IDENTIFYING REQUISITE CHANGES TO SUPPORT MODERN MAINTENANCE PRACTICES

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ABSTRACT

Modern data science and processing require the use of modern maintenance records. With traditional recordkeeping practices, the isolated nature of the data, as well as the presence of handwritten maintenance work orders and incomplete service logs, severely limit the amount of progress that can be made towards advanced condition-based maintenance. These condition-based methods of diagnostics, prognostics, and maintenance planning are a primary goal of next-generation plant operations and maintenance strategies, and are all dependent on the availability of quality plant data including maintenance data. By implementing changes to maintenance record-keeping practices, such as the use of a computerized maintenance management system, key data will become available to allow for implementation of state-of-the-art data analysis methods. This paper covers the benefits of utilizing digital record systems to increase maintenance data availability in terms of condition-based maintenance and asset management. The ability of these methods to enable state-of-the-art practices within industrial organizations is discussed to offer insight into ways that these improvements to operating strategy will contribute to improvements in world-class maintenance excellence. A discussion of the future of asset management in terms of data analytics, maintenance decision support, and data integration is provided to illustrate the changing landscape of plant management. The result is an examination of innovative maintenance strategies and discussion of challenges related to the future of asset management and implementing modern maintenance practices.

Key Words: maintenance, condition, monitoring, asset management

1 INTRODUCTION

The nuclear industry and most other industrial organizations do not properly record, store, or utilize information related to equipment maintenance. Methods of facilitating maintenance information collection and usage are not well-defined or standardized across industry or in many cases even within specific companies. This creates a challenge when attempting to utilize maintenance information to gain understanding of operating behavior, failure patterns, and maintenance effectiveness.

Before diving into the specifics of how maintenance is controlled and information is collected, there needs to be a common understanding of the general maintenance objective. In industrial settings, the naivest purpose of maintenance is to repair equipment so that it can function properly. While this is a very basic way to interpret the *purpose* of maintenance, there is a much more elaborate maintenance *objective*. When one begins looking at the overall intent of continued maintenance, the objective shifts from a position of reaction to a proactive stance. Rather than identifying issues with equipment and conducting maintenance after issues have presented themselves, the proactive maintenance objective is to maximize equipment performance so that systems operate effectively and efficiently. This is done by optimizing maintenance strategies so that component faults and failures are avoided and/or the resulting losses from these events are minimized [1]. In simplest terms quality maintenance attempts to operate in a more knowledgeable manner than traditional maintenance. This paper explores revolutionary maintenance practices, and the industry changes that are needed to support these evolving strategies.

1.1 Utilizing Maintenance Information to Improve Asset Management

While there may be inadequacies in the way that maintenance data is collected and stored in industry, it is critical that the raw utility of maintenance information is described in order to validate the need for improvements in maintenance recordkeeping practices. In terms of overall asset management there are five critical questions that define the amount of knowledge possessed:

1. What do you own?
2. What is it worth?
3. What is the condition?
4. What is the Remaining Useful Life (RUL)?
5. What should be fixed before time t ?

While questions 1 and 2 are often well understood, most organizations cannot adequately answer the remaining three [2]. This paper investigates a claim that improving maintenance record practices will facilitate solutions to these unanswered questions by improving the availability of maintenance data for use in pioneering solutions.

2 CONDITION BASED MAINTENANCE, CONDITION MONITORING, AND COMPUTERIZED MAINTENANCE MANAGEMENT SYSTEMS

Many innovative maintenance programs are transitioning to Condition Based Maintenance (CBM). In traditional Planned Maintenance (PM) (also preventive/scheduled maintenance) maintenance times are set by defined intervals of operating time. These intervals may be based on historical failure times (warranty data) or on expert knowledge. Unlike PM, condition based maintenance is performed when equipment condition has degraded to an unacceptable level. This means that maintenance is done "as needed" and therefore does not waste potential healthy operating time with unnecessarily scheduled maintenance. In a location where CBM is utilized, there are often several "modules" that support its goals. The primary module is the Condition Monitoring (CM) system, which is in control of monitoring the equipment data and performing individual diagnostics for components. The CM system can track changes in behavior of the components and quantify these changes as equipment degradation. These *degradation parameters* can be passed to a prognostics module, which uses individual component models in order to predict machine failures before they occur [3]. It must be noted that in order to develop these predictive models (and often CM methods), information related to historical failure times and maintenance conducted must first be collected. For modern applications this information comes from a Computerized Maintenance Management System (CMMS), which is tasked with providing maintenance event data collection, storage, and availability.

2.1 Condition-Based Maintenance

Case studies involving organizations utilizing CBM strategies show that it has substantial advantages over reactive and preventive maintenance, which has resulted in CBM becoming the state-of-the-art maintenance practice [4]. One of the advantages of CBM over other maintenance strategies is the improved and focused definition of failure. In traditional maintenance the time when maintenance is conducted is based on information such as the failure times of historical cases, warranty data, simulations, and time constraints. This creates a definition of failure based around average components under average or nominal conditions. In contrast CBM uses degradation estimates based on measured data to quantify system health during operation. Thresholds are applied to the degradation level, and maintenance is conducted when the system passes the threshold. This shifts the failure definition from average components under average conditions to that of a specific component under specific conditions.

CBM-related research has been thoroughly conducted in the field of industrial asset management. While most literature is focused on cost-based optimization of CBM strategies, alternative CBM models have been shown to be capable of increasing safety, production output, production quality, and availability as well as reducing unplanned accidents and failures [5] [6] [7]. One such method of facilitating CBM is the predictive maintenance focus area. Predictive, or prognostic, maintenance uses information that is predicted with advanced models, such as predictions of RUL or Time-Of-Failure (TOF), and current condition data in order to reduce unnecessary maintenance events by only conducting maintenance when required [8]. This is slightly different from standard CBM, which only uses the current value of system condition to make maintenance decisions [6]. Traditional CBM relies on diagnostic techniques to quantify equipment health and schedule maintenance, whereas modern CBM utilizes prognostics tools to translate diagnostic results into a prediction of failure [5]. Both diagnostic and prognostic methods of CBM require advanced data processing and modeling. This is often achieved with a suite of tools that provide information on operations and explicitly solve diagnostic and prognostic modeling challenges. Two sources of information used in these models are the CM system and CMMS.

2.2 Condition Monitoring

The CM system is tasked with quantifying the equipment condition and providing preliminary diagnostic support. In terms of CBM maintenance can be optimized for condition-based strategies through results of CM system implementation in order to identify the critical maintenance times [9]. Expert-level CM systems have capabilities to analyze measurements, diagnose faulty behavior, and quantify individual signal degradation levels compared to normal behavior. In advanced CM systems this signal degradation can be trended in order to track expected degradation levels over time [6]. The main challenges associated with implementing a CM system are sourcing the expert knowledge that is required to turn individual CM tools into a functional solution, utilizing data that is produced in an effective and efficient way, and translating quantitative results into a qualitative asset health indicator that improves maintenance scheduling [4]. An example of these challenges is a system with numerous redundant sensors and/or sensors that are not correlated with system degradation. In this example excessive amounts of data are produced from the CM system that may not have significant utility, which can be onerous for the person attempting to quantify system health, faults, and degradation. The result of this exorbitant data stream is an increase in the data mining and preprocessing complexity, as well as increased model development time. When data that is critical to system health assessment is obscured in this fashion, there arises a need for detailed data to aid in identifying valuable information. One such source of information is maintenance data stored within a CMMS or other digital maintenance database.

2.3 Computerized Maintenance Management Systems

There are many reasons that the maintenance system within an organization may choose to adopt a CMMS. Traditionally, manual (handwritten) maintenance records have been plagued with incomplete entries, lack of standardization, and missing events that contribute to the disadvantages of physical recordkeeping compared to digital [1]. Studies show that even minimal improvements in asset management and maintenance strategy have significant Return on Investment (ROI) in both operational and cost perspectives [10]. As a result, the implementation of more advanced maintenance practices scales with the complexity of the organization. The use of a CMMS, as well as preventive and predictive maintenance, are the major opportunities for improved maintenance [11] and are commonly used to reduce operating expenses and increase performance.

In modern maintenance there is an overall movement towards the use of CMMS. These software solutions have been adopted across many sectors of industry for asset management and improved maintenance policies [4]. There are many providers of CMMS software, but it generally consists of five constituents: work order management, inventory control, maintenance reporting, preventive/predictive strategy, and historical data storage [1] [6]. These make CMMS very valuable to world-class maintenance organizations and quality competitors by providing better operations insight and planning capabilities [12]. While the exact benefits of CMMS implementation are situational, there are several generalized improvements to operation that may be achieved: increased inventory control and subsequent improved communication between maintenance and operations (or production), improved planning and automated scheduling of maintenance events, enhanced data analysis and reporting capabilities, and facilitation of preventive/predictive maintenance strategies [6] [11] [6] [7]. Of these potential benefits, the one of most interest for world-class maintenance organizations is the ability to utilize data from a CMMS and develop or improve proactive maintenance strategies. As there is a shift away from reactive maintenance within industry, there is a need to support this change with preventive and predictive capabilities. In settings where reactive maintenance is used, historical failure information from within the CMMS database can support the establishment of PM intervals. For organizations that already utilize PM, CMMS can provide reports on premature failures in order to effectively modify the intervals, provide failure reports to aid in identifying problem equipment, and facilitate advancement to predictive maintenance [13] [3] [14].

In the overall scope of CBM, the capabilities of a modern CMMS do not inherently reduce the total amount of information that must be processed by the maintenance organization in order to establish effective strategies. Instead a robust and properly implemented CMMS will support the increases in complexity that an organization undergoes and aid in the overall knowledge available for decision support [11]. When suitably utilized, information stored within the CMMS can also help process the data from other sources to improve failure data extraction, pattern recognition, event and operating condition classification, and lifecycle degradation analysis. While an effective CMMS is useful for organization, equipment failure information, and maintenance planning, it cannot replace a CM system's ability to directly monitor sensor data and equipment health (and vice versa). In order to effectively avoid unanticipated failures and also reduce unnecessary maintenance, both CMMS and CM systems must be implements and the information from each must be combined [6].

3 FUTURE OF ASSET MANAGEMENT

As the landscape of business strategy changes, the importance of effective asset management is increasing to support organizations' competitiveness [4]. Many industrial assets have substantial influence on operations, and the health of assets is directly related to their performance and availability; therefore, the relationships between maintenance practices, equipment availability, and an organizations performance are interconnected [10] [11]. With this in mind, the future of asset management involves changing existing maintenance strategies in order to improve the inclusive system reliability over time, which requires a shift in focus away from short-term equipment issues towards long term goals of optimized decision support and efficient maintenance (e-maintenance) [1] [8] [15].

When industrial companies adopt e-maintenance plans the goal is often to provide maximum performance (output and quality) with the minimum number of failures at the lowest required cost. Intermediate improvements of adopting e-maintenance include reduced outage time during repair, minimized spare inventory, overall increase in quality and availability of information, innovative lifecycle support, and advanced fault detection, diagnostics, and prognostics [15]. This e-maintenance ideology is part of a World Class Maintenance (WCM) philosophy that includes the use of digital solutions such as CMMS and CM systems, effective implementation of preventive/predictive maintenance strategies, and improved availability of information [1]. An investigation by Swanson et al. has concluded that "the link found between preventive and predictive maintenance, CMMS, lateral relations and maintenance performance… supports the importance of [these] *world class* maintenance practices" [11].

In order to facilitate WCM in existing organizations, a connection between predictive software and a CMMS can be established to support automated scheduling of maintenance. This requires implementation of a CM system, development of predictive models, and installation of a CMMS. This Predictive Maintenance Program (PMP) is integrated into the existing maintenance policies in order to improve operations [8]. This is one method of enabling WCM practices and can be made more or less complex given the specific needs of the organization. An example of a recent PMP is the F-35 aircraft, which relies on predictive models and information from an advanced CMMS to provide health assessment and decision support [16]. An example of WCM with a simplified maintenance policy is provided by [1], where a CMMS is installed. The results of improving the organization's maintenance records include increased equipment availability, reduced spare part inventory, increased employee optimism, reduced number of unanticipated failures, and significant operations and maintenance savings. The cost of the CMMS implementation was estimated to be £122,000, and the savings after (less than) one year were estimated to be over £250,000.

3.1 Future of Prognostics for Asset Management Support

Diagnostics is a well understood discipline of health monitoring, but prognostics is less universally comprehended. Both diagnostics and prognostics are based on assessing the condition of a system, but unlike diagnostics, prognostics attempts to predict future behavior and degradation trends. Both diagnostics and prognostics are tools to aid in asset management support but must be properly applied to result in significant improvements. If prognostics is the tool, then predictive maintenance is the solution. Predictive maintenance provides improvement to operational safety, quality, and equipment availability across industrial plants by allowing for dynamic maintenance scheduling [8] [6].

As mentioned previously, the complexity of an organization's maintenance program (such as the use of predictive maintenance methods and CMMS) follows the complexity of the industrial operations environment. Companies with large or multifaceted processes should investigate the potential benefits of implementing advanced diagnostics, prognostics, and maintenance management programs in order to improve operations and maintain competitive capabilities across individual trades [11] [8] [6]. Similar to the shift from reactive to proactive maintenance, companies will be faced with one of two futures; either the company will proactively innovate with the pace of progress within industry, or the company will have to react to competitors and adopt these plans to prevent loss of investment/production/profit afterwards. There are many different ways in which an industrial organization can choose to innovate and retain their competitive ability, but each will have varying strengths and weaknesses in terms of ROI. It is believed that the future of competition will be improved operations and maintenance through the use of decision support enabling technologies. Jardine et al. state that these next generation diagnostics and prognostics systems will have advanced capabilities for continuous monitoring and automated decision support, but are dependent on development in the several exploration areas in order to facilitate mass implementation across industry [5]. These dependencies include the utilization of CMMS with advanced maintenance tracking capabilities, the deployment of CBM with diverse maintenance action opportunities, and development of tool packages for innovative industrial data analytics.

The field of research for industrial analytics is developing and evolving at a rapid pace. Tools for industrial data analytics are quickly becoming readily available, as well as platforms to implement them as effective decision support solutions such as IBM Watson and GE Predix. With the implementation of CMMS systems across industry, these tools could be utilized in the near future for virtually immediate ROI. The future of diagnostics and prognostics within asset management depends on vital information stored within CMMS. Data such as maintenance conducted, maintenance/failure times, and periodic inspection is invaluable, and in many cases required, for effective model development and validation. This is closely related to the utilization of CBM; information about specific maintenance conducted within the CMMS will improve CBM efforts (e.g. diagnostic and prognostic models). While characteristic CBM utilizes either CM systems or CMMS, employment of CBM by integrating both systems can result in an exponential improvement compared to either arrangement independently [6].

3.2 Disparate Data Integration

Diagnostics and prognostics are part of an overall goal to increase knowledge of a system by providing capabilities for decision support, including operating parameters and maintenance actions [5]. In order to employ these tools, information from multiple data sources is needed. This data is collected and stored across independent or isolated systems, which can make it difficult access and utilize. Together these disparate data could provide a new level of system information quality if data from each are integrated into a singular correlated source [6] [17].

In maintenance the two most common sources of information are fittingly the CMMS and CM systems, which are unfortunately disparate in nature [6]. The CMMS is often a third-party software package with little or no capabilities to be integrated with other industrial systems (outside of the CMMS ecosystem). Similarly, a CM system may be made of several smaller sub-systems that are integrated together but is not inherently designed to communicate with a maintenance management system to improve work order scheduling or maintenance optimization. While it may not be possible to effectively combine these disparate sources into a singular efficient system, there is a need to integrate the condition data from the CM with maintenance information within the CMMS in order to identify how these data are related to prognostic capabilities and maintenance decision support. These relationships between data availability and efficacy of utilization are relatively unstudied and poorly identified [6] [4]. If understanding the link between maintenance actions and system condition is improved, opportunities for increasing profit and productivity are possible. Studies of properly implementing integrated CBM systems have shown a capacity for improvement of 75% in emergency maintenance, 25% in purchasing expenses, 95% in inventory management accuracy, and 200% in proactive maintenance capabilities [12] [18]. While accurate understanding and identification of links between disparate data sources are not clearly defined, research is already occurring to improve knowledge. Mathew et al. provides a study of data integration, and proposes a potential framework for facilitating effective CBM [4].

4 CHALLENGES AND STANDARDS

As industry evolves and improves, there is a constant demand on maintenance managers to improve work and preserve efficiency, while reducing or retaining competitive operational expenses [1]. This is a common paradigm of maintenance throughout industrial history, and has increased the need for cutting-edge methods of asset management and development of supporting tools. In terms of the future of asset management, proactive maintenance is revolutionizing organizations' ability to properly maintain their equipment, improve decision support, and optimize operations. The greatest challenge associated with implementing these innovative plant asset performance solutions is the disparate nature of the data required to define, create, develop, validate, and evolve advanced diagnostic and prognostic tools [6]. Focusing on CMMS and CM systems, the connection between these data sources is still underdeveloped and poorly understood, which has resulted in issues such as obstructed information flow channels, incomplete maintenance communication strategies, and improper data handling and processing [4] [15]. Another challenge associated with implementing advanced maintenance management tools is their incorporation into existing legacy systems and programs [2]. Links between the CMMS, CM system, Supervisory Control and Data Acquisition (SCADA), and legacy systems must all be identified and defined before effective improvements to asset management can be expected. Once all of this is complete, there is still the challenge of defining how maintenance workers should communicate and act on the results of predictive models and decision support tools [6]. All of these challenges are significant and should not be overlooked when planning any implementation of an advanced asset management program.

One of the major contributing reasons to the challenges listed above, is the lack of standards across maintenance management, diagnostics, prognostics, and decision support. Investigating the scope of existing standards results in limited guiding principles for sensor modules, low-level condition monitoring frameworks, and diagnostic programs. These ideals are partially developed and are not robust to integration with predictive systems or digital maintenance management programs. Both CMMS and prognostic systems are immature in terms of standards and technique guidelines for effective development/implementation. Focus must be applied to researching and establishing standards in these areas, as well as standards for future decision support modules [15]. If one considers these systems together as part of a PMP, there are some specific needs for standardization of the entire program.

Implementation of a CMMS is considered a requirement for an industrial PMP [8]. However, standards on information within the CMMS must be defined and developed. If data from a CMMS and CM system is to be integrated for predictive capability, then there must be information on time between maintenance events, specific maintenance conducted, explicit identification of systems and equipment, and availability of historical maintenance records. While standardizing the specific format of CMMS entries is not inherently necessary, there should be capabilities for data export and import, so that maintenance information can be integrated with other data sources, and decision support modules can feed back into the CMMS to improve/automate maintenance planning and strategies. Within the individual CMMS records there should be standardized options for maintenance workers to choose from. This is an issue as maintenance programs where failure type and/or maintenance action taken is not standardized in some fashion, CMMS entries for the same system, failure, and repair event may be vastly different as a result of different workers making an entry. These systems require advanced natural language processing to extract any useful information to improve maintenance strategies and are inherently problematic for organizations that wish to simplify and optimize operations. To this end, in organizations that implement CMMS systems for the end goal of effective PMPs, standards on event entries should be well defined to aid in future data extraction, processing, and analysis.

Once information from CMMS and CM systems has been extracted and collected, predictive models must be developed to characterize system degradation and make predictions of RUL. These prognostic models are typically developed by applying thresholds, degradation trend analysis, and advanced statistical methods to failure data in order to accurately quantify system health and extrapolate current conditions to impending failure. There are no generic models or frameworks for developing these prognostic models in practice. This lack of standards results in unique model development and results for each application. Two individuals developing a predictive model using the exact same information will likely make starkly different models with significant differences is final prediction results. Industry is currently focused on improving diagnostic “standards” and has deferred predictive model parameter and framework decisions to expert knowledge and end-user historical experience [6]. While the exact disadvantages of the lack of prognostic modeling standards is impossible to quantify, it does pose a challenge for resulting decision support methods. Without a standardized way of developing prognostic models or quantifying predictive results, each model requires different interpretation within the subsequent decision support system. This increases the complexity of the model development process and requires additional expert knowledge to define and explicate. At this stage of prognostics and decision support, it is not reasonable to expect perfect standards to be developed or defined. Instead, as prognostic systems are implemented within PMPs, care should be given to carefully identify steps taken and the purpose of specific modeling techniques in order to retain the value of results. Without this, additional system health information may be available, but the utility of the information and ability to improve decision-making will be lost or tarnished.

5 CONCLUSIONS

As industry evolves, organizations must begin taking steps to innovate and improve. One of the most important and most quickly advancing areas of improvement is maintenance practice and asset management. New data collection, data processing, fault diagnostics and prediction, and decision support techniques are being developed that have the capacity to improve maintenance efficiency and operational performance. The goal of these methods is to increase knowledge of system behavior and improve maintenance management. To this end, the two most common repositories of maintenance information are the CMMS and CM systems. While either system can be an effective tool, combining information from both is more valuable and often necessary in systems where predictive maintenance methods and decision support are desired. The need for CMMS implementation and data integration are validated in the scope of diagnostic and prognostic tool development. After identifying these systems and the future of industrial asset management, discussion of challenges associated with data integration, development, and the need for standards was discussed. This material can be used to aid the process of implementing new maintenance practices/standards within organizations to support efficient decisions and avoid unwanted limitations.

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7 REFERENCES

1. C. O'Donoghue, J. Prendergast, "Implementation and benefits of introducing a computerized maintenance management system into a textile manufacturing company," *Journal of Materials Processing Technology*, **153**, pp.226-232 (2004).
2. D. Vanier, "Why Industry Needs Asset Management Tools," *Journal of Computing in Civil Engineering*, **15**, pp.35-43 (2001).
3. S. Wang, L. Xi, "Condition Monitoring System Design with One-class and Imbalanced-Data Classifier," *Industrial Engineering and Engineering Management IE&EM 16th International Conference*, China, 21-23 October (2009).
4. A. Mathew, S. Zhang, L. Ma, T. Earle, D. Hargreaves, "Reducing maintenance cost through effective prediction analysis and process integration," *Advances in Vibration Engineering*, **5**, pp.87-96 (2006).
5. A. Jardine, D. Lin, D. Banjevic, "A review of machinery diagnostics and prognostics implementing condition-based maintenance," *Mechanical Systems and Signal Processing*, **20**, pp.1483-1510 (2006).
6. D. Galar, M. Palo, A. Horenbeek, L. Pintelon, "Integration of disparate data sources to perform maintenance prognosis and optimal decision making," *The Ninth International Conference on Condition Monitoring and Machinery Failure Prevention Technologies CM & MFPT*, London, UK, June (2012).
7. M. Marseguerra, E. Zio, L. Podofillini, "Condition-based maintenance optimisation by means of genetic algorithms and Monte Carlo simulation," *Reliability Engineering & System Safety*, **77**, pp.151-165 (2002).
8. M. C. Carnero, "An evaluation system of the setting up of predictive maintenance programmes," *Reliability Engineering & System Safety*, **91**, pp.945-963 (2006).
9. E. Jantunen, E. Gilabert, C. Emmanoulidis, A. Adgar, "E-MAINTENANCE, A MEANS TO HIGHER OVERALL EFFICIENCY," *Proceedings of the 4th World Congress on Engineering Asset Management*, Athens, Greece, 28-30 September (2009).
10. D. Galar, A. Thaduri, M. Catelani, L. Ciani, "Context awareness for maintenance decision making: A diagnosis and prognosis approach," *Measurement*, **67**, pp.137-150 (2015).
11. L. Swanson, "An information-processing model of maintenance management," *International Journal of Production Economics*, **83**, pp.45-64 (2003).
12. S. Pinjala, L. Pintelon, A. Vereecke, "An empirical investigation on the relationship between business and maintenance strategies," *International Journal of Production Economics*, **104**, pp.214-229 (2006).

13. D. Travis, L. Casinger, “Five causes of -and remedies for- maintenance manager headaches,” *Plant Engineering*, **51** (1997).

14. J. Lee, L. Liao, E. Lapira, J. Ni, L. Li, “Informatics platform for designing and deploying e-manufacturing Systems,” *Collaborative Design and Planning for Digital Manufacturing*, L. Wang and A. Nee Ed. Springer, London (2009).

15. A. Muller, A. Marquez, B. Iung, “On the concept of e-maintenance: Review and current research,” *Reliability Engineering and System Safety*, **93**, pp.1165-1187 (2008).

16. E. Brown, N. McCollom, E. Moore, A. Hess, “Prognostics and Health Management: A Data-Driven Approach to Supporting the F-35 Lightning II,” *Aerospace Conference*, Montana, USA, 03-10 March (2007).

17. D. Galar, U. Kumar, R. Villarejo, C. Johansson, “Hybrid prognosis for railway health assessment: an information fusion approach for PHM deployment,” *Chemical Engineering*, **33** (2013).

18. R. Sivalingam, “Applying best practices to maintenance: a 12 step programme for moving down the road to recovery,” *Plant Engineering*, **51** (1997).