Research Article

Designing a Resilient Building Maintenance Program: Integrating Preventive and Predictive Maintenance at the U.S. Navy

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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 prefailure 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: interviews, 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 longterm 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.

INTRODUCTION AND OBJECTIVE

Equipment and utility distribution systems of a building must remain operational to support tenants and their various enterprises. Ensuring facility and utility systems remain operational while maximizing equipment efficiency allows facility and utility managers to best support tenants by maximizing their operation time while minimizing maintenance downtime. A well-developed maintenance plan can ensure that equipment and operations remain sustainable and resilient, thus avoiding extra costs.

According to the Facility Readiness Evaluation System (FRES), the U.S. Navy owns 25,214 buildings (excluding family housing), with an average age of 49 years and a replacement value of $365.2 billion. The deferred maintenance backlog in 2020 was $16.28 billion (US Navy, Facility Readiness Evaluation System, unpublished report). To sustain this real property portfolio, the Navy's total combined budget in 2020 for maintenance and repairs was approximately $3 billion. About three quarters of the budget ($2.2 billion) was spent on repairs, with the remainder spent on maintenance (Commander Navy Installations Command, FY20 Targeted Facilities Investment Strategy Execution End of Year Report, 2020). The Navy, like any other agency with limited funding, is constantly seeking ways to get the most out of maintenance funding to further avoid repairs and reduce its deferred maintenance backlog. Therefore, the objective of this paper was to investigate Navy's current practice associated with a facility maintenance program and other evolving or advanced facility maintenance programs to identify strategies for further consideration and implementation.

RESEARCH METHOD

The following research method was implemented: (1) data collection through existing literature and interviews with owners and private sector subject matter experts and (2) data analysis. The following sections describe the study's rationale and process in detail.

Existing Literature

Advanced facility maintenance programs: The term "maintenance" is defined as a series of tasks and/or activities carried out to restore an item to perform its designated function (Ahmad and Kamaruddin 2012). Maintenance can be divided broadly into two categories: corrective maintenance (CM) and preventive maintenance (PM). This paper focuses on PM, which includes all type of maintenance tasks or actions usually performed before equipment failure. Many types of PM exist. Here we examine two: time-based preventive maintenance and conditioned-based predictive maintenance (PdM). Both are fundamental to most maintenance programs in use today (Gulati and Smith 2009).

Navy's current facility maintenance program: The Navy and the Commands that oversee its properties, facilities, and building systems have developed multiple publications, guides, and instructions/policies for managing these assets. For this paper, five documents (Naval Facilities Engineering Command, P-1205 Public Works Department Management Guide, 2008; Naval Facilities Engineering Command, P-501 Condition Based Maintenance Management (CBMM) Management, 2016; Naval Facilities Engineering Command, P-803 Navy Smart Grid Concept of Operations (CONOPS), 2019; Naval Facilities Engineering Command, P-504 Planned Maintenace Guide (PMG), 2019; Navy and Marine Corps, Smart Grid Capability Development Document, n.d.) were assessed to understand the Navy's current and future maintenance programs and facilitate transition to a sustainable maintenance program. The Navy's goal of a more sustainable maintenance program leverages existing advanced metering infrastructure (AMI), building control systems (BCS), and utility control systems (UCS) with Smart Grid (SG) and advanced analytics.

INTERVIEWS

Based on the literature, a questionnaire was developed. The clarity and length of the questionnaire was pilot-tested with three University of Washington facility maintenance personnel. The questionnaire focused on assessing (a) owners' or clients' current maintenance methods for facilities, (b) experience and lessons learned in performing preventive maintenance, and (c) information on associated costs or energy-savings from the maintenance program. Interviews engaged both public sector owners and private sector subject matter experts to perform a pulse check on the current best practices and to understand how to achieve a more sustainable building maintenance program.

DATA ANALYSIS

Advanced facility maintenance programs: Time-based preventive maintenance involves performing systematic inspections and replacing components 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 inspection, which may produce an additional work order for needed repairs (Gulati and Smith 2009). Time-based PMs are associated with fewer breakdowns, lower emergency labor hours, time for better planned maintenance, safer equipment, improved equipment availability, reduction in overall repairs, reduction in size/scale of repairs, and reduced exposure to potential liability (Levitt 2011).

Advantages of a time-based PM strategy when compared to no maintenance or reactive maintenance include that it has low start-up costs and can be performed based on either experience in facility management among technicians and staff or recommendations from the original equipment manufacturers (OEM) (Ahmad and Kamaruddin 2012). Advantages also include flexibility in the maintenance period, energy savings through cyclical equipment upkeep, and increase in equipment's useful life (Sullivan et al. 2010).

A disadvantage of time-based PM is that catastrophic failures can still occur. If, for example, maintenance is scheduled every other week or once per month, the time interval between maintenance periods lacks oversight. This interval could allow enough time for equipment to go into catastrophic failure quickly with or without warning. Other disadvantages include the amount of labor and material costs needed to complete these recurring maintenance tasks, which can be significant when multiplied by the number of systems a technician may oversee, as is the case at a large naval base or university. This issue is compounded by the cost of performing maintenance when it may be unneeded, as well as possible damage to components during such unneeded maintenance procedures (Sullivan et al. 2010). OEM companies may also harbor hidden agendas in recommending short maintenance intervals, maximizing charges for spare parts replacement through frequent PMs (Ahmad and Kamaruddin 2012). Furthermore, OEM recommendations for maintenance only take in to account limited operating conditions, they do not take in to account plant requirements for operation or varying environmental conditions which affects equipment reliability and does not optimize equipment use. (Tam et al. 2006).

By contrast, conditioned-based PdM is maintenance planned and based on the condition or physical state of equipment using technologies that can detect and measure the onset of degradation (Sullivan et al. 2010). Condition-based PdM measures can predict failures early on, compared to time-based PM measures, allowing maintenance to be scheduled and parts ordered before cost becomes significant. To examine PdM effectiveness in determining failures, one case study on rolling element bearings concluded that, when vibration monitoring was used over selected time intervals, diagnosis of defects could be performed as equipment was running, the remaining life of bearings estimated, and future failures detected in time to schedule maintenance (Orhan et al. 2006). Another case study examining the effectiveness of PdM used on thermography on electrical systems concluded that when an intelligent thermal defect identification system was used to analyze data sets, the system could accurately diagnose electrical defects in order to schedule the proper maintenance (Huda and Taib 2013).

Common PdM technologies include infrared thermography, vibration, chemical-particle lubricant/fuel sampling and analysis, electrical (ampere-monitoring), visual/physical, combustion analysis, and performance. With advanced technology, the sensing equipment can be placed in-line with or on the equipment, thus allowing measurements to be taken while equipment is in operation (Gulati and Smith 2009). This direct condition monitoring as equipment is operating provides large amounts of data, depending on the frequency of the reading sets. The addition of Artificial Intelligence (AI), Machine Learning (ML), Deep Learning (DL), Digital Twin (DT) modeling and other advanced analytics has provided a means of analyzing these large quantities of data. These large data sets, analytics tools, and key performance indicators (KPI) can be used to perform a variety of analytics that can diagnose anomalies through root cause analysis, provide high-fidelity forecasts of failures, and prescribe corrective actions (Kibria et al. 2018).

Condition-based PdM offers many advantages for prolonging the life of equipment and reducing bottom line costs, but it can also require large upfront investments for the advanced technology behind various monitoring options (Sullivan et al. 2010). Three main disadvantages noted by a Department of Energy, Pacific Northwest National Laboratory report (Sullivan et al. 2010) on operation and maintenance best practices are as follows: a significant capital cost is incurred for sensor equipment and program/data management per building; an increased training investment is required for staff to understand the various devices and how to analyze the data; and the return on investment is not initially evident on the annual budget, which may reduce support for these methods over time (Sullivan et al. 2010).

In summary, Table 1 summarizes the advantages and disadvantaged of the time-based PM and condition-based PdM.

TABLE 1.—Comparison of Time-based PM and Condition-based PdM

Characteristics	Time-based PM	Conditioned-based PdM
Initial capital	Low	High
Maintenance workforce training needs	Low	High
Frequency of unforeseen breakdowns	Medium	Low
Long Term costs	Medium-High	Medium-Low

Interview Respondent Characteristics: A total of 32 interviews was conducted with 21 follow-up email correspondents. Interviews were conducted with public sector owners and private sector subject matter experts who provided building maintenance services for large owners. The breakdown of respondent characteristics is shown in Table 2. The average length of experience in their fields was 19.3 years. The semi-structured interviews allowed for probing and follow-up questions, providing a deeper understanding of specific hardware, analytics, and holistic solutions when appropriate.

RESULTS

Analyzing the literature on advantages and disadvantages of the time-based PM and condition-based PdM underscored the need to develop context-sensitive solutions. In the case of the Navy, interviews with NAVFAC pointed to a pilot program at NAVFAC Hawaii that uses reliability-centered maintenance (RCM). This mid-step discovery served our study's purposes as RCM was focused on improving asset reliability and resilience from premature failures with recommended changes in which assets were best suited to a time-based PM approach versus a conditioned-based PdM approach (Jacobs Engineering Group Inc. NAVFAC Hawaii Asset Optimization/RCM Pilot Program Information, 2018). In sum, relevant project-related reports were analyzed in connection with the qualitative data obtained from the subject matter experts.

Navy's existing maintenance program: The Navy uses 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 for Navy facility assets based on risk. The condition assessments consist of 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, the focus was on dynamic assets, also known as assets associated with preventive maintenance. Although PMs vary by type of equipment, annual condition assessments are completed only annually. The CBM asset analysis completed by Maximo uses input from technicians and facility management teams to develop degradation models and calculate future requirements and costs (Naval Facilities Engineering Command, P-501 Condition Based Maintenance Management (CBMM) Management, 2016).

TABLE 2.—Summary of the interview respondent's characteristics

Respondent #	Organization Type (Respondent last name | year interviewed or had personal communication)	Agency or Business Focus	Years of Experience (Unknown if question skipped)
1	Public/Owner (Moncayo 2021)	NASA	42
2	Public/Owner (Fujii 2021)	NAVFAC	30
3	Public/Owner (Wachi 2021)	NAVFAC	18
4	Public/Owner (Rajendran 2021)	NAVFAC	30
5	Private (Bernhard 2021)	Nikola Labs	10
6	Public/Owner (Mitchell 2021)	NAVFAC	19
7	Private (Foley 2021)	Deloitte Consulting	17
8	Public/Owner (Chun 2021)	NAVFAC	30
9	Public/Owner (Petow 2021)	NAVFAC	20
10	Public/Owner (West 2021)	NAVFAC	20
11	Public/Owner	NAVFAC	Unknown
12	Public/Owner (Thet 2021)	NAVFAC	5
13	Public/Owner (Min 2021)	NAVFAC	4
14	Public/Owner (Abubakari 2021)	NAVFAC	15
15	Private (Ruland 2021)	International Business Machines	5
16	Private (Poitras 2021)	International Business Machines	31
17	Private (Hanneken 2021)	Midnight Sun Technologies LLC	Unknown
18	Private (Kirk 2021)	Jones Lang LaSalle Inc	Unknown
19	Public/Owner (Jeffreys 2021)	NAVFAC	33
20	Public/Owner (Crittenden 2021)	NAVFAC	15
21	Public/Owner (LaVerdiere 2021)	NAVFAC	20
22	Public/Owner (Gagner 2021)	NAVFAC	32
23	Public/Owner (Barnidge 2021)	Reliable Industrial Group	15
24	Public/Owner (Hickle 2021)	NAVFAC	11
25	Private (Ziegler 2021)	Advanced Technology Services	2
26	Private (Haseltine 2021)	Uptake	Unknown
27	Public/Owner (Hoffmann 2021)	NAVFAC	27
28	Public/Owner (Smitter 2021)	NAVFAC	27
29	Public/Owner (Lockett 2021)	NAVFAC	5

In managing maintenance, the PM program uses five key elements: continuous inspections, work input control, planning and estimating, shop scheduling, and management reporting. For time-based PM's, workers are tasked with performing continuous inspections that allow them to identify deficiencies in equipment, systems, and infrastructure. This continuity provides the promptest method for detecting asset deficiencies and faults prior to a catastrophic failure (Naval Facilities Engineering Command, P-1205 Public Works Department Management Guide, 2008). Such "eyes-on" evaluation determinations are based on workers' visual acuity, experience, technical knowledge, and any historical asset data available.

As research was being conducted on NAVFAC's current maintenance programs and their capability for using predictive maintenance measures, two unanticipated disclosures surfaced that affected the course and structure of this research. The first was a conversation that brought up a maintenance pilot program centered on reliability and conducted from 2015-2018 at NAVFAC Hawaii. After reviewing that report, we interviewed the Business Line Director for NAVFAC Hawaii and the Energy Program Manager, both of whom helped reveal what would drive the second turn in this research: the Smart Grid (SG) system that NAVFAC HQ was currently implementing. The system provides better security, reliability, and resiliency of the naval infrastructure, as well as facility and utility assets, among other advantages. It also improves efficiency of the utility and building energy systems through operation management and maintenance using conditioned-based PdM techniques and advanced analytics.

The mission of Smart Grid (SG) 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 SG to improve the security, reliability, resiliency, and efficiency of their utilities and building energy systems (Naval Facilities Engineering Command, P-803 Navy Smart Grid Concept of Operations (CONOPS), 2019). The basic concept of SG is an interconnected system consisting of controls, computers, automation, and new IoT technology and equipment including sensors and testing devices, that allow 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 far more control and ability to react to any rapidly changing environment or situation (U.S. Department of Energy n.d.).

Experience and lessons learned: While SG offers tremendous innovation, fully incorporating it into NAVFAC operations requires a large undertaking that brings not only infrastructure challenges, but the challenge of integrating new and aging technology within the same system. Those challenges must be surmounted to attain the goals of ensuring the reliability, efficiency, resilience and sustainability of facility and utility equipment. Via our interviews and correspondence with key NAVFAC stakeholders in various regions, other concerns or gaps were identified, all of which can be summarized as six key issues.

- Asset Management Data – Given the sheer multitude of existing assets throughout Naval facilities and the wide range of methods used to install or replace equipment, a comprehensive asset management inventory and data set is in some cases incomplete and in others altogether lacking within existing authoritative databases such as iNFADS and MAXIMO. Although the Navy is working to validate information on all assets at various levels within the organization, the process is long and tedious (P. Hoffman, personal communication, 2021). The first step in moving toward PdM and having an effective maintenance program is to secure updated and accurate information.
- Connection to a control system (CS) – Some regions indicated that key infrastructure and equipment lacked connection to any type of BCS or UCS (R. Petow, personal communication, 2021). Other equipment and infrastructure that were connected to a CS may prove unable to connect with the CSPE (Control System Platform Enclave; NAVFAC's cyber secure private cloud for facility-related control systems) and thus into SG because they are either antiquated, located in remote locations that do not have the communication infrastructure, or require cyber security authority in order to operate within the CSPE (P. Hoffman, personal communication, 2021). Other systems that are connected encounter difficulties with a redundant hardwired fiber optic line, which is necessary for resiliency of network oversight and control (R. Gagner, personal communication, 2021). This information was echoed by several interviewees.
- Sensors for effective PdM – The existing sensors associated with the various control systems may prove insufficient for a truly effective PdM program (Smitter, Shawn, and Jeremy Lockett, "Electronic Correspondence - Smart Grid Transition Questions - MIDLANT", 15 June 2021). However, analyzing existing data might allow NAVFAC to fall between being prescriptive and indicative of faults or issues (J. Crittenden, personal communication, 2021). One additional interviewee agreed that existing sensors from CS could not provide a true PdM program.
- Existing Labor shortfalls – For any program that does utilize PdM, installations may lack sufficient labor resources, whether in terms of numbers or core competencies, to execute the system effectively (R. Gagner, personal communication, 2021).
- Reliability Concerns – Several sources voiced concerns regarding CSs being affected by regular patches and upgrades that, in the past, have affected critical mission operations, impacting local control of key utilities (R. Gagner, personal communication, 2021). Also, because facility maintenance has been under-funded during the last few decades, too many potential failures might render sensors unreliable. Control systems themselves are prone to failure, and, given the existing budget, installations are able to fix only a small portion of these issues (C. Hickle, personal communication, 2021).
- Regional central control out of tune with local on-site control – SG centralization at a regional location may fail to properly coordinate maintenance activities (R. Gagner, personal communication, 2021). When those with direct control are miles away and potentially unable to react to rapidly changing local environments and/or scenarios, local authorities' loss of local control over major facility systems may affect mission operations.
- High costs lead to lack of investment in infrastructure – Costs of investing in infrastructure upgrades to existing systems are high and difficult to justify (C. Hickle, personal communication, 2021). When resources are limited, funding is usually used to repair multiple non-functioning pieces of equipment rather than upgrading a functional single area or piece of equipment.

Associated cost or energy-savings: The financial investment and impacts associated with PdM can be seen via the pilot program conducted out of NAVFAC Hawaii. In a portion of the case study pilot program, HVAC assets were experiencing issues with recurring failures that were costly and often premature. The report (Jacobs Engineering Group Inc. NAVFAC Hawaii Asset Optimization/RCM Pilot Program Information, 2018) indicated that some items NAVFAC needed to improve were predictive maintenance procedures, information and documentation, and the 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 be reduced by 49% annually (material costs and staff PM effort). Initial capital costs were estimated at $1.8 million, but savings would exceed $8 million over a five-year span for NAVFAC Hawaii (Jacobs Engineering Group Inc. NAVFAC Hawaii Asset Optimization/RCM Pilot Program Information, 2018).

Industry interviews also spoke to implementation costs and general findings regarding what they had witnessed and what sensor technology was more prevalent. Implementation comprises the greatest expense in the cost of monitoring and performing predictive maintenance. From this perspective, three major drivers are a) the number of concurrent users, b) IoT data volume and throughput, and c) deployment options (on site server, cloud-based, managed service). Some companies charge by the number of sensors installed and the amount of data 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, such as single axis vibration or triaxial and speed. One company charged a flat fee for each sensor and transmitter and a flat fee per month based on the number of data streams used for throughput – for example,

$999/month for two-hundred channels of throughput, where one triaxial sensor requires four channels (Petasense 2019). Another company charged a flat rate for sensors from $25-40/sensor-month, a cost that could change based on the quantity used (Z. Ziegler, personal communication, 2021).

The work of companies interviewed or corresponded with ranged from hardware monitoring to asset management and machine health monitoring to oil analysis. Each company responding supplied a different view on what PdM method was being used most in their industry. One company used a higher percentage of people-based route systems, for which contractors came in at regular intervals to assess equipment and obtain measurements at 12 measurements per year (Z. Ziegler, personal communication, 2021). An oil analysis company taking oil samples from companies stated that, though a variety of companies are transitioning to online monitoring, those companies still obtain analyses from labs in order to confirm monitored findings using the real time data, thus enacting no real change in business.

A senior solutions architect for a hardware and analytics company summed up his thoughts 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" (M. Bernhard, personal communication, 2021).

DISCUSSION

Over the past year, increasing instances of extreme weather events have strained our electrical grids and affected localities' ability to function. As temperatures continue to rise around the world, many countries, including the United States, have increased their commitment to active changes in combating climate change, which include helping to strengthen climate resilience. (Dewan, 2021) Leveraging advancing and newer technology will help ensure that facilities and utilities maintain their function, efficiency, and resilience.

Predictive maintenance measures have been shown to improve and maintain efficiency via online sensors and artificial intelligence/machine learning 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 on 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 soon as they start to occur. Although active sensor monitoring and advanced analytics can predict and diagnose faults, most are not equipped to determine root causes. This issue may be alleviated as advanced analytics and sensor technologies mature. For example, inline oil sensor technology cannot be replicated for elemental analysis; samples must still be sent to a lab for analysis. Despite this type of issue, existing sensors like those for inline oil systems should be used at least as warning systems for near term failure.

As more advanced systems come on the market, such as wireless sensors that do not require batteries or plug-in power connection, and as more renewable power and storage systems get combined with existing facilities and power grids, integration and cyber security of these interconnected systems become more important. Integrating existing smart infrastructure and control systems within a cyber secure smart grid provides an ideal way to monitor equipment, identify changing conditions with live data, and react to those conditions by changing equipment operation or energy use.

Variations in the type of PdM program to be implemented will depend on the type of maintenance program. Two major scenarios are as follows. Scenario one is for those organizations that have mature, in-house technicians who can execute maintenance and repairs. Scenario two concerns those organizations that contract their maintenance program to a third-party vendor.

For either scenario, the first step is to validate the existing assets and identify and prioritize which are critical. In scenario one, to fully transition to a full PdM model may prove too costly, depending on the company's fiscal constraints, so a phased approach may be more appropriate. As noted above, a better approach would be to design a program that uses both PM and PdM to counter the extreme costs of sensors and infrastructure. Should a mixed model be chosen, the organization should then decide how maintenance should be performed on each asset by performing a Reliability Center Maintenance analysis (ie. break down maintenance, time-based PM, conditioned-based PdM, or a combination), which should be based on criticality and risk to mission/operations.

In scenario two, in which maintenance is contracted out, it is to be noted that companies hired for only 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. Most would be disinclined to invest time and initial capital costs to install infrastructure and sensors, procure advanced data analytics software, or train personnel.

Innovative contracting methods may alleviate this challenge. For instance, NASA's Langley Research Center (LaRC) first started implementing predictive testing and inspection in 2000. From 2014 to 2020, they have enjoyed a cost avoidance of $5.8 million from catastrophic equipment failure, increased availability of equipment, avoidance of 1,403 unplanned failures, and a 50% reduction trouble calls (National Aeronautics and Space Administration, Langley Research Center Maintenance Program, presented at Langley Research Center, 2021). 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 in the contract. Within the IDIQ portion of the contract are Firm-Fixed Price (FFP) and CPAF components. Due to the complexity of maintenance and justification for cost savings, the contract was awarded for a ten-year period instead of the normal five-year period (McNally, 2012).

Both scenarios are viable. No ideal percentage of maintenance types will fit all organizations. These decisions should depend on what the installation owner and facility/utility management team deem critical and what cost limitations the organization faces. However, 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. It is therefore important to investigate and build a case for creating a sustainable maintenance program.

DATA AVAILABILITY STATEMENT

Some or all data, models, or code generated or used during the study are proprietary or confidential in nature and may only be provided with restrictions.

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