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Using Reliability-Centred Maintenance to Develop an Optimal Maintenance Strategy for A Micro-Grid System; A Case Study

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Abstract - Reliability-centred maintenance is an approach to analysing how and when equipment fails to maintain a desired level of performance or functionality. It employs the documentation of failure modes, failure effects and criticality analysis to rank potential failures, and combines this rank order with the use of a prescribed decision logic process to determine what maintenance tasks should be performed and when. Reliability-centred maintenance analysis has been used by the aviation industry to develop and update maintenance programs for their aircraft for many years. The practise has shifted to other industries. While the energy sector has prescribed the use of reliability-centred maintenance analysis to develop maintenance programs for new acquisitions like maintaining wind turbines, the use of this analysis to revise and update their current maintenance programs on existing renewable energy power plants like micro grids, is relatively new. Once the analysis yields maintenance tasks and intervals, this analysis must be successfully implemented in an optimized maintenance program to be effective. This research proposes a solution to successfully implement reliability-centred maintenance analysis results in an optimized maintenance strategy for the micro grid power generation system.

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Dr. Phil Murray have provided me the perfect mix of latitude and guidance in accomplishing this research, and I am very thankful.

My family is at the heart of everything I do. I dedicate this work to my son Gabriel, who passed away whilst I was doing my research.

W. Mondo

I. INTRODUCTION

Background

In Papua New Guinea (PNG), more than 90% of the population (mostly rural dwellers) has no electricity (Kaur & Segal, 2017). In urban centres, the power supply is often unreliable. According to PNG's Medium-Term Development Plan by the Department of National Planning and Monitoring (2010), the progress in providing electricity to rural PNG has been slow. In some cases, the level of electrical services has been deteriorating because of insufficient funding for maintenance. There is a lack of investment in maintaining infrastructure and performing operational maintenance on existing power generation, transmission and distribution assets. This contributes to the frequency of power shortages and ultimately means higher social and economic costs are borne by the country.

Maintaining a renewable energy system generation is difficult to achieve especially in remote rural areas of PNG, which has led to low system availability, reliability issues and unsuccessful and/or hindrance for new energy development projects in the country. Maintenance is routine recurring work, which is necessary to retain equipment in a state in which it can perform its intended function (Tarar, 2014). Maintenance is performed to ensure equipment availability in industry so to compete in the market. Maintenance has changed more than any other management disciplines during the past seventy plus years.

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In the early years, the main maintenance strategy was breakdown maintenance, as there was no awareness of downtime. But with passage of time, increased complexity of machines led to the preventive maintenance in, and then maintenance strategies and objectives have rapidly changed from preventive maintenance to condition monitoring. In the current era, the importance of effectiveness of operational equipment has increased dependent on plant capacity (Raouf, 2004). Therefore, the implemented strategy must have a balance between maintenance cost and plant reliability.

In 1960s, the concept of Reliability Centred Maintenance (RCM) evolved. Initially RCM was used in aircraft industries, and it was oriented towards airplane maintenance (Dekker, 1996). A study by Cotaina et al. (2000) indicated the possibility of RCM implementation in other industries. RCM is a structured framework and a logical process of optimizing maintenance resources for a physical asset's maintenance in its operating context. RCM is

focused on preserving system functions, rather than preserving physical asset. The RCM process analyses the functions and potential failures of equipment based on a seven- review step philosophy to evaluate reliability features, with risk management. As supported by Samanta et al. (2001), with the help of RCM it is possible to select an effective maintenance strategy that will offer "inherent reliability" of equipment. This research is proposing RCM as a maintenance tool within the renewable energy system generation for micro grid.

Problem Statement

Maintenance is one of the key issues hindering the uptake and continued use of renewable energy developments in PNG. The outcomes of poor maintenance practices are indicated by;

- Higher costs of operation and maintenance
- Longer period of downtime
- Low availability of resources (money, parts, and technical knowledge and expertise)

These indicators must be controlled to increase the benefits of the uptake and use of renewable energy. The study argues that an optimal maintenance strategy could vary directly or indirectly the above-mentioned indicators and accelerate the renewable energy development in PNG.

Research Question

The focus of this research effort is to answer the research question: How can RCM adequately support a micro grid system maintenance for a sustainable future in PNG?

Investigative Questions

To answer the research question, this research addresses the following investigative questions through a case study approach to assess the following:

1. What is the current maintenance strategy used in PNG Power Ltd and Digicel PNG Ltd to maintain their power generation assets?
2. How is this maintenance strategy, as identified in question one, used in PNG Power Ltd and Digicel PNG Ltd so far?
3. What are the associated benefits and challenges of the maintenance strategy used, in which RCM analysis is involved?

Methodology

Through a literature review, an insight and in-depth understanding of RCM is gained, including its origins, concepts, methods, and implementation steps. This builds on an understanding of the differences in maintenance strategies also gained through extensive literature review.

A case study approach is used to analyse the place of maintenance strategy in PNG industry related to renewable energy. The industry participants involved in this study are Digicel PNG Ltd and PNG Power Ltd. An analysis of the country's sole provider

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of electricity, PNG Power Ltd.'s maintenance and implementation of their maintenance strategy was performed via a case study. This included reviewing the available literature from the analysis and strategy development, and interviews with those involved in the analysis and strategy development for the power generating system.

Another case study will analyse the development of maintenance strategies from PNG's telecommunication company, Digicel PNG Ltd. This company has many of its base stations in remote locations powered by solar/battery hybrid system. By including an understanding of the salient characteristics of the maintenance strategies used, as well as the significant differences between them, could provide insight as to which aspects are applicable to an optimized maintenance strategy for the micro grid system in PNG.

By employing the insight and understanding of RCM analysis and implementation gained during the literature review, and synthesizing this information with an in-depth analysis of the maintenance strategies from the collective case study, an understanding of how to successfully incorporate the analysis being done in this research into an effective optimized maintenance strategy for a micro grid was gained.

Limits and Scope

Due to a limited amount of available time and available resources for travel, certain concessions had to be made during this research. While a case study involves an extended, in-depth analysis of a process, the depth of experience to be gained on any portion of this collective case study will be limited because the maintenance implementations studied will have already occurred. Additionally, though it would be

desirable to implement the proposed solution and analyse the results, the timing for submission and defence of this research will not allow for this to happen, and would certainly not afford enough time to evaluate whether the implementation of the maintenance strategy is successful.

The data for this research was collected in the form of interviews. One limitation of interviews is in objectivity – there is a tendency to blur actual observations with interpretations of those observations. To mitigate this risk all interviews were digitally recorded, with prior permission from the respondents, in their entirety. The full transcripts of the interviews are included as appendices to the text of this research report.

As to scope, this research is limited to the successful implementation of an optimized maintenance strategy for the micro grid power generating asset, not all transmission, and distribution and/or retailing assets. This is largely because of the wide disparity between maintenance concepts, processes and procedures from one system to another throughout the power systems inventory. While there was no time for research so broad in scope, numerous opportunities for follow-on research resulted from this research and are included in the concluding chapter.

Summary

In an era when resources are becoming increasingly scarce and mission requirements increasingly diverse, the renewable energy micro grid system must continue to search for more efficient methods of mission accomplishment. To that end, RCM analysis has been mandated for use in the development of optimized maintenance strategy not only for new acquisitions, but also for existing power systems. As the analysis is completed, the next challenge will be to successfully implement the results of this analysis into an effective maintenance strategy for the micro grid. This research offers a solution to this challenge, based on a synthesis of maintenance understanding, experience and lessons learned from the experiences of professionals and researchers, in the fields of renewable energy and power system maintenance strategy developments and implementations.

II. LITERATURE REVIEW

Chapter Overview

Maintenance has become an accepted practice in many different industries as a means of preserving the value and function of several types of equipment, increasing reliability and preventing equipment failure. Maintenance strategies are developed based on a variety of factors. The concept of reliability is embedded in the concept of maintenance, since a primary goal of maintenance is to improve or increase the reliability of a component or a system. RCM is a concept that has largely replaced the historical notion of the reliability curve that fits every strategy. In addition, instead of focusing on preventing equipment, components, or systems

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from breaking, RCM focuses on enabling the equipment, component or system to perform certain necessary functions. The acceptance and adoption of the concepts of RCM have caused wholesale changes in the development of maintenance strategies. Since this research deals with finding a way to successfully use RCM analysis to develop an optimized maintenance strategy for the micro grid, it is important to first gain an understanding of maintenance strategies and the RCM approach. After exploring these concepts, this chapter next closes with an overview of a micro grid system.

Maintenance Strategies

Many researchers have described different strategies for maintenance management. Bateman (1995), described basic types of maintenance programs, including reactive, preventive and predictive maintenance. Preventive and predictive maintenance represent two proactive strategies by which companies can avoid equipment breakdowns. Amik and
S.G. (2006) added another approach in the description of the maintenance continuum by including Total Productive Maintenance (TPM). TPM is a corrective maintenance approach that seeks to improve equipment performance while continuing to avoid equipment failures. Each maintenance strategies are discussed as follows.

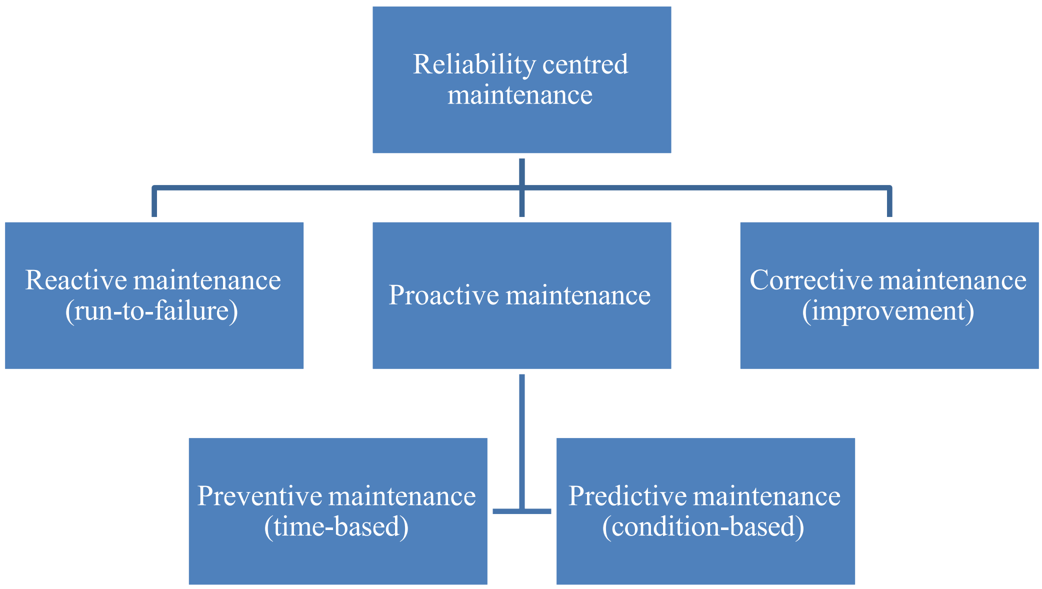

Figure 1. Common applications of maintenance strategies for RCM program, modified (NASA, 2008; Nowlan & Heap, 1978)

Reactive maintenance may be described as a fire-fighting approach to maintenance. Equipment is allowed to run until failure. Then the failed equipment is repaired or replaced (Paz & Leigh, 1994). Sometimes this strategy can be referred to as, breakdown or run-to-failure (RTF). Under reactive maintenance, temporary repairs may be made in order to return equipment to operation, with permanent repairs put off until a later time (Gallimore & Penlesky, 1988). Reactive maintenance allows a plant to minimize the amount maintenance manpower and money spent to keep equipment running (Gavriel, 2001). However, the disadvantages of this approach include unpredictable and fluctuating production capacity, higher levels of out-of-tolerance and scrap output, and increased overall maintenance costs to repair catastrophic failures (Bateman, 1995; Gallimore & Penlesky, 1988).

Proactive maintenance is a strategy for maintenance whereby breakdowns are avoided through activities that monitor equipment deterioration and undertake minor repairs to restore equipment to proper condition. These activities, including preventive and predictive maintenance, reduce the probability of unexpected equipment failures.

Preventive maintenance is often referred to as time-based maintenance (TBM). It is comprised of maintenance activities that are undertaken after a specified period of time or amount of machine use (Gits, 1992; Herbaty, 1990). It is sometimes known as periodic maintenance. This type of maintenance relies on the estimated probability that the equipment will fail in the specified interval. The work undertaken may include equipment lubrication, parts replacement, cleaning and adjustment. Production equipment may also be inspected for signs of deterioration during preventive maintenance work. For performing time-based preventive maintenance, a decision support system is needed, and it is often difficult to define the most

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effective maintenance intervals because of lacking sufficient historical data (Mann et al., 1995). In many cases when time-based maintenance strategies are used, most machines are maintained with a significant amount of useful life remaining (Mechefske & Wang, 2003). This often leads to unnecessary maintenance, even deterioration of machines if incorrect maintenance is implemented.

Predictive maintenance is often referred to as condition-based maintenance. Maintenance decision is made depending on the measured data from a set of sensors system when using the condition-based maintenance (CBM) strategy. To date a number of monitoring techniques are already available, such as vibration monitoring, lubricating analysis, and ultrasonic testing. The monitored data of equipment parameters could tell engineers whether the situation is normal, allowing the maintenance staff to implement necessary maintenance before failure occurs. This maintenance strategy is often designed for rotating and reciprocating machines, e.g. turbines, centrifugal pumps and compressors. But limitations and deficiency in data coverage and quality reduce the effectiveness and accuracy of the condition-based maintenance strategy (Al-Najjar & Alsyouf, 2003).

A corrective maintenance strategy goes beyond efforts to avoid equipment failures. A corrective maintenance strategy, like TPM, seeks to improve overall equipment operation. Maintenance may participate in these improvements through involvement in efforts to improve the design of new and existing equipment. Team-based activities play an important role in TPM. Team-based activities involve groups from maintenance, production and engineering. The technical skill of engineers and the experience of maintenance workers and equipment operators are communicated through these teams (Nakajima, 1989). Maintenance prevention teams work to improve equipment performance through improved equipment design. The maintenance function works with the engineering department during the early stages of equipment design. This allows the team to design and install equipment that is easy to maintain and operate (Adair-Heeley, 1989; Nakajima, 1989) . Maintenance involvement in team-based activities has several benefits. The efforts of maintenance improvement teams should result in improved equipment availability and reduced maintenance costs.

The RCM program (Figure 1) is gaining favour because it combines the strengths of reactive, preventive, predictive, and proactive maintenance strategies (Gill, 2009). In other words, RCM is a technique used mostly to select appropriate maintenance strategies for physical assets. To set the stage for tying this discussion of maintenance strategies to the concept of RCM, it is important to understand how its features has evolved.

Reliability-Centred Maintenance

Having gone through 30+ years of evolution since 1980 (Figure 2 and Figure 3), the salient features of RCM are now mostly agreed upon.

1950s	Traditional maintenance approaches were found to be inadequate for post war "modern" aircraft.
1960s	FAA/ Airline industry reliability program FAA/ Manufacturers Maintenance Steering Group (MSG)
1970s	MSG-1 applied to Boeing 747 MSG-2 applied to other aircrafts, DC-10 and L1011
1980s	RCM coined by United Airlines (original decision diagram published) MSG-3 developed and applied to B-754, B-767 (RCM-I: Revised decision diagram)
1990s	RCM applied in the nuclear industry RCM being applied in a variety of industries (RCM-II: Environment added to decision diagram)
2000s	RCM-III: Risks added to decision diagram.

Figure 2. The development of reliability-centred maintenance (Kennedy, 2015)

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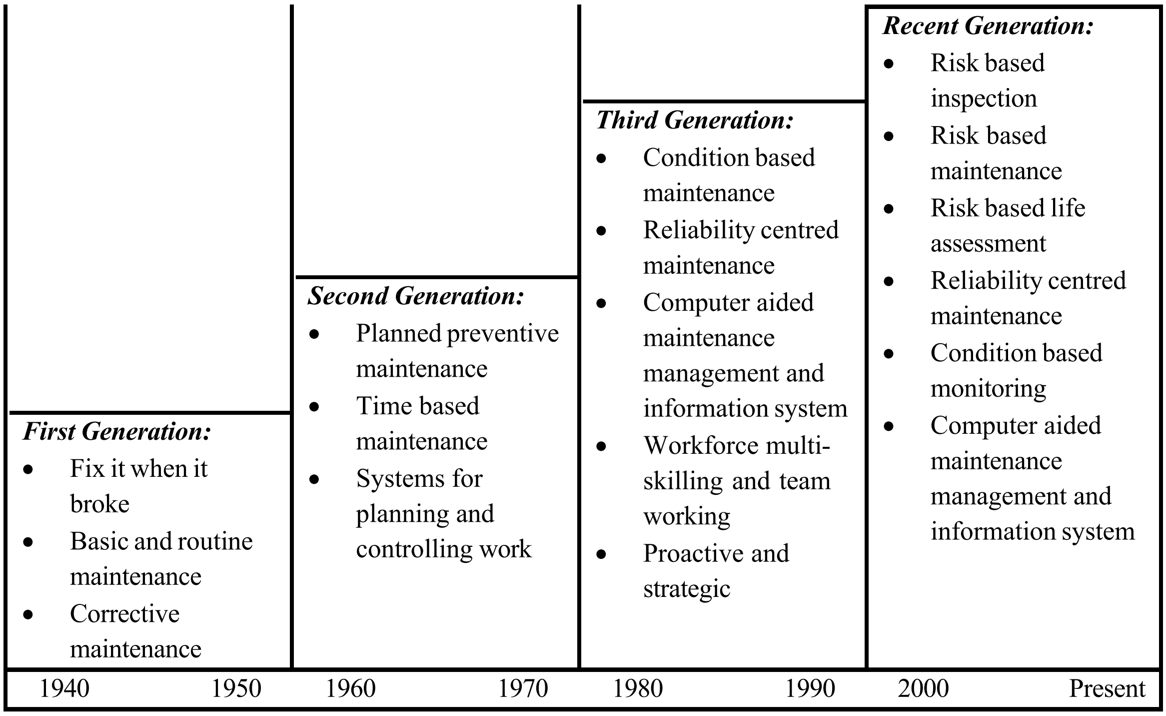

Figure 3. The development of maintenance strategies (Odoardi, 2016)

Smith (1993) and supported by Deshpande and Modak (2002) describes four basic features of RCM.

The first feature is “the primary objective of RCM is to preserve system function” (Smith, 1993, p. 49). In contrast to earlier preventive maintenance philosophies whose aim was to prevent failure, RCM recognizes that failure is not always preventable and that, in some cases, attempting to prevent failure actually causes failure earlier than if the system were left alone. Take, for instance, performing preventive maintenance in the form of an overhaul when the system or component is in operational condition would actually bring the system to early failures if not properly done, affecting other components or systems. Additionally, every system or component is not equally important, so the maintenance program should not devote resources to prevent failure or loss of function on equipment that has minor impact on the function of the system when it does fail.

The second feature states “since the primary objective is to preserve system function, then loss of function or functional failure is the next item of consideration” (Smith, 1993, p. 50). Considering functional failure means looking at the actual equipment in the system, and analysing it for all possible ways in which it could fail to perform its required function.

Feature three as Smith (1993) states:

In the RCM process, where our primary objective is to preserve system function, we have the opportunity to decide, in a very systematic way, just what order or priority we wish to assign in allocating budgets and resources. Thus, we want to prioritize the importance of the failure modes. (p. 50)

This feature brings to light the efficiency factor in RCM analysis. By prioritizing, or rank ordering, the ways each component or system can fail, we can address those with the most severe impact on system functionality first, and lessen the time and energy spent on failures or degradations that have little or no significant impact on system functionality.

Smith’s (1993) fourth feature of RCM is:

Each potential maintenance task must be judged as being ‘applicable and effective.’ Applicable means that if the task is performed, it will in fact accomplish one of the three reasons for doing preventive maintenance (i.e., prevent or

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mitigate failure, detect onset of a failure, or discover a hidden failure). Effective means that we are willing to spend the resources to do it. (p. 51)

Of importance in these definitions is that Smith combines the traditional meaning of efficient in his definition of effective. Merriam-Webster Online (2017) defines efficient as "productive of desired effects; especially productive without waste." It is the aspect of eliminating or minimizing waste that is most often associated with efficiency, while effectiveness is usually associated with completeness, or accuracy. Smith uses the one word - effective - to connote the efficiency aspect by stating that a willingness to expend resources to perform the task must exist. This definition points not only to the ability of the task to get the job done (effectiveness), but also the idea that money will not be expended needlessly (efficiency). This nuance in Smith's definition is important to understand as we continue to explore what RCM is. The concept of applicability and effectiveness is not limited to Smith, as Nowlan and Heap (1978) stated 15 years earlier "proposed tasks are evaluated according to specific criteria of applicability and effectiveness" (p. 8).

Another area of convergence over the years has resulted in the accepted definitions of RCM being quite similar. Kelly (1997) claims "in RCM strategy is formulated via a structured framework of analysis aimed, in principle, at ensuring the attainment of a system's *inherent reliability*, i.e. the reliability that it was designed to attain" (p. 218). Nowlan and Heap (1978) stated "RCM refers to a scheduled maintenance program designed to realize the inherent reliability capabilities of equipment" (p. 2). Moubray (1997) defines RCM as "a process used to determine what must be done to ensure that any physical asset continues to do what its users want it to do in its present operating context" (p. 7).

Further description of how realization of this inherent reliability is to be approached is contained in the various reasons for performing RCM. Pham (2001) states,

The premise of RCM is that a more efficient and effective life-cycle maintenance program for equipment can be developed by addressing individual component failure modes, the consequences of failures, and the actual proactive maintenance tasks to be done. The primary objective of RCM is to preserve equipment function by preserving component operation. (p. 154)

In order to achieve this more efficient and effective program, RCM adheres to a slightly different overarching concept of the purpose of proactive maintenance. As stated earlier, RCM does not seek to prevent failures, it seeks to preserve the critical functions of components and systems.

The way in which RCM seeks to preserve this critical function was summed up in a general sense by RCM pioneers Nowlan and Heap (1978) in their DoD-sponsored report on RCM: "The principles of RCM stem from a rigorous examination of certain questions that are often taken for granted:

- How does a failure occur?
- What are its consequences?
- What good can preventive maintenance do?" (p. 6)

These three basic questions have been further refined and developed into what have become known as the seven basic questions of RCM. Moubray (1997) states,

The RCM process entails asking seven questions about the asset or system under review, as follows:

- *what are the functions and associated performance standards of the asset in its present operating context?*
- *in what ways does it fail to fulfil its functions?*
- *what causes each functional failure?*
- *what happens when each failure occurs?*

- *in what way does each failure matter?*
- *what can be done to predict or prevent each failure?*
- *what should be done if a suitable proactive task cannot be found?* (p. 7)

As Moubray states, answering these seven questions forms the framework of the RCM process. The first question is answered by defining the functions of each component or system. Defining the functions must be done in a thorough and specific enough manner to allow downstream analysis of the possible failures associated with these functions. Functions should be described such that loss of that function has one effect whenever possible. If more than one effect is possible from the loss of the function, the function may need to be separated into two or more functions. Additionally, functions are specifically defined and include performance metrics where applicable. For instance, the function of a battery charge controller might be correctly defined as: provide a constant

60amps of charging current at a variable temperature between 30deg Celsius max and 10deg. Celsius min.

Determining how a system or component fails to fulfil its functions is the first step in a process called Failure Modes, Effects, and Criticality Analysis (FMECA). In fact, questions two through five, (What are the functional failures? What causes each functional failure? What is the effect of each functional failure? How critical is each functional failure?), are all answered through the course of performing the failure modes, effects and criticality analysis.

In the FMEA process, every mode of failure or malfunction of each component of the system must be considered. Then the effects of the failure are determined in order to assess the ultimate effect on the system performance. Criticality is the combination of probability of failure occurrence and the level of severity. It may be the best way to assess the effect of a failure mode on the reliability of a component. The failure mode, effects, and criticality analysis (FMECA) is probably the most widely used and most effective design reliability analysis method (Dai & Wang, 1992, p. 178).

To paraphrase the FMECA process, then, every function that was identified in answering the first question is examined, and every feasible way in which this function could fail is listed. Recall that for each function, the description was such that it provided quantifiable performance metrics. A functional failure, then, is "defined in terms of a deviation from the quantified performance standard provided by the function"(Moubray, 1997). To further define terms, "a failure mode is what went wrong; a failure cause is why the failure occurred in the first place, and the failure effect is how the failure impacts the equipment" (Pham, 2001, p. 161). Developing a list of every possible failure mode for each of the previously named functions serves to answer question two and three. Subsequently, every failure mode is analysed for its effect on the system. The effects of the failure modes answer question four. These effects of the failure modes can then be used to rank the failure modes into categories of criticality. The most widely used system of categorization employs a two-step process. The purpose of the first step is to separate hidden failure modes from evident failure modes, and the second step should clearly distinguish events (failure modes and multiple failures) that have safety and/or environmental consequences from those that only have economic consequences (operational and non-operational consequences (SAE, 2009). The criticality analysis portion of the failure modes, effects and criticality analysis answers question five. This process is depicted in Figure 4. Note that while Figure 4 is derived from the logic tree

analysis used for a manufacturing plant, the logic is universally applicable to any failure modes, effects and criticality analysis.

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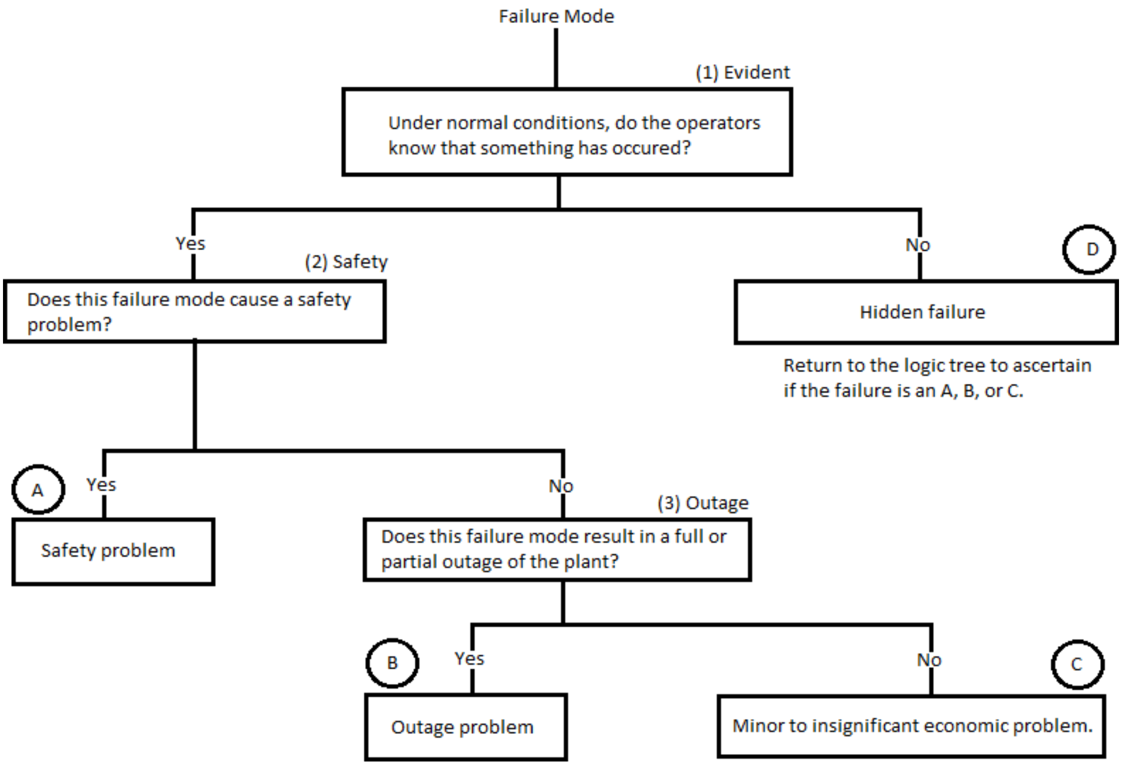

Figure 4. Logical tree for the failure mode, effects and criticality analysis (Smith, 1993, p. 93)

"So, we usually choose to address maintenance priorities as:

1. A or B/D
2. B or D/B
3. C or D/C" (Smith, 1993, p. 93)

The RCM analysis process then moves on to question six: what can be done to predict or prevent each failure? Again, a decision tree is employed to determine which maintenance tasks can be applied to predict or prevent the failure modes identified through FMECA as deserving attention. This process is called task selection. It is important to understand a bit more about the types of tasks employed in a maintenance program.

Typically, maintenance tasks are broken down into four categories: time-directed (TD), condition-directed (CD), failure-finding (FF), and run-to-failure (RTF). It is immediately obvious that run-to-failure involves no proactive maintenance at all. This is not an oversight, but intended, since some failure modes may be so insignificant or have such a non-critical, negligible impact on the component or system's function that it is actually preferable to allow the equipment to run-to-failure, and then employ corrective maintenance as the method of choice. Since this is a conscious decision made as part of a

maintenance program, run-to-failure is included as the fourth category of the maintenance tasks. Time-directed tasks are category of proactive maintenance tasks. Time-directed tasks are aimed directly at failure prevention. The keys to categorizing a task as TD are:

1. *the task action and its periodicity are pre-set and will occur without any further input when the pre-set time occurs,*
2. *the action is known to directly provide failure prevention benefits, and*
3. *the task action requires some form of intrusion into the equipment.* (Smith, 1993, p. 12)

Condition-directed tasks are aimed at detecting the onset of a failure or failure symptom. The keys to classifying a task as CD are:

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1. *we can identify a measurable parameter that correlates with failure onset,*
2. *we can also specify a value of that parameter when action may be taken before full failure occurs, and*
3. *the task action is nonintrusive with respect to the equipment.* (Smith, 1993, p. 13)

If a failure mode is identified as hidden, or not evident to the operator, it is called a hidden failure. Recall from Figure 4 that hidden failures may range in criticality from safety-related to minor/insignificant. In the occurrence of hidden failures, "we find it most beneficial to exercise a prescheduled option to check and see if all is in proper working order. We call such an option a *failure-finding* (FF) task" (Smith, 1993, p. 14). With the four categories of tasks available, a roadmap such as the one depicted in Figure 5 is employed to match the correct task with each failure mode from the FMECA. Note that this roadmap employs the same categorization system for failure modes used in Figure 4: A or D/A – Evident/hidden safety problem, B or D/B – Evident/hidden outage problem (full loss of functionality), and C or D/C – Evident/hidden minor or insignificant problem.

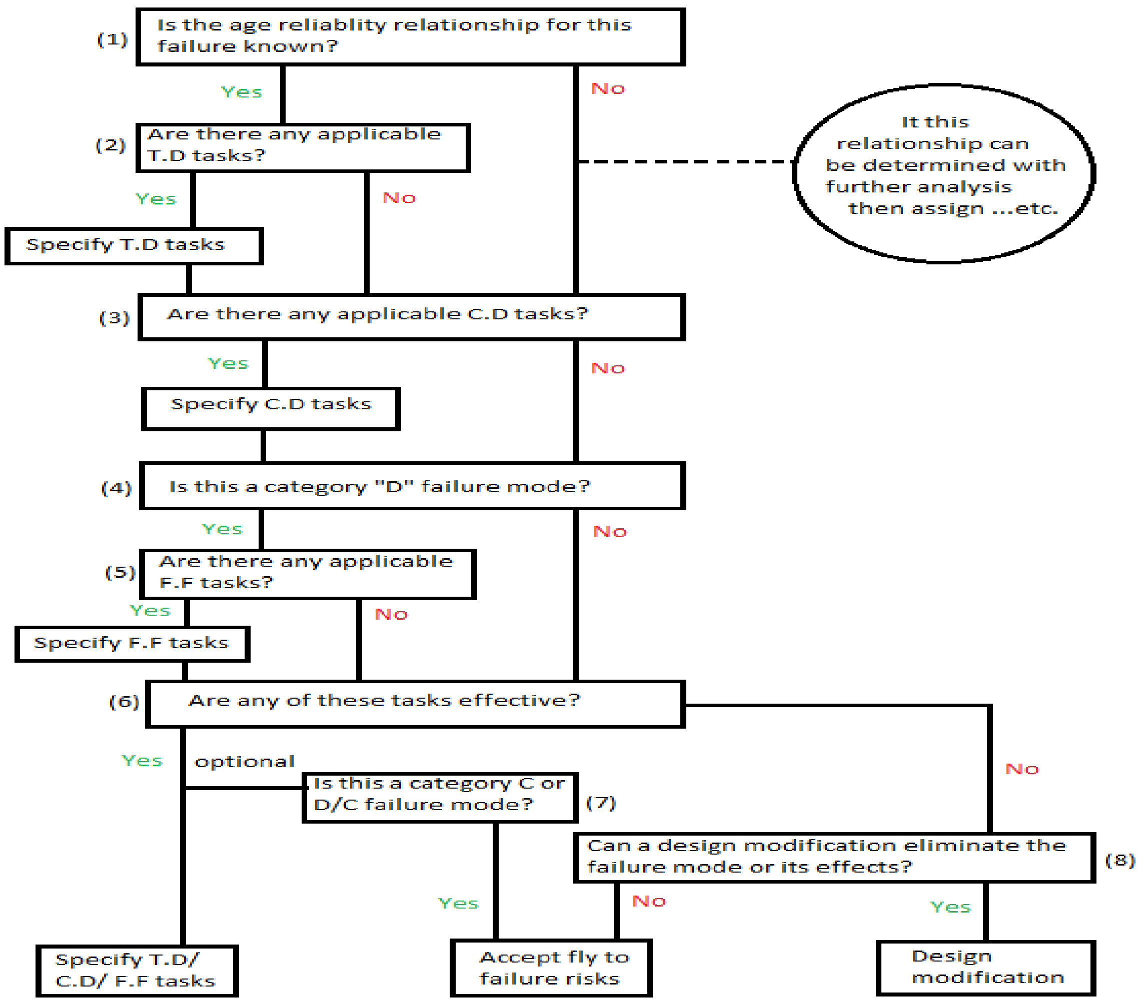

Figure 5. Task selection roadmap (Smith, 1993, p. 95)

Given the goal of the RCM process, preserving system functionality, this roadmap should make sense. Following the logic, if a TD task is applicable and effective in preventing a given failure mode, it should be employed first, since TD tasks are aimed at preventing failure in the first place. Note, however, that it is important to once again understand Smith's definition of effective in order to employ Smith's task selection process accurately. Without understanding the implied facet of efficiency in Smith's definition of effective as it applies to using a TD task first, other RCM subject matter experts such as Nowlan and Heap would disagree with Smith's logic tree. In order to be used first, the TD task must also be efficient, according to Nowlan and Heap (1978), because:

Whenever an on-condition task is applicable, it is the most desirable type of preventive maintenance. Not only does it avoid the premature removal of units that are still in satisfactory condition, but the cost of correcting potential failures is often far less than the cost of correcting functional failures, especially those that cause extensive secondary damage. (p. 56)

Moving on with Smith's logic, if no TD task is applicable, effective and efficient, then a CD task should be considered, since CD tasks are used to restore functionality after degradation is encountered, but before full loss of functionality occurs. Next, a determination as to whether the failure mode is hidden or evident is made. If an applicable FF task is effective in detecting the hidden failure mode, then it should be applied. By following this logic tree, suitable proactive tasks are aligned with each failure mode. Again, RCM is not designed to be overprotective, or inefficient. According to Nowlan and Heap (1978):

Each scheduled maintenance task in a RCM program is generated for an identifiable and explicit reason. The consequences of each failure possibility are evaluated, and the failures are then classified according to the severity of their consequences. Then for all significant items – those whose failure involves operating safety or has major economic consequences – proposed tasks are evaluated according to specific criteria of applicability and effectiveness. The resulting scheduled-maintenance program thus includes all the tasks necessary to protect safety and operating reliability, and only the tasks that will accomplish this objective. (p. 8)

This last sentence points again to the efficiency aspect of RCM, in that only the tasks that actually are proven to contribute to safety and operating reliability are included. In this way, RCM has the potential to achieve huge cost savings over less efficient methods of task selection for proactive maintenance programs.

At this point in the RCM analysis process, we have identified and prioritized failure modes, and have used a logic tree process to assign tasks and periods at which to accomplish these tasks to most failure modes. There will remain, however, some failure modes for which an applicable and effective task has not been found.

The seventh question remains to be answered: what should be done if a suitable proactive task cannot be found? "When an item cannot benefit from scheduled maintenance, in some cases product improvement may be necessary before the equipment goes into service" (Nowlan & Heap, 1978, p. 70). If the failure mode is not critical enough to be addressed specifically, run-to-failure should be considered (as per Smith's definition of run-to-failure tasks above). Corrective maintenance is possible as design improvement when necessary.

Overview of Micro Grid System

Having seen what maintenance strategies are available and, especially the featured RCM strategy, it is now useful to understand what is needed with regard to RCM and micro- grids. Therefore, the next area to explore involves an understanding of a micro grid system to view the importance of adopting RCM in its maintenance programs.

Micro grids tend to transmit power over low-voltage distribution networks from interconnected local generation sources such as micro-hydro, photovoltaics or wind turbines to a relatively small number of users via a shared distributed system. The electricity is usually distributed at a low voltage and the micro grid can function completely independently of the central electricity grid. In many senses, micro grids are smaller versions of traditional centralized electricity grids. According to one expert, micro grids are defined as local power networks that use distributed energy resources and manage local energy supply and demand (Adelfang, 2017). At the most basic level, micro grids are "micro" (small) and offer a "grid" (an interconnecting system of links).

There are many structures of micro grids to be considered. Experts and practitioners have not fully agreed on a naming convention or categorization of micro grids. For example, Navigant Research (2016) has divided up the micro grid market into five categories based on the end-user:

1. Remote systems
2. Commercial/ Industrial

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3. Community/ Utility
4. Institutional/ Campus
5. Military

HOMER Energy developer Lilienthal (2013) delineates four categories of micro grids based on grid connection and size:

1. Large grid-connected micro grids (e.g. Military bases and campuses)
2. Small grid-connected micro grids (e.g. Single gensets to backup unreliable central grids)
3. Large remote micro grids (e.g. Island utilities)
4. Small remote micro grids (e.g. Villages)

This research, focus specifically on Navigant's "remote systems" category or HOMER's "small remote micro grids" category, specifically in rural areas of developing countries and with a particular concentration on renewable energy-based generation. The micro grid structure depicted in Figure 6 is chosen. This structure brings no implication to the grid, since it is isolated. In this case, the generating units must supply the load at all times, so the storage device maybe useful. The general structure assumes the possibility of AC loads.

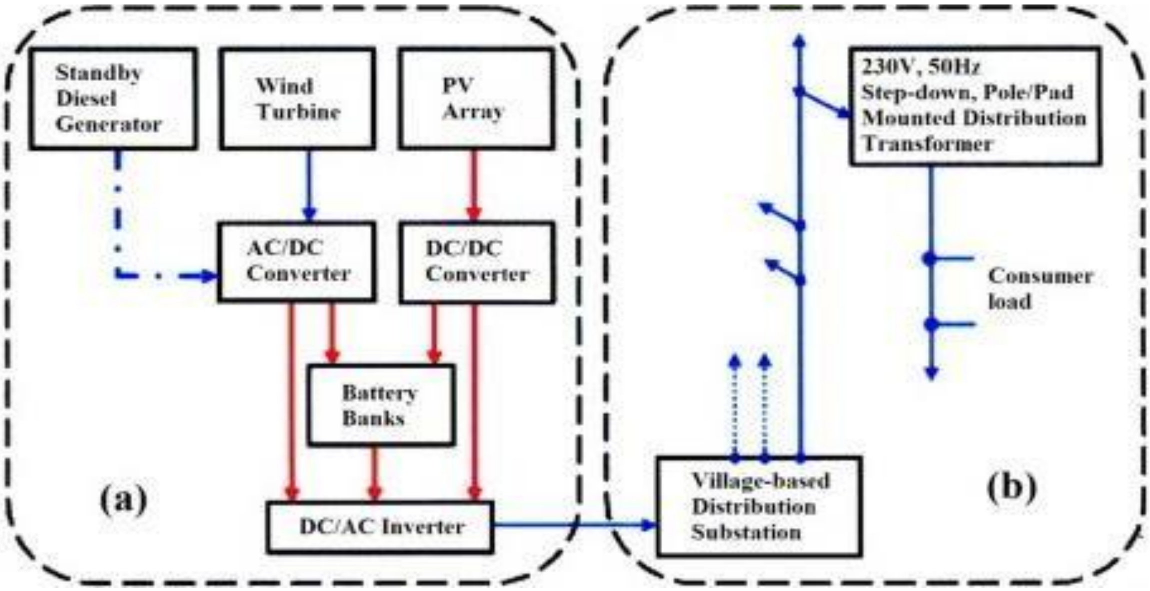

Figure 6. Village-level micro grid distribution system with mixed generation (Xu et al., 2016)

Electric power systems are usually divided into four parts, interconnected with each other: generation, transmission, sub-transmission and distribution (Machowski et al., 1997). For a low voltage or 48-120 VDC distribution system as in this micro grid system, no complex transmission and distribution assets are required. However, the concept of micro grid system would require more than one energy generating sources as shown in Figure 6 (a), PV array and wind turbine.

In order to develop the concept of RCM for micro grid system, it is necessary to evaluate each component of the subsystems and choose the right maintenance strategy. In this research, focus will be on the generation assets Figure 6 (a) and not distribution Figure 6 (b).

The wind turbine as one of the generation subsystems in the micro grid is used to illustrate RCM concept (Figure 7).

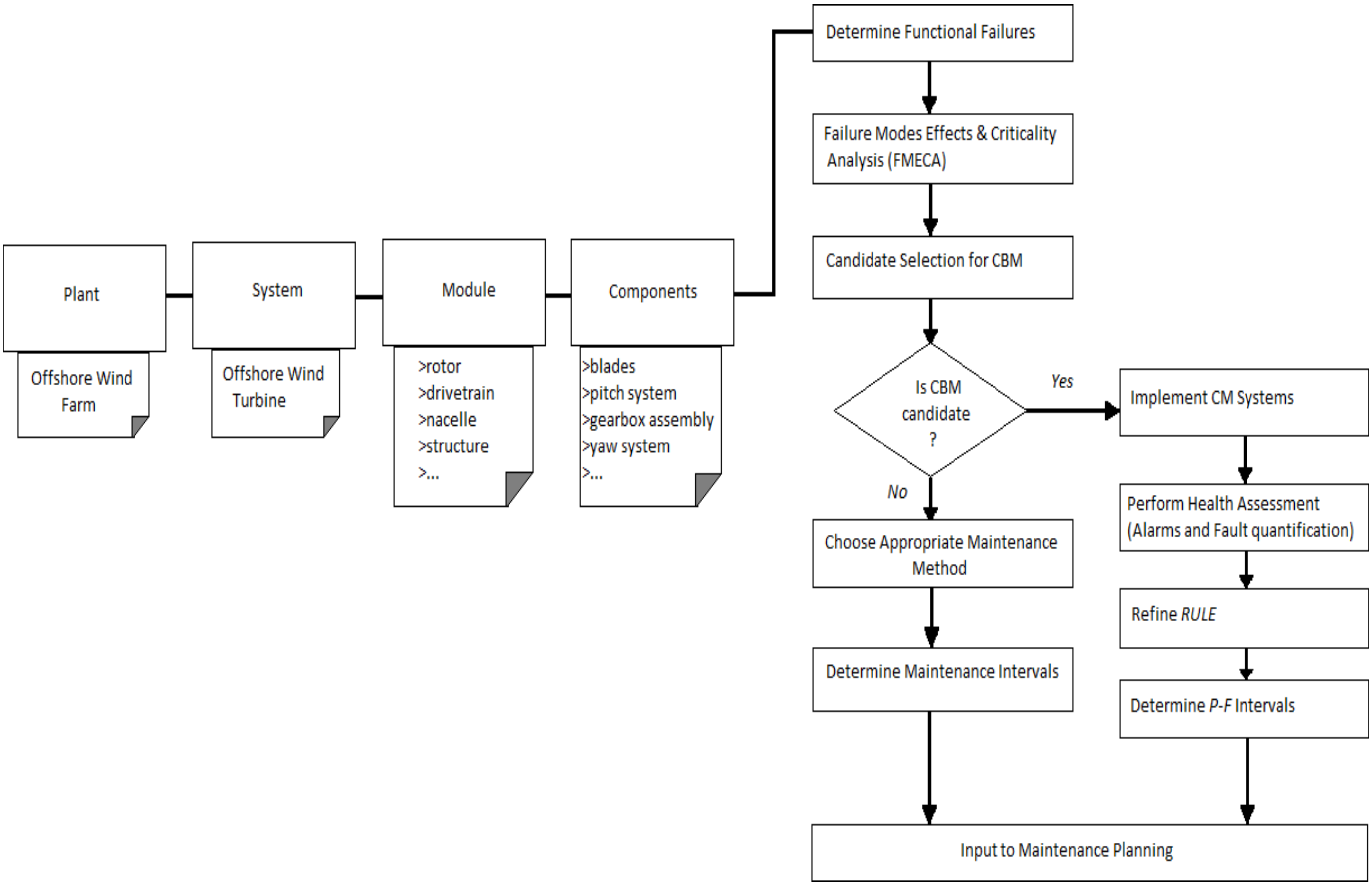

Figure 7. Selection of suitable maintenance procedure for each component (Tavner, 2012)

The wind turbine taxonomy (Tavner, 2012) which is now generally accepted in the wind turbine industry as depicted in Figure 7, is necessary to zoom into component level and identify high priority failure modes and with the inclusion of RCM analysis (FMECA), to justify the needs of a condition-based maintenance as the best maintenance option for wind turbine.

From previous section, the sixth step (*what can be done to predict or prevent each failure?*) in the RCM analysis after FMECA is maintenance tasks selections. This can be either, time-based (TD), condition-based (CD), failure finding (FF) and/ or run-to- failure (RTF). Wind turbine fulfils the three keys highlighted in the earlier section to determine possibility of CD tasks. 1-measurable parameter, 2-specific value of that parameter and 3-task action nonintrusive to system. In wind turbine system, parameters that require attention are vibration sensing, oil debris analysis and temperature monitoring. Parameter operational values are usually set by manufactures to determine PF-intervals. PF-intervals is a period in the condition of the component as it ages, is likely to start experience potential failures before reaching functional failure, which will lead to breakdown. As such, condition-based maintenance is paramount for especially offshore wind turbines. This also implies the importance of RCM analysis to maintenance considerations as:

- Isolated Off-grid (in this case not connected to central grid electricity)
- Intermittency from renewable energy sources would be a problem and require improved maintenance on additional hardware installed for reliability.
- Remoteness could mean high maintenance costs and delayed response time thus increased mean time to

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repair or increased down time.

Summary

This chapter opened with a discussion of maintenance strategies, and moved into the subject of reliability, specifically as it applies to the development of an all-in-one maintenance program, that is RCM. A referencing on the originality of RCM was introduced and then followed, including the evolution key features of RCM, and the process of RCM. Finally, this chapter closed with a description of the micro grid system applicable to rural Papua New Guinea. And using wind turbine to illustrate the point importance of RCM analysis.

III. METHODOLOGY

Chapter Overview

This chapter will describe the research design employed for this report, a discussion of the validity and reliability of the methods employed, the type of data collected and the data collection method, and a description of the data analysis technique employed.

Research Design

"Colloquially, a research design is *a logical plan for getting from here to there*, where *here* may be defined as the initial set of questions to be answered, and *there* is some set of conclusions about the questions" (Yin, 2013, p. 20). For this research, *here* is defined by the research and investigative questions posed. *There* is comprised of the synthesis of the data analysis that answers those questions. The research design chosen was the collective case study. The remainder of this section will discuss and justify that choice.

When this topic for research was chosen, it was with the understanding that the use of RCM analysis to update maintenance strategy for a micro grid system in the renewable energy sector was a relatively new concept. Though the other conventional energy sectors have extensively relied on RCM-based maintenance programs for their assets since 1980's (Wilmeth & Usrey, 2000), the renewable energy sector is starting to explore its use as described by Quinlan (1987) with a first application of RCM to an early generation wind turbine. By employing the case study design, the intent was to explore what worked (and what didn't work) in the power generating sectors, maintenance strategies, and synthesize the common features into a viable implementation for the RCM analysis in a micro grid system. The case study as a research design is ideal for this purpose as to contribute to knowledge of individual or group (Yin, 2013).

Table 1 - *Relevant Situations for Different Research Strategies (Yin, 2013, p. 5)*

Strategy	Form of Research Question	Requires Control of Behavioural Events?	Focuses on Contemporary Events?
Experiment	how, why?	Yes	Yes
Survey	who, what, where, how many, how much?	No	Yes
Archival analysis	who, what, where, how many, how much?	No	Yes/ No
History	how, why?	No	No
Case Study	how, why?	No	Yes

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This research endeavour met all three of these criteria as stated by (Yin, 2013) in Table 1. The research question fundamental to this effort is *How* can the RCM analysis being performed as case study be successfully implemented as an optimized maintenance strategy for the micro grid? A researcher, could have little or no control over the actual effort that is underway to revise the micro grid maintenance program based on the results of RCM analysis. Neither could a researcher have any control over the way the commercial aviation industry had employed RCM analysis in the past. Since the RCM analysis is still new concept at the renewable energy sector, and since this analysis is yet to be implemented, the events are certainly contemporary, and have a real-life context. Meeting these three criteria strongly supports the use of the case study methodology in this research.

Leedy and Ormrod (2001) list four common features of research: universality, replication, control, and measurement. Because of the research and investigative questions this project was designed to answer, data that was primarily qualitative in nature was collected. As a result, the way this research design fulfils these four features is not as cut and dried as it might be for a research design that relied exclusively on quantitative data, but these criteria still serve as a good starting point for describing and justifying the research design.

To be considered universal, this research relies on the analysis of data collected through interviews to form a collective case study, and interviews were not exclusive in any way relating to access granted, any competent person could also be expected to carry out this same research (Leedy & Ormrod, 2001). The contact list used is not exclusive, and the subject matter experts interviewed are available to any researcher or practitioner who seeks them out. The path that led to contact with these four respondents for this research was an evolutionary process. After initial contact with the quality manager at the PNG Power Ltd, the manager was able to provide contact information for the maintenance planner (Appendix B) and the assistant reliability engineering manager (Appendix C). After searching the internet for different maintenance-related information, contact via email was made with the PNG Power team and after a week, upon agreed time, interview began at separate days. Alternatively, arrangement with Digicel PNG team, via similar process, the power system engineer (Appendix D) and the performance engineer (Appendix E) were interviewed. Interview done with duplicate questions for PNG Power Ltd and Digicel PNG Ltd.

Replication refers to how repeatable the research is. Since the data collected from the subject matter experts who were interviewed is mostly historical, another researcher asking the same questions this researcher asked should expect to get the same answers. The concept of replication does, however, bring up one of the inherent danger areas in interviewing to collect qualitative data. It is crucial that the interviewer, in an effort to remain objective and meet the intent of the characteristic of replication, must not lead the respondent. To this end, an attempt was made to interject as little as possible in the interviews as they were conducted, even to the point of not asking questions unless necessary. Though the interview process started out with a basic list of questions that were used for every interview, the respondent was allowed to answer them as the interview progressed. If, therefore, in the course of their discussion, they had already fully answered questions that were further down the list, the interviewer would keep quiet and let the respondent continue in their discussion. This technique was useful in maintaining objectivity.

"The researcher must isolate, or control, those factors that are central to the research problem" (Leedy & Ormrod, 2001, p. 94). Though this factor is much more prevalent and critical in an experimental research design, or when collecting quantitative data, it is still an important consideration for qualitative data collection such as that performed in the course of this research. Again, starting with a list of questions to be asked of each respondent was helpful in keeping the interview on track, and not going off in a way that would not help answer the research and investigative questions. At the same time, the interview format affords the flexibility to explore different ideas as they come up in the course of the interview. This flexibility was very helpful as the interviews progressed, and necessary breadth of perspective was gained from each respondent during the course of the interviews.

Leedy and Ormrod (2001) state "the data should be susceptible to measurement"(p. 94). One method of measurement is comparison, and that is the primary method of measurement chosen for use in this research endeavour. By asking the same questions of the subject matter experts interviewed during the course of this research, it was possible to compare their answers against each other. In this way, it was possible to measure one response against another or one response against a group of responses to the same question. This measurement was very helpful as the research progressed the data collection phase to the data analysis phase, where organization and categorization of the collected data were important first steps.

Validity and Reliability

Many researchers agree "the development of case study designs needs to maximize four conditions related to design quality: (a)

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construct validity, (b) internal validity (for explanatory or causal case studies only), (c) external validity, and (d) reliability" (Yin, 2013, p. 19). Again, though not as clear-cut as research that uses quantitative data, the case study utilizing qualitative data, if properly designed, should satisfy all four of these conditions.

Construct validity is defined as "the extent to which an instrument measures a characteristic that cannot be directly observed but must instead be inferred from patterns in people's behaviour" (Leedy & Ormrod, 2001, p. 98). In other words, a design that measures what it was intended to measure. Through employing the collective case study design and relying on interviews with subject matter experts in the field of power system generation maintenance, the questions used in this collective case study are designed to measure what actions and decisions were actually beneficial in implementing RCM analysis into the maintenance strategies for power generation asset maintenance.

"The internal validity of a research study is the extent to which its design and the data that it yields allow the researcher to draw accurate conclusions about cause-and-effect and other relationships within the data" (Leedy & Ormrod, 2001, pp. 103-104). This researcher sought to determine which actions and decisions contributed to the successful implementation of RCM analysis in proactive maintenance programs. One strategy recommended by Leedy and Ormrod to meet the criteria of internal validity is triangulation. To employ the strategy of triangulation, "multiple sources of data are collected with the hope that they all converge to support a particular hypothesis or theory. This approach is especially common in qualitative research" (Leedy & Ormrod, 2001, p. 105). The design of collective case studies employs this strategy of triangulation, and was used specifically to find commonality in the responses of numerous subject matter experts to the same questions, thus adding internal validity to the overall design.

"The external validity of a research study is the extent to which its results apply to situations beyond the study itself" (Leedy & Ormrod, 2001, p. 105). In other words, the extent to which the conclusions drawn can be generalized to other contexts. One of the strategies used to enhance this external generalisability is the use of a representative sample (Leedy & Ormrod, 2001). Given the particular category of power systems generation maintenance at which this research is aimed, interviewing subject matter experts from the PNG Power Ltd and Digicel PNG Ltd constitutes a representative sample of the narrower category of power systems generation maintenance, from which inferences about the category can then be made. Leedy and Ormrod (2001) call this an example of inductive reasoning. Inductive reasoning begins with an observation. For instance, if you put your hand immediately over the flame of a candle, you get burned. No matter how many times you repeat this action, the result is the same. You may then hypothesize that if you put any combustible material immediately over the flame of a candle, it will ignite. This is an example of inductive reasoning. Inductive reasoning is the cognitive tool used in the case study design of this research. The approach employed was to find a pattern in successful implementations of RCM analysis in other venues and use the recurring themes, ideas, or concepts to develop an optimized RCM implementation for the micro grid.

Yin (2013) defines reliability as "demonstrating that the operations of a study – such as the data collection procedures – can be repeated, with the same results" (p. 34), and recommends use of the case study protocol and developing a case study database (Table

2) as tactics to increase this reliability. In this research, the case study protocol recommended by Yin (2013) was used. Yin (2013) advocates a protocol containing: an overview of the case study project, field procedures, case study questions, and a guide for the case study report.

Table 2

Case Study Tactics for Four Design Tests (Yin, 2013, p. 34)

Tests	**Case Study Tactic**	**Phase of research in which tactic occurs**
Construct validity	• Use multiple sources of evidence • Establish chain of evidence • Have key informants review draft case study report	data collection data collection composition

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Internal validity	• Do pattern-matching • Do explanation-building • Address rival explanations • Use logic models	data analysis data analysis data analysis data analysis
External validity	• Use theory in single-case studies • Use replication logic in multiple-case studies	research design research design
Reliability	• Use case study protocol • Develop case study database	data collection data collection

To develop an overview of the case study project, Leedy and Ormrod (2001) process for constructing the research proposal was followed. In order to identify the research and investigative questions for the research, extensive literature review was done. Having complied the need to be addressed in Chapter 1, we move on to the field procedures and case study questions.

The field procedures include "access to the case study 'sites', general sources of information, and procedural reminders" (Yin, 2013, p. 69). Early research into the topic area led the researcher to the selection of possible respondents, which will be discussed in place of the sites referred to by Yin, since the case studies were performed as interviews of subject matter experts, not as visits to physical locations. The search for interest in this research project led the researcher to interaction with the quality manager at the PNG Power Ltd, and was assigned to the company's maintenance planner to be the point of contact, who became the logical first respondent. Subsequent conversations led the

researcher to the inclusion of assistant reliability engineering manager. During an internet search for literature review material on the subject of RCM, a journal (Rao et al., 2016) that referenced the micro grid was found. Following the contact link on the journal allowed contact with two members of the research group, who agreed to provide information regarding RCM application in renewable energy systems, especially PV micro grid. The information encountered during the literature review for this research formed a comprehensive list of sources of general information which was used to formulate interview questions and to gain enough of an understanding of what RCM is and is not to be able to comprehend what the respondents were likely to discuss so that the researcher could intelligently lead the interview and make sure the required information was collected. As to procedural reminders, Yin (2013) cautions "the nature of the interview is much more open-ended, and an respondent may not necessarily cooperate fully in answering the questions." The procedural reminders, therefore, should exist to assist the researcher in collecting the data they set out to collect, not veering too far off course, and certainly not omitting or missing any data they intended or needed to collect. The case study questions are a key means to accomplish this focus for interviews.

"The protocol's questions, in essence, are your reminders regarding the information that needs to be collected and why" (Yin, 2013, p. 74). As more was learned about the evolution of RCM and its use, not only in the aircraft industry, but in other areas such as power systems maintenance, a list of questions was developed. The list was developed such that the questions would be suitable to bring out those salient characteristics of RCM implementations that might be applicable in answering the research question. As the literature review process was continued, the list of questions lengthened, and then was cut, in order to better focus on the aspects of RCM implementations which were applicable to answering the research question. Before these questions could be effectively used to gain the needed insight, the list had to be organized. Yin (2013) recommends "every question should be accompanied by a list of likely sources of evidence" (p. 74). Since the list of possible contacts was being generated at the same time the literature review was being performed, this was an iterative process. The list was repeatedly reviewed, and with each review, possible sources of the information to answer the question were added. Eventually, this process led to four separate lists of questions, sorted by probable source. These four lists became the questions used to gather data in the interviews, and are found at Appendix A.

Yin (2013) recommends adhering to three principles to maximize the benefits gained from the source of evidence employed in the data collection, and to establish "the construct validity and reliability of the case study evidence" (p. 97). These principles are:
(1) use multiple sources of evidence, (2) create a case study database, and (3) maintain a chain of evidence (Yin, 2013). To support the first principle, using multiple sources of evidence, Yin (2013) refers to the idea of "triangulation," stating "the most important advantage presented by using multiple sources of evidence is the development of converging lines of inquiry" (pp. 97-

98). Leedy and Ormrod (2001) support this concept when they define triangulation, stating "multiple sources of data are collected with the hope that they all converge to support a particular hypothesis or theory" (p. 105). Since the aim of this research is to analyse and synthesize data from various RCM implementations into an effective implementation for the micro grid, the concept of triangulation is integral to the methodology employed. Yin (2013) states:

A case study database increases markedly the reliability of the entire case study, but states too often, the case study data are synonymous with the narrative presented in the case study report, and a critical reader has no recourse if he or she wants to inspect the raw data that led to the case study's conclusions. (pp. 101-102)

Again, every interview conducted during the course of this research was digitally recorded and transcribed. These transcriptions are available in their entirety in Appendices B, C, D and E.

Finally, Yin (2013) tells the researcher to "maintain a chain of evidence", "similar to that used in forensic investigations," asserting this chain of evidence will "increase the reliability of the information in a case study" (p. 105). In order to meet the requirements of this principle, the derivation of the methodology employed has been listed in this chapter, the case study protocol used has been described in detail, the evolution of the case study questions used has been illustrated, and the verbatim responses to these questions gained during the interviews have been transcribed and provided.

Data and Data Collection

One of the first considerations for researcher who has settled upon a research question is what type of data to collect. There are two basic divisions of data: quantitative and

qualitative. Leedy and Ormrod (2001) state "quantitative research is used to answer questions about relationships among measured variables with the purpose of explaining, predicting, and controlling phenomena" (p. 101). On the other hand, "qualitative research is typically used to answer questions about the complex nature of phenomena, often with the purpose of describing and understanding the phenomena from the participants' point of view" (Leedy & Ormrod, 2001, p. 101). Given the research question to be answered here, it is logical that the data collected would be primarily qualitative data. The primary data collected during the interviews is qualitative data. It is this qualitative data which, after collection, analysis, and synthesis, is the primary source of uncovering the answer to the research question.

Leedy and Ormrod (2001) list "observations, interviews, documents (e.g. newspaper articles), past records (e.g. previous test scores), and audio visual materials" (p. 149), as data sources for the case study. Yin (2013) cites six sources of evidence: "documentation, archival records, interviews, direct observations, participant-observation, and physical artefacts" (p. 85). While documents were very useful in the literature review stage of this research, only a few of the many documents reviewed were actually helpful in answering the research question. *A novel fault diagnostic strategy for PV micro grid to achieve reliability-centred maintenance (Rao et al., 2016)*, is one such example, since it details the guidance for how RCM should be employed in the maintenance of PV micro grid. Because successfully and completely answering the research question involved gathering information on numerous RCM implementations, all of which happened in the past, the people who played key roles and were intimately involved with the process form the key pool of valid information sources. The fact that the implementations used as data sources happened in the past made direct observation impossible, but the people involved in those implementations are still available. Similarly, the other data sources recommended by the authors were either impractical or not applicable. As a result, the interview was the most logical choice for data collection for this research.

It is important to note that case study interviews do not follow the rigid, structured setup commonly employed by journalists. Marshall and Rossman (2014) state "typically, qualitative in-depth interviews are much more like conversations than formal, structured interviews. The researcher explores a few general topics to help uncover the participant's meaning perspective, but otherwise respects how the participant frames and structures the responses" (p. 82). The interviews will appear to be guided conversations rather than

structured queries supports Yin (2013), who goes on to define three types of case study interviews: the open-ended, the focused interview, and the survey. Yin (2013) also stated:

A second type of interview is a focused interview, in which a respondent is interviewed for a short period of time – an hour, for example. In such cases, the interviews may still remain open-ended and assume a conversational manner, but you are more likely to be following a certain set of questions derived from the case study protocol. (p. 89)

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A decision to primarily employ this focused interview technique was made, using the lists of previously developed questions as a starting point, then allowing the interview to flow naturally as an open-ended conversation, referring back to the question list to ensure all the required material was covered before ending the interview. Yin (2013) cautions interviews are "subject to the common problems of bias, poor recall, and poor or inaccurate articulation" (p. 92). To combat these problems, a digital voice recorder was used to record every interview conducted in its entirety. Yin (2013) advocates recording interviews to improve the accuracy of the data collected during the interview, but further cautions about the use of recording devices, stating:

However, a recording device should never be used when (a) an interviewee [respondent] refuses permission or appears uncomfortable in its presence, (b) there is no specific plan for transcribing or systematically listening to the contents of the electronic record – a process that takes enormous time and energy, (c) the investigator is clumsy enough with mechanical devices that the recording creates distractions during the interview itself, or (d) the investigator thinks that the recording device is a substitute for listening closely throughout the course of an interview. (p. 92)

To address these concerns, each respondent was asked for permission to record the interview prior to starting to record, the transcription was used as the first part of the analysis of the data, the function and setup of the recording equipment was checked before each interview, and the respondent that was ensured that the interviewer was focused on the conversation by interjecting acknowledgement often during the interview. In this manner, the benefits of accuracy were achieved, avoiding bias and recall issues, while negating the possible negative consequences of using recording equipment. As a result of this forethought and preparation, no mechanical difficulties, missed

conversations, or awkward disruptions were encountered during the course of conducting and recording the interviews.

DATA ANALYSIS METHODOLOGY

Yin (2013) lists five possible specific analytic techniques for case study research. These techniques are: pattern matching, explanation building, time-series analysis, logic models, and cross-case synthesis. Pattern matching "compares an empirically based pattern with a predicted one. If the patterns coincide, the results can help a case study to strengthen its internal validity" (Yin, 2013, p. 116). Since this research employed the collective case study design to search for commonalities between successful RCM implementations in various venues, no predicted pattern was supposed or developed. The explanation building technique was also not selected, since it is a "special type of pattern matching" (Yin, 2013, p. 120). Time-series analysis utilizes "the match between a trend of data points compared to (a) a theoretically significant trend…(b) some rival trend…versus (c) any other trend" (Yin, 2013, p. 124). Since the interviews conducted to collect data for this research relied on the memories and experiences of subject matter experts, with RCM implementations, there were no time-specific series of events to rely on. For this reason, use of the time-series analysis was inappropriate. The logic model technique starts with the researcher proposing a "repeated cause-and-effect pattern" (Yin, 2013, p. 127) of events and actions over time that lead to an outcome. "The case study analysis would organize the empirical data to support (or to challenge) this logic model" (Yin, 2013, p. 128). This analytic technique was not chosen because "a key ingredient is the claimed existence of repeated cause-and-effect sequences of events, all linked together" (Yin, 2013, p. 128), and this research made no such claims at the outset.

Cross-case synthesis was chosen as the analytic technique to be employed for this research. "This technique is especially relevant if…a case study consists of at least two cases" (Yin, 2013, p. 133). This technique "treats each individual case study as a separate study" and helps to synthesize ideas and concepts by "aggregating findings across a series of individual studies" (Yin, 2013, p. 134). One method recommended by Yin to accomplish the cross-case synthesis is the use of word-tables "that display the data from the individual cases according to some uniform framework" (Yin, 2013, p. 134). Once various word-tables were constructed and examined, "the analysis of the entire collection of word-tables enabled the study to draw cross-case conclusions" (Yin, 2013, p. 135). Yin

goes on to point out that a danger in using cross-case synthesis is that it relies "strongly on argumentative interpretation" (Yin, 2013, p. 137), but also points out "this method is directly analogous to cross-experiment interpretations" (Yin, 2013, p. 137) and the key to countering this danger is "to develop strong, plausible, and fair arguments that are supported by the data" (Yin, 2013, p. 137). In order to facilitate organizing the data from the two interviews conducted in this research, the data analysis technique specified for case study research forwarded by Leedy and Ormrod (2001) was employed. They list the following five steps as typical for data analysis in case studies:

1. Organization of details about the case.

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2. Categorization of data.
3. Interpretation of single instances.
4. Identification of patterns.
5. Synthesis and generalizations.

These five steps were followed in the analysis of the data for this research.

The first step in organizing the details of the cases was transcription of the digitally recorded interviews. Though this was a long, tedious process, it also afforded the opportunity to closely analyse the responses to the questions and initially identify common and recurring themes.

Categorization of the data was accomplished by using the investigative questions as a framework. Word-tables were created to search for data that pertained to each of the investigative questions. Again, the investigative questions for this research are:

1. What is the current maintenance strategy used in PNG Power Ltd and Digicel PNG Ltd to maintain their power generation assets?
2. How is this maintenance strategy, as identified in question one, used in PNG Power Ltd and Digicel PNG Ltd so far?
3. What are the associated benefits and challenges of the maintenance strategy used in which RCM analysis is involved?

A word-table cataloguing maintenance strategies utilized by the respondents was constructed to help answer investigative question one. A second table that catalogued how the strategies were used was constructed to help answer question two. Four word- tables were created to help answer question three, one that listed the associated benefits

and one that listed how these were accomplished. Followed by, one that listed challenges encountered and one that listed the measure(s) used to deal with these challenges. The completed word-tables are shown as

Table *3* through Table 10.

Once the word-tables were completed, analysis continued by reviewing Table 5 through Table 9, which contained the associated benefits, the means of acquiring each benefit, the roadblocks encountered, and the solutions to those roadblocks. This review was performed to search for both single instances and recurring themes and ideas. Unless a single instance of an associated benefit was clearly shown to be significant, it was not included in further analysis. Those items that showed up in more than one line of the word-table, i.e., ideas, associated benefits, roadblocks, and solutions to roadblocks that were evident in more than one interview were further analysed as possible elements to the solution for the micro grid implementation. The result of this step in the analysis was a final list of associated benefits with how these benefits were accomplished, and a list of potential roadblocks with how these problems were eliminated or mitigated by the respondents. These lists are shown in Table 10.

The final step was synthesis, where these ideas were applied to the specifics of the micro grid implementation in order to answer the research question. In addition to the knowledge attained during the research process, the experience of the researcher as a power system trouble-shooter in the hybrid power systems was a primary tool used during the synthesis phase. In addition to the items gleaned from the word-tables, the concerns of the PNG Power Ltd team and the Digicel PNG Ltd team were incorporated to ensure the problems they foresaw were addressed.

Having ensured the concerns of the PNG Power team and Digicel PNG team would be considered in the recommended solution, it was time to synthesize the recommended actions listed above into a recommended solution for the micro grid. The results of this analysis are contained in Chapter Four.

Summary

In this chapter, the use of the collective case study as the research design employed for this thesis were discussed and justified. Additionally, the collection of qualitative data as the most effective means of answering the research question posed was

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supported. A

discussion of the ways in which this research methodology met the requirements of validity and reliability followed. Finally, the data collection method employed was described in detail and substantiated. Having dealt with methodology issues for the research itself and the data collection process, we move on to the analysis of the data collected.

IV. INTERVIEW RESULTS AND DISCUSSION

Chapter Overview

In this chapter, the data collected during the course of the multiple case study conducted for this research effort will be analysed, and the results of this analysis will be synthesized to answer the fundamental question of this research: How can RCM adequately support a micro grid system maintenance for a sustainable future in PNG? The analysis will be broken down into the investigative questions posed to develop the answer to the research question:

1. What is the current maintenance strategy used in PNG Power Ltd and Digicel PNG Ltd to maintain their power generation assets?
2. How is this maintenance strategy, as identified in question one, used in PNG Power Ltd and Digicel PNG Ltd so far?
3. What are the associated benefits and challenges of the maintenance strategy used in which RCM analysis is involved?

Question One

What is the current maintenance strategy used in PNG Power Ltd and Digicel PNG Ltd to maintain their power generation assets?

In order to effectively apply lessons learned about the various maintenance strategies; to understand the successful elements of each strategy; and methods to mitigate challenges from these strategies, it is important to identify the strategies being performed by the respondents by their right name. The word-table below,

Table *3*, shows the different maintenance strategies employed by the four respondents.

Table 3

Word-Table for Question One

Respondent	**What is the current maintenance strategy used in PNG Power Ltd and Digicel PNG Ltd to maintain their power generation asset?**
1	• Reactive maintenance (default), • proactive maintenance (preventive, periodic), and • corrective maintenance
2	• Preventive maintenance (periodic and predictive), • corrective maintenance,
3	• Scheduled maintenance, • condition monitoring maintenance, and • run-to-failure maintenance (default)
4	• Reactive maintenance, and • corrective maintenance

Note. Respondent 1 & 2, Maintenance Planner and Assistant Reliability Engineering Manager respectively from PNG Power Ltd. Respondent 3 & 4, Power System Engineer and Performance Engineer respectively from Digicel PNG Ltd.

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The maintenance strategies employed by the respondents vary widely. And yet surprisingly contained all maintenance strategies as shown in Figure 1**Error! Reference s ource not found.** with some variation of RCM logic practiced knowingly and unknowingly with respect to each company and each respondent. Both respondents from PNG Power Ltd are well aware of the maintenance strategies being employed in their company and they easily identify these strategies by their name. Whereas the respondents from Digicel PNG Ltd, can very well describe the maintenance process involved, so together the researcher and the respondents had to tag the maintenance strategies' names during the interview.

It is reasonable to assume the variations of RCM decision logic. Referring to the standards listed in SAE Standards JA1011[1], the variants are at least similar enough to the maintenance strategies or analysis performed by each respondent as to facilitate comparison of their salient characteristics. However, the differences in how these strategies were implemented, warrant further discussion.

[1] This SAE Standard for reliability-centred maintenance (RCM) is intended for use by any organisation that has or makes use of physical assets or systems that it wishes to manage responsibly. Link for more information and document revisions: http://standards.sae.org/ja1011_200908/

Question Two

How is this maintenance strategy, as identified in question one, used in PNG Power Ltd and Digicel PNG Ltd so far?

Despite the commonality displayed in the maintenance strategies employed by the four respondents, the way the strategies were used vary significantly in such that, using the key word, FMEA/ FMECA, the interviewer was able to differentiate the involvement of RCM analysis. From the study of RCM in the literature review section, FMECA is known to be the significant tool in the RCM analysis process. The results of the data analysis for Question Two are contained in Table 4.

Table 4

Word-Table for Investigative Question Two

Respondent	How is this maintenance strategy, as identified in question one, used in PNG Power Ltd and Digicel PNG Ltd so far?
1	• Failure modes and effects analysis (FMEA) with tailored MSG-2 logic for generators.
2	• Failure modes, effects and criticality analysis (FMECA) with MSG-3 decisionlogic on thermal generator – LM2500 and MSG-2.
3	• Used to predict failures, estimate mean time between failure (MTBF) and reliability, rank order components or systems by work unit code as to which needed most attention.
4	• Bucket analysis[2] from historical data to categorize the financial risks and prioritize maintenance on high revenue sites.

Note. MSG-2, use a documented logical process which consider failures starting at component level up. MSG-3, looks from system level, top down.

While the strategies of respondents one and two were used to develop RCM analysis (as determined by the inclusion of FMEA/ FMECA), the strategies performed by respondents three and four were used only to target systems and components for attention in an effort to improve reliability and/or predict the failure time or rate and using historical data for financial risk evaluation,

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respectively. In this respect, the use of the strategy is

[2] An investigative strategy called the "bucket approach," developed by Nobel Memorial Prize winner James Tobin, recommends dividing investment into high-risk and low-risk "buckets" and then trying to achieve the highest possible return for each bucket.

significantly different for respondents three and four, and the use of RCM analysis is undefined, thus is not applicable to answering investigative question two.

Again, none of these differences are such that they present a problem with applying common themes to a strategy for the micro grid system, but an understanding of the differences is important in order to put the differences in techniques utilized and the results of those techniques into proper perspective. In formulating a response to Question Two, only the data from the word-tables for respondent one and two will be used to answer question three and the overall research question.

Question Three

What are the associated benefits and challenges?

This section is important in the analysis as it collates the benefits with their essential elements of success and the challenges with their solutions (if any) in four word-tables (Table 5 to Table 9).

Table 5 contains the data gathered from the four respondents pertaining to the associated benefits for their maintenance strategies.

Table 5

Word-Table for Investigative Question Three - Benefits

Respondent	What are the associated benefits?
1	• Availability[3] and reliability[4] improve very much. • Decrease in RTF maintenance
2	• Reduce downtime, maintenance costs and increase reliability. • Efficient maintenance planning.
3	• Improved maintainability and supportability. • Site visits reduced.
4	• Visibility of the assets ease tracking. Prediction of spare parts.

[3] Availability is the ability of a system to be kept in a functioning state. It depends on reliability and maintainability. Maintainability is determined by the ease with which the product or system can be repaired or maintained. Increased maintainability implies shorter repair times.

[4] Reliability is a system's ability to perform a specific function under stated conditions without failure for a given period of time.

As stated previously to look only into response from respondent one and two, they pose a similar response of improved reliability and availability. Respondent two stated availability differently as reduced downtime.

An equally important question to investigate further and support the investigative Question Three regarding benefits, is the question asked in the survey; What went "other than as planned" with the implementation? In other words, the question helps discover new ways or essential elements of success behind these benefits during the implementation. Table 6 shows the response related to the essential elements of success.

Table 6

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Essential Elements of Successful Maintenance Implementation

Respondent	New findings/ essential elements of successful implementation.
1	• Leadership support at program management levels. • On-site maintainer participation – view of reality. • Business case. • Written guidance on how to conduct RCM analysis and implementation.
2	• Performance Engineering leadership support • Cleansed data. • Involvement of field engineers in evaluating proposed changes before implementation.
3	• Resource support. • Continuous program with constant data collection, re-evaluation and updates.
4	• Grassroots support from maintainers in the field. • Business case.

Since the maintenance strategies conducted by respondents three and four were not used to improve an existing RCM analysis program, the data from respondents three and four will not be used to answer this investigative question. In the remaining two interviews, the essential elements of success, along with their frequency listed, are: leadership support (2), maintainer participation (2), business case (1), cleansed data (1) and written guidance (1). Thus, leadership support, maintainer participation and business case (stated by respondent four), showed up in more than one interview as an essential element of success. Combining these points with the experience of the researcher, these items all make sense for inclusion in the micro grid solution.

Without leadership support, an Operations and Maintenance Unit (O&M) will quickly find themselves in a position where necessary prioritisation means a maintenance program will not get the time, attention, and resources necessary to see it through. Because of the scarcity of resources throughout PNG Power Ltd, and continued efforts to reduce the manpower pool of the O&M unit to meet goals, leadership support is vital to any program or effort being continued.

Since responsibility for the successful execution of the maintenance strategy falls on maintenance personnel, the participation of these personnel is essential for the success of an optimized maintenance strategy. Training them and involving them in the process, gives the maintenance personnel a sense of ownership and understanding in the new strategy, which are vital to reduce any resistance to change.

Presentation of a successful business case is also vital in an environment of scarce resources, since the business case justifies both the leadership commitment and resource allocation necessary to successfully implement the strategies.

The remaining items were given only once, and thus deserve more scrutiny before determining whether they warrant consideration for inclusion in the micro grid, since triangulation of data greatly contributes to the validity of the research and its outcomes. To effectively consider these singularly occurring elements, it is beneficial to also look at how they were achieved. The data on how these essential elements were achieved is contained in Table 7.

Table 7

How the Essential Elements were Achieved

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Respondent	How were these elements achieved?
1	• Visits by leaders to show them what was being done and how it was beneficial. • Direct involvement of those maintainers and officers most familiar with power system generation in maintenance analysis and implementation. • Used RCM to counter rising periodic maintenance costs by determining proper interval for programmed periodic maintenance. • RCM Handbook and, to a lesser degree, Inspection Manual, which mandates use of RCM for all maintenance strategy changes.
2	• Written statement from the General Manager of O&M supporting the Integrated Maintenance Concept based on RCM, letters from engineering/logistics supporting RCM when necessary. • Functional teams with practical experience to analyse data to root causes via a line by line review of all data in data collection system. • Performance Engineering unit for affected power system generation consulted for input before recommendation for change made to Reliability Engineering Unit.
3	• Cost avoidance data to show the benefits far exceeded the costs. • Leadership commitment and strong facilitation to implement and maintain program.
4	• Effective communication of program to maintainers as it was developing. Also, retired maintainers on engineering staff that were known and respected by maintainers in the field. • Show cost avoidance data as soon as it's available.

Though written guidance was only given by one interviewer as an essential element of success, it warrants consideration for inclusion in the solution proposed by this research. In the experience of the researcher, programs without specific written guidance do not succeed. In the absence of written instructions, personnel at all levels implement what they think will work best resulting in stove-piped processes which do not interact effectively with processes in other functional areas. Once the business case(s) support for the micro grid solution, and implementation of the RCM analysis for the micro grid yields a greatly improved maintenance program, a written guidance should be considered.

The use of cleansed data and a continuous program, while each listed once as essential element of successful implementation, are actually components of a true RCM analysis procedure. Both of these components were included in the bucket analysis performed by Digicel PNG Ltd for its assets, and so do not need to be re-addressed in the implementation phase.

The key challenges encountered by the respondents during their respective maintenance strategies implementations are listed in Table 8.

Table 8

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Word-Table for Investigative Question Three - Challenges/ Roadblocks

Respondent	What are the associated challenges?
1	• Lack of program management-level buy-in due to lack of effective communication between program management and engineering. • Lack of on-site maintainer buy-in.
2	• Lack of funding for a sustained program often leads to breakdown maintenance. • Resistance to program by upper management. • Lack of maintainer buy-in.
3	• Resistance to change throughout the organization.
4	• Difficulty in maintaining consistency across programs

The measures employed or observed by the respondents to eliminate or mitigate the impact of these challenges are shown in Table 9.

Table 9

How the Implementation Challenges were Dealt with - Measures

Respondent	How were the challenges dealt with?
1	• Not fixed, but Reliability Engineering unit is attempting to solve by facilitating communication and education on benefits of properly implemented RCM analysis. • Education and involvement in the process.
2	• Education of leadership that, to be successful, the program must be continuous, and the savings will outweigh the costs. • Business case made with individual component. • Involved maintainers in the process.
3	• Education and training, reinforced by leadership commitment.
4	• Workforce Management (WFM) Software installed on computer to track Work Orders

Resistance to change was identified as a key problem by Respondent One, and Respondent Two identified resistance to the program by upper management. The basis of the resistance that Respondent two encountered was concern that the program would be a waste of time, so that resistance also falls under resistance to change. The program management-level buy-in also identified by respondent one was primarily caused by lack of effective communication between engineering and program management, and, while it

does fall under the category of resistance to change, the attempted solution by the Reliability Engineering unit is to facilitate communication and education. Since the measures proposed by respondent one incorporates education and training, reinforced by leadership commitment, the resistance encountered by respondent two can be categorized under the same umbrella as that encountered by respondent one. Thus, resistance to change is included in the list of potential problems to be addressed in the micro grid program.

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Lack of maintainer buy-in was identified as problematic by two Respondents, and as such deserves inclusion in the micro grid program. However, maintainer buy-in is already included as an essential item for success, so while it does not need to be listed as a potential problem, the solutions listed by the respondents who encountered lack of maintainer buy-in as a problem should be considered in the micro grid program.

Lack of funding was listed once as key problem areas. The resource funding issue has been included as a necessary key benefit of successful implementation.

Research Question

How can RCM adequately support a micro grid system maintenance for a sustainable future in PNG?

As stated in Chapter 3, the first step in synthesizing the data collected via the multiple case studies into information applicable to answering the research question was analysis of the data in the word-tables from investigative question three. The first sub-step of this first step corresponds to Leedy and Ormrod's (2001) third step of case study data analysis: "Interpretation of single instances," which involves examining the available data for "the specific meanings that they might have in relation to the case" (p. 150). Since this is a multiple case study, a single occurrence or mention of an element which was deemed essential to success by a respondent needed to be examined to determine whether it did, or did not, warrant consideration as an essential element of success for the micro grid RCM implementation. This process was begun when the word-tables were examined individually and in pairs to answer the previous investigative questions, and the single instances of essential items for success and potential problems were analysed and either included or deleted for consideration during that stage of the analysis.

Leedy and Ormrod's (2001) next step in case study analysis is "identification of patterns" (p. 150). This step was also accomplished as the individual word-tables were analysed, and items identified by more than one respondent were all selected for inclusion on the list of items that should be incorporated into the micro grid system.

The final step in Leedy and Ormrod's (2001) analysis framework is "synthesis and generalizations" (p. 150). The first sub-step in this analysis to accomplish this synthesis is to bring together all the items that were selected for inclusion in the micro grid system from the previous steps, as well as how these essential elements were achieved and how the problems were addressed. This information is contained in Table 10.

Table 10

List of Recommended Components to be Addressed in Micro Grid Program and Given Means to Achieve Each Essential Item and Given Methods to Solve Problems

Essential Elements	Means of Achieving Essential Elements
Leadership Support	• Visits by leaders to show them what was being done and how it was beneficial. • Written statement from the General Manager of O&M supporting the Integrated Maintenance Concept based on RCM, letters from engineering/logistics supporting RCM when necessary.
Maintainer Participation	• Direct involvement of those maintainers and officers most familiar with power system generation in maintenance analysis and implementation. • Performance Engineering unit maintaining generation assets consulted for input before recommendation for change made by Reliability Engineering unit. • Maintainers' education and involvement in the process.

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Successful Business Case	• Show cost avoidance data as soon as it's available. • Business case made with individual component. • Used RCM to counter rising periodic maintenance costs by determining proper interval for programmed periodic maintenance.
Key Challenging Areas	**Solutions Utilized to Counter Problem Areas**
Resistance to Change	• Education of leadership that, to be successful, the program must be continuous, and the savings will outweigh the costs. • Facilitating communication and education on benefits of properly implemented RCM analysis.

- Business case made with individual component.

Summary

The keys to success, challenges encountered, and solutions offered to those challenges by the four respondents were gleaned from the text of the interviews conducted and categorized by investigative question in word-table format. These key elements were then considered for inclusion in the micro grid system, and consolidated into Table 10, which contains the keys to successful implementation offered by the respondents along with how the respondents achieved these essential benefits. Additionally, the one consistent problem encountered, resistance to change, along with how the respondents mitigated its negative effects were added to the table. The inclusion of these essential items, along with addressing resistance to change, form the basis of a successful implementation of RCM analysis in an optimized maintenance program for the micro grid.

V. CONCLUSION AND RECOMMENDATIONS

Chapter Overview

The preceding chapter discussed the three investigative questions derived to be used to answer the research question posed by this research effort. In this chapter, the answers to the investigative questions will be synthesized to answer the research question by making recommendations to ensure the successful implementation of the RCM analysis being

performed on a micro grid system. In addition, recommendations for future research will be made.

Recommendations

Table 10 contains the recommended elements of a successful implementation of the RCM analysis for the micro grid system. These essential elements are: leadership support, maintainer participation, successful presentation of a business case and a response to the anticipated problem area of resistance to change. To determine specifically how to best, achieve each of these elements, further analysis of the methods the respondents used was combined with personal experience of the researcher and the specified concerns and desires of the initial discussion with the quality manager of PNG Power Ltd.

Leadership support was gained by the respondents by bringing leaders to their site for educational update visits and tailored briefings to familiarize them with the program. This support was evidenced to one respondent in the form of written policy directives from O&M manager. The level of leadership support that was expressed as a concern by the Maintenance Planner is the Performance Engineering unit (PE) and the Reliability Engineering unit (RE) at Headquarters PNG Power Ltd. Since PE is an Asset Management unit and the RE is a Maintenance Improvement unit, it is first important for the Asset Management unit leadership to have buy-in on the implementation of the RCM analysis.

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Since Asset Management Unit recently hosted a Reliability-Centred Maintenance Summit to discuss how best to proceed with the use of reliability-centred maintenance analysis throughout the PNG Power Ltd, there appears to be support for the use of RCM. However, this support may be limited to the directorates directly involved in using RCM techniques, and senior leadership support is necessary. This can best be accomplished, as evidenced by the respondents, though the education, training, and involvement of Asset Management leaders in not only the specifics of the RCM process Reliability Engineering unit is performing, but in the basics of RCM.

Maintainer participation was accomplished by the respondents through consulting with maintainers during the analysis process, providing education and training to the maintainers and involving the engineers performing the analysis and field-level maintainers view. Reliability Engineering unit has already involved maintainers from the

main hydro power plants; the gas-fired thermal and the diesel-fired thermal power plants during their ongoing RCM analysis. As the changes to the Condition Monitoring Manual for the vibration analysis, oil analysis, thermal analysis and ultrasound analysis are published, this fact should be communicated to the rest of the maintenance fleet, including PE units who maintain the power generation plants. Additionally, the maintainers should be educated on what RCM is and why it was used to revise the current maintenance strategy for the company. Additionally, the Training Program for maintenance could be updated to contain background on what RCM is, how it is used, and the impact maintainers can have on the cleanliness of the data used to make decisions by ensuring accuracy when completing jobs in the computerised maintenance data collection systems (CMMS). Finally, a short course on RCM could be added to the annual recurring training (commonly referred to as block training) required for regional maintainers with skills and knowledge of process efficiency.

The respondents presented successful business cases in support of their RCM analysis implementations primarily by demonstrating cost avoidance and cost savings realized through individual component or program implementations. Since Reliability Engineering unit has already performed numerous component reviews in addition to the four system level reviews already completed, there are choices available for the micro grid system to use for implementation and presentation of a successful business case prior to the implementation of the analysis results for the major systems in an optimized maintenance program. It is recommended the micro grid system choose a pilot trial, gain approval and implement the recommended changes and compare the actual cost avoidance/savings realized to those projected by the standard analysis. This comparison should then be used to further strength the case for implementing the major systems analysis in an optimized maintenance program.

The respondents who listed resistance to change as a major obstacle were able to overcome it by education, leadership support and presentation of a successful business case. Since all of these solutions are part of accomplishing the essential items identified above, the micro grid system should be able to successfully counter the inevitable resistance to change they encounter by recognizing that it will be encountered, remaining vigilant for signs of resistance to change, proactively applying the methods listed above and actively and effectively communicating with all the agencies who are involved in the process for the micro grid.

CONCLUSIONS

Implementation of the recommendations supported by this research will enable the micro grid to successfully implement the RCM analysis being performed by PNG Power Ltd in a revised proactive maintenance program for the micro grid. This research is important for a number of reasons. First, the money that has been spent performing the analysis will be wasted if the analysis is not used to revise the current maintenance strategy for the micro grid. Second, a potential high cost avoidance per year can be realized by successfully implementing the changes the analysis recommends. Third, the successful implementation of this analysis for the micro grid could serve as a business case for other power system assets to justify using reliability-centred maintenance to revise their maintenance strategy, resulting in significantly more savings and cost avoidance for the complete micro grid system. Finally, the business case presented could motivate leaders in the micro grid to transform the power plants to a sole organization that relies exclusively on RCM analysis as the basis of its maintenance strategies.

RECOMMENDATION FOR FUTURE RESEARCH

While the scope of this research is a solution to successfully implement an optimized maintenance strategy for the micro grid based on RCM analysis, future research into how to effectively transform the renewable energy sector that supports reliability-centred maintenance as the only basis for their maintenance program development and revision, should be undertaken. The standardised use of RCM-based maintenance programs throughout the micro grid system should result in significant cost avoidance and savings.

Since reliability-centred maintenance is being applied to more and more diverse areas, such as facility maintenance, manufacturing equipment maintenance and vehicle maintenance, research into how best to incorporate RCM analysis into existing Renewable Energy Systems maintenance programs in these and other areas could prove useful.

The PNG Power Ltd.'s current method of data collection, the SCADA (supervisory control and data acquisition) is not user friendly and has been scheduled for replacement or integration by various new information systems over time. The current maintenance information system slated to integrate is the Computerized Maintenance Management System (CMMS). Though originally slated to replace the SCADA in 1997, the CMMS is still not fully operational and partially implemented on thermal power plants only.

Research into the proposed design and functionality of an integrated CMMS and how this design and functionality could be improved to better accommodate the use of RCM data collection and analysis would be very beneficial.

There are many elements of the SCADA's data that necessitate time-intensive and costly scrubbing before the data can be used for RCM analysis. Research into the effects of such maintenance actions as cannibalization and removal to facilitate other maintenance could save time and money in future iterations of analysis based on this data.

RESEARCH SUMMARY

Reliability-Centred Maintenance provides a framework for developing and sustaining an efficient, effective preventive maintenance program for many different applications. Though its roots are in commercial aviation, reliability-centred maintenance has since been successfully applied to vehicle, plant, and mass transit applications. Through the course of this research, the researcher has gained an understanding and an appreciation of reliability-centred maintenance and how successful a preventive maintenance program based on reliability-centred maintenance analysis can be. It is therefore the sincere wish of this researcher that the recommendations forwarded in answering the question of this research be applied successfully and a revised preventive maintenance program for the micro grid based on the reliability-centred maintenance analysis.

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Appendix A: Interview Questions

Note: Focus is on the power generation assets to support the demand (load). Exclusion of transmission, distribution, retailing and/or other assets.

Section A: Current Maintenance Strategy and Methodology

1. What is the type of maintenance strategy used by the company to maintain its power generation assets? <option>
2. What are the processes involved in the chosen type of maintenance? <list>
3. Can you briefly describe each of the process involved (methods)? How they are performed? <descriptions>

Section B: Current Maintenance Strategy - Benefits and Challenges

4. What went well with the implementation? <benefits>
5. What went poorly with the implementation? <challenges>
6. What went “other than as planned” with the implementation? <new findings>

Section C: Proposed Maintenance Strategy - RCM

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7. How familiar are you with the reliability-centred maintenance (RCM) analysis process?

Appendix B: Interview One

Interviewer: "The research that I'm doing, was to identify an optimal maintenance strategy. I was looking at trying to incorporate some concepts and methodology into a micro grid maintenance process. Micro grid system is actually an off-grid power system which will be powered by renewable energy sources. Supplying electricity to remote village communities."
Respondent: "Ok."

Interviewer: "So my concern was we're doing all this great work maintaining assets, but if we don't effectively and correctly implement this stuff, it's all wasted time and energy and money. So I asked myself, 'What about doing some research on how can we most effectively implement a maintenance strategy that will save cost, energy and time.' So, I was fortunate enough to do an Internet search and get in touch with Mr. XXXX XXXX, and he pointed me in your direction. I want to perform a case study and analyse what's worked for maintainers, what hasn't worked and what the essential components were for a successful implementation. And I hope to use them into a plan for how we can effectively use the RCM analysis to maintain the micro grid system."
Respondent: "Sounds great."

Interviewer: "So it's a pretty exciting project, and so far *em go orait*. [going pretty well]" Respondent: "*Gutpla* [great]"
Interviewer: "So, along those lines, just for background, what are the company's current maintenance strategies? You can respond with reference to the Information Sheet I emailed earlier or *laik blo yu* [up to you]."
Respondent: "My first employment was with the thermal generator - LM2500 program for Moitaka Substation, and basically they were developed using what we called a tailored MSG-2 logic. So, in their maintenance planning documents, they basically had the FMEA and a tailored MSG-2 logic diagram. That was what determined their maintenance requirements. I came to work with the program in 2009. And basically, I started out as a graduate engineer and working with that process, supporting it, and then after a couple of years *ol putim mi lo wok olsem* [they designated me as the] maintenance planner for the program.
Ok, basically, we had a lot of maintenance strategies within the analysis… we had the thermal generator – LM2500, which is a lot changing from DG technology into the thermal generator - LM2500 system. There are a lot of new systems that were designed as well. And we wanted to collect some data in regard to those systems. MSG-2 is a preventive maintenance practice so we had preventive maintenance, both periodic and predictive as well a corrective maintenance which include the manufacturers."
Interviewer: "Was the thermal generator - LM2500 considered a new acquisition, then? Was it different enough from the diesel generators?"
Respondent: "Yes, it was a fairly significant a change from the DG technology. The technology was a leap above what we have known, and especially the control systems, *em gat gas power turbine* [has gas turbine] and things of that sort. The basic operations of the systems such as for inlet section, compressor, combustor, turbine and exhaust system, were different bearings being used. So those are areas we also wanted to keep our eyes on and collect some good operational data. Kind of like you talk about for the micro grid technology is new and has lots of systems."
Interviewer: "So you were developing an initial preventive maintenance program for the new, well, what was considered a new generator, the thermal generator - LM2500, right?" Respondent: "Exactly. In the maintenance planning process, and using the FMEA that was in that and the tailored MSG-2 logic we did identify maintenance requirements.
Some requirements gathered from the thermal generator were new requirements and we were very much involved in that process with the manufacturer (IHI) at that time. We periodically had gotten together with them and were developing a maintenance plan for going through the logic to determine the maintenance requirements were meeting with IHI engineers, our logisticians, as well as our fleet maintainers very frequently on these different maintenance plans and subsystems, to come to consensus on the maintenance requirements and the analysis."
Interviewer: "So did IHI have an initial set of hey, here's what we recommend for inspection and maintenance type actions as the manufacturer?"
Respondent: "Yes they did a very good job. They were one of the, and still in my mind, one of the best efforts from an RCM standpoint."
Interviewer: "So they used RCM for their initial requirements?"

Interviewer: "Well, it was the tailored MSG-2 logic. It wasn't classical RCM, but they did stick to that logic, and did a good job with interacting with us, especially with our experience on the DG technology. We provided a lot of great feedback in regard to

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operational data and things of that sort. So, we worked very well together looking at that data in the operations of the systems and together coming to a consensus on the maintenance requirements to use and the maintenance plan, the logic we had in there."

Interviewer: "The initial idea to collect required data will be important, and I can imagine you came across a lot of challenges. How do you address those challenges?"

Respondent: "Like I said there was a lot of engineering hands-on involvement. Mainly involved with helping collect the information. The initial goal was to try to get the inspection data, have a bulletin that we would send out and, you know, have them go out and get the inspections for us. And we tried that for a while. We were not getting the quantitative data that we needed. We would get the data feedback sheets back from these bulletins and, just looking at the data you could tell that they had inspected incorrectly or didn't know how to read the instruments. And due to that we wound up having a lot more engineering involvement in helping collect that data. And being that we have the engineering support team here at Moitaka Power Station, and received the maintenance team leader that worked very well for us. And the engineer who was involved was also the engineer who was assessing the data and analysing the failure modes. And he knew firsthand what the analysis needed to show."

Interviewer: "Are there any other challenges you would want to discuss?"

Respondent: "Yes, well it's not a problem with a shortfall in the process or buy-in to the process. Especially down at the engineering logistics working level, when trying to execute it. It's mainly at the program management level and their buy-in and their support of it from a resource standpoint. The thermal generator - LM2500 had excellent support and communication between program management and the engineering logistics team. They took RCM as the hub of everything they did, to ensure that we had an active data collection, analysis and feedback program. So that's why they've been so successful."

Interviewer: "Are you able to demonstrate from the thermal generator - LM2500 program being now, what 18, close to 20 years old are you able to demonstrate a business case based on what you've done to show that using the RCM is cost effective in the long run?" Respondent: "Oh yes, as you can imagine getting resources you have to justify to the nth degree to the funding source that those resources will be put to good use. So, we have always had a very active stay on top of the scenario and looking at things, the unscheduled and scheduled maintenance trends. Looking at the cost benefit to some of the things we've implemented based on performing RCM correctly, which is collecting the data, analysing the data, and then using the decision logic to come up with the right solution to the failure mode you're addressing. So, we spent a lot of time doing that and our local management supported that and program management at headquarters believed in the local management. So basically, that support was there, and we just made sure that

they stayed in tune with what we were doing here, and with the turnover that you have in program management. We had new program managers coming into the program, and we would make sure that we got in at the beginning when they first took that duty. And we got in there and make sure they understood what we were doing down here and get them started off on the right foot from day one. We were very active in doing that."

Interviewer: "One of the important things you talked about was having that leadership commitment to the program. What specific actions, guidance, or correspondence-type things did you see that supported that leadership commitment to what you were doing?" Respondent: "What we would do is basically we would schedule leadership to come to our site. One of the most successful ways of doing that was having them come here and we'd show them firsthand the data were collecting, the analysis. We showed them the components that we were doing the data collection and analysis efforts on. We showed them the things that we had done. I won't call it a show-and-tell, but that is probably the closest thing. And that was very successful, doing that. We had them come down here and show them what we were doing. And they always left with a positive view of the process. And that usually resulted in the resources continuing to help us execute it. We did have a few years on the program where money got significantly tight, and we didn't have the resources to continue the sustainment process like we had been resulting in run-to-failure maintenance."

Interviewer: "Resources are always a challenge. What other kind of challenges did you face with the initial implementation on the thermal generator - LM2500?"

Interviewer: "Resources would be the main one. Trying to get some others to understand, others that were involved with our process, like the fleet maintainers. Trying to get them to understand hey here's the process we use to justify maintenance tasks and their intervals. The process prior to that and a lot of other programs was basically, you know, having the ultimate or having some major maintenance meeting. Maintainers and others come in and say, 'I saw this and, therefore I want to implement this new maintenance task.' And unless you have this engineering-based decision logic process, unless you have everyone using that, or at least understanding it at a minimum, because you know, we don't just implement tasks because you've seen a problem. We had to collect data and we show that there is a certain failure mode, we run it through the process, and then we determine what's the best solution for it. So, we had to educate people on that. I mentioned the age exploration depot inductions. And the depot, basically,

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they're in the mindset of when an asset comes into our facility basically, we totally disassemble it and

we rework it to a like new condition, and then we turn it around as quickly as possible to get back to the customer. It took a while to educate them on here's our spec, here's what we're doing. We're inspecting these areas to collect engineering data. So, we can monitor these areas and make the right decision, we're not here just to rework this asset. So that took a while to get them in the proper mindset for that."
Interviewer: "Anything else from the thermal generator - LM2500 experience you think would be important as far as crossing over to what I'm trying to do here?"
Respondent: "I can't really think of anything additional right now. I'll kind of sleep on that and if I do come up with something I give you some feedback on it. I think I've pretty much captured most of the points."
Interviewer: "Now if I understand correctly, you're now the maintenance planner. How have you seen the analysis techniques and the application of RCM analysis evolve in the company since your initial experience with the thermal generator - LM2500?"
Respondent: "We've made some progress in regard to our initial documents, RCM handbook and Inspection Manual. Having a steering committee, which are practitioners as well as engineers, knowledgeable of statistical techniques and data analysis techniques, having a steering committee that can get together and discuss some of these real-world concerns or issues has been very beneficial. Having that steering committee, which can make more consistent how we're performing the process across all of our assets and all the different sites has been very beneficial."
Interviewer: "When you initially were standing up this pseudo steering committee I would imagine that you probably had some program management offices that were already on board with RCM and some that maybe had a different way of developing their maintenance requirements. Did you encounter any resistance from some of the offices saying, 'Hey, we're pretty happy with the way we're doing things and we don't think that going to RCM is the way to go? And if you did encounter that, how did you get them on board?"
Respondent: "I don't recall any serious concerns from any of the programs in regard to not wanting to play. I mean some were, maybe they were less knowledgeable of the process and how it was being done on other programs, but they really didn't say, basically 'We're doing it this way, and that's how we're going to continue to do it. You go and do your RCM thing. That's not going to work for us.' We really didn't have any barriers such as that."
Interviewer: "Sure that makes sense. Well, Sir, that's all I have for you at this point."

Appendix C: Interview Two

Interviewer: "Well, as we talked about very briefly before over the email, the idea of what I'm doing is: identifying an optimized maintenance strategy. PNG Power, I think has a lot more experience with that. I'm talking with some guys who actually have a working group/steering committee kind of thing and I got some good information from them. But I also wanted to get some different aspects, different perspectives from people who have been involved with RCM analysis and implementation, and so that's what I was hoping to get - some information from you is with your experience with PNG Power."

Respondent: "That's fine. And you must have known, I assume, that we're doing this maintenance on the gas turbine generators and hydro turbine generators?"

Interviewer: "Well, I spoke with XXXX XXXX earlier last week. And he had some good information, not only on what's going on with the gas turbine generators, but he had some history with the diesel generators as well as far as the RCM – well, not purely RCM, but the concept of MSG-2."

Respondent: "Yes, if we go to the full extent we're going to get into a lot of conversation here, because really I think there's so much that you need to know about, what reality is. There's a lot of published stuff, but there's a lot of reality as well. So, I would hope to be able to share all of that with you."

Interviewer: "Definitely, that sounds good. So, your current capacity as far as what you're doing right now is that RCM analysis is that your primary focus right now or what are the maintenance strategies used?"

Respondent: "We're doing it all. What we're doing is a complete MSG-3 on the hydro power plants with working into the process of a maintenance program to support that. And that includes RCM. And those words in themselves, maintenance program, is a very important couple of words in that if you look in the document of the MSG-3 document, I don't know if you've done that ever. You will see in there that it tells you that after you go through all of that analysis and develop the tasks, you have to develop a maintenance program to make it work. And that's all it says. Now it's up to you to figure out how to do that. It's written loosely

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in that document, because the maintenance program is a

competitive issue with the various assets. So, there are some guidelines that is now an obsolete one because it refers to MSG-2. But if you access MSG-2 document, there's lots of neat stuff in there. Some neat direction and guidelines on how the other industries apart from airlines are supposed to set up their reliability programs."

Interviewer: "Can I get that from the FAA a web site?"

Respondent: "Yes, you can so that's a good starting point. A good starting point is also to get yourself a copy of the MSG-3 document. That's very important stuff, if you got that you… But those are very useful tools to get a good, a fairly good understanding of the whole process. Now several things, and I don't know if I'll remember to do them all, but as we get through this, different things will come into my mind. I've got a sort of a scattered brain. It's all over the place."

Interviewer: "*em orait ba mi go wantaim yu* [I tend to talk my way through things]."

Respondent: "Exactly, a couple of key items is that in order to implement successful RCM. Excuse me reliability. In order to implement a successful reliability program. You have to have several things that we've recognized very early that the DG program did not have. One of the main things is cleansed data. The DG program, let me back up. The thermal generators – LM2500 had a program. But it wasn't with cleansed data. So, the data they got was in many cases misleading. Misleading data is worse than no data, and how many people hang their hat on misleading data?"

Interviewer: "Because it's what they have and what's convenient."

Respondent: "That's right. So, at what we did right from the get go and what we call… We've got two entities that are dealing with reliability. One is called a Performance Engineering (PE) unit, and the other one is called Reliability Engineering (RE) unit.

PE is looking at maintaining or improving financial reliability. RE is looking at improving process to perform the expectations of PE. So, they're really both the same thing in reality, they both use their data from the same source as the cleansed data, but they're different in the respect that one looks for the trends across the broad systems and the other looks for a bad actor and a system that's causing that bad actor. So that's very important to me in my world, and we've been quite successful in the initial application with the thermal generators on that. In showing the people here how well that works when

you do it right. And while I'm on the subject, I'll just give you an example of that. We've got the new thermal generator – LM2500 into the power generating process. And we're looking for trends of systems on those individual components (compressor, combustor and gas turbine), and one of the things that stood out very very strongly was the compressor. Now when you talk to the people in the field, and the people around the whole system, they said operating temperature and combustor were giving us the most problem. But when you cleansed the data down and found that it was actually the compressor. So, we said, we found this thermal generator, coming into the workshop. It was about a month away at this time, and it had terrible compressor problems. So, one of those things to companion with that is the fact that almost every DG that goes out of here, and when they do the functional check they always have compressor problems. So, we put together a team to work those compressor problems on that thermal generator and drill that down. And we set out laying up an inspection program, a very in-depth inspection program on the compressor, which didn't even exist. Many things in the compressor area they had never even dealt with. In fact, what they did for instance, is they if an actuator was bad, they would replace the actuator and that was about it. But what you find, when you have a complicated system like that, a progressive system like the compressor on the thermal generator with all of the jackscrews that go all the way in and out and you have a tapered wing, well a swept wing, is that the wear is not constant".

So anyhow, I wanted to give you that example, so you understand how one needs to measure success. The other part of this equation is that PNG Power has an interesting way of doing business. For me is they measure success by availability. Now in the industry, we measure availability, because it's very important, because we run all of our generators every day, and when you launch in the morning if you don't have that generator the whole day is shot. It's a mess. But the biggest measurement that reliability measures is, and I just said the word. The term reliability, we measure the health of the power plant, not just on availability. If the system is deteriorated and is bringing the parts down, you will not get reliability, but you can get availability. So, the measurement of reliability is very important to a successful program to a successful reliability program to be redundant on the words. But that's exactly the issue that we've been trying to turn them around on. Even though availability is a very important

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measurement I surely don't deny that. It's not the key measurement that will give you reliability. The same with parts. And there again, I can only speak for the DG, because I don't know this generally across the board. But in

the DG, if you have parts on the shelf, you don't worry about it. You just keep replacing those parts. As long as you have availability of the parts…in the world I came from the flag waves when the system or the whole power plant starts to use too many parts for whatever reason. You look at parts usage, and that's one of the very first flag wavers of a problem in reliability. And if you start using too many parts, you've probably been using too many parts, replacing parts left and right, you have to drill it down, drill it down, drill it down to that lowest common denominator and find out what is really the problem. And not all that many times you will find that the system has suffered degradation and the system is bringing down the parts."

Interviewer: "Isn't that one of the key problems with the way the company collects its data? Because it only as good as the troubleshooting skills of the technician. I mean, if he just follows the fault isolation guide and changes a part because that's what it tells him to do and doesn't look any further, then the next guy does the same thing, and the next guy does the same thing, we're not finding anything about what is causing a system to fail. It's just change the part and press on."

Respondent: "That's exactly right. Exactly, so don't hang your hat on, say, well they should do that. You need to develop a reliability group that has all of those attributes that does that. That brings that data in and cleanses it and determines, drills it down and then gives them the help they need out there. And schedules the tasks. We call that REV, a reliability enhancement visit, and we schedule a visit not maybe at the time we do a regular check, which is preferable, but if the generator is severe enough it may even be between the checks. Condition monitoring checks and like that. But what we do is we do that REV process a lot like we're talking about this compressor problem on the thermal generator there. And depending on the complexity of it is when you can do it. Now, we will bring that power plant up to its inherent reliability. And that's the key. Are you familiar with the term inherent reliability?"

Interviewer: "Yes."

Respondent: "You understand that that's the ultimate reliability you can get out of that power plant or that generator unless you upgraded in some way."

Interviewer: "It's the designed-in reliability. Corrective maintenance, right?"

Respondent: "That's right, it's as good as it gets. In one of the biggest mistakes that a lot of people make is that they think if they throw enough maintenance at the reliability, it will improve above inherent reliability. You'll never do it. You can only go to inherent reliability until you change something. So, throwing maintenance at it will not improve. If the inherent reliability is bad, you have to redesign, and the MSG-3 process uses that. Most of your categories come down to either a recommended redesign or in the case of the safety categories, a mandatory redesign. And so that's part of that process. It's a very good part of that process, and helps to identify when it is practical and required to do an upgrade. You get a lot of supporting information to sell that. The other part of that is what we do here…"

(Telephone line got disconnected, called back.)

Respondent: "I tell you I don't know what happened. You want me to continue on?" Interviewer: "Please, please."

Respondent: "Okay, the thing I was talking about was the yeah! But anyhow, one of the other items that's so important to us from the industry is how we deliver. You make a maintenance program change, you do an MSG-3. You come up with a whole revised maintenance program. How do you deliver that to the maintainer? In the DG again, that's the only one I can use for comparison, the work cards just say, 'do the task.' And then maybe give you a reference and then maybe not, sometimes they do sometimes they don't. But it's very brief, just 'do this task.' In the world that we came from, we found out that we had to go several steps further. And we have what we call the commercial style work cards. We have a tracking system that will allow them to do that. So, you know that if the maintenance manual changes, your work card gets changed automatically that kind of thing. That's been in the industry today, and it's part of the production management database. I don't know if you've heard that term before or not. CMMS, a computer database that has all the attributes of the maintenance program, and everything is linked with SCADA. So, on your work cards, you link all your work cards to that. So, when a change comes down, it recognizes that that change has to happen on the work cards or the maintenance manual or whenever you're working with."

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Interviewer: “Do you have that level of leadership commitment that you had at PNG Power with the thermal generator project?”

Respondent: “Excellent leadership, we have had tremendous support right from the start. Is it safe to say names?”

Interviewer: “I don't know whether I'll be able to include them or not, but... Do you think that leadership commitment came as a result of their self-gained knowledge of what you're doing and why it was a good thing or was it sold to them? I mean with the new leaders. Hey this is why we’re doing this, and this is why to good idea or...?”

Respondent: “Each new leader, we always give a presentation, but I don't believe by any means that that was the sole driver. I believe that there was a lot of hidden support. An example of that is XXXX was constantly going to overseas, supporting this program. So, for some reason or another, funding always became available. I don't know the intricacies of the government/ PNG Power and how that works so I couldn't even talk about that, other than to say somehow the support was there. That's all I know.

My boss just walked in sorry. So, the bottom line is you have to be in control of your maintenance program. You have to have a rational program to do that. And we have a lot of these little bywords that we say, if you don't give the maintainers are rational maintenance program that they can understand and buy into they will design their own. And now you've lost control and the rest is predictable, isn't it? And I know those are simplistic things, but they are so real. For a maintainer, I just know that you can buy into that. A lot of hire people engineers and that they can't quite understand that they don't see it that way, but they don't know how dependent they are on that maintainer to do the right thing. They don't understand that that your bread-and-butter out there. That's the whole thing up there. But anyhow, I get talking too much, sorry about that.”

Interviewer: “Did you have the same problem with un-scrubbed data at Yonki hydro turbine generators as you initially saw with the thermal gas turbine generators or is the data collection in a different way or…?”

Respondent: “Yes, that's an excellent question, and you have to go back a way on that. There was a time when we had problems with un-scrubbed data the original people…and I was fortunate to be a part of O&M Team and we were the ones who started. We had the computer system that was built for that purpose using SCADA, and it’s still used for that today. We were one of the initial industry in the country to do that kind of thing, to do that reliability work and build that in a computerized fashion, a reporting system. The

now PNG Power was once known as ELCOM had a hard copy system. So, they only had key items that something was brought to their attention. It was key. And the rest was impossible. So, O&M Team was doing a fairly good job of getting on that reliability trail. There was a very negative approach to the stuff. So again, the culture change, it took a long time to get that right. So, the scrubbed data was well, in fact there was no scrubbing taking place there for a while. They just took the data and they didn't have any clue to do what with it. So, finally we had to get to the point we had people describe that data. That's when the maintenance program specialist position was designed and put in place, and the reliability positions. And they worked closely hand-in-hand. I was a maintenance program specialist. The reliability people did just reliability. But what the reliability people did, once we got our funding on track, was they reviewed every write up every day, every write up to look for its accuracy if they couldn't figure it out, they would get on the phone and talk to mechanics and say, ‘what did you mean by this?’ Well then, what happens when you've got that type of oversight is it starts to drive accuracy tremendously.”

Interviewer: “This was a full-time job for that person?” Respondent: “This was a full-time.”
Interviewer: “Have there been things that have gone other than as planned with the work you're doing on the thermal generator or hydro turbine generator now?”

Respondent: “Oh absolutely, to say the least.” Interviewer: “Any common themes there?”
Respondent: “Well, there's so much that went on. One of the things that happened, as we’re talking about the DG. When we first started. We're working with strictly DG people. Then they decided to retire the DG, and I guess they're still in that process. So, they moved all of the DG people into the thermal generator environment. While now all of a sudden everybody wanted to do it like the DG did.”

Interviewer: “Because you're bringing in that culture.”

Respondent: “Yes, and boy that is still tough today, we are still running into a lot of resistance on that. I met with an engineer this morning and went to the whole process with him and went over and over again until finally he caught it. That was

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labour-

intensive this morning, but I've got to do that. I've got to get everybody to understand how it works, and the value of why it works. And that's a tough deal. That happens constantly, and that was a major roadblock that came in our face, but, you indicated before, that the people who knew where we wanted to go stood tall and stayed the course. The chief engineer, especially XXXX, all those people I talked about they stood tall. And we keep fighting those battles until we when we got to. If you try to change a culture, and you back down because it's going to get difficult, then you should not have gotten into the culture change business. It's the wrong business to be in.

Nothing good is easy, no truer words were said when it comes to change at that level. But it's been tough. There are a lot of things that we predicted in a lot of things we didn't predict that have happened. One of the other items that keeps and you're probably very familiar being a Performance Engineering person at main office, people there keep changing.

And we first had them on board and everything looked good, and then they changed all kinds of people. And then we're right back where we started again. So, it's just constant its constant, but you have to keep fighting it because it's worth it. It is worth the time and effort to get this on the right track. The outcome, the results are just going to be excellent. And you have to work for that."

Interviewer: "Yes, it's just refinements of additions to, correct?"

Respondent: "The big difference is that RCM was written as a general application so that people could do it on trucks, tanks, whatever. Plant maintenance, whatever. MSG-3 is specifically designed for a new aircraft coming down the assembly line. That's the way it was originally designed to develop a maintenance program for their plan. So, it's very conditioned to that. You see a maintenance program developed to the methodology of MSG-3. You don't necessarily see that in RCM. You see tasks developed, and you then have to develop what your needs are to a maintenance program, but other than that they are exactly the same thing. They are in the same world, and you use a lot of the same methodologies."

Interviewer: "Well I'll tell you what, I think I've probably got about a million more questions, but I think I have enough right now that I need to get my head around.

Respondent: "That would be perfectly alright with me."

Interviewer: "Great, I really appreciate that. Thank you." Respondent: "Goodbye."

Appendix D: Interview Three

Interviewer: "Just to kind of to refresh you on what I'm doing. My research centres on the reliability centred maintenance analysis in maintenance practice. The intent is to optimize maintenance program for the micro grid system on that RCM analysis. This is still a relatively new concept for the renewable energy system.
So, what I'm doing is conducting interviews and then comparing responses across those interviews to try to figure out... I've spoken with folks in the PNG Power, I've spoken with folks with RCM experience and some other offices who are just now starting to try to incorporate RCM or variations of RCM into what they do. My hope is to kind of cross that spectrum of backgrounds and experiences to come up with some common themes in common answers that we can use to successfully implement this analysis for the micro grid. So, you've been with the Digicel PNG for quite a while is that true?"
Respondent: "Actually, I've been with the Digicel PNG since the inception of the solar program. And it quite new, started in 2007"
Interviewer: "Fantastic. And when you say the program do mean the inception of RCM with Digicel asset maintenance?"

Respondent: "No, I am sorry to say but we do not perform RCM. As I looked into the information sheet you sent before, I can tell you what maintenance programs we use."
Interviewer: "OK, so shall I ask what are the current maintenance strategies used by the company to maintain its assets, especially power systems?"
Respondent: "Yes, I'll give you a little bit of a background. In the Digicel, until 2014, they had no condition monitoring program. I don't know who introduced them to the idea, but somehow, one of the system managers at the headquarters in Port Moresby decided that it was about time to implement such a program. Now I say system manager, I mean the guy who was the officer who was responsible for the entire company asset maintenance. We still have them, but the responsibilities of changed over the years

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and they were different from what they were back then. But the system manager, we had one system manager, or we sometimes call them NOC manager, and we basically had four regional managers, and then we had field engineers and sub-contractors. But I was dealing primarily with, at the very beginning, with the system managers. As I was saying at the end of 2014, they decided to start such a program. And they were looking, from what I was told, I don't have any paper trail, but this is what they've told me. They were looking to find somebody who would have ties to computer programming, and so I applied for the job and I was hired. By the wat I am a Computer Science graduate and not an Electrical Engineer."
Interviewer: "And that's as the Power System Trouble-shooter?"

Respondent: "Yes, to establish the condition monitoring program and do the root cause analysis."

Interviewer: "So that is the newly introduced maintenance program. What about before that?"
Respondent: "Yes, before that and still ongoing, the company practice scheduled maintenance on especially the major and minor overhaul maintenance of the generators according to the run hours. Also schedule time for refuelling the DG. At most time we are faced with lack of resources that causes run-to-failure."
Interviewer: "Resources are always a challenge. What other kind of challenges did you face with the initial implementation on the condition monitoring?"
Interviewer: "Resources would be the main one. Trying to get some others to understand, others that were involved with our process, like the fleet maintainers. Trying to get them to understand hey here's the process we use to justify maintenance tasks and their intervals. The process prior to that and a lot of other programs was basically, you know, having the ultimate or having some major maintenance meeting. Maintainers and others come in and say, 'I saw this and, therefore I want to implement this new maintenance task.' And unless you have this engineering-based decision logic process, unless you have everyone using that, or at least understanding it at a minimum, because you know, we don't just implement tasks because you've seen a problem. We had to collect data and we show that there is a certain failure mode, we run it through the process, and then we determine what's the best solution for it. So, we had to educate people on that. It took a while to educate them on here's our spec, here's what we're doing. We're inspecting these areas to collect engineering data. So, we can monitor these areas and make the right decision, we're not here just to rework this asset. So that took a while to get them in the proper mindset for that."
Interviewer: "Anything else from the condition monitoring you think would be important to consider?"
Respondent: "Yeah, I think it was a combination of…they were busy doing their thing and really didn't put much emphasis or focus on it and others were like, well it does make sense. And like I said earlier, the main reason that programs wouldn't promote the process or play is due to lack of resources. The data collection side of it is more intensive and resource intensive and some couldn't support that to the degree that they needed to, but we're really didn't have any naysayers who said now we don't play in this process. And it was fairly successful and as headquarters came more on board and help promote the process more, which usually resulted in more resources being given to the programs that were lacking, then that made the whole situation a lot better."
Interviewer: "Sure that makes sense."

Respondent: "So I want to talk more on condition monitoring, where we installed remote site controllers with sensors that they are able to supply equipment condition in real-time basis to the dispatch engineers in the NOC room to generate work orders for the field engineers and sub-contractors. Sensors for example, DG fuel level, DG automation, battery state of charge, battery ambient temperature, battery voltage and so on."
Interviewer: "Condition monitoring is doing a good job?"

Respondent: "Yes, for the start then, we are having communication problem with the NOC server and the remote site controllers and some sensors were tempered by the sub- contractors.
When it was working fine, we basically used it to predict failures, estimate mean time between failure (MTBF) and reliability, rank order components or systems by work unit code as to which needed most attention. That was how we analyse."
Interviewer: "So I see, do you know and practice failure mode, effect and critical analysis in anyways?"

Respondent: "No, I see what you meant, but we did not."

Interviewer: "OK, what are the associated benefits of the condition monitoring practice?" Respondent: "To state it directly is we saw improved maintainability and were able to very much support the entire power system in terms of resources to prevent failures before it actually happens. And another thing unnecessary site visits by the sub-contractors were reduced which means cost savings."

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Interviewer: “To add one more question for clarification, what is the positivity you saw from condition monitoring practice, or what is the essential element for the implementation?”
Respondent: “As I was saying earlier, we had resource support. There is continuous program with constant data collection, re-evaluation and updates as long as there is good connectivity between the NOC server with the remote site controllers.”

Interviewer: “Yes, I would appreciate that. Well, I think we've covered all the questions I had, again, I really take appreciate you taking the time to answer my questions.” Respondent: “No worries.”

Appendix E: Interview Four

Interviewer: "All right hey I really appreciate you taking the time to let me interview you for this research?"

Respondent: "No problem. How is New Zealand?"

Interviewer: "*Orait orait tasol* [Not bad] Thank you for asking. I had a good conversation with XXXX and he talked about some of what they're doing as a Power System Troubleshooting team in the company as far as maintenance concern. If I understand correctly you worked previously together is that correct?"

Respondent: "Yes, we did and now I am with the Performance Engineering Unit."

Interviewer: "And did you have any RCM analysis or implementation going on at that time or even currently, and what was the background of what you were doing?"

Respondent: "My background is, I've been a telecommunications engineer for 10 years now. My area of expertise was Radio Frequency Planner. And as I was doing that job, I was looking around at the other things that are going on within the company. This is in the early 2014, and I had to shift to Performance Engineering to fill in the vacancy without proper handover and training for the particular job. So, to answer your question I don’t know if we have practice the RCM analysis. To be honest, I heard about reliability but not reliability-centred maintenance and such.”

Interviewer: "Anyways, do you know what maintenance strategies (you can always refer to the information sheet I emailed to you earlier); the company is implementing to maintain its assets? I am only interested to know if some kind of maintenance being done on the remote power systems especially the power generation assets. You know what I mean right?"

Respondent: "Yes, yes, Digicel PNG has more than 300 telecommunication sites in the remote parts of the country where there is no access to PNG Power, so the sites are powered by solar, backup by battery and DG. As a Performance Engineer, I only update the Managed Services team regarding the number of downtime issues, faults and the causes of these issues as I collect feedback from the Network Operations Centre (NOC). That is a compiled data of analysis of those down sites done by transmission engineer, radio base station engineers and power system engineer. I do bucket analysis, categorizing the issues to low and high risks in terms of revenue generation for the company. I can recall the management team then prioritized maintenance for the high revenue sites followed by low revenue sites. So, they want to direct all necessary resources to the high priority site to restore first.

Historical data was important here as we experienced high failure rates of MPPTs, so the management had to involve the manufacturers to investigate root cause analysis and find design issues if possible. One of their proposed solution was to remove the surge protection in the junction box of the solar array. Still not much reduction in failure rate so this investigation is currently ongoing."

Interviewer: "So I see you are practicing corrective maintenance.”

Respondent: "Yes, you might say. I also note that due to high failure rate of certain hardware, we run out of stock or spare parts. The weather also delayed maintenance activity leading to reactive maintenance as I refer to your Information Sheet you provided. These factors and the low priority sites are often left to run-to-failure.”

Interviewer: "Tell me something essential in the implementation and how you achieved that?"

Respondent: "Cost avoidance was a beneficial, I don't want to say that, say a side benefit. I was more concerned with power

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availability. You know, having like enough battery juice out and ready to go when they were needed to go. That was something we were all

is getting beat up on; you'd see especially batteries down in the field. Down in the en- routes for things that could easily have been done, you know, somewhere else a lot cheaper and a lot faster."

At Digicel PNG…can you hold on just a second, Chief?" Interviewer: "Sure."
Respondent: "Chief, I hate to do this, but I am urgently needed by the boss." Interviewer: "Understand."
Respondent: "I can certainly phone you back later today if that works for you." Interviewer: "That's fine with me, probably around three."
Respondent: "That sounds perfect. Okay thanks Chief, bye."

Interview continued that afternoon.

Interviewer: "What other difficulties did you encounter as far as getting support? What challenges did you face?"

Respondent: "Well, to be honest, we didn't really take the idea of involving maintainers (sub-contractors) up until we had done as much stuff as we could do at the lower levels. One of the things we did is we just went out to the field guys (field engineers), you know, we only had about twenty field engineers, so imagine having 1000 + telecom sites and those guys. We just went out to the units and just sat down with the maintainers and said, 'OK.

Here's some ideas that we think we can help you keep the power system supply better and keep your home a lot more. And here's what we need you to do to do that. We need better data and we need some cooperation. You know, pick up the phone and call us if you got an issue going on. Let us know.' Just keep open lines of communication, and we started it kind of the grass-roots level, got those guys excited about it and they could see what we were doing and how the information they were giving us was going to help them and only after we got it started good, did we try to go up the chain with it. It seems like the things we were trying to do were completely different than anything people had done

before, and it usually works better when it starts in the bottom and bubbles up than if it starts at the top and gets shot down. If you know what I mean."

Interviewer: "Being a maintainer we would be at least sceptical about something that no maintainers were involved and as far as here's a great new way to maintain this power supply."

Respondent: "And that's where having XXXX and XXXX and XXXX helped an awful lot, too, because they were maintainers all their lives and they went out and spoke the language. We engineering types were there and we took off our ties and would go out to the field, but having those guys there, and a lot of field units knew them already from their time as Digicel field reps and headquarters and other places. Their reputations kind of preceded them somewhat and that made it a lot easier."

Interviewer: "Do you think there are any things that, looking back, you think, 'Man I wish we would have done that a different way or we could have saved ourselves a lot of hassle, had we done it this way instead of that way' as far as implementing the changes concerned?"

Respondent: "I can't think of anything right off that we could have done a whole lot different. If we had the data or..."

Interviewer: "Even as far as the change management. You know, how do you sell it up and down, you said you started more at the grassroots level and got the support there." Respondent: "Absolutely, I think one of the things that I would have done differently is I would have gone out to the field units as we were going through the changes. I would've gone to the regional offices in each province that manage those particular items and explained up front the benefits from making a lot of these time change items instead of fun to fail items. And the benefit is they get a steady demand or at least a more steady demand, maintainability, support and in time to come reduce site visits. And they get that predictability in how many they have to fund for repair or purchase. The regional office get a lot more stable workload, and they like that a lot better. It just makes life... It eliminates a lot of those up and down saw-tooths that we find all the time. You know, you fly along until one unit finds something broke. And then they start looking at all their airplanes and the word gets out to the other bases and everyone starts looking at the same thing and they're all broken, and you have to go out and buy 1000 units to replace them all

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and then you don't need any of them for another 5 years. Then you go through another whole cycle, and it's really, really ugly. Think if we had gotten those folks more involved upfront, you know as far as change management and changing the supply side we probably would've been better off."

(Telephone line got disconnected, called back.)

Respondent: “I tell you I don't know what happened. You want me to continue on?” Interviewer: “Please, please.”

Respondent: “Okay, the thing I was talking about was the business case. Once you recognize what you identify, a degradation of some sort, whatever it is. The key, of course, is to build a business case to justify that. That's such an important part that I see in the company, when introducing especially new systems, where the skill did not exist to do that. I see engineers totally frustrated, ‘Well, I tried to convince them to fix this and to fix that and they won't do it.’ Well yeah, because all you bring is costs to them. You never bring benefits, and you've got to do that. You've got to dig in there and show them that in the long run you’re going to save money. The business case we did on the slats showed them over the year saving bunches of money. And I can’t remember the exact number, I don’t have it in front of me, but it came out in thousands of kina. The standard has always been and always will be: it is cheaper to use. And once you recognize that, once you accept that. And you understand you've got to build a business case to prove that. Then you'll get your changes that you need: improvements or whatever it is that you need to get the power system reliable. At Digicel PNG, because Digicel PNG is like all of the other businesses, very competitive, we had to justify every penny. Every penny, and at times, that sounded ridiculous to me. But I realized more and more as I was into it that you know, it's absolutely mandatory because it's got to pay for itself. And if you do it right, it will pay for itself. The time element of when it pays for itself is sometimes quite variable. But it will eventually pay for itself if you do it right. If you do the justification. So that's a big part of a properly run maintenance program. Another part of a properly run maintenance program is you cannot manage a maintenance program from a cubicle. Big problem in many cases, people try to manage from a cubicle. You've got to get in there. You've got to be able to talk to field engineers and sub-contractors, you've got to be up to speak their language. You got to know what reality is, and that's a big item that in this case in the remote solar power system. Most of the maintenance program decisions are made by engineers up in the cubicle. And then they wonder why when they apply something out there, it doesn't get done the way they thought it should be done. So being an old maintainer, you can probably associate with that quite well.”

Interviewer: "Is there anything that you thought, I wish he would've asked that but I didn't?"

Respondent: "No not really."

Interviewer: "I think I've pretty much got what I need. Thanks again for being flexible on getting back with me and everything. I do appreciate it."

Respondent: "No problem.”