Creating a more sustainable building by choosing the right maintenance program

A look into Preventive Maintenance vs Predictive Maintenance

11/1/21

Nathan Pluméy
UNIVERSITY OF WASHINGTON AND THE US NAVAL FACILITIES ENGINEERING SYSTEMS COMMAND

Abstract

Building equipment failure can have drastic effects on a company's operations and budget. This paper presents two types of maintenance approaches that if done effectively, can prevent or significantly reduce the failure of building equipment assets. The first is traditional time-based preventive maintenance (PM), which conducts pre-failure inspections and tasks in a cyclic time-based approach. The second, is predictive maintenance (PdM), which conducts maintenance functions based on the condition of the equipment found through continuous or cyclic measurements and analysis during machine operation.

The purpose of investigating these maintenance approaches is to determine whether we can improve on the U.S. Navy's (Navy) existing facility maintenance program, helping to reduce overall costs while improving sustainability, equipment resiliency, and efficiency. By presenting each maintenance program and leveraging today's technologies we show that these advancements in technology can directly improve the Navy's operational mission and warfighter readiness.

Research was conducted through the following methods: books, third party reports, journal articles, industry websites and articles that focus on equipment maintenance. The Navy, the National Aeronautics and Space Administration (NASA), and the University of Washington provided case studies, existing facility/utility maintenance data, and budget information used in this research. The results show that PdM approaches using advanced analytics are more effective in diagnosing equipment, prescribing equipment problems, and predicting equipment failure. It will also show that when a PdM model is used, building tenants have less operational impacts as equipment operates longer with less downtime between maintenance events. By changing to a PdM program, facility managers and owners can improve asset efficiency and resilience, directly improving environmental sustainability and lowering overall long-term costs. It highlights the significant capital costs of a fully online PdM program and the benefits of using a hybrid model of PM and PdM.

This research concludes with an overview of how building maintenance is currently being conducted on Navy bases by Naval Facilities Engineering Systems Command (NAVFAC), and how they are transitioning to a more sustainable maintenance program leveraging existing advanced metering infrastructure (AMI), building control systems (BCS), and utility control systems (UCS) with Smart Grid (SG), OSI Pi, and advanced analytics. In addition, major gaps in this transition are identified, and solutions are proposed to optimize these building system investments.

Table of Contents

1. Introduction

Building usage relies on ensuring that the equipment and utility distribution systems remain operational to support building tenants and their various usage needs. Ensuring facility and utility systems remain operational in conjunction with maximizing equipment efficiency, allows facility and utility managers to best support tenants by maximizing their operation time through minimal maintenance downtime. A well-developed maintenance plan can ensure equipment and their operations are sustainable, resilient, and can provide cost savings and cost avoidance.

Navy

The total combined budget for sustainment (maintenance and repairs) is $3.01 billion. Currently the Navy spends roughly $802 million (26.6 percent) in total maintenance, with $325 million (10.8 percent) of that in planned preventive maintenance. Of the remainder the Navy spends a total of $2.2 billion (73.4 percent) in maintenance and repair work, with about two-thirds of that total going in to facility project investments. (Commander Navy Installations Command, 2020) The Facility Readiness Evaluation System (FRES) reports that the Navy owns twenty-five thousand two-hundred fourteen buildings (excluding family housing), with an average age of forty-nine years old, a replacement value of $365.2 billion, and a deferred maintenance backlog of $16.28 billion (US Navy, 2020). The wide dispersion of Navy bases across the U.S. and the world enables the Navy to meet its various mission sets. It is important to understand the key elements that affect building systems to meet building management objectives.

These elements include:

- average age
- proximity to ocean climates and environmental conditions

- how facilities are used
- how recap plans and maintenance of these vital buildings and systems are managed
- quality/standards of construction

Understanding these elements and the effects on building systems are vital in ensuring building operation, and for the Navy, operational readiness.

University of Washington

For the University of Washington, building systems are vital in supporting their mission, which focuses on academics, teaching, conducting research, and administrative support. The maintenance of these building systems directly affects the quality and effectiveness of these administrative, learning, and research environments. Currently the University of Washington spends about $6.5 million in planned maintenance for three hundred seventy-one buildings, which are similar to the Navy in that they vary by size, use, and age (John Carroll, 2020). Uses vary from residential spaces, office spaces, laboratories, and other specialty facilities. Specialty facilities include a power generation plant, a stadium, multiple auditoriums, and libraries. Though the University's maintenance budget is only a fraction of the Navy's, the dollar value is still significant and any reduction in maintenance and energy costs, and improvements in resiliency of building support equipment is important.

Maintenance

The term maintenance is defined as a series of tasks and/or activities that are done to restore an item in order for it to perform its designated function (Rosmaini Ahmad, 2012). Choosing the proper maintenance that maximizes equipment performance ensures buildings stay in operation longer between repairs, reducing overall maintenance costs. Advancement in technology has evolved traditional maintenance programs, creating more efficient and cost-effective options for those who maintain building support systems.

Maintenance can be divided broadly into two categories: corrective maintenance and preventive maintenance. Corrective maintenance (CM) means maintenance that is executed after a piece of equipment has reached a fault, and no longer runs as it did while it was in normal operation. This is also known as "run-to-failure or reactive maintenance" (Rosmaini Ahmad, 2012) .

This classification is broad. This paper will use one classification system presented by Ramesh Gulati in his book Maintenance and Reliability Best Practices which breaks out maintenance practices further (Gulati, 2021). In figure one, we identify two maintenance approaches that are fundamental to most existing maintenance programs found today and are the focus of this paper, time-based PM and conditioned-based PdM.

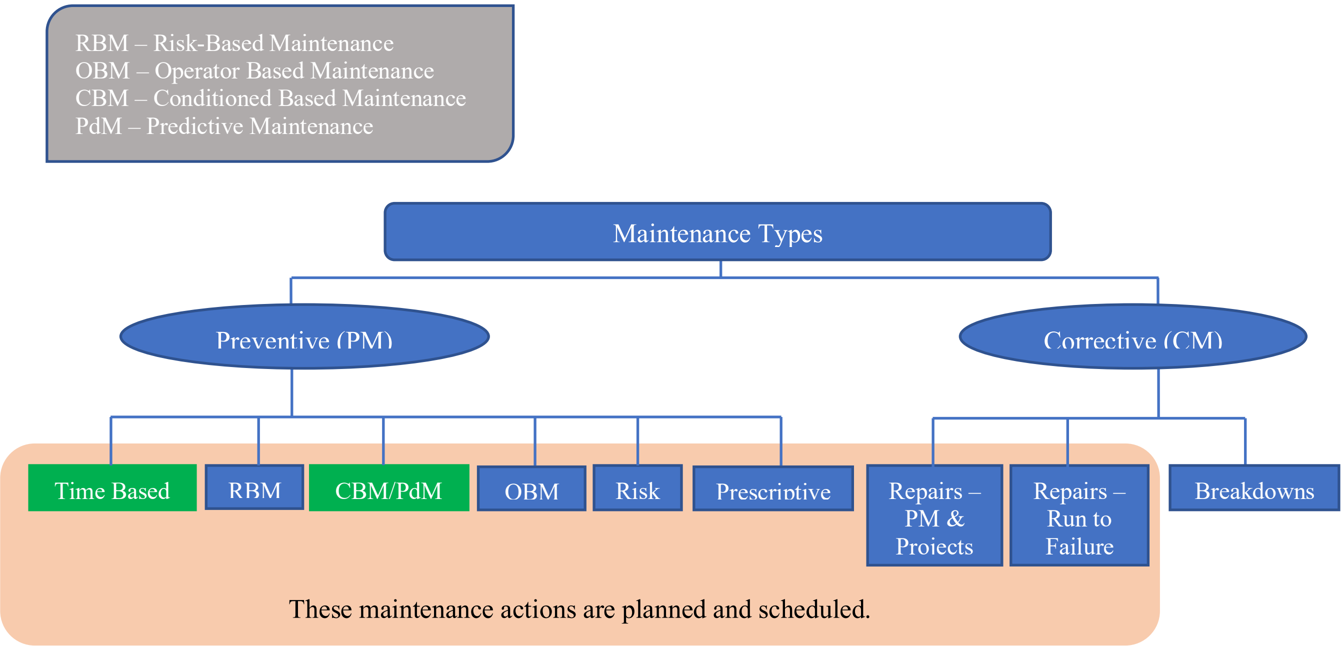


Figure 1 Maintenance Practices (Gulati, 2021).

Time based **PM** is maintenance that is focused on ensuring equipment does not fail and is completed prior to failure. It involves planned systematic inspections and component replacement at regular intervals. The condition of the equipment does not necessarily determine the interval of this maintenance. Condition of the equipment is assessed at the time of the inspections and may involve an additional work order for any repairs (Gulati, 2021).

Conditioned-based maintenance, or **PdM,** is maintenance that is planned and based on the condition or physical state of the equipment by using technologies that can detect and measure the onset of equipment degradation (G.P. Sullivan, 2010).

The focus and objective of this research is to conduct a comparative study of these two maintenance approaches PM and PdM, so that building managers and owners can make a sound decision when determining a maintenance approach. It will provide a justification of which maintenance program is more beneficial and why. It will review the NAVFAC's existing maintenance program model and what a PdM model might look like for naval facilities.

2. Problem Statement

PM and PdM maintenance methods are well documented in the industrial sector, but information where facility departments actively utilize PdM to maintain their facilities and utilities is not holistically reviewed. This study will provide an overview of both methods and discover why and how either PM, PdM or a combination of the two could be used on installations with multiple buildings of various types.

Specifically, we will answer:

1. What are the advantages and disadvantages between PdM and PM?
2. Which maintenance program enables building managers/owners an avenue to reduce overall costs, reduce labor hours, and minimize operational work stoppages by maximizing equipment operation?
3. How can the right maintenance program create a more “green” or sustainable building?

We finalize this research by using the Navy’s transition to SG as a case study. We will discover some aspects of how the Navy will transition to SG, as well as how they will leverage existing technology and SG technology to perform PdM maintenance. We will also discover the advantages and challenges in using SG to perform PdM, and how this program will be implemented with their existing PM program.

3. <u>Background</u>

3.1. <u>Preventive Maintenance</u>

Maintenance programs are intended to extend the life of equipment and keep the equipment in a condition that it can produce at its full functional capability (Gulati, 2021). The United States Department of Energy developed a guide estimating that there is a twelve to eighteen percent cost savings in performing PM in comparison to performing breakdown maintenance. Breakdown maintenance refers to maintenance repairs made after equipment has gone to fault or fails to perform its function (G.P. Sullivan, 2010).

Advantages of a PM strategy when compared to no maintenance or reactive maintenance, is that it has low start-up costs and can be performed using either facility management experience from technicians, staff, or by the original equipment manufacturers (OEM) recommendations (Rosmaini Ahmad, 2012). Advantages also include flexibility for adjustment of the maintenance periodicity, energy savings through cyclic upkeep of the equipment, and increase in equipment useful life (G.P. Sullivan, 2010). Additionally, there are also fewer breakdowns, lower emergency labor hours, time for maintenance to be planned, safer equipment, improved equipment availability, reduction in overall repairs, reduction in size/scale of repairs, and reduced exposure to potential liability (Levitt, 2011).

The major disadvantage of this type of maintenance is that catastrophic failures are still likely to occur. If for example maintenance is scheduled every other week or every month, the time interval between maintenance periods allows for a period with no oversight. This interval could allow enough time that the equipment could go into catastrophic failure quickly with or without any warning following the trend in figure two. Figure two, shows where PM is on the Potential Failure – Failure Curve, and the example provides some context as to why. The figure shows that the time interval between operation within the PM stages and catastrophic failure is short, and the resistance to failure drops off quickly while costs needed to repair the potential failure start to increase more rapidly. Other disadvantages include the amount of labor and material costs needed to complete these recurring maintenance tasks can be significant when multiplied by the number of systems a technician may have oversight of, like in the case of a large naval base or university. This issue compounds with performance of maintenance when it may be unneeded, as well as possible damages to components which may occur during these unneeded maintenance actions (G.P. Sullivan, 2010). OEM companies may also have hidden agendas in recommending maintenance intervals, maximizing spare parts replacement through frequent PMs (Rosmaini Ahmad, 2012). Furthermore, OEM recommendations may not be optimal and may vary greatly based on the environmental setting and operating conditions (A.S.B. Tam, 2006).

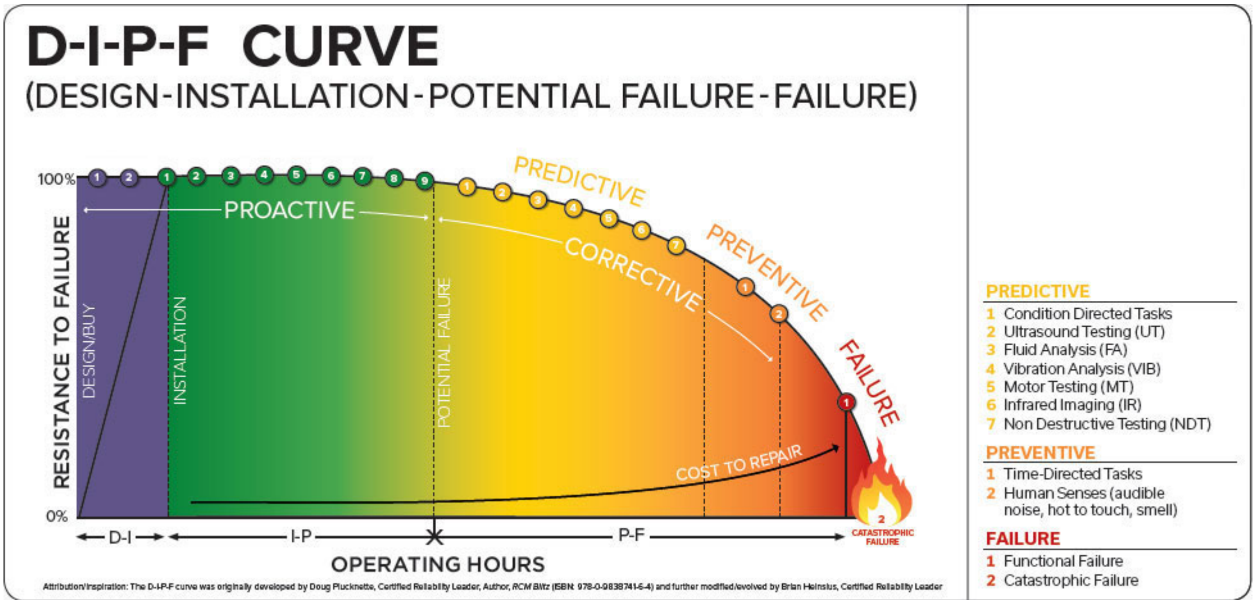


Figure 2 - The D-I-P-F Curve, modified to focus on the P-F portion of this graphical representation of the health of building equipment (Plucknette, 2011).

3.2. Predictive Maintenance

In contrast to time-based PM is PdM. Again, PdM focuses on detecting onset system degradation through various measurement techniques in order to plan maintenance that will eliminate equipment problems that would lead to significant deterioration in mechanical/electrical equipment (G.P. Sullivan, 2010). Figure two above shows a D-I-P-F curve, notice where PdM and PM lie in comparison to one another. Identify the type of maintenance measures or technology that make up each maintenance type along the curve. See how sharply the curve goes down as the equipment continues operating toward catastrophic failure. Also note the cost of repair curve along the bottom of the graph. What you see is that PdM measures can predict failures early on in comparison to PM measures, allowing maintenance to be scheduled and parts ordered before costs become significant.

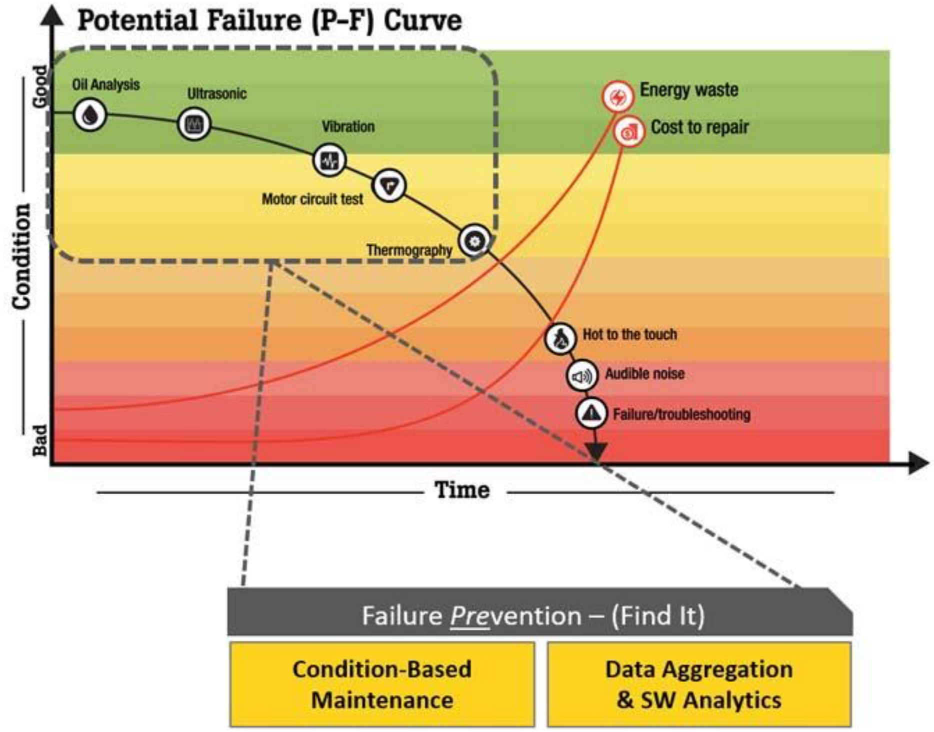


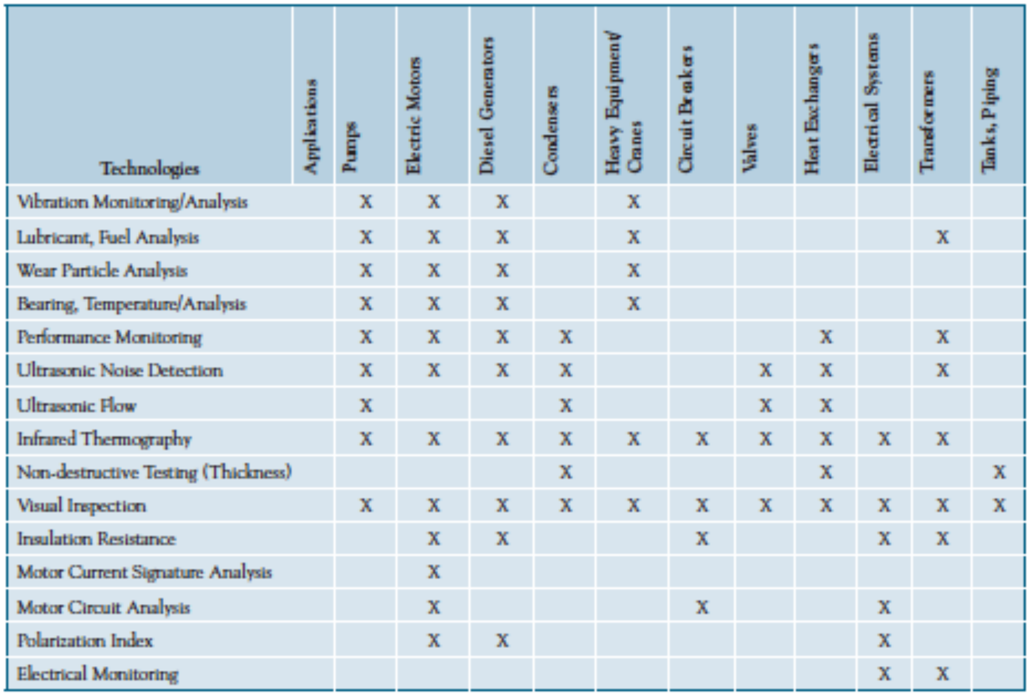
Figure 3 - DIPF Curve, highlighting conditioned-based PdM & data aggregation and software analytics within the dotted lined box with the energy waste and cost to repair curves (Perry, unk.).

Figure three, highlights various PdM and PM methods for sensing failures. It also emphasizes the energy waste and the cost to repair as time progresses toward catastrophic failure. These are both important to highlight as they both directly affect bottom-line operational costs. Predictive maintenance offers many advantages to prolonging the life of equipment and reducing bottom line costs, but it is also very technical with large upfront investments for the various monitoring options (G.P. Sullivan, 2010).

In discovering PdM effectiveness in determining failures, one case study on rolling element bearings concluded that when vibration monitoring was used over selected time intervals, the remaining life of the bearings can be estimated, diagnosis of defects can be done while equipment is running, and future failures can easily be detected in order to schedule maintenance (Sadettin Orhan, 2006). Another case study looked at the effectiveness of thermography on electrical systems in the use of PdM, and it concluded that when an intelligent thermal defect identification system was used to analyze the data sets, it could diagnose electrical defects with better accuracy in order to schedule the proper maintenance (A.S. Nazmul Huda, 2013).

The following are examples of the various PdM technologies: infrared thermography, vibration, chemical-particle lubricant/fuel sampling and analysis, electrical (ampere-monitoring), visual/physical, combustion analysis and performance. These methods sometimes involve training on technology-driven monitoring processes like thermography, sound, and vibration in order to diagnose potential problems. They can be done either periodically, or because technology has become more advanced, the sensing equipment can be placed in-line with or on the equipment, thus allowing measurement data to be taken while equipment is in operation (Gulati, 2021).

This direct condition monitoring as equipment is operating, provides large amounts of data from sensing equipment, depending on the frequency of reading sets. The addition of Artificial Intelligent (AI), Machine Learning (ML), Deep Learning (DL), Digital Twin (DT) modeling and other advanced analytics have provided an avenue for analyzing this enormous amount of data. These large data sets, analytics tools and the use of key performance indicators (KPI) can be used to perform a variety of analytics. Analytics that can diagnose anomalies through root cause analysis, be predictive and provide high-fidelity forecasts of failures, and be prescriptive on corrective actions (Mirza Kibria, 2018). This is key when the purpose of creating an engineering solution to planned maintenance is “to deliver the right task, to the right component, using the right tool, at the right frequency to avoid or detect the failure” (Levitt, 2011).



Technologies	Applications	Pumps	Electric Motors	Diesel Generators	Condensers	Heavy Equipment/ Cranes	Circuit Breakers	Valves	Heat Exchangers	Electrical Systems	Transformers	Tanks, Piping
Vibration Monitoring/Analysis		X	X	X		X						
Lubricant, Fuel Analysis		X	X	X		X					X	
Wear Particle Analysis		X	X	X		X						
Bearing, Temperature/Analysis		X	X	X		X						
Performance Monitoring		X	X	X	X				X		X	
Ultrasonic Noise Detection		X	X	X	X			X	X		X	
Ultrasonic Flow		X			X			X	X			
Infrared Thermography		X	X	X	X	X	X	X	X	X	X	
Non-destructive Testing (Thickness)					X				X			X
Visual Inspection		X	X	X	X	X	X	X	X	X	X	X
Insulation Resistance			X	X			X			X	X	
Motor Current Signature Analysis			X									
Motor Circuit Analysis			X				X			X		
Polarization Index			X	X						X		
Electrical Monitoring										X	X	

Table 1 - More examples of PdM methods and the facility systems/equipment they are used with (G.P. Sullivan, 2010).

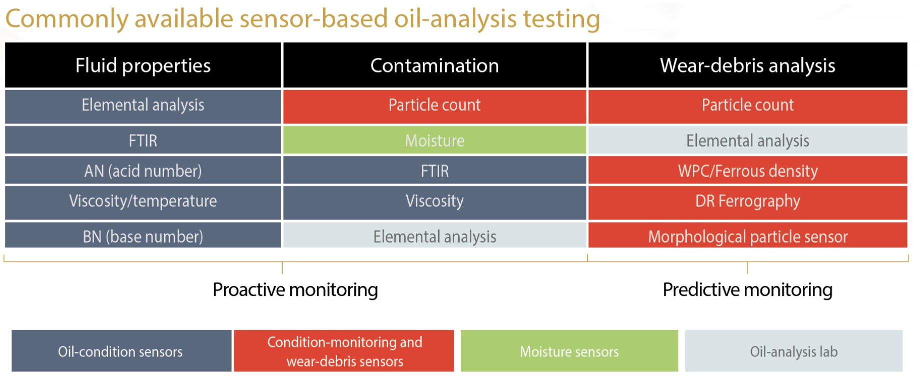
As stated earlier, PdM methods and proper programming can either continuously monitor or periodically monitor these facility assets and trigger alerts based on predetermined normal operational setpoint conditions. Table one shows a majority of the existing predictive maintenance methods used and the corresponding facility system or equipment that it is used with (G.P. Sullivan, 2010). A few of the major PdM methods are described below to show the effectiveness of these methods at determining faults to allow technicians to perform specific maintenance:

Vibration monitoring, which is used primarily on rotating equipment, uses vibration sensors to detect variations that would indicate damage or degradation (Rosmaini Ahmad, 2012). These sensors provide an electrical output/signal that reflects the vibrational displacement, velocity, or acceleration (G.P. Sullivan, 2010). In a case study on rolling element bearings evaluated over three-hundred days, vibration monitoring was used on a cylindrical rolling element bearing. In this study the bearing, most often found in motors in facility support equipment, was part of a fan motor which was periodically monitored. This PdM technique was able to identify a fault in the fan motor outer bearing which was allowed to continue operation and delay any maintenance repair since the fault was still within predetermined operating limits (Sadettin Orhan, 2006). This example of early detection by vibration monitoring allows building operators to identify the prescribed issue using data analytics and determine the optimal time to repair based on labor and parts availability.

Infrared thermography is a method that converts heat signatures of an object's surface into a visual image (A.S. Nazmul Huda, 2013). Heat signature analysis is critical in monitoring electrical equipment. When current passes through a resistant component it will generate heat at the defective point. For example, in oil-cooled transformers, high temperatures in certain areas of the transformer can reveal faults at the primary/secondary bushing connections, the cooling fins, the cooling fans, and the internal bushing connections (A.S. Nazmul Huda, 2013). In electrical panels a heat signature may be produced by a particular circuit breaker that is starting to fail and by use of this PdM method the automatic opening of the circuit breaker can be prevented, and maintenance executed without effect to operations. In mechanical rooms the use of thermography in the identification of steam leaks is ideal. In a case study of the sustainability performance of a boiler room through condition-based maintenance, it utilized thermography which led to corrective maintenance of leaking steam traps that positively impacted overall energy savings (Masoud Behzad, 2019).

In **oil/lubricant analysis**, chemical and physical parameters are used to determine the condition of both the lubricant and the internal machinery (Carnero, 2005). Chemical analysis quantifies the condition of the oil additives, while analysis of the physical properties consist of the viscosity of the oil and possible contaminants like water, silicon, dirt particles. In addition, the oil/lubricant is analyzed for wear particles, providing information about a particular part being worn down through contact or physical wear taking place in a portion of the machine. This technique usually involves sending oil samples to an off-site lab which are relatively inexpensive (G.P. Sullivan, 2010). Oil analysis by the off-site lab is more extensive than what can be tested by existing in-line oil analysis sensors. Table two below shows commonly used oil analysis tests with readily available sensors. This table indicates that only elemental analysis, which reports the concentration of wear metals, specific contaminants, and inorganic additives, is the only analysis that cannot be replicated by use of a sensor (Barnes, 2020). Table three shows an expanded set of test procedures that oil test labs can perform. These tests and procedures are based on the type of oil and the testing specifications developed by the following organizations: the Society of Automotive

Engineers (SAE), American Petroleum Institute (API), the International Organization for Standardization (ISO), and the American Gear Manufacturers Association (AGMA) (Loren Green, 2014).

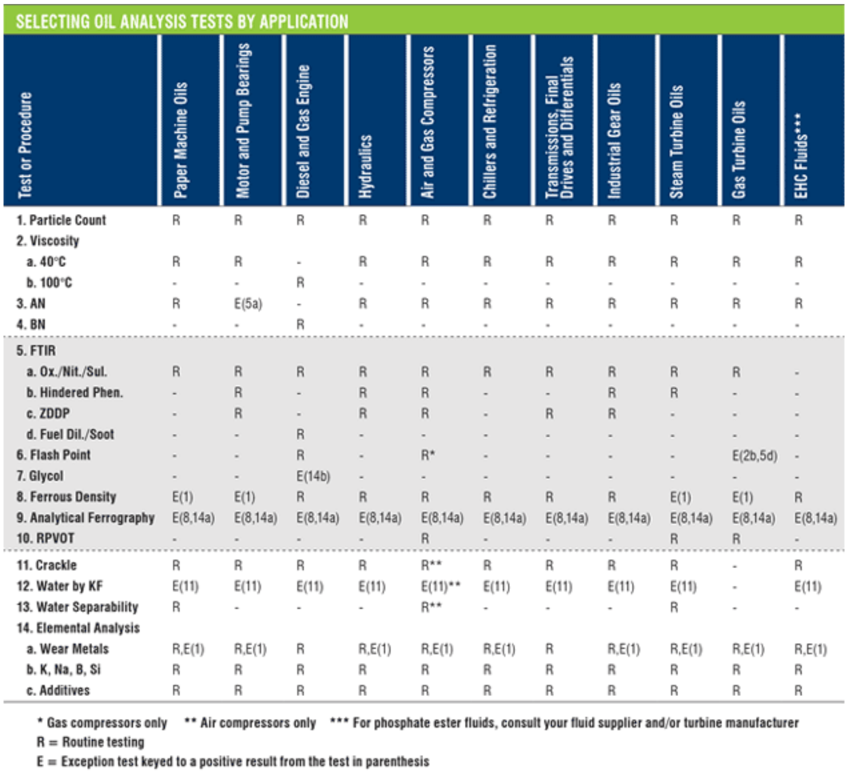


Commonly available sensor-based oil-analysis testing

Fluid properties	Contamination	Wear-debris analysis
Elemental analysis	Particle count	Particle count
FTIR	Moisture	Elemental analysis
AN (acid number)	FTIR	WPC/Ferrous density
Viscosity/temperature	Viscosity	DR Ferrography
BN (base number)	Elemental analysis	Morphological particle sensor
Proactive monitoring		Predictive monitoring

Oil-condition sensors	Condition-monitoring and wear-debris sensors	Moisture sensors	Oil-analysis lab

Table 2 - Common oil analysis testing and existing sensor types (Barnes, 2020).



SELECTING OIL ANALYSIS TESTS BY APPLICATION

Test or Procedure	Paper Machine Oils	Motor and Pump Bearings	Diesel and Gas Engine	Hydraulics	Air and Gas Compressors	Chillers and Refrigeration	Transmissions, Final Drives and Differentials	Industrial Gear Oils	Steam Turbine Oils	Gas Turbine Oils	EHC Fluids***
1. Particle Count	R	R	R	R	R	R	R	R	R	R	R
2. Viscosity											
a. 40°C	R	R	-	R	R	R	R	R	R	R	R
b. 100°C	-	-	R	-	-	-	-	-	-	-	-
3. AN	R	E(5a)	-	R	R	R	R	R	R	R	R
4. BN	-	-	R	-	-	-	-	-	-	-	-
5. FTIR											
a. Ox./Nit./Sul.	R	R	R	R	R	R	R	R	R	R	-
b. Hindered Phen.	-	R	-	R	R	-	-	R	R	-	-
c. ZDDP	-	R	-	R	R	-	R	R	-	-	-
d. Fuel Dil./Soot	-	-	R	-	-	-	-	-	-	-	-
6. Flash Point	-	-	R	-	R*	-	-	-	-	E(2b,5d)	-
7. Glycol	-	-	E(14b)	-	-	-	-	-	-	-	-
8. Ferrous Density	E(1)	E(1)	R	R	R	R	R	R	E(1)	E(1)	R
9. Analytical Ferrography	E(8,14a)	E(8,14a)	E(8,14a)	E(8,14a)	E(8,14a)	E(8,14a)	E(8,14a)	E(8,14a)	E(8,14a)	E(8,14a)	E(8,14a)
10. RPVOT	-	-	-	-	R	-	-	-	R	R	-
11. Crackle	R	R	R	R	R**	R	R	R	R	-	R
12. Water by KF	E(11)	E(11)	E(11)	E(11)	E(11)**	E(11)	E(11)	E(11)	E(11)	-	E(11)
13. Water Separability	R	-	-	-	R**	-	-	-	R	-	-
14. Elemental Analysis											
a. Wear Metals	R,E(1)	R,E(1)	R	R,E(1)	R,E(1)	R,E(1)	R	R,E(1)	R,E(1)	R,E(1)	R,E(1)
b. K, Na, B, Si	R	R	R	R	R	R	R	R	R	R	R
c. Additives	R	R	R	R	R	R	R	R	R	R	R

* Gas compressors only ** Air compressors only *** For phosphate ester fluids, consult your fluid supplier and/or turbine manufacturer
R = Routine testing
E = Exception test keyed to a positive result from the test in parenthesis

Table 3 - Component specific routine and exception tests performed by oil-analysis labs for a majority of equipment used in most plants (Loren Green, 2014).

Given the variety of methods and advantages to PdM it is important to note the disadvantages. Three main disadvantages noted by a Department of Energy report on operation and maintenance best practices are: there is a significant capital cost in sensor equipment and program/data management per building; there is an increased investment in staff training to understand the various devices and how to analyze the data; and lastly, the return on investment is not initially self-evident on the annual budget, which may reduce support for these methods over time (G.P. Sullivan, 2010). In an article by Gregory Perry, a Senior Capacity Assurance Consultant at Fluke Reliability, stated that PdM does not predict the longevity or the point when the failure of the asset will occur, but it does provide significant data that allows the technician to more accurately, effectively, and fiscally schedule maintenance and enable increased availability of the asset (Perry, unk.). This argument assists in identifying that solely using PdM techniques does not result in a solution for performing maintenance, but it involves someone or something to analyze the data, provide the insight for the asset condition, then provide a maintenance solution.

To fully harness the benefits of in-line PdM techniques involves significant investment and infrastructure. These inline techniques are known as “on-line” monitoring/testing where sensors can either be installed permanently and hardwired or they can be installed using remote wireless Internet of Things (IoT)-enabled smart sensors. These sensors can perform online “continuous” monitoring or take measurements at periodic intervals (Gulati, 2021). The data that PdM IoT sensors would create would need the addition of the following: data management systems & infrastructure allowing for communication/storage of the data; analytic tools to analyze the large amounts of data; visualization tools to provide technicians and stakeholders the right analytics in an easy-to-understand format; and an asset/work-order management system with integrators that enable the creation of an effective maintenance program for that asset.

4. Research Procedures

Predictive Maintenance (PdM) and Preventive Maintenance (PM)

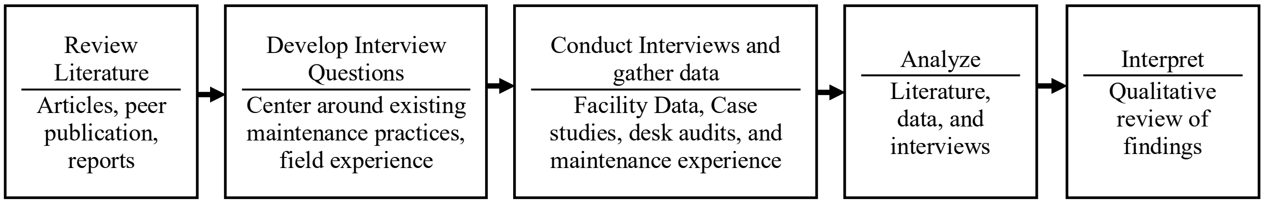


Figure 4 - Research process. Research included a pilot program for the U.S. Navy. Desk audits, reports, and data provided by the U.S. Navy, NASA, and the University of Washington.

Navy Maintenance Program

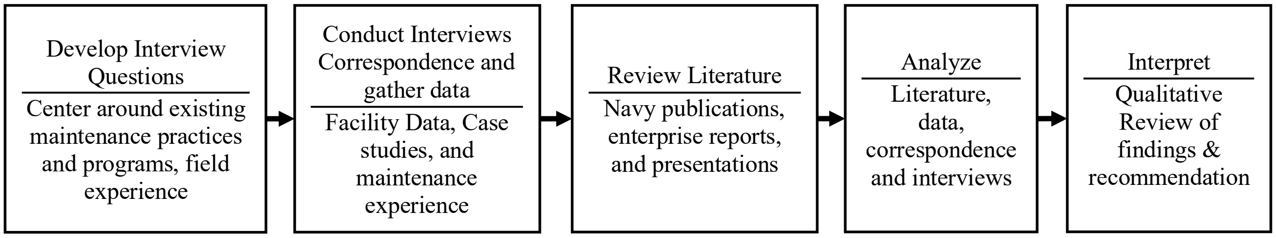


Figure 5 - Research process for the Navy maintenance program.

5. Research

5.1. Literature and Case Study Review

5.1.1. Review of Literature and Case Studies – PdM and PM

Research literature centers around the topic of PM. More information is needed to understand the full breadth of PdM which is a subset to PM. A reference review summary table is included in appendix 9.A. The case studies and journal articles vary, but provide unique examples of predictive maintenance applications and results. Case studies include:

- Two audit reports from the University of Washington, which show the building systems, energy use and end-use consumption information, as well as energy conservation measures needed for Mary Gates Hall and William Gates Hall (University of Washington Facilities Services, 2014).
- A case study from Naval Facilities Command Hawaii was a pilot study that focused on an alternate concept of maintenance that served as a proof-of-concept for improving the reliability of the various building systems. This concept of maintenance, known as reliability-centered maintenance (RCM), heavily relies on predictive maintenance to evaluate and diagnose equipment failure (Jacobs Engineering Group Inc., 2018).
- Information from the National Aeronautics and Space Agency (NASA) provided information and a case study on their Langley Research Center, Condition-based Maintenance Program which provided great insight to the various benefits of using PdM measures (NASA - National Aeronautics and Space Administration, 2021).
- The remaining peer reviewed publications focused on specific predictive maintenance techniques used to determine faults or failures in specific dynamic equipment (ie. Rolling element bearings, electric equipment, boiler room equipment, rotating machinery, etc.)

Other literature included a report from the Department of Energy that discussed operation and maintenance best practices and included a breakdown of maintenance types and predictive maintenance technologies. Various web sites and website articles provided initial background of maintenance types, building support equipment, power usage information and predictive maintenance measures. Some websites include: Reliable Plant, US Energy Information Administration, Maintain X, Control Engineering, and Plant Services.

5.1.2. Literature Review Navy

The Navy and the commands that oversee their properties, facilities, and building systems have developed multiple publications, guides, and instructions/policies for managing these assets. For the focus of this paper, five documents were used to understand current and documented overall policies and procedures in place for the Navy's maintenance program and the concept of operations to transition to SG. In addition to the standard publications there were multiple presentation slides and correspondence with various naval facility managers, utility managers, and stakeholders that supplemented the information needed to understand the SG program and the existing naval maintenance programs.

Major policies and instructions include:

- NAVFAC publication 1205, is the Public Works Management guide and was used for its overview of their Preventive Maintenance Programs (PMP) (Naval Facilities Command, 2008).
- NAVFAC P-501, the Condition Based Maintenance Management Manual was used as background, as it provides details and instructions on how to conduct inventory management, condition assessments, analysis, and work planning (Naval Facilities Engineering Systems Command, 2016).
- NAVFAC P-503, Planned Maintenance Guide is a document that's goal is to convey consistent corporate processes to reduce maintenance and operations costs over a facility asset's life cycle through the PM programs across the Navy (Naval Facilities Command, 2019).
- NAVFAC P-803 the Navy Smart Grid Concept of Operations was used to understand how the Navy would transition to smart grid, the goals for the system, and how the system will be operated with existing AMI, BCS, and UCS control systems (Naval Facilities Engineering Systems Command, 2019).
- NAVFAC document named "Why use the Control System Platform Enclave?" was used as background to understand how the Navy would ensure control and cybersecurity using facility related control systems and the smart grid on a digitized network (Naval Facilities Engineering Systems Command, unk.).
- Navy and Marine Corps Smart Grid Capability Development Document was used as background to better understand how the smart grid system will meet the overarching goals set by Navy and Marine Corps.

5.2. Interviews and Correspondence

5.2.1. Questionnaire Development, Interviews and Correspondence – PdM and PM

Using the information found through case studies, articles, and other literature, assisted in developing three questionnaires. The first questionnaire focused on University of Washington personnel, with an average length in experience within their field of 16.3 years, and their personal experience in relation to the University of Washington maintenance program. The three interviewees were documented through notes taken during the interview and using the questionnaire as the base for questioning.

The first questionnaire focused on current maintenance methods used in the field, their experience with performing predictive maintenance, and any cost or energy related information that they could share regarding these methods. Preliminary interviews were completed with staff from within the hierarchy of the university's facility maintenance department.

A second questionnaire was developed for private industry companies, with an additional four interviews conducted. The purpose of this separate questionnaire was to understand industry best practices when performing PdM on building systems, implementation, and associated capital costs. Companies were chosen based on the PdM service they provide, falling into three categories: hardware, analytics, and holistic solutions. Although twelve companies were chosen, only six responded.

Table four and figures six and seven provide a visual breakdown of interviews, correspondence and site visits performed. Thirty-six total interviews and email correspondence were used to conduct this study. The average length of experience in their fields were 19.7 years, with a standard deviation of 10.7 years. A majority (58 percent) of the communications conducted were done through unstructured interviews.

Count of NAVFAC / NASA /	**Column Labels**				
Row Labels	**NASA**	**NAVFAC**	**Private Contractor**	**University of Washington**	**Grand Total**
Correspondence Only		3	2	1	6
Site Visit		1			1
Structured Interview		4	1	3	8
Unstructured Interview	1	14	6		21
Grand Total	**1**	**22**	**9**	**4**	**36**

Table 4 - Numbers by communication type conducted shown by organization/sector.

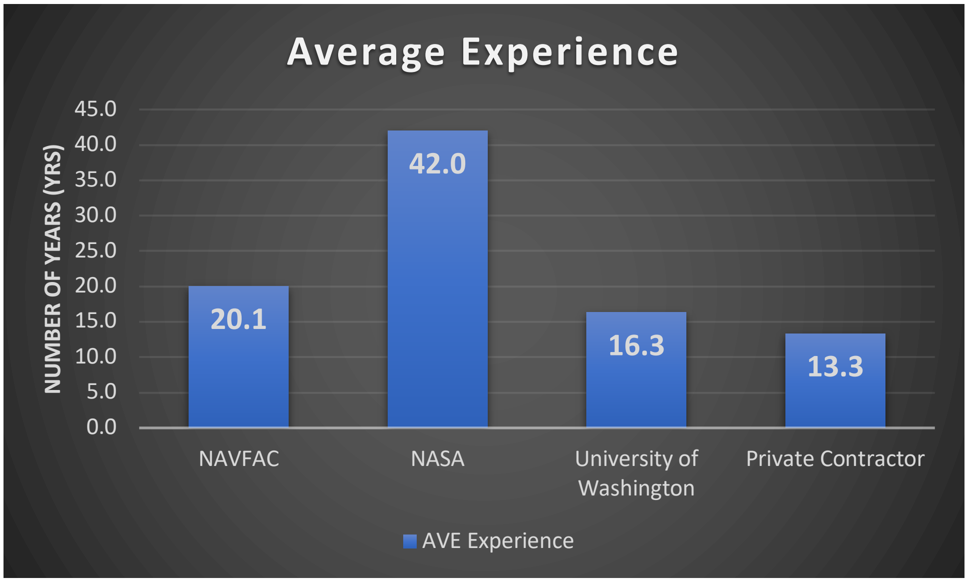


Figure 6 - Average number of years of experience by organization/sector.

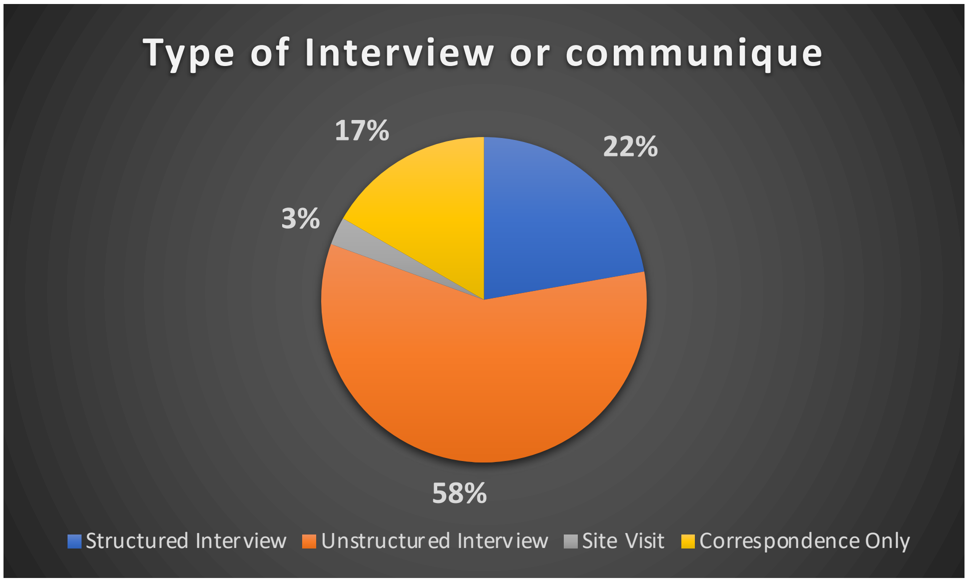


Figure 7 - Types of communication by percentage.

5.2.2. Questionnaire Development, Interviews and Correspondence – Navy

After initial research was conducted to determine the arguments for and against PdM and PM, the next phase was to conduct research on the Navy's existing maintenance program and the pilot program utilizing reliability-centered maintenance (RCM) at NAVFAC Hawaii. Since there was significant information and navy publications about the existing maintenance program, the focus of the Navy interviews was on the RCM pilot. The initial goal for the interviews was to determine how effective RCM was in Hawaii and whether this maintenance program could be replicated in other regions as it incorporated PM and PdM. After a few interviews and private discussions with various stakeholders and facility program managers, the findings led to the future of NAVFAC's maintenance program involving SG. These interviews also revealed that RCM was no longer being done to the extent recommended by the pilot program.

Interviews were then conducted to determine the current state of the Navy's maintenance program and the transition to SG in the following regions: Hawaii, Mid-Atlantic (Northeast), Southwest, Northwest, and Southeast. In addition to reviewing the transition to SG, a portion of the questioning was used to understand major gaps in this program. Understanding these gaps was important to ensure the Navy was getting full benefit of using PdM, which would affect the Navy's bottom line and meet the intent of improving efficiency, resiliency, and sustainability of their building systems.

Three official interviews were conducted that focused on the Hawaii RCM pilot program. An additional fourteen unstructured interviews were given with key stakeholders and program managers to comprehend the SG program and the current position of each region's maintenance program and their transition of integrating SG.

5.3. Qualitative Analysis and Findings

5.3.1. PdM and PM Findings

The University of Washington performs a mixture of time-based PM and condition-based maintenance under a time-based PM approach. Some of the methods used included electrical monitoring/electrical signal analysis, vibration analysis, thermography, and oil analysis (Roberge, 2020). The use of pressure and temperature sensors that are integrated with a direct digital control system provide for some constant oversight for determining faults or areas of failure, and are in line with the intent of a PdM model (Gaynor, 2020).

Time-based PM is used by both the Navy and the University of Washington maintenance groups because it is a simpler method for ensuring equipment does not run to failure, and because it does not require a large capital cost to initiate the maintenance program like a PdM program would. The time-based PM model does not apply a tailored-as-needed maintenance schedule created from regularly monitored, live data, nor does it apply asset redundancy into risk factors that would initiate maintenance like a PdM program could do.

A Lead Mechanical Technician at the University of Washington with thirty-two years of experience stated, “staffing levels and the experience of the technician decide how well a PM program operates” (Roberge, 2020). An energy engineer at the University of Washington with thirteen years of facility engineering experience, identified risks with both maintenance programs. There is a large risk to the quality of the data when a PM is missed and is not physically performed by a technician. In contrast, by having inline sensors actively gathering data and by not having a technician physically conducting maintenance, there is a potential risk of missing a causation to failure when it is not something that is being measured by a PdM technique, like corrosion (Gaynor, 2020). This supports the argument against having a solely PM program or solely PdM program. Faults that are not found due to missed PM’s, can lead to catastrophic failures. In contrast, with solely a PdM program that continuously monitors and measures data, equipment faults might be identified early, but may not prevent all failures due to the limitation of what sensors are being used to identify. Unless there are multiple sensors installed covering every type of failure, there is a need for a regular time-based PM technician inspection to catch possible faults that may not be measured by any sensor. These arguments and the significant initial capital costs for a PdM program support this mixed maintenance approach.

Understanding the scope and size in numbers of Navy buildings allows for an understanding of the impact that maintenance can have on the overall budget. A 2018 report by the GAO provided the overall quantity of facilities throughout the Department of Defense (DoD), as well as the Navy. It provided the Plant Replacement Value of all the DoD facilities on record, $880 billion, showing the financial investment that these buildings are for the Government and why maintaining these facilities are important (U.S. Government Accountability Office, 2018).

This financial investment and impacts can be seen by a pilot program conducted out of NAVFAC Hawaii. In a portion of the case study pilot program, HVAC asset failures were experiencing issues with recurring failures that were costly and often premature (Jacobs Engineering Group Inc., 2018). It was noted in the report that some of the item's NAVFAC needed to change were improved predictive maintenance procedures, information and documentation, and additional capabilities to their data management operating system. Based on these and other changes, which involved analysis of gathered data and risk decision-making, the report estimated that Navy HVAC maintenance costs could reduce by forty-nine percent annually (material costs and staff PM effort), with the initial capital costs equating to \$1.8 million, but saving more than \$8 million over a five-year span for NAVFAC Hawaii (Jacobs Engineering Group Inc., 2018).

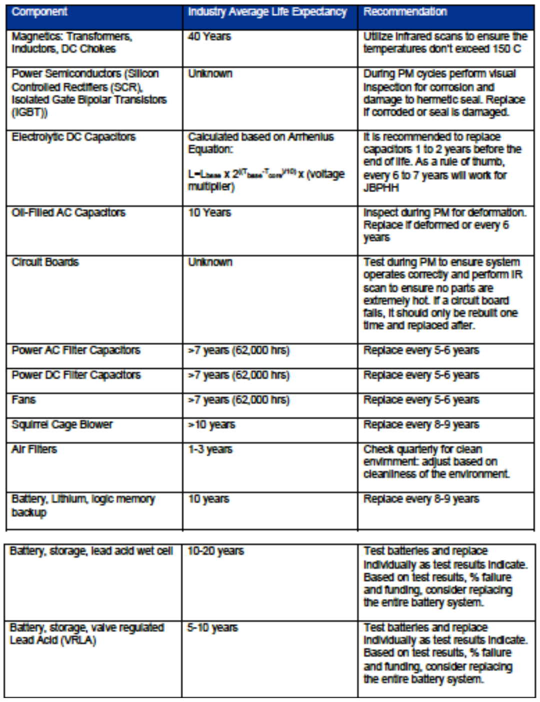
Industry interviews speak to implementation costs and general findings regarding what they are seeing and what sensor technology is more prevalent. Implementation is the largest impact to the cost of monitoring and performing predictive maintenance. From this perspective three major drivers are number of concurrent users, IoT data volume and throughput, and deployment option (on site server, cloud-based, managed service) (Ruland, 2021). Some companies charge by the number of sensors placed and the data that needs to be monitored. Costs range from \$25/point monitored each month to \$1200/point monitored each month, based on the company, type of sensor, and capability, like single axis vibration or triaxial and speed. One company charged a flat fee for each sensor and transmitter used and a flat fee per month based on the number of data streams used for throughput, an example being \$999/mo for two-hundred channels of throughput, where one triaxial sensor needs four channels. (Petasense, 2019). Another company had a flat rate for sensors from \$25-40/sensor-month, and that cost could change based on the quantity used (Ziegler, 2021).

The companies interviewed or corresponded with ranged from a focus on hardware and monitoring, machine health monitoring and asset management, and an oil analysis. Each company that had a response gave a different view to what PdM method was being used most in this industry. One company used a higher percentage of people-based route systems where contractors come in at regular intervals to assess equipment and get measurements at twelve measurements a year (Ziegler, 2021). An oil analysis company has seen no change in business when taking oil samples from companies, and stated that even though a variety of companies are transitioning to online monitoring, those companies still get analysis done by labs in order to make sure that everything is as good as it seems using the real time data (Barnidge, 2021).

A senior solutions architect for a hardware and analytics company summed up his thoughts when asked about industry and reliability monitoring:
"There is no one size fits all solution when it comes to asset reliability monitoring. We believe that it will come down to who is flexible enough to work with the other companies to get everything talking to a central command" (Bernhard, 2021).

RCM and the relation to PM and PdM

The 2018 NAVFAC Hawaii pilot program that tested the Reliability Centered Maintenance (RCM) Program's viability in improving asset reliability and resiliency from premature failures also recommended changes in what assets would best use a time-based PM approach versus a conditioned-based maintenance approach (Jacobs Engineering Group Inc., 2018). They recommended predictive testing and inspection for the conditioned-based maintenance approach, which is a more labor-intensive form from on-line live data monitoring/testing. Figure 8 is a prime example of the components of an Uninterruptable Power System (UPS) and the comparison between industry standard average life expectancy and recommendations for maintenance Jacobs Inc. proposes for the Navy, time-based maintenance (PM) or condition-based (PdM) maintenance.



Component	Industry Average Life Expectancy	Recommendation
Magnetics: Transformers, Inductors, DC Chokes	40 Years	Utilize infrared scans to ensure the temperatures don't exceed 150 C
Power Semiconductors (Silicon Controlled Rectifiers (SCR), Isolated Gate Bipolar Transistors (IGBT))	Unknown	During PM cycles perform visual inspection for corrosion and damage to hermetic seal. Replace if corroded or seal is damaged.
Electrolytic DC Capacitors	Calculated based on Arrhenius Equation: $L=L_{base} \times 2^{(T_{base}-T_{core})/10} \times$ (voltage multiplier)	It is recommended to replace capacitors 1 to 2 years before the end of life. As a rule of thumb, every 6 to 7 years will work for JBPHH
Oil-Filled AC Capacitors	10 Years	Inspect during PM for deformation. Replace if deformed or every 6 years
Circuit Boards	Unknown	Test during PM to ensure system operates correctly and perform IR scan to ensure no parts are extremely hot. If a circuit board fails, it should only be rebuilt one time and replaced after.
Power AC Filter Capacitors	>7 years (62,000 hrs)	Replace every 5-6 years
Power DC Filter Capacitors	>7 years (62,000 hrs)	Replace every 5-6 years
Fans	>7 years (62,000 hrs)	Replace every 5-6 years
Squirrel Cage Blower	>10 years	Replace every 8-9 years
Air Filters	1-3 years	Check quarterly for clean envirnment: adjust based on cleanliness of the environment.
Battery, Lithium, logic memory backup	10 years	Replace every 8-9 years
Battery, storage, lead acid wet cell	10-20 years	Test batteries and replace individually as test results indicate. Based on test results, % failure and funding, consider replacing the entire battery system.
Battery, storage, valve regulated Lead Acid (VRLA)	5-10 years	Test batteries and replace individually as test results indicate. Based on test results, % failure and funding, consider replacing the entire battery system.

Figure 8 - Table of Uninterruptable Power System comparison, industry average life expectancy of parts versus recommended maintenance action/or replacement, based on the Jacobs study (Jacobs Engineering Group Inc., 2018).

This RCM approach to maintenance encompasses a combination of time-based preventive maintenance, conditioned-based and predictive maintenance methods when managing building systems to minimize the probability of failures. Yet it also includes options for maintenance tasks that support failure of equipment based on economic decision making and, in this model, is known as reactive maintenance or run-to-failure (Gulati, 2021). This RCM approach is best visualized in Figure eight, NASA's RCM flow chart, which shows where time-based PM and conditioned-based PdM maintenance approaches are used.

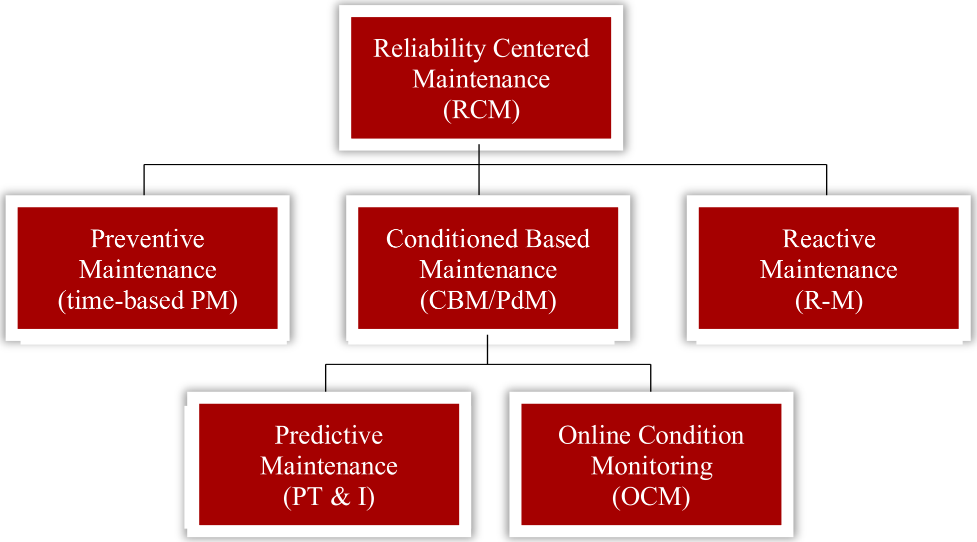


Figure 9 - NASA Reliability Centered Maintenance approach flow diagram (National Aeronautics and Space Administration, 2021).

The purpose in showcasing RCM in this report is to show that both time-based PM and conditioned-based PdM are fundamental to an RCM approach and work together functionally. RCM can optimize an existing maintenance program that may only utilize PM. A principle of an RCM program also recognizes that not all the equipment in a facility is of equal importance or priority in the overall maintenance program. The maintenance task chosen will be the most optimal and effective strategy for the performance of the organization by preventing or mitigating asset failure, detecting the onset of failure, or discovering a hidden failure (Gulati, 2021). The U.S. Department of Energy provides their maintenance task breakdown by percentage of top-performing facilities in their Operations and Maintenance Best Practices report, see Figure nine (G.P. Sullivan, 2010). Even with this recommendation it is important to note that RCM is not a one-time event, it is a living maintenance program that continually improves. In this program the maintenance team is constantly evaluating, validating and making adjustments where needed (Gulati, 2021). These percentages are not set in stone and each maintenance program may be vastly different in their approach based on their budget and their priorities when determining asset criticality. In an interview with the Assistant Branch Head of NASA Langley Research Center’s Maintenance Operation Branch, with forty-two years of maintenance experience, echoed the same conclusion when asked what percentage of his assets would be ideal to monitor when using a PdM approach. “Once we redefine asset criticality…I can give you a better answer…But it all depends on asset criticality and the costs” (Moncayo, 2021).

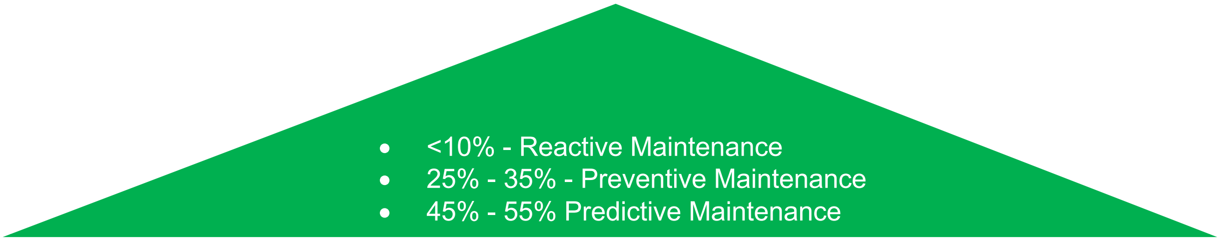


Figure 10 - Department of Energy's Reliability Centered Maintenance (RCM) breakdowns of continually top performing facilities (G.P. Sullivan, 2010).

5.3.2. <u>Navy's Existing Maintenance Program</u>

The Navy utilizes a time-based Preventive Maintenance Program (PMP) approach in conjunction with a subjective Conditioned-Based Maintenance (CBM) program to develop a targeted maintenance investment strategy based on risk for navy facility assets. The condition assessments are periodic evaluations by in-house staff or hired contractors and are documented in the Navy's computer maintenance management system (CMMS), IBM's Maximo. For this research topic, we will only focus on dynamic assets, also known as assets that have preventive maintenance associated with them. Although PMs vary by type of equipment, annual condition assessments are completed annually. The CBM asset analysis done by Maximo, using input from technicians and facility management teams, develops degradation models to calculate future requirements and costs. (Naval Facilities Engineering Systems Command, 2016)

The PM program uses five key elements in managing maintenance: continuous inspections, work input control, planning and estimating, shop scheduling and management reporting. In the performance of time-based PM's, workers are tasked with performing continuous inspections allowing them to determine deficiencies in equipment, systems and infrastructure. This provides the Navy with their earliest method in detecting asset deficiencies and faults prior to a catastrophic failure. (Naval Facilities Command, 2008) These "eyes-on" evaluation determinations are based on their sensory abilities, experience, technical knowledge, and any historical asset data available.

As research was being conducted on NAVFAC's current maintenance programs and their capabilities for using predictive maintenance measures, two course corrections occurred that lead to the current structure and state of this research. The first was a conversation that led to a reliability centered maintenance pilot program that was conducted from 2015-2018 at NAVFAC Hawaii. After reviewing that report and interviewing the Business Line Director for NAVFAC Hawaii and the Energy Program Manager, they identified what would be the second turn in this research, the SG system being implemented by NAVFAC HQ. The system provides a variety of uses which include providing better security, reliability, and resiliency of our naval infrastructure and facility and utility assets. It also improves efficiency of the utility and building energy systems through operation management and improvements in maintenance using conditioned-based PdM techniques and advanced analytics.

5.3.3. Transition to Smart Grid

The mission of Smart Grid's use in the Navy is "to aggregate, integrate and analyze data from the Navy's inventory of smart meters and building/utility energy Control Systems (CS) to produce actionable information regarding system operations and energy consumption in the Common Operating Picture (COP)." The Navy is transitioning to Smart Grid (SG) in order to improve the security, reliability, resiliency, and efficiency of their utilities and building energy systems (Naval Facilities Engineering Systems Command, 2019). The basic concept of SG is that it is an interconnected system consisting of controls, computers, automation, and new IoT technology and equipment including sensors and testing devices, allowing two-way communication between the utility/facility and the users/customers. These interconnected systems work in tandem with users and operators, making them "smart" and allowing for more control and the ability to react to any rapidly changing environment or situation (SmartGrid.gov, 2021). Figure ten provides a visual of how the information will flow from existing systems through the SG infrastructure through to the business systems that users and operators use.

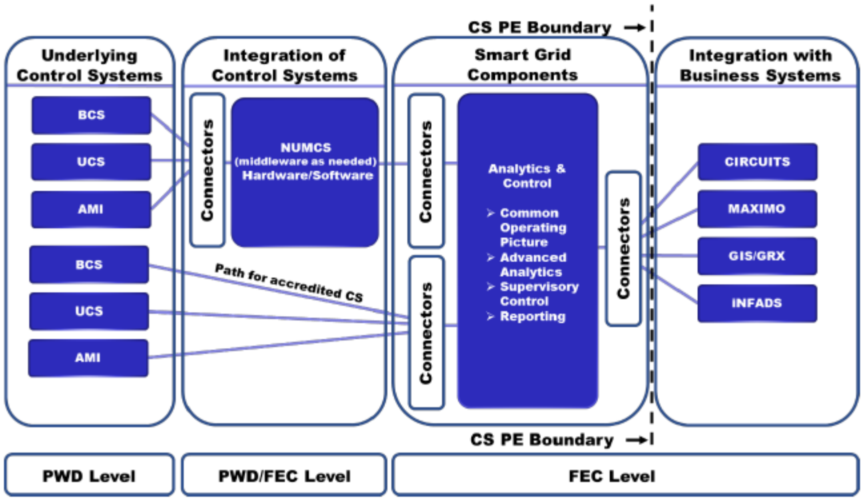


Figure 11 - The Navy Smart Grid information flow diagram. (Naval Facilities Engineering Systems Command, 2019)

As you can see in the figure above, the existing BCS, utility control systems (UCS), and advanced metering infrastructure (AMI) will be used to connect facility and utility equipment through OSI Pi, a data management platform for industrial operations. OSI Pi will collect, store, contextualize, and provide visualizations on various trends of the data. It will then integrate and share that data with the various business systems (CIRCUITS, MAXIMO, GIS/GRX, & iNFADS) or third-party advanced analytics systems which will include artificial intelligence (AI), machine learning (ML), and digital twin modeling (OSI Soft, 2021). Information that flows between the control systems to the OSI Pi server make up the regional level SG. Third party analytics are used due to limited capabilities of analysis by the Pi system. The SG is controlled within a regional Control System Platform Enclave (CSPE) which is the NAVFAC's cyber secure private cloud that provides security and resiliency to facility-related control systems (FRCS) (Naval Facilities Engineering Systems Command, unk.).

The final piece to the Navy's smart grid program is the SG Installation Workstations (SGIWS) and the Facility Energy Operations Centers (FEOCs), which are, respectively, the local and regional control centers that connect workers, assets, processes, data and decision-making capabilities. These control centers provide a common operating picture of all FRCSs but also enhance energy management and efficiency through live data monitoring and analytics. The live data and analytics can provide better-quality maintenance programs which can improve the reliability of our building and utility systems, reducing overall costs. (Naval Facilities Engineering Systems Command, 2019) Figure eleven provides a visual of how the system integrates data from BCS, UCS, AMI, and other external data sources to not only create a common operating picture but provide predictive analytics that can inform maintenance and facility teams through existing enterprise systems.

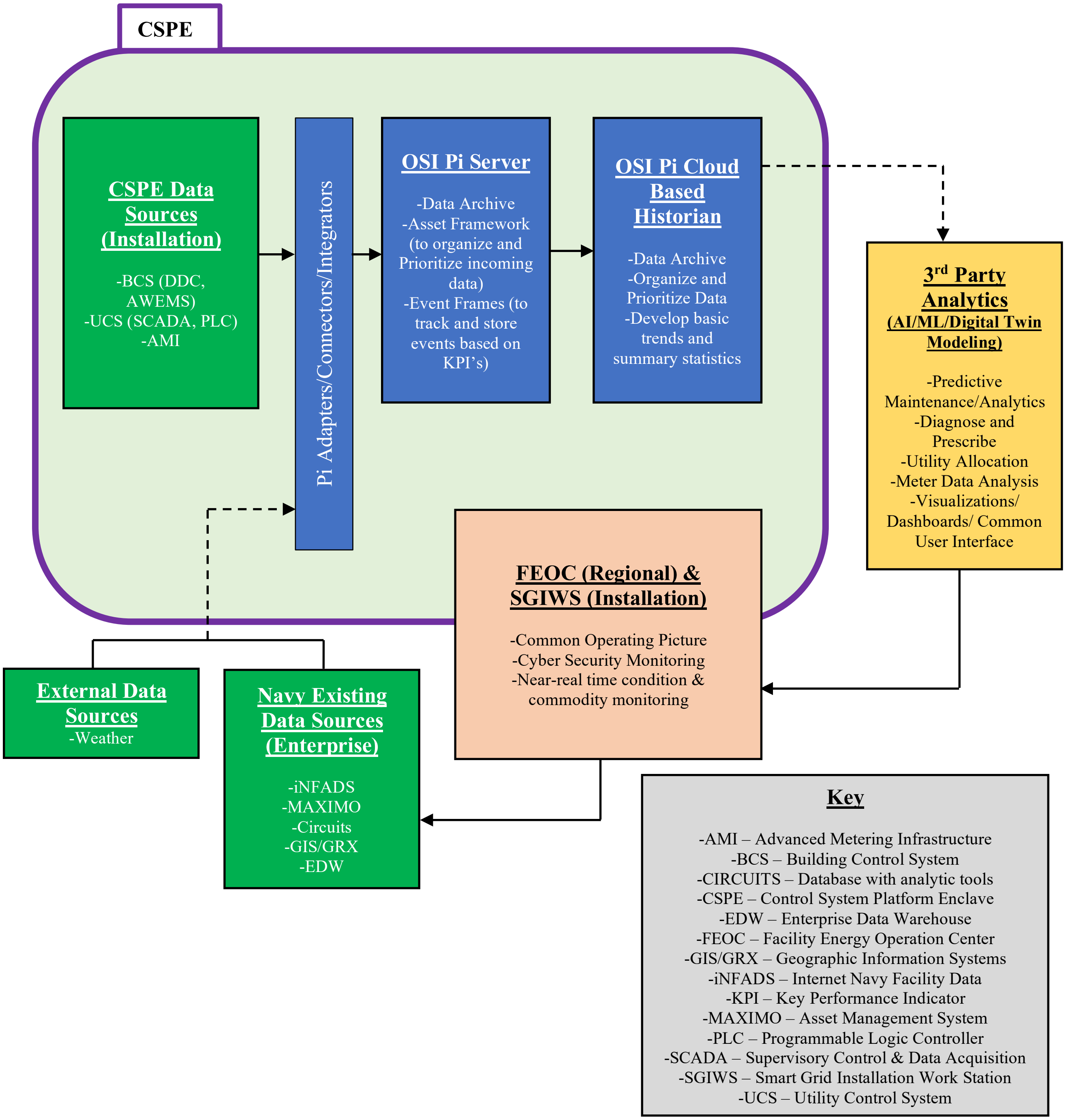


Figure 12 - Navy Smart Grid with OSI Pi and 3rd Party Analytics (Naval Facilities Engineering Systems Command, 2019) (Naval Facilities Engineering Systems Command, unk.) (Naval Facilities Engineering Systems Command, 2021) (OSI Soft, 2021).

The data being provided by BCS, UCS, and AMI sensors are part of the conditioned-based PdM approach. When used with the advanced analytics mentioned earlier, operations and maintenance can be optimized, increasing efficiency, lowering costs, and providing comprehensive energy/demand management. The analytics can draw conclusions, proactively correct issues, and notify stakeholders or maintenance personnel when maintenance is needed, as opposed to using a time-based PM approach (Naval Facilities Engineering Systems Command, 2019).

The Navy has not fully implemented this transition but has started deployment at three of the nine regions it operates in. Initial deployment for CSPE by region will start with integration of data for at least two installations, ten buildings with functioning CSs, and two UCS and AMI. The Navy is currently awarding a research and development contract at one base as a pilot program to resolve some key problems facing SG. A portion of the contract will be used to develop a conditioned-based PdM approach to their existing PM program. The goals of the PdM portion of the contract will be to: one, use existing facility related control systems, advanced analytics, and asset data to perform conditioned-based predictive maintenance to identify maintenance issues, two, develop a prioritization of maintenance activities based on level of importance, and three, integrate that data with the Navy's MAXIMO asset management system (Naval Facilities Engineering Systems Command, 2021). The integration with MAXIMO will allow a service request to be automatically created based on the PdM identification of the point where failure starts to occur, which would eliminate the need for on-site analysts at the FEOC to physically initiate the request for work.

While the new R&D contract is being awarded to perform a pilot test, the transition to SG for the Navy is ongoing in the various regions around the continental United States (CONUS). The information below provided by various interviews and email correspondence expand on where each region is toward implementing SG and having active PdM capabilities on their bases.

Mid-Atlantic (Northeast) Region – This region is in the early stages of the transition and has a FEOC. They have a small percentage of building control systems and utility control systems on the smart grid. The region is actively working to get more BCS and UCS systems online. The region is also working to consolidate building management systems (BMS) to reduce the variations. The largest hurdle for the region is funding to upgrade and consolidate aged BMS so that they are in compliance with cyber security and can be integrated into SG (Smitter, 2021).

Southeast Region – This area is in the beginning stages of smart grid with investments needed to apply resources to the most critical missions (West, 2021).

Northwest Region – Currently SG is not currently established in the NW, but the existing schedule shows April 2022 for completion of installation and verification testing. The vast majority of the utility control systems are not remotely controllable. The existing building control network is made of five-hundred fifty interconnected buildings (seventy-five percent of the buildings) communicating through a Niagara framework on the necessary cyber secure infrastructure or control system platform enclave (CSPE). The Niagara system functions similarly to OSI Pi. Skyspark is currently used for analytics but it has been removed from SG. Currently work orders are submitted manually with information provided by technicians and the systems currently in place, like Skyspark. The current plan is to connect ten buildings and existing smart meters to SG (Hickle, 2021).

Southwest Region – Some portions of the SG system are operational. The regional FEOC was stood up and staffed in October of 2021. Two systems are currently operating on the CSPE, the AMI system is on all 10 installations in southwest and the Area-Wide Energy Management System (AWEMS) which is the BCS system for only the installations in the San Diego metro area. Smart Grid S3 software is not currently operational as it needs Navy cyber security authorization to operate. The biggest advancement in the SG transition so far has been adding dedicated FEOC SG and BCS analysts to monitor, observe, tune-up, recommission, identify issues, etc. In addition, the FEOC staff will be able to work with technicians in the field to correct identified issues. Currently the region is auditing the asset inventory, getting controllers back on line, fixing downed equipment, adjusting equipment schedules, fixing programming errors, and correcting or creating graphics and user interfaces (Hoffmann, 2021).

Hawaii Pacific Region – Current UCS, BCS, and AMI systems are disparate and disconnected from each other and SG. They have established a CSPE for the region and currently have fourteen BCS connected, another eight projects where BCS are already incorporated, and projects awarded or being awarded. There are nineteen buildings with BCS in the military construction project (MILCON) P-178, with hopes of the project being awarded in fiscal year (FY) 2021-22. The goal for the region is to connect a total of seventy-six buildings through FY23. Smart grid is currently awaiting Navy cyber security authorization to operate and once approved upgraded software will be installed and the system can then be used.

5.3.4. Gaps in Transition to Smart Grid

The transition to SG is a large undertaking with not only infrastructure challenges, but the ability to communicate and control new and aging technology on the same system. Those challenges must be overcome to accomplish the same goals of ensuring the reliability, efficiency, resilience and sustainability of facility and utility equipment. OSI Pi offers the solution to communicating across various pieces of equipment and funneling that data to Pi servers and the cloud-based historian in preparation for analytics. The research and development pilot program, which is currently in the review and award process, plans to solve other communication, data management, and analytics problems that are needed for an effective SG and initial PdM program. As for initial installation implementation, only two installations are planned for at each region with a SG Installation Stations only being installed at one of them, which is concerning if immediate local control is a concern to mission functions and changing environments.

When interviewing or corresponding with key NAVFAC stakeholders in the various regions, other concerns or gaps were identified and can be summarized into six key issues.

- Asset Management Data – Due to the sheer amount of existing assets throughout Naval facilities and the various avenues used to install or replace equipment, asset management inventory and data within existing authoritative databases like iNFADS and MAXIMO is either lacking or non-existent. Although the Navy is working to validate this information on all assets at various levels within the organization, it is a long and tedious process (Hoffmann, 2021). The first step moving toward PdM and having an effective maintenance program will require this updated and accurate information.
- Connection to a CS – Some regions identified that some key infrastructure and equipment are not connected to any type of BCS or UCS (Petow, 2021). For other equipment and infrastructure that are connected to a CS, they may not be able to be connected to the CSPE and into SG due to either age, location or lack of cyber security authority needed to operate within the CSPE (Hoffmann, 2021). Other systems that are connected have difficulty with having a redundant hardwired fiber optic line, which is necessary for resiliency of network oversight and control (Gagner, 2021). This information was echoed by two other stakeholders.
- Sensors for effective PdM – The existing sensors associated with the various control systems may not be enough for a truly effective PdM program (Smitter, 2021). However, analyzing existing data might allow NAVFAC to fall between being prescriptive and indicative of faults or issues (Crittenden, 2021). One additional stakeholder agreed that existing sensors from CS will not provide a truly PdM program.
- Existing Labor shortfalls – For any program that does utilize PdM, installations may not have the labor resources with sufficient numbers or core competencies to execute effectively (Gagner, 2021).
- Reliability Concerns – There are concerns with CSs being affected by regular patches and upgrades that in the past affected critical mission operations, like loss of local control for key utilities (Gagner, 2021). Also, due to underfunding of facility maintenance over the last few decades, there are too many potential causes for failures rendering sensors unreliable. Control systems themselves are run to failure, and with the existing budget, installations are only able to fix a small portion of this compounding issue (Hickle, 2021).
- Regional central control leading to lack of local on-site control – SG centralization at a regional location may lead to poorly coordinated maintenance activities which leads to degraded system stability and performance (Gagner, 2021). Loss of local direct control of major facility systems may affect mission operations when those with direct control are miles away and may not be able to react to rapidly changing local environments and/or scenarios (LaVerdiere, 2021).
- High costs lead to lack of investment in infrastructure – Investing in infrastructure upgrades to existing systems are high and it has been difficult to justify the expense (Hickle, 2021).

6. Sustainability Discussion

As the world moves toward becoming more sustainable and reducing greenhouse gas (GHG) emissions, the concept of environmental stewardship and how we choose to mitigate those effects in all aspects of our business becomes more important. In January 2021, the President of the United States emphasized this importance when he formally requested that the United States (U.S.) rejoin the Paris Climate Agreement, a commitment of one-hundred ninety-seven world leaders. On the same day he issued an Executive Order on Restoring Science to Tackle the Climate Crisis by "promoting and protecting our public health and the environment… In carrying out this charge, the Federal Government must be guided by the best science and be protected by the processes that ensure the integrity of Federal decision making" (Joseph R. Biden, 2021).

In order to be sustainable and reduce our impact on the environment we need to reduce our electrical generation/usage which directly correlates with the GHG produced. Figure twelve below illustrates the GHG emissions by economic sector. Energy generation and commercial/residential consumption produces thirty-eight percent of GHG in the U.S. Improvements in equipment maintenance can help reduce power consumption by ensuring that all our assets take advantage of the best science and not only improve efficiency but preserve efficiency throughout their operational life.

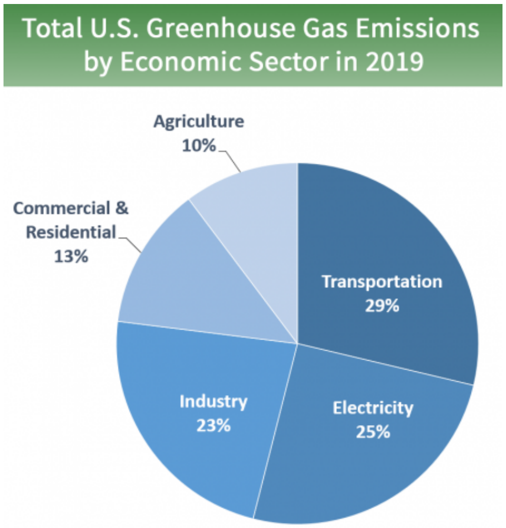


Figure 13 - EPA Total U.S. Greenhouse Gas Emissions by Economic Sector (U.S. Environmental Protection Agency, 2019).

Online PdM techniques like thermography, oil analysis and vibration fault corrections allow for early prevention of equipment failure and degradation due to inefficiencies, without interruption to operations. This identification of inefficiency not only benefits the environment, but provides a cost savings from reduced unscheduled downtime, improved utilization of manpower, increased production capacity of the plant, reduced maintenance expenditures, and increased life of the asset. (A.S. Nazmul Huda, 2013) In a case study that utilized both thermography and vibration analysis in a boiler room, they identified and corrected steam leaks using thermography which led to a fifty-two percent energy savings by consuming less gas and reducing water consumption. For corrections identified by vibrational faults, the largest cost savings was made by circulation pumps, where a ninety-seven percent electrical savings occurred. Both methods of PdM were used to identify steam/water leakage, steam trap failures, pipe insulation failure, valves, flanges, vessels, and electro-motor faults. Annually, overall maintenance costs were reduced causing a thirty percent cost savings. This case study reviewed factors of sustainability using four criteria: environmental, social, economic, and technical. Finalizing these findings determined that performing corrective maintenance using PdM methods leads to at least a twenty-eight percent improvement on sustainability performance. (Masoud Behzad, 2019)

A majority of building power is used by HVAC equipment operation, approximately forty-nine percent. (US Energy Information Administration, 2018) Taking that information into account and using the information from the boiler room case study, improvements made from transitioning from a traditional PM program to one that utilizes PdM methods, data gathering and analysis for scheduling the proper maintenance on major portions of HVAC system should improve the sustainability of any building. Using PdM sensors and data management maintenance software which is able to periodically or continuously monitor and analyze sensor readings would enable all buildings to perform continuous commissioning protocols thereby optimizing efficiency and performance, and reducing energy costs.

7. Results and Discussion

Over this last year there have been increasing numbers of extreme weather events that have strained our electrical grid and affected our ability to function. As temperatures continue to soar around the world many countries including the US have increased their commitments to active changes in combating climate change which include helping to strengthen climate resilience. (Dewan, 2021) Leveraging advancing and newer technology will help ensure facilities and utilities maintain their function, efficiency, and resilience.

Predictive maintenance measures have been shown to improve and maintain efficiency with their online sensors and their AI/ML predictive analytics. The ability to remotely track systems and infrastructure either within a building or throughout a local area allows organizations to focus their limited labor resources to critical areas. This type of maintenance also provides a safer way of performing maintenance by reducing the need for unnecessary dangerous inspections and catching failures as they start to occur. Even though active sensor monitoring and advanced analytics can predict and diagnose faults there are limitations to determining root causes. This issue may be alleviated as advanced analytics and sensor technologies mature. As an example, inline oil sensor technology cannot be replicated for elemental analysis. Samples will still need to be sent to a lab for analysis. Despite this type of issue, existing sensors like those for inline oil systems should be used at a minimum as warning systems for near term failure.

As more advanced systems come on the market like wireless sensors that no longer need batteries or as more renewable power and storage systems get integrated with existing facilities and power grids, it is important that our support systems can integrate and be cyber secure. Integrating existing smart infrastructure and control systems within a cyber secure smart grid is ideal in providing a way to see our equipment, identify changing conditions with live data, and react accordingly to those conditions by changing equipment operation or energy use.

For any variation of a PdM program to be implemented will depend on the type of maintenance program being run. There are two major scenarios I will provide some insight on. Scenario one are those companies that have in-house technicians that can execute maintenance and repairs. Scenario two are those companies that contract their maintenance out to another company.

For either scenario the first thing needed is to validate the existing assets, and identify and prioritize critical assets. In scenario one, it may be too costly depending on the company's fiscal constraints to fully transition to a full PdM model and a phased approach may be more appropriate. Earlier it was noted that a better approach would be to have a program that uses both PM and PdM to counter the effects of the extreme costs of sensors and infrastructure. Should a mixed model be chosen, the company should then decide how maintenance should be performed on each asset by performing a Reliability Center Maintenance analysis (ie. breakdown maintenance, time-based PM, conditioned-based PdM, or a combination) which should be based on criticality and risk to mission/operations. There are a variety of books on this subject some of which have been referenced but the important thing to note is that knowing function of the assets and prioritizing your assets is critical. Then deciding based on that information and the company's budget how it should be accomplished, and whether a phased approach or one large capital expenditure is more beneficial.

In scenario two, where maintenance is contracted out, it is important to note that companies that are only hired for a year or even a few years may have little incentive to invest in predictive measures. Additionally, they may want to reduce risk and maintain a PM structure for a fixed price short term contract. They would not invest time and initial capital costs to install infrastructure, sensors, procure advanced data analytics software, or train personnel.

NASA's Langley Research Center found success when they awarded a Cost-Plus-Award-Fee (CPAF) maintenance contract with an Indefinite Delivery Indefinite Quantity (IDIQ) element to the contract. Within the IDIQ portion of the contract are Firm-Fixed Price (FFP) and CPAF components and due to the complexity and justification for cost savings the contract was awarded a ten-year period versus the normal five-year (McNally, 2012). Key justification highlights include:

- CPAF contract allows for flexibility in dynamic environments, future budget uncertainties, and changing priorities.

- CPAF subjective metrics allow for effective motivation for a contractor to perform exceptionally while addressing key performance standards required to meet any mission or operation objectives.
- CPAF allows changes to contractor level of effort based on changing budgets and priorities, which are not easily carried out in a FFP contract. FFP could require change orders and requests for equitable adjustments adding significant complexity and cost in contract administration. FFP also carries larger risk to the contractor and higher overall costs to the Owner in contract award.
- Award Fee allows for changing conditions like changes to critical missions or extreme weather, without sacrificing performance or cost. It gives the ability of the Owner to make unilateral changes in evaluation criteria in order to refocus Contractor performance based on changing conditions and priorities.
- An award fee considers the Contractor’s efforts to meet schedule and cost constraints to meet objectives or overcome obstacles. It incentivizes technical and schedule performance while effectively managing costs.
- The use of the ten-year period of performance ensures the continuity of knowledge and skills for the contractor as well as incentive to hire, invest and plan long term.
- The longer period of performance supports region and installation long term plans and goals, and maximizes incentive for the Contractor to invest in critical equipment, leverage innovative maintenance and data management techniques, and perform above expectations.
- Longer period of performance allows for process improvements and capital investments which in turn allows Contractors to amortize their investments over a longer period and still be innovative in times of declining budgets.
- Increased time also allows for better contract performance through a more integrated team member, which allows for a stronger sense of mission accomplishment and ownership for overall successes.
- These longer periods allow for workforce stability, which improves on the Contractor’s performance to attract, hire, train, develop, and retain competitive and competent employees with critical skills.
- Trend Analysis over a longer period provides better data and decision-making.
- Improved competitive bidding, which can attract the most capable and experienced companies. These contracts can foster local industry partnerships with a variety of vendors, which improves competition for subcontractors and suppliers.
- Although the period of performance is longer, the Owner has the right and ability not to exercise the option years providing a low-risk capability for the owner.

Both scenarios are viable and a transition toward a maintenance approach that leverages existing and advanced technology is inevitable if organizations want to reduce overall costs and increase the longevity of their critical building and utility systems.

Some of the existing challenges being faced by the Navy should be discussed as they are actively transitioning to smart grid. It was found that one concern of a regional control center was the loss of local control and possible catastrophic operational failures by operators sometimes hundreds of miles away. A solution to that is hierarchical control, starting with the local installation at their SGIWS. The region would have oversight but not control. This control to the region would be given from the local installation only during agreed upon scenarios (ie. a workstation is down for maintenance or the workstation cannot be manned), and an override capability should be onsite at the equipment location as a safety measure. In addition, the current transition plan should add SG Installation Workstations at every base to allow overall responsibility and control locally which would provide a benefit should a quick response or action need to be taken.

When transitioning to a heavy remote sensor technology maintenance program there are existing risks which can be mitigated based on how maintenance budget is determined and takes those risks into account. As one Program Manager stated, “Current NAVFAC control systems are run to failure” based on underfunding of the entire maintenance program. (Hickle, 2021) Ensuring we are providing adequate maintenance dollars to the systems that are monitoring our equipment is vital to ensuring these technologies continue to work for the Navy or any organization, as they age and encounter the varying environments of the locations they are installed.

8. Conclusion

It is evident that PdM methods are superior to a time-based PM model for diagnosing equipment faults/failures and keeping equipment in operation. By detecting deterioration earlier this gives technicians more time to procure the right parts, schedule, and repair the asset before it becomes an unscheduled catastrophic event. (Levitt, 2011) With today’s data analytic tools, asset failure forecasts and prognosis can provide more fidelity to the maintenance program.

Though multiple case studies support PdM, the following reports by Department of Energy, Jacobs DON, and Department of Commerce identify the bottom-line concern, which is high initial capital investments from sensing equipment and infrastructure costs. Infrastructure costs include web-based systems that connect sensors/data sources and integrative data analytic systems. These systems ingest the multiple data sources, change the information into a common language that can be stored and analyzed, and then present the information through dashboards, reports and notifications that technicians and stakeholders can easily understand and use to make decisions.

Due to these high initial costs, time-based PM will and should be used. As in RCM, PM should be used in conjunction with PdM and should be based on those items mentioned earlier, which is priority/criticality and budget. Despite any initial startup costs, the increase in asset reliability and decrease in equipment downtime affecting operations can be seen through cost avoidance, reduced labor hours, increased availability and reduced trouble calls. An example of this data can be seen through NASA’s Langley Research Center (LaRC), which first started implementing predictive testing and inspection in 2000. From 2014 to 2020, they have seen a cost avoidance of $5.8 million from catastrophic equipment failure, increased availability of equipment, avoiding 1,403 unplanned failures, and reducing trouble calls by fifty percent. (NASA - National Aeronautics and Space Administration, 2021)

To conclude, there is no right answer to what percentage of maintenance types are right for an organization. The decision relies on what is deemed critical to the installation owner and/or the facility/utility management team and what the cost limitations are for the organization.

9. Appendix

A. Reference Review Summary Table
B. Data
C. Questionnaires Developed

**NOTE: All other supporting data, interview notes, transcripts, emails, articles, and reports are available upon request.

References

A.S. Nazmul Huda, S. T. (2013). Application of infrared thermography for predictive/preventive maintenance of thermal defect in electrical equipment. *Applied Thermal Engineering*, 220-227.

A.S.B. Tam, W. C. (2006). Optimal Maintenance Intervals for a multi-component system. *Production Planning and Control Vol. 17, No. 8*, 769-779.

Armstrong, M. M. (2020, December 4). *Cheat sheet: What is a Digital Twin?* Retrieved from IBM: https://www.ibm.com/blogs/internet-of-things/iot-cheat-sheet-digital-twin/

Barnes, M. P.-C. (2020, Feb 12). *Real-Time Oil Analysis Has Arrived.* Retrieved from Efficient Plant: https://www.efficientplantmag.com/2020/02/real-time-oil-analysis-has-arrived/

Barnidge, K. (2021, Jun 24). Area Sales Manager - Reliable Industrial Group (RIG). (N. Plumey, Interviewer)

Bernhard, M. (2021, Jun 23). Senior Solutions Architect - Nikola Labs. *Email Correspondence - Predictive Maintenance Discussion*.

Carnero, M. (2005). Selection of diagnostic techniques and instrumentation in a predictive maintenance program. A case study. *Decision Support Systems*, 539-555.

Commander Navy Installations Command. (2020). *Unclassified - FY20 Targeted Facilities Investment Strategy Execution End of Year Report - Unclassified.* US NAVY.

Crittenden, J. (2021, May 7). Conditioned Based Maintenance Program Ashore Program Manager. *Email Correspondence - Questions Regarding PdM and NAVFAC*. Washington DC.

Dewan, A. (2021, July 4). *Unprecedented heat, hundreds dead and a town destroyed. Climate change is frying the Northern Hemisphere*. Retrieved from CNN: https://www.cnn.com/2021/07/04/world/canada-us-heatwave-northern-hemisphere-climate-change-cmd-intl/index.html

G.P. Sullivan, R. P. (2010). *Operations and Maintenance Best Practices - A guide to achieving operational efficiency.* unk.: U.S. Department of Energy, Energy Efficiency & Renewable Energy.

Gagner, R. (2021, June). Deputy Public Works Officer. *Smart Grid Transition Question - PWD MAINE*. Kittery, ME.

Gaynor, R. (2020, November 17). Energy Engineer in Resource Conservation. (N. Plumey, Interviewer)

Gulati, R. (2021). *Maintenance and Reliability Best Practices.* South Norwalk: Industrial Press, Inc.

Hickle, C. (2021, June). Regional Energy Program Manager. *Smart Grid Transition Questions*. WA.

Hoffmann, P. (2021, June). ICS/Smart Grid Team Lead. *Smart Grid Transition Question*. San Diego, CA.

Jacobs Engineering Group Inc. (2018). *NAVFAC Hawaii Asset Optimization / RCM Pilot Program Information.* Hawaii: unk.

John Carroll, R. G. (2020, December). University of Washington Facility Data. *None*. Seattle, WA.

Joseph R. Biden, J. (2021, Jan 20). *Executive Order on Protecting Public Health and the Environment and Restoring Science to Tackle the Climate Crisis*. Retrieved from The White House: https://www.whitehouse.gov/briefing-room/presidential-actions/2021/01/20/executive-order-protecting-public-health-and-environment-and-restoring-science-to-tackle-climate-crisis/

LaVerdiere, L. (2021, June 16). Production Division Director, Public Works Department Maine. (N. Plumey, Interviewer)

Levitt, J. (2011). *Preventive and Predictive Maintenance.* New York: Industrial Press Inc.

Loren Green, N. C. (2014). *How to select the right oil analysis.* Retrieved from Machinery Lubrication: https://www.machinerylubrication.com/Read/29890/oil-analysis-tests

Masoud Behzad, H. K. (2019). Improving sustainability performance of heating facilities in a central boiler room by condition based maintenance. *Journal of Cleanr Production*, 713-723.

McNally, W. (2012, August 21). NASA - Assistant Administrator for Procurement. *NASA - Authority to Utilize a Cost-Plus-Award-Fee Contract Type for the Center Maintenance, OPerations and Engineering Contract*. Washington, DC: NASA.

Mirza Kibria, K. N. (2018). Big Data Analytics, Machine Learning, and Artificial Intelligence in Next Generation Wireless Networks. *IEEE Access, Vol 6*, 32328 - 32338.

Moncayo, K. (2021, June 11). Assistant Branch Head, MOB NASA. (N. Plumey, Interviewer)

NASA - Allied Inspired Reliability Report to NASA 2013. (2013). *CBM Integration - Evaluation Report.* Hampton: Allied Inspired Reliability.

NASA - National Aeronautics and Space Administration. (2021). *Langley Research Center Maintenance Program Presentation Slides.* Langley: NASA.

NASA - National Aeronautics and Space Administration. (unk, unk unk). NASA Langley Research Center Maintenance Data Presentation Slides. *None*. Hampton, VA: NASA.

NASA Langley Research Center. (2021, June 25th). Email on In-Line Oil Analysis. Hampton, VA.

National Aeronautics and Space Administration. (2021, January). LaRC Maintenance Program (Brief) - January 2021. *NASA*. Hampton, VA, USA: NASA.

Naval Facilities Command. (2008). *Public Works Department Management Guide NAVFAC P-1205.* Washington Navy Yard: Naval Facilities Command.

Naval Facilities Command. (2016). *P-501 Condition Based Maintenance Management (CBMM) Manual.* Washington Navy Yard: Naval Facilities Command.

Naval Facilities Command. (2019). *P-803 Navy Smart Grid Concept of Operations (CONOPS).* Washington Navy Yard: Naval Facilities Command.

Naval Facilities Command. (unk.). *Why use the Control System Platform Enclave (CSPE)?* Washington Navy Yard: Naval Facilities Command.

NAVFAC. (2021). Advanced Analytics Tools for Facilities and Utilities Management Technical Info Attachment. Wahington Navy Yard, Washington DC: NAVFAC.

Navy & Marine Corps. (unk.). *Navy and Marine Corps Smart Grid Capability Development Document.* Washington Navy Yard: Navy & Marine Corps.

OSI Soft. (2021). *PI Core*. Retrieved from OSI Soft: https://www.osisoft.com/pi-system/pi-core

Perry, G. (unk.). *Successfully Navigating Condition-Based Maintenance Language.* Retrieved from Reliable Plant: https://www.reliableplant.com/Read/31852/cbm-language

Petasense. (2019). *Asset reliability that scales with your needs*. Retrieved from Petasense: https://petasense.com/products/pricing/

Petow, R. (2021, Jun 9). Utilities Manager, NAVFAC SE NAS Jacksonville. *Email Correspondence - Smart Grid Transition*. FL.

Plucknette, D. (2011, November 21). *Reliability Centered Maintenance using RCM Blitz.* Retrieved from Reliabilityweb.com: https://reliabilityweb.com/articles/entry/completing-the-curve

Roberge, J. (2020, November 18). Lead Technician at University of Washington. (N. Plumey, Interviewer)

Rosmaini Ahmad, S. K. (2012). An overview of time-based and condition-based maintenance. *Computers and Industrial Engineering*, 135-149.

Ruland, Z. (2021, Jun 28). Technical Specialist (Maximo APM and IoT technology). *Email Correspondence - Quick Question - Predictive Maintenance Discussion*.

Sadettin Orhan, N. A. (2006). Vibration monitoring for defect diagnosis of rolling element bearings as a predictive maintenance tool: Comprehensive case studies. *NDT&E International*, 293-298.

SmartGrid.gov. (2021). *The Smart Grid*. Retrieved from smartgrid.gov: https://www.smartgrid.gov/the_smart_grid/smart_grid.html

Smitter, J. L. (2021, June 15). Smart Grid Transition Questions - MIDLANT. VA.

Thomas, D. S. (2018). *The Costs and Benefits of Advanced Maintenance in Manufacturing.* unk: National Institute of Standards and Technology, Department of Commerce.

Trout, J. (unk.). *Reliable Plant - Types of Maintenance, a comparison*. Retrieved from Reliable Plant: https://www.reliableplant.com/types-of-maintenance-31812

U.S. Environmental Protection Agency. (2019). *Greenhouse Gas Emissions*. Retrieved from U.S. EPA: https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions

U.S. Government Accountability Office. (2018). *DoD Financial Management - The Navy Needs to improve internal control over its buildings.* Washington, DC: US GAO.

University of Washington Facilities Services. (2014). *Resource Conservation Program Audit Report: Mary Gates Hall.* Seattle: University of Washington.

University of Washington Facilities Services. (2014). *Resource Conservation Program Audit Report: William Gates Hall.* Seattle: University of Washington.

US Energy Information Administration. (2018, September 28). *EIA*. Retrieved from Use of Energy, Energy use in commercial buildings: https://www.eia.gov/energyexplained/use-of-energy/commercial-buildings-in-depth.php

US Navy. (2020, December). *FRES*. Retrieved from Facility Readiness Evaluation System: fres.cnic.navy.mil

Van Tung Tran, B.-S. Y. (2012). An intelligent condition-based maintenance platform for rotating machinery. *Expert Systems with Applications*, 2977-2988.

West, S. (2021, June). Smart Grid Transition Questions - South-East. FL.

Ziegler, Z. (2021, Jun 23). Demand Generation Representative. *Email Correspondence - Advanced Technology Services, Inc. Follow up*.

Appendix A: Reference Review Summary Table

Number	Reference
1	A.S. Nazmul Huda, S. T. (2013). Application of infrared thermography for predictive/preventive maintenance of thermal defect in electrical equipment. *Applied Thermal Engineering* , 220-227.
2	A.S.B. Tam, W. C. (2006). Optimal Maintenance Intervals for a multi-component system. *Production Planning and Control Vol. 17, No. 8* , 769-779.
3	Armstrong, M. M. (2020, December 4). *Cheat sheet: What is a Digital Twin?* Retrieved from IBM: https://www.ibm.com/blogs/internet-of-things/iot-cheat-sheet-digital-twin/
4	Barnes, M. P.-C. (2020, Feb 12). *Real-Time Oil Analysis Has Arrived.* Retrieved from Efficient Plant: https://www.efficientplantmag.com/2020/02/real-time-oil-analysis-has-arrived/
5	Barnidge, K. (2021, Jun 24). Area Sales Manager - Reliable Industrial Group (RIG). (N. Plumey, Interviewer)
6	Bernhard, M. (2021, Jun 23). Senior Solutions Architect - Nikola Labs. *Email Correspondence - Predictive Maintenance Discussion* .
7	Carnero, M. (2005). Selection of diagnostic techniques and instrumentation in a predictive maintenance program. A case study. *Decision Support Systems* , 539-555.
8	Commander Navy Installations Command. (2020). *Unclassified - FY20 Targeted Facilities Investment Strategy Execution End of Year Report - Unclassified.* US NAVY.
9	Crittenden, J. (2021, May 7). Conditioned Based Maintenance Program Ashore Program Manager. *Email Correspondence - Questions Regarding PdM and NAVFAC* . Washington DC.
10	Dewan, A. (2021, July 4). *Unprecedented heat, hundreds dead and a town destroyed. Climate change is frying the Northern Hemisphere* . Retrieved from CNN: https://www.cnn.com/2021/07/04/world/canada-us-heatwave-northern-hemisphere-climate-change-cmd-intl/index.html
11	G.P. Sullivan, R. P. (2010). *Operations and Maintenance Best Practices - A guide to achieving operational efficiency.* unk.: U.S. Department of Energy, Energy Efficiency & Renewable Energy.
12	Gagner, R. (2021, June). Deputy Public Works Officer. *Smart Grid Transition Question - PWD MAINE* . Kittery, ME.
13	Gaynor, R. (2020, November 17). Energy Engineer in Resource Conservation. (N. Plumey, Interviewer)
14	Gulati, R. (2021). *Maintenance and Reliability Best Practices.* South Norwalk: Industrial Press, Inc.
15	Hickle, C. (2021, June). Regional Energy Program Manager. *Smart Grid Transition Questions* . WA.
16	Hoffmann, P. (2021, June). ICS/Smart Grid Team Lead. *Smart Grid Transition Question* . San Diego, CA.
17	Jacobs Engineering Group Inc. (2018). *NAVFAC Hawaii Asset Optimization / RCM Pilot Program Information.* Hawaii: unk.
18	John Carroll, R. G. (2020, December). University of Washington Facility Data. *None* . Seattle, WA.
19	Joseph R. Biden, J. (2021, Jan 20). *Executive Order on Protecting Public Health and the Environment and Restoring Science to Tackle the Climate Crisis* . Retrieved from The White House: https://www.whitehouse.gov/briefing-room/presidential-actions/2021/01/20/executive-order-protecting-public-health-and-environment-and-restoring-science-to-tackle-climate-crisis/
20	LaVerdiere, L. (2021, June 16). Production Division Director, Public Works Department Maine. (N. Plumey, Interviewer)
21	Levitt, J. (2011). *Preventive and Predictive Maintenance.* New York: Industrial Press Inc.
22	Loren Green, N. C. (2014). *How to select the right oil analysis.* Retrieved from Machinery Lubrication: https://www.machinerylubrication.com/Read/29890/oil-analysis-tests
23	Masoud Behzad, H. K. (2019). Improving sustainability performance of heating facilities in a central boiler room by condition based maintenance. *Journal of Cleanr Production* , 713-723.
24	McNally, W. (2012, August 21). NASA - Assistant Administrator for Procurement. *NASA - Authority to Utilize a Cost-Plus-Award-Fee Contract Type for the Center Maintenance, OPerations and Engineering Contract* . Washington, DC: NASA.
25	Mirza Kibria, K. N. (2018). Big Data Analytics, Machine Learning, and Artificial Intelligence in Next Generation Wireless Networks. *IEEE Access, Vol 6* , 32328 - 32338.
26	Moncayo, K. (2021, June 11). Assistant Branch Head, MOB NASA. (N. Plumey, Interviewer)
27	NASA - Allied Inspired Reliability Report to NASA 2013. (2013). *CBM Integration - Evaluation Report.* Hampton: Allied Inspired Reliability.
28	NASA - National Aeronautics and Space Administration. (2021). *Langley Research Center Maintenance Program Presentation Slides.* Langley: NASA.
29	Naval Facilities Command. (2008). *Public Works Department Management Guide NAVFAC P-1205.* Washington Navy Yard: Naval Facilities Command.
30	Naval Facilities Command. (2016). *P-501 Condition Based Maintenance Management (CBMM) Manual.* Washington Navy Yard: Naval Facilities Command.
31	Naval Facilities Command. (2019). *P-803 Navy Smart Grid Concept of Operations (CONOPS).* Washington Navy Yard: Naval Facilities Command.
32	Naval Facilities Command. (unk.). *Why use the Control System Platform Enclave (CSPE)?* Washington Navy Yard: Naval Facilities Command.
33	NAVFAC. (2021). Advanced Analytics Tools for Facilities and Utilities Management Technical Info Attachment. Wahington Navy Yard, Washington DC: NAVFAC.
34	Navy & Marine Corps. (unk.). *Navy and Marine Corps Smart Grid Capability Development Document.* Washington Navy Yard: Navy & Marine Corps.
35	OSI Soft. (2021). *PI Core* . Retrieved from OSI Soft: https://www.osisoft.com/pi-system/pi-core
36	Perry, G. (unk.). *Successfully Navigating Condition-Based Maintenance Language.* Retrieved from Reliable Plant: https://www.reliableplant.com/Read/31852/cbm-language
37	Petasense. (2019). *Asset reliability that scales with your needs* . Retrieved from Petasense: https://petasense.com/products/pricing/
38	Petow, R. (2021, Jun 9). Utilities Manager, NAVFAC SE NAS Jacksonville. *Email Correspondence - Smart Grid Transition* . FL.
39	Plucknette, D. (2011, November 21). *Reliability Centered Maintenance using RCM Blitz.* Retrieved from Reliabilityweb.com: https://reliabilityweb.com/articles/entry/completing-the-curve
40	Roberge, J. (2020, November 18). Lead Technician at University of Washington. (N. Plumey, Interviewer)
41	Rosmaini Ahmad, S. K. (2012). An overview of time-based and condition-based maintenance. *Computers and Industrial Engineering* , 135-149.
42	Ruland, Z. (2021, Jun 28). Technical Specialist (Maximo APM and IoT technology). *Email Correspondence - Quick Question - Predictive Maintenance Discussion* .
43	Sadettin Orhan, N. A. (2006). Vibration monitoring for defect diagnosis of rolling element bearings as a predictive maintenance tool: Comprehensive case studies. *NDT&E International* , 293-298.
44	SmartGrid.gov. (2021). *The Smart Grid* . Retrieved from smartgrid.gov: https://www.smartgrid.gov/the_smart_grid/smart_grid.html
45	Smitter, J. L. (2021, June 15). Smart Grid Transition Questions - MIDLANT. VA.
46	Thomas, D. S. (2018). *The Costs and Benefits of Advanced Maintenance in Manufacturing.* unk: National Institute of Standards and Technology, Department of Commerce.
47	Trout, J. (unk.). *Reliable Plant - Types of Maintenance, a comparison* . Retrieved from Reliable Plant: https://www.reliableplant.com/types-of-maintenance-31812
48	U.S. Environmental Protection Agency. (2019). *Greenhouse Gas Emissions* . Retrieved from U.S. EPA: https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions
49	U.S. Government Accountability Office. (2018). *DoD Financial Management - The Navy Needs to improve internal control over its buildings.* Washington, DC: US GAO.
50	University of Washington Facilities Services. (2014). *Resource Conservation Program Audit Report: Mary Gates Hall.* Seattle: University of Washington.
51	University of Washington Facilities Services. (2014). *Resource Conservation Program Audit Report: William Gates Hall.* Seattle: University of Washington.
52	US Energy Information Administration. (2018, September 28). *EIA* . Retrieved from Use of Energy, Energy use in commercial buildings: https://www.eia.gov/energyexplained/use-of-energy/commercial-buildings-in-depth.php
53	US Navy. (2020, December). *FRES* . Retrieved from Facility Readiness Evaluation System: fres.cnic.navy.mil
54	Van Tung Tran, B.-S. Y. (2012). An intelligent condition-based maintenance platform for rotating machinery. *Expert Systems with Applications* , 2977-2988.
55	West, S. (2021, June). Smart Grid Transition Questions - South-East. FL.
56	Ziegler, Z. (2021, Jun 23). Demand Generation Representative. *Email Correspondence - Advanced Technology Services, Inc. Follow up* .

Reference Review Summary Table

Works Cited Reference #	Predictive Maintenance								Preventive Maintenance							
	Description	Detecting onset system degradation through various measurement techniques in order to plan maintenance that eliminates causal stressors that would lead to significant deterioration in equipment components.							Description	Actions that can be performed on a time-based schedule that should be in intervals that preclude physical degradation to the point of failure, leading to an extension of useful life of the equipment.						
	Advantages				Disadvantages				Advantages				Disadvantages			
	A	B	C	D	E	F	G	H	A	B	C	D	E	F	G	H
1	X	X		X					X					X		
2									X			X		X		
3		X														
4	No relevant information in these categories															
5	X		X	X												
6	X		X	X												
7	X			X		X										
8	No relevant information in these categories															
9		X		X												
10	No relevant information in these categories															
11	X	X	X	X	X		X		X	X	X	X		X		X
12	No relevant information in these categories															
13	X			X												
14	X	X	X	X	X		X				X	X		X		X
15	No relevant information in these categories															
16	No relevant information in these categories															
17	X	X	X	X					X	X	X	X				X
18	No relevant information in these categories															
19	No relevant information in these categories															
20	No relevant information in these categories															
21	X		X	X					X	X	X			X	X	X
22				X												
23	X	X		X												
24	No relevant information in these categories															
25	X	X														
26	X			X							X			X		
27	X	X	X	X										X		
28	X	X		X												
29									X		X					
30												X				
31	X	X		X												
32	X	X		X	X											
33	X															
34	X	X		X												
35				X												
36	X	X		X									X			X
37	No relevant information in these categories															
38	No relevant information in these categories															
39	X					X								X		
40				X												
41	X	X	X		X		X		X			X		X		
42	No relevant information in these categories															
43	X		X													
44	No relevant information in these categories															
45					X											
46	X	X	X	X	X								X			
47	X	X	X		X		X			X	X					X
48	No relevant information in these categories															
49	No relevant information in these categories															
50	No relevant information in these categories															
51	No relevant information in these categories															
52	No relevant information in these categories															
53	No relevant information in these categories															
54	X			X												X
55	No relevant information in these categories															
56	No relevant information in these categories															
SUBTOTALS	**25**	**17**	**11**	**23**	**7**	**2**	**4**	**0**	**7**	**4**	**7**	**6**	**2**	**9**	**1**	**7**

KEY	
CODE	DESCRIPTION
A	Cost Savings/Cost Avoidance
B	Improved Asset Performance
C	Prolonged Life of Asset
D	Improved Sustainability/Reliability/Efficiency
E	Significant Costs
F	Catastrophic Failure Likely/Operational Impacts
G	Significant Training Needed
H	Labor Intensive

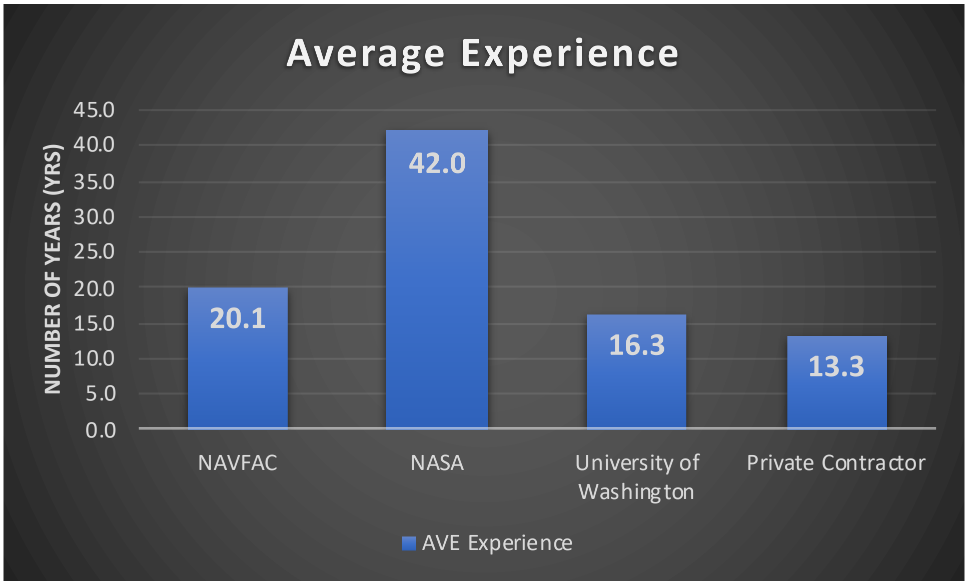
Appendix B: Data

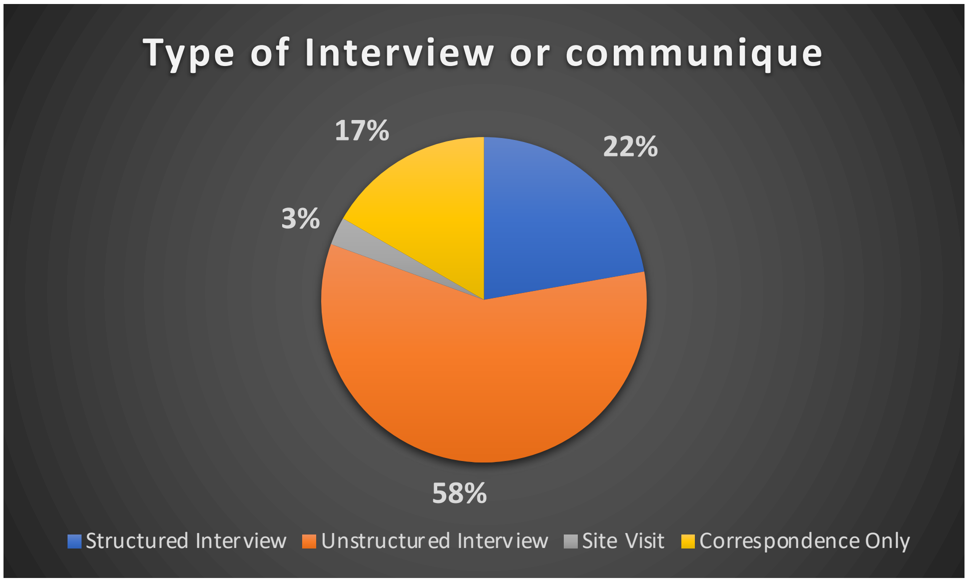
Predictive Maintenance Companies Information Data Comparison

	Company Name	**Program Focus**	**Contact Number**	**Email**	**Location**	**Sensors**	**Associated Costs**	**Analytics and Monitoring**	**Associated Costs**	**Asset Maintenance Management**	**Additional Notes**
	PETASENSE	Hardware	800-215-1485	sales@petasense.com	San Jose, CA	Vibration - 3 Axial	$ 549.00	IoT - Communications Network	200 Channel ($/Mo)	None	
						Transmitter	$ 799.00	Cloud Storage	$ 999.00		
						Temperature	$ 149.00	Analytics	1000 Channel ($/Mo)		
						Pressure	$ 249.00	Diagnostics	$ 2,499.00		
						Current 200A	$ 119.00	Reports	More than 1000 Channels		
						Current 400A	$ 369.00		Contact for pricing		
						Ultrasound	$ 749.00				
						Vibration - 3 Axial & Speed	$ 1,199.00				
	NIKOLA LABS	Hardware	844-464-5652	info@nikola.tech	Westerville, OH	Vibration - 3 Axial	$25/Monitoring point-Month	IoT - Communications Network			These sensors require no batteries and operate using RF-DC power
						Transponders		Analytics			
						Temperature		Diagnostics			
								Prescriptive			
	Reliable Industrial Group	Oil Analysis	504-655-3480	kevin@therigteam.com	Overland Park, KS	Sample Analysis, 23 types of tests (particles, viscosity, water content, etc.)	$65-70/Test sample	Analytics			
	Advanced Technology Services (ATS)	Machine health monitoring system	306-693-6351	zziegler@advancedtech.com	Peoria, IL	Vibration - 3 Axial	$25-40/sensor-month, based on qty of sensors and types	Condition monitoring and analytics		Currently the most common maintenance program involves a team of technicians using PdM equipment to take measurements once a month. ATS is working on using sensors to eliminate this labor burden and sensors are placed and monitored by off-site Reliability Engineers allowing for more frequent measurements at 8 readings a day.	
						Temperature					
						Power consumption					
						air quality					
						coolant health					
						Oil analysis					
						Thermography testing					
						Ultrasonic leak detection					
	IBM	Asset management and analytic Software and 3rd party sensors				Existing customer sensors or partner with a 3rd Party who specializes in sensor technologies.	Drivers of cost: Size of project, number of users, IoT data volume and throughput, and deployment options (cloud-based, on-site server, managed service).	*Date of asset failure. *Probability of asset failure. *Root Cause Analysis *Anomaly Detection related to failure. *Predicting end of asset life.			

Interviewees – Predictive & Preventive Maintenance

	NAVFAC	NASA	University of Washington	Private Contractor	Total	Total Percentage	NAVFAC	NASA	University of Washington	Private Contractor
AVE Experience	20.1	42.0	16.3	13.3	19.0					
STD Deviation	9.8		14.3	10.4	11.2					
Type of Interview or communique										
Structured Interview	4	0	3	1	8	22%	50%	0%	38%	13%
Unstructured Interview	14	1	0	6	21	58%	67%	5%	0%	29%
Site Visit	1	0	0	0	1	3%	100%	0%	0%	0%
Correspondence Only	3	0	1	2	6	17%	50%	0%	17%	33%





Appendix C: Questionnaire's Developed

Discussion Questions on Predictive Maintenance (Initial Questionnaire)

1) What are your general thoughts on the benefits of doing Predictive Maintenance vs Preventive Maintenance? Is one better than the other?

2) What do you think are the risks with running a Predictive Maintenance model?

3) How did you go about choosing the predictive maintenance method(s)?

4) Have you seen any one of those work the best/worst for diagnose problems?

5) How did you prioritize which equipment you would monitor? What was the specific criteria?

6) What 2 pieces of equipment do you think would benefit from doing predictive maintenance monitoring?

7) Have you been able to see any benefits with doing predictive maintenance on the equipment you are currently monitor? Are there any cost benefits? Energy saving or efficiency benefits (one in the same)?

8) What were the start up costs to transition from Preventive maintenance to Predictive? Let's take the equipment you mentioned.

Specific to Jerrett's email:

9) It sounds like you were doing Preventive and Predictive Maintenance simultaneously to see what needs to be replaced/repaired and when. Do you see any benefit from sensoring remotely? Vice going to each piece of equipment and keeping that data via a log? Do I have that wrong and you are sensoring remotely on some things? What are they?

10) Jerrett stated that larger complicated units like compressors, turbines, and diesel generators are harder to diagnose and need the full spectrum of diagnosis methods. What are they?

11) Vibration analysis(fans and motors) and thermography(lug connections) have proven to identify potential problems more readily.

12) Fluting problems with motor bearings caused by the VFD. Keen sense of hearing to determine issue. This goes with experience. Would you recommend any measures to collect data on in order to determine this issue?

**Maybe collecting live data on sound frequency via a monitor and then you can mark your limit of what frequency you would start to see an issue with the bearings.

13) In all it seems like the most important things would be to collect live active data continuously to monitor changes, knowing and setting the limits of variation for those pieces of equipment would give an advantage for determining maintenance but would it give us an advantage for cost savings

Predictive (PdM) and Preventive (PM) Maintenance Questionnaire
(Industry)

By Nathan Pluméy

General Views of Maintenance Systems:

1. What is your name, position/ title, and the company you work for?
2. What are your views of using PM vs PdM? Can you expand on some of the benefits or disadvantages each type of system?
3. How do you promote the use of PdM and transitioning from a time-based maintenance program?
4. (Data Mgt) Can you give me an overview of how your data system works in to gathering, analyzing, and initiating maintenance?
5. (Data Mgt) What are the major benefits of using your company's system vice a competitor?

Capital Unit Costs:

6. Can you go over the capital unit costs of implementing this maintenance model? (sensor costs, connections, data gathering and analytics, system programming, training on-site personnel)
7. (Data Mgt) Can you go over initial capital unit costs? (Data system, initial training of on-site personnel)

Implementation:

8. What steps does your company take when a company is deciding whether to transition to a PdM model? Is it a full PdM model or a mixture of PdM and PM, also known as *Reliability Centered Maintenance* (RCM)?
9. What is your company's process once a client DOES decides to use your system?
10. Given this standard list what PdM sensing equipment would you recommend?
    a. Boiler
    b. Pump
    c. Generator
    d. Compressor
    e. Air Handler
    f. Switch Gear
    g. Mechanical Gate
    h. Motor
    i. Chiller

Lessons Learned, recommendations and trends:

11. Are there specific equipment or times you would not recommend PdM methods to be used? (Types or sizes of equipment)
12. Are you aware of building assets that already come with PdM sensing equipment or which can be added as a kit when purchasing equipment directly from the manufacturers?
13. Are you seeing a trend in companies transitioning from PM to PdM or even RCM?
14. Do you recommend any data management systems that work well with PdM equipment? Which are you seeing that are the most widely used?
15. (Data Mgt) Do you recommend any PdM equipment to go with your data management software? Are there specific brands that you are seeing more than the others?

Sustainability and the Environment

16. Based on the importance for being more environmentally conscious as well as reducing carbon emissions, do these improvements in maintenance improve and reduce the impacts to the environment?
17. Life Cycle Cost (LCC) Data is a measurement of the costs and profitability of products and services over their lifetime. Has your company completed any life cycle costing analysis or any data regarding the costs of the system over the life of the equipment being used to analyze building assets?
18. Life Cycle Analysis (LCA) is a process that measures the environmental impact, giving a full life cycle analysis which shows things like Global Warming Potential (tonnes of CO2eq), Acidification Potential, Ozone depleting potential, and smog potential. Has your company performed a Life Cycle Analysis or have any data regarding these impacts to the environment or the positive changes made by transitioning to your program?

Predictive (PdM) and Preventive (PM) Maintenance Questionnaire
(NAVFAC Case Study Stakeholders)

By Nathan Pluméy

JACOBS Engineering Group conducted a Reliability Centered Maintenance pilot program at NAVFAC HI. They focused on optimizing asset operations and possible cost savings in HVAC systems, compressed air systems, and critical power systems. The following questions relate to this pilot program, successes/failures and initial capital costs, which will conclude in a recommendation for/against implementing a maintenance plan that includes Predictive Maintenance in whole or as part of a complete maintenance program through BOS contracts or by our in-house workforces.

1. What is your name, title/position, and what organization do you work for?

Current Status of the Program

2. Is RCM still being conducted today at NAVFAC HI?
3. Can you elaborate on the current status of the program, now 5 years into the pilot? (positive or negative / benefits or disadvantages)

Implementation

4. Can you describe the time aspects of implementing these measures? (From procurement of measuring equipment to installation of sensors and ensuring program interfaces are in place and implemented as part of Maximo. Also, time needed to get technicians trained to perform these PdM methods).

Actual Costs

5. How familiar are you with the costs to implement this program? Can you provide any clarity or data on costs for converting/adding PdM measures (sensors and any measuring equipment, user interfaces (ie. Maximo added software used to gather and analyze the data for performance parameters), and technician training.

Lessons Learned

6. Can you elaborate on some of the lessons learned from implementing this program?
7. What is your biggest takeaway from this pilot program?
8. Any additional thoughts?
9. Do you know of anyone else that might be beneficial to talk to that could provide additional perspective on this pilot program and how it has progressed over the years? (Clients within the building, technicians or other NAVFAC stakeholders)

Appendix D: Acronyms

Acronyms

AGMA	American Gear Manufacturers Association
AI	Artificial Intelligence
AMI	Advanced Metering Infrastructure
API	American Petroleum Institute
AWEMS	Area-Wide Energy Management System
BCS	Building Control System
BMS	Building Management System
CBM	Conditioned Based Maintenance
CM	Corrective Maintenance
CMMS	Computer Maintenance Management System
COP	Common Operating Picture
CPAF	Cost Plus Award Fee
CS	Control System
CSPE	Control System Platform Enclave
D-I-P-F	Design, Installation, Potential Failure, Failure
DL	Deep Learning
DT	Digital Twin
EDW	Enterprise Data Warehouse
FA	Fluid Analysis
FEOC	Facility Energy Operations Center
FFP	Firm Fixed Price
FRCS	Facility-Related Control System
FRES	Facility Readiness Evaluation System
GIS	Geographic Information System
GRX	GeoReadiness Explorer
IDIQ	Indefinite Delivery Indefinite Quantity
IoT	Internet of Things
IR	Infrared Imaging
ISO	International Organization for Standardization
KPI	Key Performance Indicators
LaRC	Langley Research Center
MILCON	Military Construction
ML	Machine Learning
MT	Motor Testing
NASA	National Aeronautics and Space Administration
NAVFAC	Naval Facilities Engineering Systems Command
Navy	Unites States Navy
NDT	Non Destructive Testing
OBM	Operator Based Maintenance
OCM	Online Condition Monitoring
OEM	Original Equipment Manufacturer
PdM	Predictive Maintenance
PLC	Programmable Logic Controller
PM	Preventive Maintenance
PMP	Preventive Maintenance Program

Acronyms

RBM	Risk Based Maintenance
RCM	Reliability Centered Maintenance
SAE	Society of Automotive Engineers
SG	Smart Grid
SGIWS	Smart Grid Installation Workstations
UCS	Utility Control System
UPS	Uninterruptable Power System
UT	Ultrasound Testing
VIB	Vibration Analysis