primarily in the CM approach, as the PM is similar for both concepts. The only possible difference would be the potential need for more frequent PM if wear and tear to the system calls for it. However, in general, the PM approach should already account for this, so there should be no real difference between the two.

Time-based CM means the replacement of parts or entire system at pre-determined intervals. While this would theoretically reduce the probability of failure due to age, there is additional cost tagged to the early replacement. On the other hand, CBM allows the system to be used almost to the point of failure, and maximizes the utility generated for the system. The problem for CBM is the cost and the accuracy of the sensor required to make the judgement call of when to replace a system. Koeneman (2009) suggests that the judgment to replace a system for a no-preventive maintenance approach depends primarily on inspection, which is usually done for building mechanical and electrical systems. The frequency of inspection, however, varies across organizations, but in general is not real-time. A good quality sensor installed and monitored by a central monitoring system such as a Building Automation System (BAS) allows real-time monitoring of the equipment status, and could lead to his conclusion of a long-term average cost savings of 66%. With a poor quality sensor, however, Koeneman (2009) found that the long-term average cost of CBM would exceed that of a no-preventive maintenance approach.

Hence, the availability of a good quality sensor could provide cost savings to CBM as opposed to no-preventive maintenance approach. As compared to time-based corrective, the key is the cost of implementing the good quality sensor as opposed to the savings generated from operating the system to its full lifespan, subject to the error made by the sensor.

The implementation of a quality sensor is not a simple exercise, as it requires designing the sensor into the system itself. In general, ad-hoc sensors such as hand-held thermal sensors could not be real-time, and would only aid in increasing the accuracy of analysis on the system's condition during inspection, as opposed to the effective real-time monitoring of systems with built-in design. Building mechanical and electrical systems are generally commercially off the shelf (COTS) products and mass produced across different industries. The customization of these systems would exponentially increase the mass production cost, and hence could only be done cost effectively in-house. However, an in-house redesign of the system could negate the warranty of the system, leaving increased financial risk. A third alternative is to incorporate an external sensor, which would limit the use of technology such as a vibration monitor (except in a rough sense where the overall vibration is monitored, which would not allow isolation of fault) and focus more on thermal and noise sensors.

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VI. ANALYSIS OF SUITABILITY OF MAINTENANCE TO CI

The suitability of maintenance approach for individual systems and the suitability of maintenance contracts for different maintenance approaches are analyzed to ascertain the appropriate maintenance strategy for the systems. The analysis first discusses the suitability of maintenance approach for different CI, which influences the choice of the maintenance contracts for the CI. The utilization of a computerized maintenance management system to enable tracking of the maintenance of the systems and the contracts that maintain the systems, followed by the need for a proper configuration management system are discussed in Appendix B.

A. SUITABILITY OF MAINTENANCE APPROACH TO DIFFERENT CI

Koeneman (2009) suggested that the use of different maintenance approaches could result in different operational availability of a system. The same types of maintenance approaches Koeneman used is adopted, namely the no-preventive maintenance approach, and the condition-based maintenance approach, as well as the time-based maintenance approach and assesses their suitability with regards to the types of critical infrastructure based on the criteria of observability of failure and availability of a good sensor.

The three main groups of critical infrastructure analyzed are mechanical systems, electrical systems and civil systems. The mechanical systems to be analyzed here are cooling systems, blast doors and fire protection systems and piping systems, namely water distribution systems and fuel distribution systems, while the electrical system is the power distribution system. Finally, the airfield pavement system is the third system analyzed.

The three maintenance approaches, namely the no-preventive maintenance approach, the time-based maintenance approach, and the condition-based maintenance approach can result in different availability. Systems that experiences observable failure should be maintained using the no-preventive maintenance approach, unless the benefits to implementing the condition-based maintenance approach outweighs the cost. Further, systems that experiences unobservable failure should be maintained using the time-based maintenance approach, condition-based maintenance approach, unless the benefits to implementing the condition-based maintenance approach outweighs the cost.

This section first discusses the optimal choice of the maintenance approaches from the perspectives of the observability of failure and availability of a good sensor. However, other factors such as cost and availability can change the final choice of maintenance approach. A simple example is used to make an assessment using the perspectives of risk-adjusted cost and availability (Appendix C). The thesis then performs an analysis of the suitability of the contracting mechanisms for the purpose of building maintenance from the organization perspective, the use of configuration management principles to achieve high availability of critical infrastructure, and the use of computerized maintenance management system as an enabler (Appendix B).

Different types of systems experiences different failure mode. However, the two primary modes of failure are observable failure and unobservable failure. Based on the mode of failure, different systems may be efficiently maintained by different maintenance approaches. Further, the availability of a good sensor would also help in determining the possibility of using the condition-based maintenance approach. This section discusses the types of systems which are suitable for the various types of maintenance approaches. See Table 8 for a summary of the suitability of maintenance approach for the critical infrastructure analyzed.

1. No-Preventive Maintenance Approach

While PM should be done for most systems, there are cases when PM may not be necessary, or could even increase the cost and reduce availability to the system. Koeneman (2009) groups systems into two distinct types: those with failures that are observable, and those that are not observable. He found that systems with observable failures could be candidates for a no-preventive maintenance approach. However, he also found that the determining factor is the quality of a sensor. The availability of a sensor that could sense a failure consistently slightly before the failure occurs would warrant the use of the sensor. If a consistent sensor or one that gave a premature warning could not be found, cost would increase and availability decrease.

Power used in the military bases can be divided into two types: the power generation system and the power distribution system. A power generation system creates electrical energy through the conversion of energy from fuel, such as the base load generator, standby generator, and mobile generator. These generators are primarily used in contingencies, and are therefore not in constant operations. Hence, failure would not be observable for such system, and a no-preventive maintenance approach may not be suitable.

A power distribution system, however, transfers power from the public utilities intake to the individual electrical appliance, and range from transformers, to switchboard in the substations, the switch rooms, the distribution boards, and the power sockets. In general, these subsystems do not generate signs of pre-existing conditions for failure. However, heat could be generated during impending failure due to short circuit or deteriorated insulation in wiring. Other observable failures include fluctuating current and the lack of current flow could also indicate failure. Further, unlike mechanical systems, there are no preventive maintenance tasks such as lubrication that could reasonably improve the lifespan of the power distribution system. The no-preventive maintenance approach should be used for the power distribution system, unless the risk of failure is high enough to call for the condition-based maintenance approach. However, inspections and periodic condition monitoring such as the partial discharge test should continue to be performed on the system to assess the need for replacement within the inspection cycle.

Similarly, the water distribution system is a mechanical system of pumps, pipes, valves, and faucets. However, as the purpose of this thesis is to study critical infrastructure, faucets are not considered. The primary failure modes for pipes are corrosion and stresses due to soil settlement; for pumps, the primary failure modes are mechanical and electrical failures; and for valves, the primary failure modes is the inability to maintain pressure due to due to wear and tear. While pipes could generally be made of fiber-reinforced plastic, water pipes are usually made of steel or copper which are strong and ductile to better withstand external pressure than fibre-reinforced plastic. In general, failure can be observable from seepage of water onto the surface or persistent flow of water even during periods of no activity, but constant monitoring may only be done at specific area with water meters. Hence, the no-preventive maintenance approach can be used for pipes within the water distribution system. However, to deter the corrosion risk of pipes to critical assets, a sacrificial corrosion system should be designed for specific areas of underground pipes to prevent failure due to corrosion.

Pumps, being mechanical in nature could experience deteriorated performance through wear and tear leading to failure to perform to the desired performance and valves can lose pressure through deterioration by wear and tear. These failures are unobservable and hence, the no-preventive maintenance approach may not be a good maintenance approach. As such, the no-preventive maintenance approach may not be suitable for the water distribution system.

Blast doors generally exhibit unobservable failure, but the lack of suitable sensors means that testing would generally be done at the depot level, and involves the disassembly, transport, and reassembly of the interconnected hydraulic or roller systems. Hydraulic systems also exhibit unobservable failure through the loss of pressure. Hydraulic doors designed based on these principles should not be managed using the no-preventive maintenance approach. However, roller systems can exhibit observable failure from vibrations during operations. Technically, the no-preventive maintenance approach could be a good approach for the roller sub-system. However, being a critical part of a functioning blast door system, the maintenance should be tied to that of the blast door system itself.

2. Time-Based Maintenance Approach

Time-based maintenance is usually PM in nature but could also include CM. In general, mechanical and electrical systems would fall under this category. Cooling systems and fire protection systems are two examples of systems that could be managed under this category.

Cooling systems can be divided into three core groups: district cooling, centralized cooling, and individual cooling. However, district cooling systems comprises the same equipment as central cooling, and can be analyzed as centralized cooling.

Centralized cooling comprises a centralized chiller plant and heat exchanger, and uses an air handling unit with a network of vents, or a network of fan coil units to disburse the cool air to different parts of a building, while individual cooling comprises a condensing unit and fan coil unit. Packaged units and variable refrigerant volume (VRV) units will also be considered centralized cooling.

Cooling systems are mechanical and electrical in nature, and can fail in unobservable ways. As such, PM tasks such as inspections, routine cleaning, and component replacements should be scheduled and performed. The CM work such as replacement of compressor, smoke detectors, and refrigerant fluid can also be performed when inspections deem it necessary. However, if the risk of failure is high enough to call for the condition-based maintenance approach, condition-based maintenance approach could be adopted for cooling systems.

Fire protection systems can be differentiated from firefighting systems. Firefighting systems includes sprinkler systems, riser systems and hose reel systems, while fire protection systems generally comprise a fire detection system working in tandem with fire suppression systems, such as the inert gas fire suppression system or foam suppression system. Fire protection systems are primarily mechanical and electrical in nature, and could be treated similarly to that of other mechanical and electrical systems. However, the purpose of the fire protection system is to protect assets, and failure should not be an option. Further, with the increasing amount of electronic components in the systems and sensitivity of systems, false alarms could not be avoided, particularly from the aging of components such as smoke detectors. As such, these systems could also adopt a time-based CM strategy, such as replacing smoke detectors based on a schedule, or even replacing aged wiring.

Finally, airfield pavements can fail in unobservable ways. As such, PM tasks such as inspections, tree pruning and clearing of foreign objects and debris should be scheduled and performed. The CM work such as runway resurfacing and spot repairs to airfield pavement should also be performed when inspections deem it necessary.

3. Condition-Based Maintenance Approach

Koeneman (2009) suggests that the condition assessment of systems could be done using sensors, while Eade (1997) specifically suggests the possibility of sensing temperature, vibration, noise, lubrication, and corrosion. The basis of condition-based maintenance is an accurate assessment of the condition of the system, and thereby implementing remedial measures before the system completely fails. Sensors could be designed into the system, or used during inspection.

Temperature is an easily measured parameter with temperature sensors. In general, most mechanical and electrical systems emit heat during operations. However, the design of the system would consider the heat emitted, and the use of sensors to measure the heat emitted at a particular point in time could alert the maintenance agency when the heat emission is excessive, a pre-cursor to electrical, electronic, or mechanical failure.

Similarly, mechanical equipment such as cooling systems generally operates with a certain vibration level. An increase in vibration would be a sign of possible issues such as misalignment or excessive wear and tear.

Noise monitoring can complement the temperature sensor, as mechanical systems generally operate with an innate noise level that could increase when bearings fail or friction or cavitation occurs, all of which are possible causes of system failure. However, this monitoring is a more difficult way to measure due to interference by other sources of sound, and may not be cost effective in the military domain.

Table 8 Summary of Suitable Maintenance Approach

Systems	Observability of Failure	Availability of good sensor	Maintenance Approach
Cooling systems	Unobservable failure	Vibration sensor	TBM/CBM
Blast doors	Observable failure	No	TBM
Fire protection systems	Unobservable failure	No	TBM
Water distribution systems	Observable failure	No	TBM
Fuel distribution system	Observable failure	No	TBM
Power distribution system	Observable failure	Heat sensor	CBM/NPM
Airfield	Unobservable failure	No	TBM

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VII. CONCLUSIONS AND RECOMMENDED APPROACH FOR HIGH AVAILABILITY OF CRITICAL INFRASTRUCTURE

This thesis corroborates the research by Koeneman when the models used in Section 7 are adjusted for a much longer $\bar{M}_{ct}$ and $\bar{M}_{pt}$, and a larger *fpt* to be consistent with ship maintenance. This validation of the infrastructure maintenance model for use with critical infrastructure confirms the functional approach, boundary conditions, and the availability assumptions used in the analysis

The results from the sensitivity analysis shows that the availability is insensitive to both frequency of maintenance and slightly more sensitive to time to perform maintenance. However, this arises from the fact that the *MTBMu* and *MTBMs* is significantly higher than $\bar{M}_{ct}$ and $\bar{M}_{pt}$ (years as compared to days and months as compared to hours, respectively).

A proper configuration management plan is recommended for critical infrastructure, and should include approval process for the use of critical infrastructure requested by cross platform systems. At the same time, there should be a single approving party as a gatekeeper for authorizing the use of the critical infrastructure. The creation a separate vote for possible upgrades and repair to the critical infrastructure are recommended.

In general, systems with observable failure can be maintained using the no-preventive maintenance approach, while the condition-based maintenance approach could also be adopted if the risk of failure is high. Further, systems with unobservable failure can be maintained using the time-based maintenance approach, while the condition-based maintenance approach could also be adopted if the risk of failure is high. Regular inspections should be scheduled and performed on all systems. Specifically, the use of the no-preventive maintenance approach for the power distribution system is recommended unless the risk due to failure of the system outweighs the cost to perform condition-based maintenance in which case the condition-based maintenance approach should be chosen for the power distribution system. The time-based maintenance approach is recommended for cooling systems unless the risk due to failure of the system outweighs the cost to perform condition-based maintenance in which case the condition-based maintenance approach should be chosen for cooling system. Blast doors, fire protection systems, water distribution systems, fuel distribution systems and airfield pavements should be maintained using the time-based maintenance approach.

A key enabler for the optimal maintenance approach is suggested by an accurate inventory management system. The system should be implemented with a good, integrated, computerized maintenance management system that fits well with the organization's process. Logically, with a good, integrated, computerized maintenance management system, the basic infrastructure to support the organization's maintenance approach would be ready. With the inventory listing, the organization can make a decision on the choice of maintenance approaches to each system. This may form the backbone of achieving the highest operational availability at the optimal cost.

The correct contracting mechanisms would also seem to be important for the implementation of the maintenance approach. The no-preventive maintenance approach requires the use of inspection and CM contracts, which can be contracted using the performance-based contract and the prescriptive contract, respectively. The time-based maintenance should comprise of the use of inspection, PM and CM contracts, which can be contracted together as a single performance-based package. Condition-based maintenance should comprise the use of inspection, PM and CM contracts as a single package, of which the first two could be performance-based and the last prescriptive.

Additionally, the organization should be careful to reduce interdependent performance indicators across different contracts in the beginning of the performance-based contracts, as these may be the key areas of conflict. And, each system was analyzed using the risk-based cost analysis to identify the most suitable maintenance approach from the cost perspective (Appendix C). Finally, steps must be taken to reduce the *MDT* for all systems to optimize the operational availability, particularly in the reduction of *LDT* and *ADT*.

VIII. FURTHER RESEARCH TOPICS

An area for further research would be the manpower and personnel requirement in the implementation of the maintenance approaches. This is from both the in-house and outsourced perspective, and requires in-depth knowledge of the workings of the DOD and the U. S. building maintenance industry.

It is also recommended that further study in the use of quality assurance and audits to ensure a robust implementation of the maintenance approaches be conducted. At the same time, an in-depth study of the reliability of various systems for the selection of maintenance approaches is recommended. In particular, the use of the loss function to determine the maintenance approach could be used for other variables than risk-adjusted cost. As this thesis focuses on both the maintenance approach and the implementation using contracts, cost was the key variable used, and a more holistic study on the use of the loss function might provide more insightful analysis.

The use of risk management strategies in the selection of maintenance approaches and contracting mechanisms is also recommended as a future scope of study.

The effectiveness of various sensor used for condition-based maintenance is also recommended for future study.

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APPENDIX A. RISK MANAGEMENT

A. RISK TOLERANCE

Risk tolerance is different in different industries. In particular, the public sector financial managers exercise caution on the use of public money, and programs can also suffer from budget issues such as budget freezes or cuts.

In terms of budget, the public sector should ensure that work done is cost appropriate. A firm fixed priced contract can transfer financial risks to the contractor but can also result in a premium for the same type of work due to the risk of rising prices which the contractor would price into the tendering bid. As such, contracts with provisions for economic fluctuations can be important in ensuring value for money year after year. However, the initial derivation of a good formula to track economic fluctuations can minimize contractor risk so that the premium charged for the risk transfer can be minimized. Hence, using a basket of items in determining the formula would provide the best solution in terms of value for money. However, provisions to adjust the individual rates of specific items in the event of unanticipated changes in prices that may cause the contractor to price in a high premium in the contract such as an embargo on granite or fuel can also reduce contractor risk.

On the other hand, with the risk of budget freeze and cuts, organizations may face the pressure to keep operations costs constant over the years. As a firm fixed priced contract would allow organizations to reduce the risk of price fluctuations of material for their maintenance needs, an acceptable budget should be established from the onset of the contracting for the entire contract period.

Hence, the decision to choose between a fixed priced or variable priced contract would primarily depend on the risk tolerance of the organization, while the decision to choose between performance-based contracts or traditional contracts would depend on the manpower available, the technical expertise of staff and the control of the system manager. The organization could then choose the most appropriate contracting mechanism based on the criteria.

B. OPTIMAL MAINTENANCE APPROACH

The choice of the optimal maintenance approach could be done using a risk management analysis. With the many qualitative methods used in the risk management industry, the key issue would be the difficulty in ascertaining the best approach from the various aspects of risk. Langford's (2012, 296) cited Taguchi et al. (2005) that a loss function "uniquely defines the relation between a loss in EMMI and the deviation of the quality characteristics from its target value." This allows a quantification of the risk due to the failure of systems, and using monetary value as a factor to provide clarity on the choice of maintenance approach. Ayyub (2014) suggested the use of the following equation as a loss function

$$Risk = likelihood * impact \tag{1.16}$$

A sample analysis is performed based on the simple illustration shown in Figure 1.

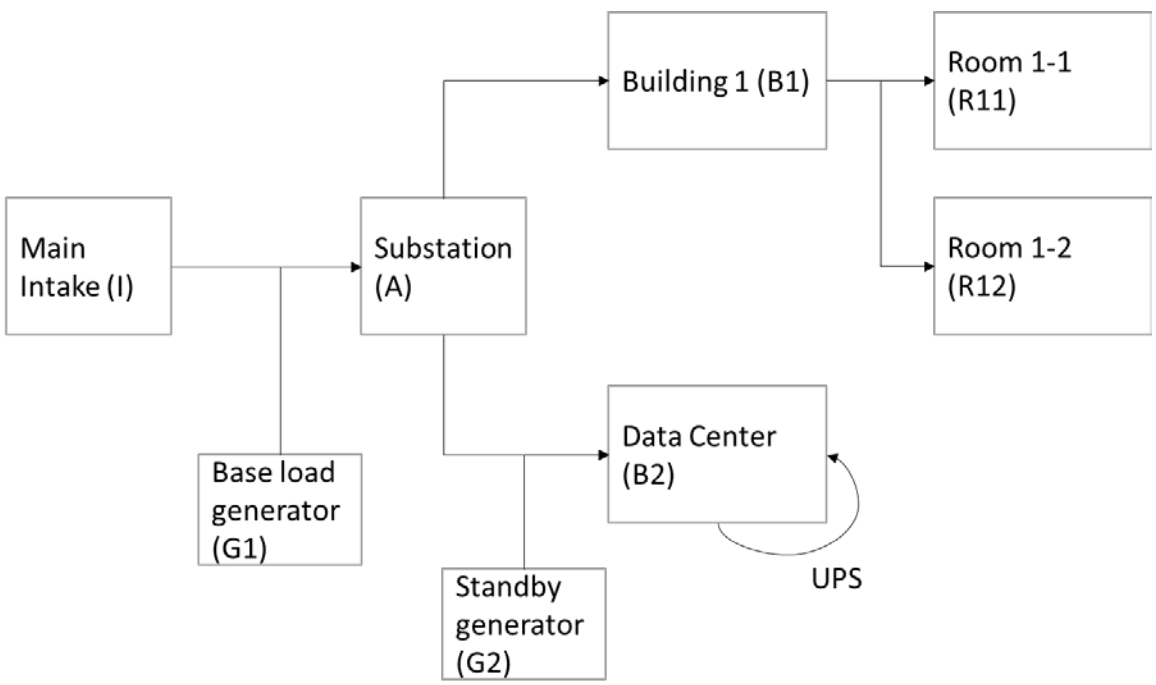

Figure 1 Illustration of Simple Electric Network

Figure 1 exemplifies the complexity of a power distribution system, as the flow of electricity is continuous and any failure can have either upstream or downstream impacts. In general, upstream impact can be mitigated by circuit breakers but there are also times when circuit breakers can fail in arresting upstream impact. This simple analysis assumes perfect arrest of upstream impact.

The direct links from illustration shown in Figure 1 are summarized in Table 9, with the probability of failure obtained from Purnomo (2015) and Electricity North West (2014), and the analysis is described in the following subsections.

Table 9 Summary of Links and Interfaces

S/N	Link	Interfaces	Annual Probability of Failure
1	Main Intake-Substation (I-A)	Step down power transformer • provide correct power voltage to the distribution network Switch Gear • distributes power to the various switch rooms or other connected substations	Transformer: 0.4% Switchgear 0.4%
2	Base Load Generator-Substation (G1-A)	Diesel • provide fuel for generation of power Changeover switch • transfers power supply to/from main intake	Base Load Generator 0.6%
3	Substation - Building 1 (A-B1)	Switch Gear • Oil, Air Gas, Hybrid, Vacuum, CO2 • stops the flow of electricity during power surge, short circuit	Switchgear 0.4%
4	Building 1 - Room 1–1 (B1-R11)	Switch Gear/ Circuit Breakers	Switchgear 0.4%
5	Building 1 - Room 1–2 (B1-R12)	Switch Gear/ Circuit Breakers	Switchgear 0.4%
6	Substation - Data Center (A-B2)	Switch Gear • Oil, Air Gas, Hybrid, Vacuum, CO2 • stops the flow of electricity during power surge	Switchgear 0.4%
7	Standby Generator - Data Center (G2-B2)	Diesel • provide fuel for generation of power Changeover switch • transfers power supply to/from main intake	Base Load Generator 0.6%

C. CHOICE OF MAINTENANCE APPROACH FROM COST PERSPECTIVE

Appendix A shows a 8x256 matrix that was created to consider all possible combinations of failure, and the probability of occurrence for each case worked out based on the data from Table 9, and from equation 1.16 the risk-adjusted cost of failure from Langford's (2012) loss function computed below

$$Rc = P(Failure)*Cost(Failure) \qquad (1.16)$$

For example: a data center is assumed to be connected to a series of systems valued at $20 million a day, while Room 1 has a value of $120,000 a day and Room 2 has a value of $40,000 a day. For the purpose of this section, a MTTR of one day is assumed for each of the systems.

Finally, the overall impact of each system is summarized in Table 10.

Table 10 Impact as a Result of System Failure

S/N	System	Probability of Failure	Risk-Adjusted Cost of Failure (Cost per Day)
1	Main Intake (I)	0.4%	$336
2	Substation (A)	0.4%	$1,438
3	Base Load Generator (G1)	0.6%	$501
4	Building 1 (B1)	0.4%	$962
5	Room 1–1 (R11)	0.4%	$804
6	Room 1–2 (R12)	0.4%	$488
7	Standby Generator (G2)	0.6%	$972
8	Building 2/ Data Center (B2)	0.4%	$80,007

The switch room in data center B2 is the critical point at which failure will have the maximum risk-adjusted cost of failure of $80,007. Condition-based maintenance could be valuable for this, and a cost analysis could be performed on the feasibility of installing sensors to it. On the other hand, the impact of a failure of the main intake and base load generator is low. A choice can be made between the no-preventive maintenance approach and the time-based maintenance approach for these, based on the type of system and the maintenance cost. In particular, the use of the time-based maintenance approach would be applicable for mechanical systems, while the no-preventive maintenance approach can be used for electrical systems. Further, the use of time-based maintenance can be a better solution for systems that are run ad-hoc as compared to those that are run continuously, due to the fact that there is no impact to operations during the maintenance.

The relative cost of time-based maintenance approach and condition-based maintenance to the no-preventive maintenance approach can also be assessed together with the data to ascertain the optimal maintenance approach for the system.

For example, based on the author's personal experience in Singapore, the typical maintenance cost per annual service of switch room is assumed to be $1,000 and for a substation, $3,000. The typical quarterly maintenance cost per service for a generator is assumed to be $300, and maintenance cost of annual service is assumed to be $1,000. The total cost is therefore $1,900 for a generator. An installation of a thermal sensor with an assumed lifespan of five years to a switchboard, including linkage to the building automations system, is assumed to be $4,000. As a generator is a backup and not run continuously, there is limited value in installing a sensor to it. As such, the cost of servicing is summarized in Table 11, assuming that:

- The sensor is 100% effective in detecting failure.
- One day of downtime is required to repair.
- The total delay time for repair due to sudden failure is two days.
- The *MTBF* of sensor is five years.

Table 11 Typical Servicing Cost in Singapore for Infrastructure for Military Bases

System	Cost of TBM (per year)	Average Annualized Cost of Installation of sensor
Main Intake (I)	NA	
Substation (A)	$3,000	$800
Base Load Generator (G1)	$1,900	
Building 1 (B1)	$1,000	$800
Room 1–1 (R11)	NA	
Room 1–2 (R12)	NA	
Standby Generator (G2)	$1,900	
Building 2/ Data Center (B2)	$1,000	$800

For example a possible cost analysis can be performed on the risk-adjusted cost of failure based on equation 1.16 as opposed to the cost to implement time-based maintenance and condition-based maintenance, and the result is shown in Figure 2 and summarized in Table 12.

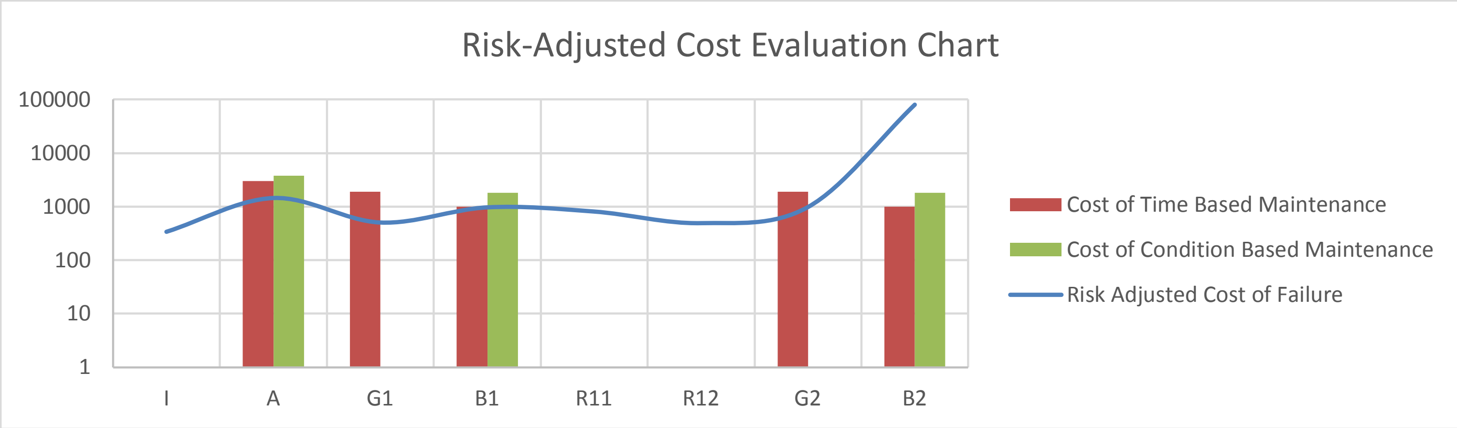

Figure 2 Risk-Adjusted Cost Evaluation Chart Comparing Cost of Failure against Cost of TBM and CBM

Table 12 Table for Selection of Maintenance Approach

S/N	**System**	**Risk-Adjusted Cost of Failure**	**Annual Cost (TPM/CBM)**	**Type of System**	**Operations Profile**	**Maintenance Approach**
1	Main Intake (I)	$336	NA	Electrical	Continuous	NPM
2	Substation (A)	$1,438	$3,000/$3,800	Electrical	Continuous	NPM
3	Base Load Generator (G1)	$501	$1,900	Mechanical	Ad-hoc	TBM
4	Building 1 (B1)	$962	$1,000/$1,800	Electrical	Continuous	NPM
5	Room 1–1 (R11)	$804	NA	Electrical	Continuous	NPM
6	Room 1–2 (R12)	$488	NA	Electrical	Continuous	NPM
7	Standby Generator (G2)	$972	$1,900/NA	Mechanical	Ad-hoc	TBM
8	Building 2/ Data Center (B2)	$80,007	$1,000/$1,800	Electrical	Continuous	CBM (sensors required)

The risk-adjusted cost can compared with the cost of TBM and CBM to assess the cost of failure. A high risk-adjusted cost of failure as compared to TBM and CBM can warrant the use of TBM or CBM, while a low risk-adjusted cost of failure can warrant the use of the no-preventive maintenance approach. The cost analysis shows the risk-adjusted cost for the switch room is significantly higher than the cost of CBM. As heat sensors are available in the market, CBM approach can be applied to the switch room at B2. While the cost of maintaining the generators is significantly less than that of the risk-adjusted cost of repair, a management decision can be made on the viability of time-based maintenance for the generators, as the generators serve as contingency to the main power supply. For the purpose of this analysis, the use of time-based maintenance for the generators is recommended as it provides backup power to the data center which can experience high cost of failure. The circuit breakers at R1-1 and R1-2, as well as the substation should undergo the no-preventive maintenance approach, while the main intake is not under the department's purview.

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APPENDIX B. OTHER CONSIDERATIONS FROM AVAILABILITY PERSPECTIVE

A. APPROACH

(1) No-Preventive Maintenance

From Section V.A.1, the use of the no-preventive maintenance approach can result in high operational availability. The key area of concern for the use of the no-preventive maintenance approach is the unpredictability of failure, which could be managed by minimizing *MDT* or by controlling the selection of systems used.

Minimize *MDT* – The switchboard consists of multiple switchgears, possibly of varying age. As the switchgears can suffer catastrophic failure, it is insufficient to depend on the standard procurement strategy to ensure high availability, as it will lead to additional *LDT* and *ADT*, which will significantly reduce the operational availability. Spare parts can be procured beforehand to ensure the minimum *LDT* for the highest operational availability. Further, a shortened emergency procurement process or pre-approval of repairs can be implemented for specific high risk systems to reduce *ADT*.

Controlled Selection of Systems – With a wide variety of makes and models of switch gears in the market, compatibility of switch gears with the existing switch board may lead to difficulty in maintaining stock of spares. Hence, the second key to ensuring high availability to the no-preventive maintenance scheme is the use of a limited selection of makes and models of systems, so that cost effective spare management strategies could be used, which could be enabled when the system manager to stay updated with the market to ensure that the approved makes and models used are not obsolete. In the event the manufacturer declares the system obsolete, sufficient spares should be purchased to ensure continuity until planned upgrade of the systems. Where possible, cannibalization could be employed to prolong the use of the systems in better condition to reduce the overall cost of the systems upgrade.

(2) Time-Based Maintenance

While the time-based maintenance approach is a common maintenance approach to use, it also has the highest *fpt* among the three maintenance approach. Hence, where possible, the condition-based maintenance should be employed.

However, for systems maintained under the time-based maintenance approach, the key to achieving high availability is to reduce the *MDT*. This can be done by reducing the *ADT* and *LDT*, which means spares should also be procured as described in section (1).

On the other hand, controlling the *fpt* could also be a means to ensure high operational availability. A baseline use of *fpt* could be in accordance to OEM recommendations. However, with sufficient data enabled by the computerized maintenance management system, the system manager could make decisions to reduce the *fpt* accordingly.

(3) Condition-Based Maintenance

Systems managed under condition-based maintenance approach should also have a low *ADT* and *LDT* using spares management strategies as described in section (1). Further, with the use of good sensors, the *MTBM* is also increased to the maximum possible, and hence, can achieve the optimal operational availability.

B. COMPARISON BETWEEN MAINTENANCE CONTRACTS

Maintenance contracts can incorporate clauses that specifies requirements such as the maximum response time to a failure and maximum recovery time to a failure that can impact the *LDT* of a system. The means of implementation of these clauses can be different or even not applicable for different contracts. The maintenance contracts generally used in the military domain are hence compared by first being grouped into performance-based contracts and prescriptive contracts, followed by a detailed comparison between the different types of contracts.

1. Performance-Based Contracts vs. Prescriptive Contracts

Performance-based contracts has generally been used for acquisition projects and building maintenance. As the key to a successful performance-based contract is objective outcomes, the initial conceptualization of the outcomes are critical. Some of the possible outcomes used in the industry include availability, response time, recovery time, and customer satisfaction because all can result in increased costs to the user. Payment to the contractors is based on their ability to achieve the pre-determined outcomes.

The performance-based contract is compared with the prescriptive contract from the perspectives of payment mode, technical expertise and efforts in tracking.

a. Payment Mode

In prescriptive contracts, the primary mode of payment would be a work order-based (demand-based) payment, which means that a work order has to be issued for each piece of work performed. However, PM work could also be amalgamated across the entire year to form a single work order. Depending on the capability of the procurement system, separate payment could be performed for each work order being done, or combined as a final payment after the entire work is completed (similar to lump sum payment for the work). For maintenance work such as PM and facilities management, a lump sum payment mode could also be used to pay for the prescriptive contracts.

On the other hand, the primary mode of payment for a performance-based contract would be the lump sum payment. Payment could be based on a firm minimum payout with a separate payout based on key performance indicators or a full payout based on key performance indicators. For the full payout mode, the performance payment could comprise performance incentives and/or deductions.

b. Technical Expertise

In prescriptive contracts, a high level of technical expertise is required in the procurement manager in determining the scope of work, managing the work, and accepting the final work to ensure accuracy of scope of work. On the other hand, in performance-based contracts, detailed scope of work could be determined by contractors and the technical expertise is more important in audits, where the scope and quality of work are checked for accuracy.

c. Efforts in Tracking Work Done

In prescriptive contracts, quality, cost, and time should be managed carefully. As each work can be managed separately, large efforts in contract management can be required to provide work such as quality control, cost finalization and management of liquidated damages. In contrast, performance-based contracting allows a non-prescriptive form of contract management. As performance indicators such as reliability and availability (quality), cost savings, and timeliness can form part of the performance indicators, the demand for efforts in tracking of work done is significantly reduced due to the transfer of responsibilities such as determining the scope of work to the contractors. However, effort should be transferred in the performance of audit and KPI monitoring.

2. Forms of Contracts

The DOD has established frameworks for various types of contracts. Kennedy and McClure (2005) performed an analysis of the types of the contracting mechanisms in place, namely traditional, firm fixed priced contracts, fixed priced contracts with provisions for economic price adjustment, fixed price incentive fee contracts, cost-reimbursable contract, cost-plus-fixed-fee contract, cost-plus-incentive-fee contract, cost-plus-award-fee contract, cost-sharing contract, cost-without-fee contract, cost-plus-award-term contract, hybrid ID/IQ cost-plus-performance-fee task order contract, ID/IQ cost-plus-fixed-fee task/delivery order contract (non-performance-based contract), and hybrid ID/IQ multi-format task/delivery order contract. The following discussion regarding contracts is meant to be representative, but not comprehensive or exhaustive.

Some of the main contracting mechanisms usually used in building maintenance are now discussed. Olanrewaju (2015) suggests that the main contracting mechanisms are fixed price, lump sum, price adjustment, cost plus percentage, cost plus fixed fee, cost plus fluctuating fee, target cost, shared savings or cost, bill of quantity, schedule of rates, and packaged deal. Hence, the contracting mechanisms analyzed are namely the fixed priced contracts, lump sum, fixed-priced contracts with economic price adjustment, cost plus (fixed fee, fluctuating fee, target cost, shared savings, shared cost), and traditional contracts.

a. Traditional Contracts

In building contracts, traditional contracts can be established using a schedule of rates which determine the cost of a certain scope of work, a certain system or component, or unit rate for labor. Work orders can be issued using the established schedule of rates, and work performed according to the contract specifications. Each work order can also be viewed as a derivative contract based on the main contract, subject to the limitations imposed by the main contract, and the overall contract value. Based on the author's personal experience, traditional contracts are primarily prescriptive contracts.

b. Comparison between Fixed Priced Contracts vs. Cost Plus Contracts

The use of fixed priced contracts can be broadly grouped into three types: firm fixed priced contracts, fixed priced contracts with incentive fee and fixed priced contracts with economic price adjustment; while that of cost plus contacts can be grouped into cost plus fixed fee contracts, cost-sharing contracts, cost plus award fee contracts, and cost plus incentive fee contracts. This section focuses on the comparison between the fixed-priced contracts and cost plus contracts.

In general, the price of maintenance works to be performed for fixed priced contracts is determined upon the award of the contract. The contractors are given the opportunity to quote for the work to be performed for a fixed quantity of systems, but the quote is generally in the form of a competitive tender. As such, the contractor quotes for the maintenance including the risk of increased cost, which in general results in a markup in cost. However, since this is a fixed-priced contract, the contractors can make more profit when costs falls, or suffer losses when cost increases. In contrast, a cost plus contract can remove the risk of cost fluctuation from the contractor, but also limits their opportunity for profit. The contractor typically charges the owner the actual cost incurred for the work, and is paid a fee for his efforts in performing the work.

From the owner's perspective, the fixed-price contract can transfer the risk of cost fluctuations to the contractor, leading to a stable maintenance cost over the duration of the contract for a price. On the other hand, the cost plus contract can improve the cost effectiveness of the contract, for example a lower price during times when the cost of material falls.

c. Types of Fixed Priced Contracts

Fixed priced contracts can occur in multiple forms, and can impose different risk levels on the contractor. For example, the firm fixed priced contracts allow the maximum transfer of risk to the contractors, and can correspondingly be the costliest.

(1) Firm Fixed Priced Contracts

In the firm fixed priced contracts, financial risk of fluctuating costs is borne solely by the contractors. In the building industry, changes to the number of systems in a building can occur frequently with each renovation or addition and alteration (A&A) work. As such, the firm fixed priced contract can be fixed for a certain quantity, and each additional item can be subjected to a fee based on a separate schedule of rates in the contract. In the firm fixed priced contracts, these rates would be binding until the end of the contract.

(2) Fixed Priced Contracts with Provisions for Economic Price Adjustment

The fixed priced contracts with provisions for economic price adjustment has a similar structure to the firm fixed priced contracts, except for a contractual clause that provides a formula for adjustment of the base rates (for both the fixed quantity and the schedule of rates). In general, the formula can comprise pre-identified economic indicators such as general inflation rates, construction cost index or building cost index, or even their sub-indices, namely materials and labor indices. Further, the formula can also be based on the price of a predetermined basket of products, or the actual cost of the labor or material. It is common for the price adjustment to be done on an annual basis. However, due to the use of indices, the price can lag the overall market and hence may only reduce the risks to the contractor slightly. As such, a large price premium would still be expected.

d. Types of Cost Plus Contracts

Cost plus contracts are primarily cost-reimbursement contracts, where the contractors are reimbursed for the cost of work being done. As such, there is little incentive for keeping costs low. To counter this, various cost plus contracts had been developed where the contractors generate their profits in different manners.

(1) Cost Plus Fixed Fee Contracts

A fixed fee can be negotiated as part of the contract, where the contractor are paid the full fee upon completion of work and is the most basic form of cost plus contracts. It also transfers the least amount of risk to the contractor. As such, the owner retained the highest level risk as opposed to the other cost plus contracts.

(2) Cost Plus Incentive Fee Contracts

As opposed to a cost plus fixed fee contract, the cost plus incentive fee contract allows the negotiated fee to be adjusted upwards or downwards within specified limits based on the amount of cost savings the contractor achieve from the target cost. This contract can incentivize the contractor to achieve some cost savings.

(3) Cost Plus Award Fee Contracts

As opposed to the cost plus incentive fee contracts, the cost plus award fee contract separates the fee into a fixed- and a performance-based portion. The fixed fee can be paid to the contractor regardless of performance, but a variable portion is generally paid to the contract based on the contractor's performance.

(4) Profit Sharing Contracts

Profit sharing contracts are not part of the Federal Acquisition Regulation (FAR) types of contracts. It is essentially a cost plus contract, but includes a clause where the contractor would receive a performance payment of a fixed percentage of the overall cost savings if the contractor achieves an overall cost savings from the target cost. While theoretically a reasonable contract to use, the establishment of the contract poses a problem in the target cost definition and the impact of rising or decreasing cost of material or labor over the life of the contract.

3. Mapping Forms of Contracts to Types of Contracts

The contract can support the organization needs in the area of manpower, technical expertise, control by system manager and risk tolerance. This would determine the use of performance-based contracts versus prescriptive contracts, and fixed priced contracts versus variable price contracts.

See Table 13 for suitable types of contracts based on the 4 parameters.

Table 13 Suitable Types of Contracts

	Performance-Based	**Traditional**
Fixed Price	Firm fixed priced contracts	Firm fixed priced contracts
Variable Price	Firm fixed priced contracts with provisions for economic price adjustment Cost plus incentive fee contracts Cost plus award fee contracts Profit sharing contracts	Firm fixed priced contracts with provisions for economic price adjustment Cost plus fixed fee contracts

a. Manpower

One of the key uses of the contracts can be to outsource tasks for building maintenance. While all the contracts allow for the outsourcing of maintenance activities, a difference between the performance-based contracts (or cost plus contracts) and traditional contracts lies in the manpower with technical expertise in building maintenance required to manage the contract.

As opposed to traditional contracts where the scope of work is determined by a technically competent staff, performance-based contracts are not prescriptive and can be determined by the contractor. Further, performance-based contractors can link up directly with the end users which reduces the interactions required between staff and end users, allowing staff to take on a larger portfolio in contract management. In essence, performance-based contracts reduce the manpower required to effectively manage the contract.

b. Technical Expertise

As previously highlighted, performance-based contracts are not prescriptive and allow the contractor to determine the optimal solution to the maintenance problem. Hence, the need for technical expertise in the front line can be greatly reduced. However, auditors who perform the check and balance function for the performance-based contracts play a much more prominent role in ensuring that a sound solution had been implemented.

As such, auditors can specialize in checking certain systems to strengthen their technical competency in a specific domain, as opposed to the more generic technical skills required for staff responsible for determining the scope of work of different systems.

Hence, in managing performance-based contracts, there is a requirement for technical expertise in a specialized domain, but this can result in an overall reduction in technically competent staff. This can be suitable in the building industry, in which the average age of staff can increase due to the difficulty for the industry to successfully attract new long-term staff in the current environment.

c. Control by System Manager

Performance-based contracts are generally non-prescriptive, and the influence by the system manager would be reduced, as the inclusion of the instructions can result in a cost increase. In the event the instruction reduces the maintenance frequency, the performance may fall, but in the event the instruction increases the maintenance frequency, the cost to the contractor can increase. Hence, a decision should be made between the need for control and cost before deciding on the mode of maintenance.

C. SUITABILITY OF MAINTENANCE CONTRACT TO DIFFERENT MAINTENANCE APPROACH

Multiple contracting mechanisms could be used to implement each maintenance approach. However, the contract is just a tool to support the organization and the maintenance approach. As such, the contracting mechanism must be robust enough to incorporate the different needs of the organizations and the maintenance approaches. Further, the tools available to the organization would also determine the usefulness of the contracting mechanism.

Different systems could be implemented by different maintenance approaches, but the maintenance approaches can be broken into three types: the no-preventive maintenance approach, the time-based maintenance approach, and the condition-based maintenance approach. In addition to the three types of maintenance approaches for PM, CM is also required for the rectification of failed items in all three approaches, while inspection is required to ensure that failure or pending failure is identified for prompt action. While CM is generally outsourced, inspection can either be done in-house or outsourced. The use of outsourced inspectors for the inspection is assumed in this section.

As opposed to the scope of work for PM, the scope of work for CM and inspection could be contracted separately for traditional contracts, under performance-based contracting, there would be synergy to combine them as a package. The contracting mechanisms support different types of maintenance approaches, but an amalgamation of different types of contracts for different systems could also be built for specially identified systems. As such, the suitability of the contracting mechanisms is shown in Table 14.

Table 14 Suitable Contracts for Maintenance Approaches

<table>
<tr><th></th><th>Performance-based</th><th>Traditional</th></tr>
<tr><td>Time-based maintenance</td><td rowspan="3">- Cost plus incentive fee contracts
- Cost plus award fee contracts
- Profit sharing contracts</td><td>- Schedule of Rates
- Firm fixed priced contracts
- Firm fixed priced contracts with provisions for economic price adjustment
- Cost plus fixed fee contracts</td></tr>
<tr><td>Condition-based maintenance</td><td>- Schedule of Rates
- Cost plus fixed fee contracts</td></tr>
<tr><td>Inspection</td><td>- Schedule of Rates
- Firm fixed priced contracts
- Firm fixed priced contracts with provisions for economic price adjustment
- Cost plus fixed fee contracts</td></tr>
<tr><td>Corrective maintenance</td><td>NA</td><td>- Schedule of Rates
- Cost plus fixed fee contracts</td></tr>
</table>

1. No-Preventive Maintenance Approach

The no-preventive maintenance approach does not require a contract, as there is no preventive maintenance work being performed.

2. Time-Based Maintenance Approach

Time-based maintenance approach could either be implemented with prescriptive or performance-based contracts. Time-based maintenance approach implemented by prescriptive contracts can generally be managed by a system manager who can change the maintenance frequency where necessary. As such, a firm fixed priced contract combined with schedule of rates for addition or removal of scope of work would be suitable. A cost plus fixed fee contract would also be suitable for such a maintenance approach.

A performance-based approach would encompass inspection, and time-based maintenance or condition-based maintenance works. As such, suitable contracting mechanisms include the cost plus incentive, cost plus award fee, or the profit sharing contracts. A fixed priced contract added with performance incentives could also be a possibility for this to reduce the risk to the organization.

3. Condition-Based Maintenance Approach

While condition-based maintenance could be done using the performance-based contracts such as the cost plus incentive fee, cost plus award fee and profit sharing contracts, it might not be the most cost-effective solution. In contrast, a prescriptive contract can be able to fully utilize the benefit of the condition-based maintenance of high availability with the lowest cost, although it also depends on the *MDT* within the organization. As such, suitable contracting mechanisms include the schedule of rates and the cost plus fixed fee contracts.

4. Inspection

Inspection can help to achieve high availability of the systems, particularly for the no-preventive maintenance approach. With a good inspection methodology and prompt action to rectify any faults, high availability can be achieved regardless of the use of performance-based or traditional contracts. However, a performance-based contract such as the cost plus incentive fee, cost plus award fee and profit sharing contracts can be used for inspections to provide incentives for the contractor to identify and to provide prompt feedback for faults, thereby helping increase the availability of the systems.

Inspection could be implemented using a separate contract as a neutral party with no other interest in the other contracts. While this would be valuable in traditional contracts, it could also result in conflicts in performance-based contracts, particularly if the final contractual performance is dependent on a separate contractor. Hence, if the maintenance is implemented using a performance-based contract, it can be good to incorporate the inspection portion and the maintenance portion, and tie the performance as a single entity in a single-performance based contract.

In contrast, if inspection is contracted separately from a traditional maintenance contract, the use of a performance-based contract for the inspection can help achieve the optimal availability of the system.

5. Corrective Maintenance

In general, CM can be best implemented using a traditional contract. This is because there is no perfect means of ascertaining the amount of CM required for a system. Hence, the price premium for a CM contract can be relatively high.

However, if PM is implemented using a performance-based contract, combining the CM work with the PM under the same package would allow the lowest *MDT* for any fault discovered to provide the highest operational availability. This can be achieved by a clause that allows for work up to a fixed amount to be undertaken either as a pre-approved scope (cost plus contracts) or to be under the liability of the contractor (fixed priced contracts). The use of cost plus contracts can reduce the amount of risk obligation by the organization and the contractor, while the use of fixed priced contracts can effectively transfer the price risk at a premium to the contractors. However, if rectification work beyond the minimum sum is required, the scope of the CM can be undertaken under a traditional maintenance scope.

If CM is performed by a different contractor from a performance-based PM contractor, conflict of interest may be a risk that the organization and the PM contractor bear, and consequently reduce availability or increase cost. Hence, if PM is implemented using a performance-based contract, it can be advantageous to also use the same contractor to perform the CM, even if the CM is contracted using a prescriptive contract.

D. TOOLS TO SUPPORT MANAGEMENT OF MAINTENANCE CONTRACTS

Regardless of the contracting mechanism chosen, the availability of tools would impact the ease of management of the contracting mechanism. In particular, a good computerized maintenance management system and real-time inputs are critical for the implementation of a good maintenance system, particularly a performance-based maintenance system.

1. Requirements of Computerized Maintenance Management System

A well-designed computerized maintenance management system can be a good tool for the implementation of performance-based contracts, while a poorly designed one will make the management of the performance-based contracts difficult. Hence, the organization should ensure that a good computerized maintenance management system is in place before implementing a performance-based contract. In particular, based on the author’s experience in implementing and managing the computerized maintenance management system for building maintenance for the Singapore Armed Forces, it is found that the computerized maintenance management system should fulfil two requirements, namely fit for purpose and ease of use.

a. Fit for Purpose

Computerized maintenance management systems may be bought off the shelf. While the use of COTS specifically designed for building maintenance provide a strong process management suite, the process may not integrate well with the organization’s process, which is usually unique. On the other hand, the organization may be using a specific system that does not integrate or interoperate well with COTS. As such, it may be advantageous to have a customizable business process management suite to cater specifically to the organization’s purpose. However, not all business process management suites are built equal, and care has to be taken in the selection of a good system that can interoperate with the existing system, yet be customizable to the needs of building maintenance. A third area to look into is the cost, in particular cost of obtaining licenses and the cost of ad-hoc customization.

Further, the complete integration of the entire business process into the computerized maintenance management system would be critical to ensure that no step is bypassed and every piece of data is captured in the system. This will be useful in future upgrades and customizable reports that will aid in future functions of the organization.

b. Ease of Use

The ease of use of different GUI may vary. As such, a familiar user interface such as a Windows-based interface can be useful in improving efficiency and adaptation time. A good business process management suite usually has the function to create a customized graphical user interface for ease of use. Hence, a system with complex data entry should be avoided where possible.

2. Attributes of an Optional, but Recommended Computerized Maintenance Management System

A good computerized maintenance management system is an important enabler to the high availability of critical infrastructure. Based on his personal experience in Singapore, the author found that the computerized maintenance management system should take care of three key areas, namely built-in process management, accurate inventory management, and real-time updates.

a. Built-in Process Management

A built-in process management system enforces the update to a system record upon the initiation and completion of an activity. The comprehensive adoption of this approach can allow precise records over time, though annual audits may still be required to ensure the system records are accurate. The precision depends on the extent of integration, which can be in the following domain.

(1) Implementation of Work

CM can commence from an official job request on a problem that was encountered, such as a breakdown or a malfunction, and processed according to standard operating procedure and end in official closure of job. The example below shows the process which should form part of the computerized maintenance management system.

Job Request – The person initiating the job request should have access to the process management system. The job request should be tagged to the correct system from the start, while the problem faced can also be included in the job request. This will enforce two issues: that the system is included in the inventory listing, and that work to be done is tagged to the correct system.

Evaluation – The evaluation can be done by the technical agency, which can make the assessment on the job request to determine the scope and cost of work to be performed. If the assessed root cause is not due to the tagged system, the technical agency should tag the failure to the correct system, and tag the work done to the correct system. The scope of work can be input to the system and tagged to term contracts if available, and converted to invitation to quote if term contract is not available.

Finance – The released scope and cost of work can be approved by the finance authority in the same system. As such, real-time information on the budget should be available in the system for the finance authority to make the decision.

Procurement – With the approved budget, the procurement process can commence. The computerized maintenance management system enables the procurement agency to approve the use of the term contract if contract sum is sufficient, and to release the invitation to quote if not, or the term contract is not available, and follow through until awarded. The procurement agency should update the estimated job completion date based on reasonableness.

Implementation – The implementation can be performed by the contractors. However, an authorized agent should be performing maintenance management, and must have access to the system, so that any contingent changes to the job could be performed and re-routed for approval. Upon job completion, the agent can work with the user to perform handing and taking over and also update the system with necessary data such as cost and dates for the acceptance officer to approve the job completion.

Acceptance – The acceptance officer ensures the work delivered is captured in the system accurately, and approve the acceptance of the work before routing the job to the payment officer and certification officer.

Payment and Certification – The payment officer processes the payment for the completed work order with inputs from the system, and route it to the certifying officer to certify the payment.

Closure – Once the payment is certified, the job is officially closed with the relevant data such as status and cost of work and date of completion captured in the database.

(2) Preventive Maintenance

In addition to CM, PM task should be part of the process management as well for two purposes: to ensure work is done, and to verify the status of the system. As such, the computerized maintenance management system should take into consideration the following.

Maintenance Planning – The computerized maintenance management system can initiate job requests for PM based on inputs from the maintenance planning phase. The maintenance agency should input the maintenance schedule and tasks into the computerized maintenance management system, which can be used to automate the financial and procurement process.

Finance – The released scope and cost of work can be approved by the finance authority in the same system. As such, real-time information on the budget should be available in the system for the finance authority to make the decision.

Procurement – With the approved budget, the procurement process can commence. The computerized maintenance management system can enable the procurement agency to approve the use of the term contract if contract sum is sufficient, and to release the invitation to quote if not, or the term contract is not available, and follow through until awarded. The procurement agency should update the estimated job completion date based on reasonableness.

Maintenance Implementation – The implementation can be performed by the contractors. However, an authorized agent should be performing maintenance management, and must have access to the system, so that any contingent changes to the job could be performed and re-routed for approval. Upon job completion, the agent can work with the user to perform handing and taking over and also update the system with necessary data such as cost and dates for the acceptance officer to approve the job completion.

Acceptance – The acceptance officer can ensure the work delivered is captured in the system accurately, and approve the acceptance of the work before routing the job to the payment officer and certification officer.

Payment and Certification – The payment officer can process the payment for the completed work order with inputs from the system, and route it to the certifying officer to certify the payment.

Closure – Once the payment is certified, the job can officially be closed with the relevant data such as status and cost of work and date of completion captured in the database.

(3) Inspection

In addition to actual PM and CM work, the computerized maintenance management system can also allow the maintenance agency to update inspection records to each system. This serves three functions: to ensure the system’s serviceability, to verify the status of the system for possible CM to be done, and to verify the current inventory. As such, the following must be taken into consideration.

Status Update – The maintenance agency should be able to initiate a change to the system status such as serviceability and description for the system manager’s approval and IT administrator’s update.

Initiate Recommendation for Corrective Maintenance Work – The maintenance agency should be able to initiate recommendations for CM work for the system manager's approval, before being routed for job request approval.

Inspection Checklist – The status can be updated as part of an inspection checklist which can translate to system performance indicators. The overall status should also be consolidated into quantitative reports on the performance indicators of the overall class of system, system of systems, or contract.

(4) Reports

In addition to inspection and the actual CM and PM work, the computerized maintenance management system should be able to consolidate the records into usable reports based on the author's experience:

Financial – The computerized maintenance management system should be able to extract financial commitment data, and payment data for work done across the platform, according to commitment dates and payment dates. The finance authority should be informed when the budget hits a pre-determined value to avoid possible over-commitment of funds or insufficiency of budget.

Contractual – The computerized maintenance management system should be able to extract contractual data such as contract sum commitment data, payment data for contract, data on contractual performance indicators such as availability and serviceability, inventory of systems within a facility and the contract, and inventory of serviceable and non-serviceable systems within a facility and the contract. The contract manager can be informed when the contract sum committed hits a predetermined value to avoid possible over-commitment of work.

System – The computerized maintenance management system should be able to extract system performance data across the platform and within facilities such as availability and serviceability, cost of maintenance, frequency of maintenance, records of work done on the system or group of systems, inventory of systems including make and model, and record of work completed as follow up from inspections.

Other – The computerized maintenance management system should be able to customize reports for other purposes based on the data stored in the database.

(5) Configuration Management

The computerized maintenance management system should be able to identify possible areas affected by a change in configuration such as addition or upgrade of a system and prompt the system manager on the areas for in depth study on the consequences of the addition or upgrade. This serves three functions: to provide required information to the change control approving authority, to allow the technical agency to determine the complete chain of work required, and to ensure all systems remain operable. As such, the computerized maintenance management system should take into consideration the following.

Complete Link Chain for Critical Infrastructure – Critical infrastructures are generally shared across various platforms. As such, data involving the consumption of the critical infrastructure must be captured in the approval process of the systems. However, the capture of the resource consumption need is not sufficient. The critical infrastructure can be linked in a hierarchical link chain. As such, the computerized maintenance management system should be able to track the total consumption of the critical infrastructure across the nodes to identify the resource requirement.

Enforce Submission of Critical Data – The importance of the critical infrastructure should mandate the approval of resource consumption data for all systems requiring the use. Failure to do so may cause system failure and significantly lower the operational availability of the critical infrastructure, if the additional consumption goes beyond the load capacity of the critical infrastructure.

Approval for Change – Approval for the change request can be managed by a single entity for better command and control. This means that if a system manager is managing the critical infrastructure, the computerized maintenance management system should route the approval process to him or her before proceeding to other parts of the process.

b. Accurate Inventory Management

An accurate inventory management system is the key to the usability of the system, whether for maintenance management or contract management. The initial update of the inventory should be critically examined in detail, and any mistakes from the initial listing would have a heavy impact on the resulting data. As such, the key assumption for a good inventory management system is an accurate initial listing.

An accurate inventory management system relies on two mechanisms: traceability to process management and accountability in audit.

(1) Traceability to Process Management

The work management process should identify the target to which the work is performed, and tag the scope of work to the target to help identify the last date a work is done on the system, and verify the last known date the system was present. Further, it can also assist the system manager in identifying the maintenance work that had been performed on the system to aid in his or her system management.

(2) Accountability in Audit

While tagging a piece of work to a system can be important to ensuring the inventory is updated, there are also systems which may not be updated as they are in continuous operations with no work being performed on the system. Hence, audits choice and results should also be built into the system and enforced. This will allow the audit to be a secondary form of inventory check.

(3) Real-Time Inputs

Real-time inputs can be critical for the accurate computation of key performance indicators, cost and reports. As such, it can be good to ensure that data is entered into the system promptly. While the general process can be automated in the system, it is difficult to implement real-time inputs in inspection and for PM and CM work. Regardless, current technology includes RFID tags for systems, and tablets can be implemented to assist in real-time updates. Current Wi-Fi technology can also help in ensuring the use of secure private networks for the purpose of process management and inventory management. At the same time, camera functions in the tablets can greatly assist in the identification and capture of defects for prompt actions.

A computerized maintenance management system without real-time updates would not be able to fully utilize its benefits, and may be prone to human errors. As such, it is recommended to provide this function before the implementation of a performance-based building maintenance contract.

E. CONFIGURATION MANAGEMENT

Building maintenance encompass a huge number of systems interacting with each other. The configuration management of the entire building system is a large project, and is manpower intensive. However, critical infrastructure and specific systems whose resources are shared with other systems must be configuration managed.

In particular, fuel, airfield, power, water, cooling, blast protection, and fire protection should be properly configuration managed so that any change necessary from the addition of a new system that consumes the resource or the removal of an existing system that consumes the resource is authorized. A good computerized maintenance management system that enforces the project implementation process would be a key enabler for this. As mentioned in section D.1.a, the entire business process should be completely integrated in the computerized maintenance management system, and the specified need for the consumption of a critical infrastructure can introduce an approval process for the use of the critical infrastructure, and effectively stop the progress of a project until lifted by the authority for the critical infrastructure based on the assessment by the system manager that the capacity of the critical infrastructure is sufficient to support the new system.

In the event the critical infrastructure is insufficient to support the new addition, the critical infrastructure should be upgraded before the implementation of the addition. However, the cost of the critical infrastructure upgrade may be significantly greater than that of the project. Hence, it can be good to have a separate fund for the purpose of an upgrade to the critical infrastructure.

APPENDIX C

Risk-Adjusted Cost Comparison

The risk-adjusted cost comparison is used as a possible means of assessing the risk of failure in monetary terms. This involves five steps:

1. Identify all possible scenarios, e.g., substation fail, everything else working.

2. Identify the probability of the scenario happening.

3. Identify the room that fails in the scenario, and tag the cost to that scenario.

4. Multiply the cost and probability for each scenario.

5. Add the total cost of the entire scenario when the system fails.

See Table 15 for summary of steps 1 to 3.

Table 15 Summary of Probability of Scenario Occurring and Associated Cost

System Available? (1=available, 2=not available)									**Cost of failure of R11**	**Cost of failure of R12**	**Cost of failure B1**	**Cost**	**Probability of Failure**
A	I	G1	G2	B1	B2	R11	R12						
0	0	0	0	0	0	0	0		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	0	0	0	0	0	0	1		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	0	0	0	0	0	1	0		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	0	0	0	0	1	0	0		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	0	0	0	1	0	0	0		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	0	0	1	0	0	0	0		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	0	1	0	0	0	0	0		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	1	0	0	0	0	0	0		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	0	0	0	0	0	1	1		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	0	0	0	0	1	0	1		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	0	0	0	1	0	0	1		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	0	0	1	0	0	0	1		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	0	1	0	0	0	0	1		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	1	0	0	0	0	0	1		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	0	0	0	0	1	1	0		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	0	0	0	1	0	1	0		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	0	0	1	0	0	1	0		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	0	1	0	0	0	1	0		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	1	0	0	0	0	1	0		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	0	0	0	1	1	0	0		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	0	0	1	0	1	0	0		$120,000	$40,000	$-	$160,000	0.00000%
0	0	1	0	0	1	0	0		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	1	0	0	0	1	0	0		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%

0	0	0	1	1	0	0	0		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	0	1	0	1	0	0	0		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	1	0	0	1	0	0	0		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	0	1	1	0	0	0	0		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	1	0	1	0	0	0	0		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	1	1	0	0	0	0	0		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	0	0	0	0	1	1	1		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	0	0	0	1	0	1	1		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	0	0	1	0	0	1	1		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	0	1	0	0	0	1	1		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	1	0	0	0	0	1	1		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	0	0	0	1	1	0	1		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	0	0	1	0	1	0	1		$120,000	$40,000	$-	$160,000	0.00000%
0	0	1	0	0	1	0	1		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	1	0	0	0	1	0	1		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	0	0	1	1	0	0	1		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	0	1	0	1	0	0	1		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	1	0	0	1	0	0	1		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	0	1	1	0	0	0	1		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	1	0	1	0	0	0	1		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	1	1	0	0	0	0	1		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	0	0	0	1	1	1	0		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	0	0	1	0	1	1	0		$120,000	$40,000	$-	$160,000	0.00000%
0	0	1	0	0	1	1	0		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	1	0	0	0	1	1	0		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	0	0	1	1	0	1	0		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	0	1	0	1	0	1	0		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%

0	1	0	0	1	0	1	0		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	0	1	1	0	0	1	0		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	1	0	1	0	0	1	0		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	1	1	0	0	0	1	0		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	0	0	1	1	1	0	0		$120,000	$40,000	$-	$160,000	0.00000%
0	0	1	0	1	1	0	0		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	1	0	0	1	1	0	0		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	0	1	1	0	1	0	0		$120,000	$40,000	$-	$160,000	0.00000%
0	1	0	1	0	1	0	0		$120,000	$40,000	$-	$160,000	0.00000%
0	1	1	0	0	1	0	0		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	0	1	1	1	0	0	0		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	1	0	1	1	0	0	0		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	1	1	0	1	0	0	0		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	1	1	1	0	0	0	0		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	1	1	1	1	0	0	0		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	1	1	1	0	1	0	0		$120,000	$40,000	$-	$160,000	0.00000%
0	1	1	0	1	1	0	0		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	1	0	1	1	1	0	0		$120,000	$40,000	$-	$160,000	0.00000%
0	0	1	1	1	1	0	0		$120,000	$40,000	$-	$160,000	0.00000%
0	1	1	1	0	0	1	0		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	1	1	0	1	0	1	0		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	1	0	1	1	0	1	0		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	0	1	1	1	0	1	0		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	1	1	0	0	1	1	0		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	1	0	1	0	1	1	0		$120,000	$40,000	$-	$160,000	0.00000%
0	0	1	1	0	1	1	0		$120,000	$40,000	$-	$160,000	0.00000%
0	1	0	0	1	1	1	0		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%

0	0	1	0	1	1	1	0		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	0	0	1	1	1	1	0		$120,000	$40,000	$-	$160,000	0.00000%
0	1	1	1	0	0	0	1		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	1	1	0	1	0	0	1		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	1	0	1	1	0	0	1		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	0	1	1	1	0	0	1		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	1	1	0	0	1	0	1		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	1	0	1	0	1	0	1		$120,000	$40,000	$-	$160,000	0.00000%
0	0	1	1	0	1	0	1		$120,000	$40,000	$-	$160,000	0.00000%
0	1	0	0	1	1	0	1		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	0	1	0	1	1	0	1		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	0	0	1	1	1	0	1		$120,000	$40,000	$-	$160,000	0.00000%
0	1	1	0	0	0	1	1		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	1	0	1	0	0	1	1		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	0	1	1	0	0	1	1		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	1	0	0	1	0	1	1		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	0	1	0	1	0	1	1		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	0	0	1	1	0	1	1		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	1	0	0	0	1	1	1		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	0	1	0	0	1	1	1		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	0	0	1	0	1	1	1		$120,000	$40,000	$-	$160,000	0.00000%
0	0	0	0	1	1	1	1		$120,000	$40,000	$20,000,000	$20,160,000	0.00000%
0	1	1	1	1	1	0	0		$120,000	$40,000	$-	$160,000	0.00001%
0	1	1	1	1	0	1	0		$120,000	$40,000	$20,000,000	$20,160,000	0.00001%
0	1	1	1	0	1	1	0		$120,000	$40,000	$-	$160,000	0.00001%
0	1	1	0	1	1	1	0		$120,000	$40,000	$20,000,000	$20,160,000	0.00001%
0	1	0	1	1	1	1	0		$120,000	$40,000 DOD.	$-	$160,000	0.00001%

										2014. Performance Based Logistics Guidebook—A Guide to Developing Performance—Based Arrangements, U.S. DOD.			
0	0	1	1	1	1	1	0		$120,000	$40,000	$-	$160,000	0.00001%
0	1	1	1	1	0	0	1		$120,000	$40,000	$20,000,000	$20,160,000	0.00001%
0	1	1	1	0	1	0	1		$120,000	$40,000	$-	$160,000	0.00001%
0	1	1	0	1	1	0	1		$120,000	$40,000	$20,000,000	$20,160,000	0.00001%
0	1	0	1	1	1	0	1		$120,000	$40,000	$-	$160,000	0.00001%
0	0	1	1	1	1	0	1		$120,000	$40,000	$-	$160,000	0.00001%
0	1	1	1	0	0	1	1		$120,000	$40,000	$20,000,000	$20,160,000	0.00001%
0	1	1	0	1	0	1	1		$120,000	$40,000	$20,000,000	$20,160,000	0.00001%
0	1	0	1	1	0	1	1		$120,000	$40,000	$20,000,000	$20,160,000	0.00001%
0	0	1	1	1	0	1	1		$120,000	$40,000	$20,000,000	$20,160,000	0.00001%
0	1	1	0	0	1	1	1		$120,000	$40,000	$20,000,000	$20,160,000	0.00001%
0	1	0	1	0	1	1	1		$120,000	$40,000	$-	$160,000	0.00001%
0	0	1	1	0	1	1	1		$120,000	$40,000	$-	$160,000	0.00001%
0	1	0	0	1	1	1	1		$120,000	$40,000	$20,000,000	$20,160,000	0.00001%
0	0	1	0	1	1	1	1		$120,000	$40,000	$20,000,000	$20,160,000	0.00001%
0	0	0	1	1	1	1	1		$120,000	$40,000	$-	$160,000	0.00001%
0	1	1	1	1	1	1	1		$120,000	$40,000	$-	$160,000	0.38737%

0	1	1	1	1	1	1	0		$120,000	$40,000	$-	$160,000	0.00156%
0	1	1	1	1	1	0	1		$120,000	$40,000	$-	$160,000	0.00156%
0	1	1	1	1	0	1	1		$120,000	$40,000	$20,000,000	$20,160,000	0.00156%
0	1	1	1	0	1	1	1		$120,000	$40,000	$-	$160,000	0.00156%
0	1	1	0	1	1	1	1		$120,000	$40,000	$20,000,000	$20,160,000	0.00234%
0	1	0	1	1	1	1	1		$120,000	$40,000	$-	$160,000	0.00234%

Finally, the cost of failure for each scenario was multiplied with the probability of the scenario occurring, and added, resulting in the results in Table 10.

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