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Publisher's version / Version de l'éditeur:

Construction Research Congress 2010: 08 May 2010, Banff, Alberta [Proceedings], pp. 1-10, 2010-05-08

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NRCC-51700

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May 2010

A version of this document is published in / Une version de ce document se trouve dans:
Construction Research Congress 2010, Banff, Alberta, May 8-10, 2010, pp. 1-10

A Decision Support System for Integrating Corrective Maintenance, Preventive Maintenance and Condition-based Maintenance

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Abstract

This paper presents a framework of decision support systems for facilities maintenance management (FMM) with the objective of integrating facilities maintenance management, real-time project management, condition monitoring systems and building information models. Multi-faceted views of maintainable assets are designed to meet the requirements of any potential functional extensions or systems integration. Basic processes for asset management, Corrective Maintenance (CM), Preventive Maintenance (PM), and Condition-based Maintenance (CBM) are implemented in a Web-based FMM prototype system. The generic aspects of the system lay in the fact that: 1) all sources of maintenance work, ranging from manually entered CM orders and system generated PM orders to individual maintenance projects, are normalized and manipulated as projects and tasks; 2) the allocation of various kinds of resources, including equipment, materials, trades, contractors, and tools, is optimized using the proposed algorithms.

1. Introduction

Every company is dependent on “facilities” (also called “assets” or “equipment”) that keep the business in business – be it a computer, a centrifuge, or a megawatt transformer. For specific enterprises whose asset replacement cost or equipment failures contribute to a significant part of their operations, efficient facility maintenance management is a top management concern. Downtime in any network, manufacturing, or computing system ultimately results not only in high costs, but also in customer dissatisfaction and lower potential market share.

Facility maintenance is always a matter of equipment uptime and the cost to support that uptime (Hoke and Craig 2008). In a manufacturing organization, the role of facility maintenance is easily neglected since it is a subsidiary stream supporting the main-stream production events. However, facility management in the construction industry has a higher expectation and it constitutes a separate element in FIATECH's Capital Projects Technology Roadmap (FIATECH 2009), in which "real-time facility and project management, coordination and control" provides a fully integrated facility planning and management system. Built facilities always require large capital investment and a relatively high maintenance and operation cost. Critical facilities like municipal infrastructures, power plants, and airports, have stricter demands on health and safety, a bigger impact on society, and much less tolerance for failures.

Based on the basic concepts of Corrective Maintenance (CM), Preventive Maintenance (PM), Condition-based Maintenance (CBM), and the philosophical relationships between them, this paper presents a framework of decision support systems for facility maintenance management (FMM-DSS). Integration issues and technologies are discussed for integrating the FMM system with real-time project management, condition monitoring systems and building information models. A prototype system for FMM-DSS has been developed using a number of leading edge Java and Web-based technologies and it will be presented at the end of the paper.

2. CM, PM and CBM

The essence of the "run-to-failure" **corrective maintenance** approach is to replace a part with a new part only when it is out of function. It is a traditional method for facility maintenance which is surprisingly, still popular in present. Failure happens in reality no matter how you want to avoid them; so an organization should always have CM processes in place as an emergency plan to handle unexpected failures. The downside is that it always implies facility downtime, low customer satisfaction and is not a programmable operation in terms of time and cost. However, depending on the criticality of facilities, and how we can accept the consequences of a failure, CM is the most economical solution among the three maintenance strategies.

Preventive maintenance involves the planning of periodical replacements of parts, scheduling at regular time intervals, independently of whether the component is still performing satisfactorily or not. PM introduces a way to facility maintenance operations that allows some sorts of controllability into the plate, including planning and scheduling of routine maintenance work of assets. Accompany with explicit definitions of maintenance intervals (frequencies), periodic maintenance jobs (for example, inspections, or routine replacements) can be pre-scheduled and budgeted. However, if the PM intervals are not fine-tuned with asset conditions, PM may lead to "deficient" or "superfluous" maintenance. Failures cannot be totally avoided in theory and in practice in that they might still happen between the intervals.

Condition-based maintenance rationalizes prevention, because the physical variables that determine the symptoms of a failure are monitored. CBM has proven capable of aiding facility managers in identifying anomalies early enough to minimize the impact of operational interruptions; avoid expensive failures, including collateral damage; and significantly reduce the cost of maintenance. Many leading companies in the manufacturing, process, paper, and power generating industries have shifted the majority of their maintenance tasks from time-based preventive to condition based. Other similar terms such as "predictive maintenance" and "pro-active maintenance" can be categorized to CBM since they all continuously monitor variables and make maintenance decisions based on the collected condition data.

Table 1 summarizes the pros and cons for the three maintenance strategies.

Table 1: Pros and cons of CM, PM and CBM

Corrective	Preventive	Condition-based
Run to failure	*Fix it routinely before it breaks.*	*Don't fix it if it is not going to break.*
+ Facility is not over maintained + No initial investment + Low costs – High risk of secondary failure – Unscheduled and possibly long downtime – High cost of spare parts – Overtime and labor arrangement – Safety hazardous	+ Maintenance is controlled + Fewer catastrophic disasters + Stored parts and cost can be controlled + Unexpected failures should be reduced – Facilities are maintained when there is no fault – Unscheduled breakdowns cannot be avoided	+ Unexpected failures are reduced + Parts are ordered when needed + Maintenance is performed when needed + Facility life is extended – High initial investment – Additional skill is required – High operation cost – Extra instruments need to be maintained

Notes: "+": pros; "-": cons

Although it sounds like the evolvement of facility maintenance management practices from CM to PM to CBM is an improvement process, the reality is that ALL three must co-exist within an organization. For example, as PM and CBM cannot screen out failures theoretically, an organization must have a formal procedure in place to handle emergent breakdowns and the subsequent consequences. Also because CBM is costly and requires high skill sets and advanced technologies, few organizations can afford CBM solutions on all assets.

Hosseini (2009) has a vision that maintenance departments should gradually transform to maintenance systems and he believes that the ultimate goal is to achieve "performance-oriented" systems that are integrated with "operation" and "support" systems. We advocate this "system" viewpoint in that an optimal facility maintenance program should be a balanced distribution of CM, PM and CBM that meets the organization's high level strategic business plans.

3. Related Work

A good number of commercial facility maintenance software tools are available on the market, which can largely be categorized into enterprise-scale asset management (EAM) and specialized computerized maintenance management systems (CMMS). The most famous EAM software is SAP Plant Maintenance (SAP 2009). The main catalyst for SAP PM's success lies in the fact that it is seamlessly integrated into the existing SAP ERP kingdom in both operating and financial aspects. The selling point of CMMS systems (for example, MAXIMO 2009) is their essence and user-friendly features that are specific to the facility maintenance management domain.

In order to somehow standardize the methodology and processes toward CBM, an early effort by Hassanain et al. (2003) proposed a comprehensive framework model to formalize and standardize the business processes of asset maintenance management in which asset management is divided into five major processes: 1) identify assets; 2) identify performance requirements; 3) asset performance; 4) plan performance; 5) manage maintenance operations. The MIMOSA's up-to-date Open Systems

Architecture for Condition-Based Maintenance (MIMOSA 2009) specifies a standard architecture and framework with seven layers (namely, data acquisition, data manipulation, signal processing, condition monitoring, health assessment, prognostic, and decision support) for implementing condition-based maintenance systems. .

In past decades, CBM technologies have been successfully applied to manufacturing, construction, chemical, power, and process industries. A large volume of academic research work has been done in the area of CBM on a variety of topics. Based on the literature review, we noticed that the developed CBM systems are usually separate modules for condition assessment (Zhang et al. 2006; Luan et al. 2006), risk analysis (Narasimhan 2008), wireless and mobile sensing (Emmanouilidis et al. 2009; Sun 2009) of specific facilities or components, for example, diesel generation units (Luan et al. 2006), power distribution (Pathak et al. 2007), and aircraft (Narayanamurthy and Arora 2008). Very little effort has been made to integrate practical asset management and CBM systems in a general purpose. Our goal of FMM research is to build a fully integrated decision support system at both strategic and operational managerial levels that provides full-scale optimization for a balanced blending of maintenance strategies. The resultant system also aims to facilitate the integration of the FMM system with other AEC/FM elements in FIATECH through building information models (BIM) and process technologies.

4. An Integrated Decision Support Framework for FMM

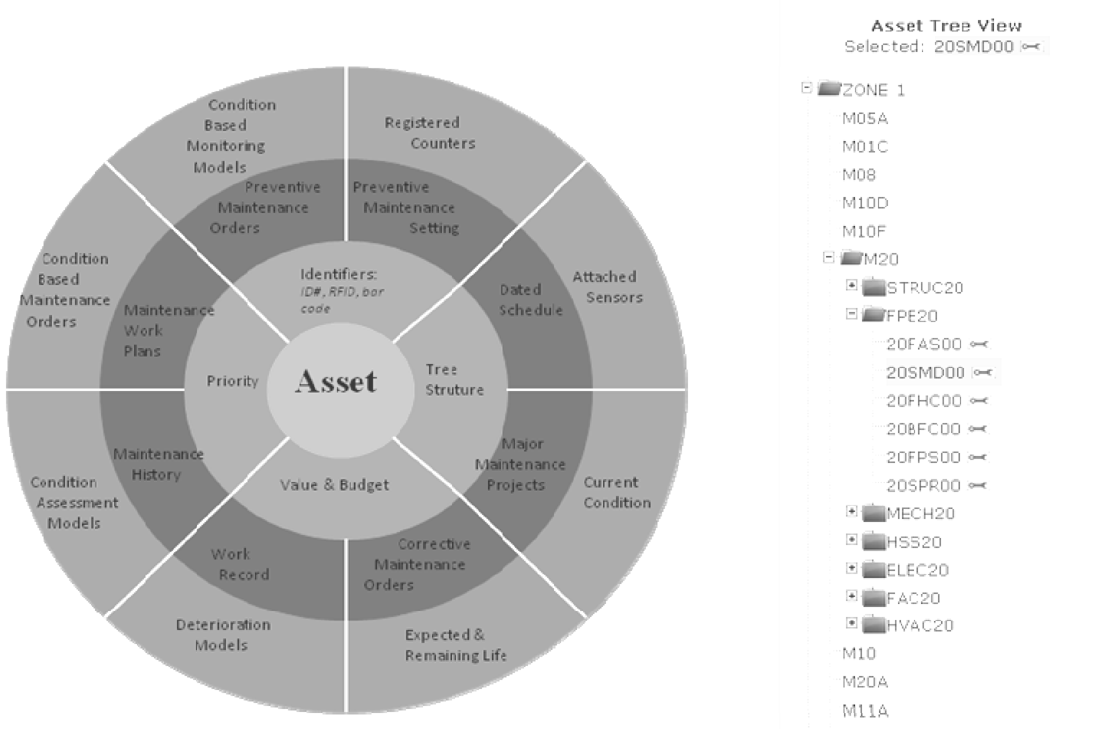


Figure 1: Asset information wheel and the tree structure

We propose a general decision support framework for facility maintenance management (FMM-DSS), in which information and business processes are all centered upon an entity - “asset”. The term asset is equivalent to “facility” or “equipment” in other systems. Figure 1 gives an overview of the general concept of an asset that contains information at three layers.

1) Basic information

The most important item in the basic information is the identification. Apart from the unique ID# that is referred to by the FMM system, an asset has other ways to distinguish itself in various environments; for example, RFID, bar code, and the GUID in BIM models. “Parent-children (1:n)” relationship is used to describe a tree structure and multiple roots are allowed in the hierarchy. In an asset tree, we distinguish two types of entities: “maintainable” and “functional” assets. The “functional assets” can be organized at different layers to group assets into sub-systems or physical maintainable assets; it is equal to the concept of “functional locations” in other EAM or CMMS systems.

2) Maintenance information

Maintenance information is a set of data that defines the rules for maintenance as well as the planned, pending, and past maintenance orders (MO). Regarding the three types of maintenance strategies, we distinguish three types of MOs - CMO, PMO and CbMO. Each maintainable asset can have multiple pre-defined rules/options (called “PM setting”) for carrying out its preventive maintenance activities. A PM setting contains the following information:

- Temporal type: periodic or scheduled
- Work type: inspection, minor repair, major repair or replacement
- Work content (trade or skill, e.g., plumbing)
- Cyclic intervals: time-based and/or counter-based
- Shifting flexibility
- Default start time
- Duration and cost
- Project template
- Resource requirements (equipment, trades, materials, tools, contractors)

3) Life cycle condition-based information and models

The information and processes at this level are focused on “condition” as to record and assess the current and future condition of an asset. With deterioration models and condition assessment models in place, life-cycle condition information can be calculated based on real-time data collected from condition monitoring systems and the planned and past maintenance data. This level of information or models can be an integral part of FMM-DSS or more likely, reside in other distributed systems and integrate with the FMM-DSS using integration techniques (Section 5).

Since preventive maintenance is so far the only one of the three maintenance strategies that is programmable and controllable, the processes related to PM are the easiest to standardize and implement. Commercial EAM or CMMS packages already set good PM practices and they are comparable in PM capabilities. The general PM planning process we developed can be divided into six major steps, as shown in Figure 2.

Among all assets defined, the preventive maintenance planning only calculates maintenance work due in the next planning cycle for “maintainable assets” according to their pre-defined PM settings. The PMOs are generated by either resuming a brand new maintenance cycle or adding cyclic intervals to the last maintenance order in the

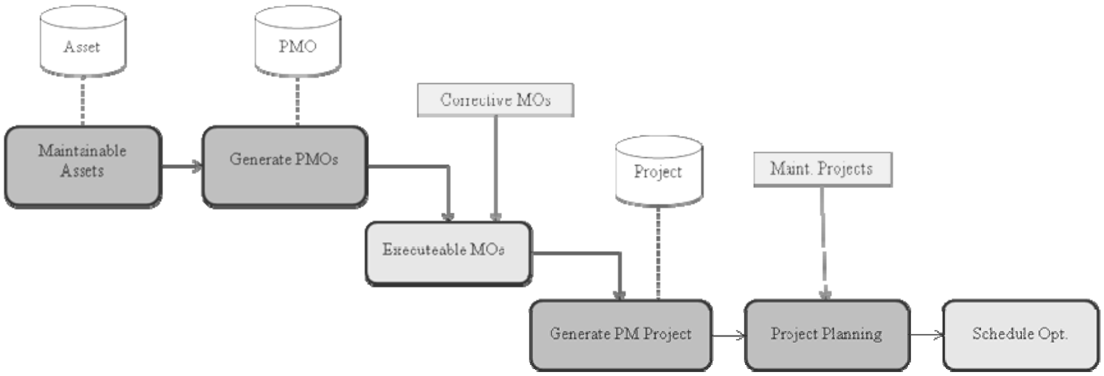


Figure 2: Preventive maintenance planning process

past planning cycle. The "executable MO" and "Schedule Opt." are two major decision points where decision supports are very much required. The objective of selecting executable MOs is to find an optimal collection of PMOs for the next PM planning cycle, based on priority, condition, remaining life, deterioration trend, and life-cycle cost leveling against a limited maintenance and operating budget base. The purpose of schedule optimization at the operational level is to maximize the performance and productivity of an organization through optimizing the daily production and maintenance activities. Multiple objectives can be considered, for example, the greatest resource utilization, lowest cost, and shortest makespan. In Figure 2, the CM and CBM processes are smoothly merged into the main FMM planning flow. Corrective MOs, entered manually by the user directly, become directly executable in the system because the decision of whether it needs to be done is already made. The same decision applies to the CbMOs generated by condition monitoring systems.

In CMMS, "task list" function is provided to group maintenance tasks, but actually it is just a simple checklist-style reminder which cannot handle complex relationships nor consolidate external resource constraints required by the industry. To settle this dilemma, we combine the PM planning and project planning in the FMM-DSS framework, which treats them equally as "projects". Treating all MOs as projects provides a good unification for maintenance orders and maintenance projects, which is one of the most distinguishing features of our framework. Complex relationships and constraints can therefore be defined on tasks and project scheduling techniques can easily be applied to resolve complex problems. We have completed significant R&D work in project management and project scheduling for aircraft periodical maintenance management in a past project (Hao et al. 2009a; 2009b).

5. Integrating FMM with Condition Monitoring Systems and BIM

Condition Monitoring (CM) is a maintenance process where the condition of equipment is monitored for early signs of impending failure. Equipment can be monitored using sophisticated instrumentation such as vibration analysis equipment or the human senses. Where instrumentation is used thresholds can be imposed to trigger condition-based maintenance activity. In reality, the scope CBM is largely dependent on requirements from specific facilities and specific industries; there is no standardized condition monitoring hardware and software tools that can consolidate all kinds of needs from different CBM models. Also, even the choice of performance indicators, theoretical modeling and algorithms are customized to the maintained assets. For these reasons, the condition monitoring systems are better to exist as stand-alone systems rather than native modules in the FMM-DSS framework. The integration of FMM-DSS with condition monitoring systems may happen at any of the top five layers in the OSA-CBM model (MIMOSA 2009) depending on the scope of the specific condition monitoring systems. If the generation of CbMOs is taken as the final output, the latest integration point would be the "executable MOs" in Figure 2. Another aspect that condition monitoring can contribute to the FMM is to assist with deciding the optimal PM strategies or settings. Traditional preventive maintenance practice is implemented through the fixed calendar-based maintenance intervals. How to determine these intervals is a pure experience-based exercise; and once decided, they are never changed. However, with dynamic condition information, one can reasonably envisage that the PM activities can be carried out smartly, in varied intervals, based on the condition of the actual facility. Sun et al. (2008) believed that the optimal PM interval is dependent on the total expected cost index, PM performance and types of PM strategies.

Building information models (BIM) provide a 3D representation of a building and contain database storage mechanisms for properties about all of the elements of the building. When one believes that BIM is a catalyst propelling the AEC industry through its biggest evolution since the introduction of the personal computer, it is hard to imagine that facility management in the 21st century will remain the same (Valentine and Zyskowski 2009). The benefits that BIM can bring to FM include:

- 3D visualization. Using the geometry information embedded in BIM's 3D models, the FMM can easily present facilities relative to their residing environment. The visualization can be very useful in designing and verifying space changes, facility movements, and renovation projects. Also linking with RFID, sensing and tracking systems, visualization would be useful in the locating and tracking of movable facilities, as well as the movement of maintenance work resources, such as materials, equipment, and people.
- Exchange of information between FMM and other up-stream systems. For facilities maintenance information other than 3D models, none of the other systems would have a better knowledge than a FMM system. Therefore, when considering what kind of interaction will be needed for integrating FMM and BIM, firstly, we need to think of what information will benefit FMM from up-stream processes and reversely, what information other processes might utilize if FMM data is available.

Most of the existing work for integrating BIM and FMM suggests a totally centralized BIM solution for facility management, where BIM provides a simple, centralized facility management data solution in one relational database (Motamedi and Hammad 2009). In contrast, we rely on a different loosely-coupled integration approach such as Web services and agents for integrating FMM, BIM and other systems along the AEC/FM processes. Please refer to our previous publication (Shen et al. 2009) for a comprehensive review of systems integration and collaboration technologies in AEC/FM.

6. Implementing the FMM Using the MVC Architecture

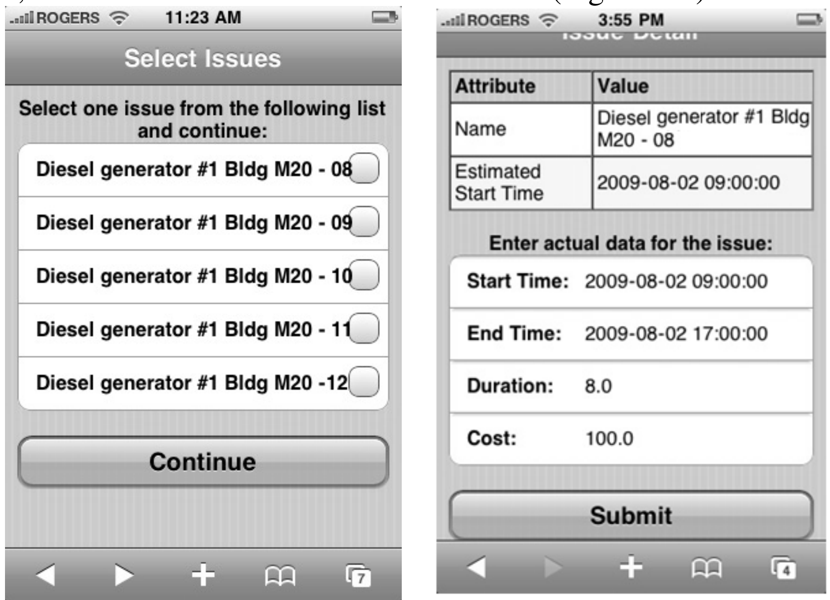
A prototype of the proposed FMM-DSS framework is developed as a pure Web-based application based on the popular Model–View–Controller (MVC) design pattern to maximize the modifiability, extensibility, and reusability of the code. Struts 2.0 framework (Apache 2009) was adopted for the MVC implementation. Other leading edge Java and Web-based technologies used in the development were: *Java EE, JSP, Tomcat, MySQL, Hibernate*, *jQuery*, *AJAX*, and *Yahoo!UI*, to name a few.

Asset management constitutes an asset browser showing an asset tree on the left and a tabbed view on the right. Each tab is implemented as a separate *JSP* page for populating the corresponding aspect of asset information on the screen. The asset management user interface with asset "ASPM-> ZONE1->M20->ELEC20->20DIE02" and the "Plan" tab opened is shown in Figure 3.

Figure 3: User interface – asset browser

Both corrective and preventive maintenance processes are implemented in the FMM-DSS system. The PM planning is executed for a given year and the strategic decision for prioritizing maintenance activities is currently implemented as a manual selection process. Research of optimization models at this layer is one objective of our future work. The optimization of maintenance activities at the operation level is done through a Workload analysis module. This module is designed to analyze and balance the resource workload (i.e., materials, tools, equipment, craftspeople, and contractors) for all maintenance activities in a given time period. The developed meta-heuristic based optimization algorithm (Zhu et al. 2010) can perform conflict detection, schedule coordination, schedule repair, and schedule optimization.

A set of user interfaces is developed for the iPhone's Safari using iUI (2009) to enter actual information for maintenance orders at the job site. When a user accesses the system's website through an iPhone, the system can automatically recognize the device and display a specific set of iPhone pages from the correct server directory. After a user is logged in, a to-do list of MOs assigned to this person's work trades are shown on the touch screen (Figure 4-a). After the user selects a maintenance item from the list, he/she can then view the detailed description of the work and after the work is done, enter the actual information of the work (Figure 4-b).



(a) (b)

Figure 4: User interface – iPhone – work list, work details and actual work recording

7. Conclusion

Based on the basic concepts of the three facility maintenance strategies, CM, PM, CBM, this paper presents a decision support framework for facility maintenance management (FMM-DSS) that aims at integrating facilities maintenance management, real-time project management, condition monitoring systems, and BIM. Multi-faceted views of assets are designed to meet the requirements of potential functional extensions and systems integration. Meanwhile, preventive maintenance orders and maintenance projects are unified in the FMM-DSS where they are equally treated as "projects". This feature allows complex relationships and constraints to be defined on or between activities within a maintenance order.

Loosely coupled integration technologies such as Web services and agents are preferable for gluing FMM, BIM, and condition monitoring systems together. Using a number of leading edge Java and Web-based technologies, a prototype FMM-DSS system has been developed for asset management, preventive maintenance planning, maintenance order management and workload analysis.

Our future work on FMM-DSS will be focused on research and development of decision support models for CBM related processes as well as the strategic prioritizing of maintenance activities that accommodate operational data deducted from condition monitoring, condition assessment and prediction models. The integration of the FMM prototype with other application systems using Web services technologies is another topic that we are currently undertaking to investigate the integration framework for asset life-cycle maintenance and management.

References

Apache. Structs 2.0. (2009) URL: http://struts.apache.org/

Emmanouilidis, C., Liyangge, J.P., Jantunen, E. (2009) Mobile solutions for engineering asset and maintenance management. Journal Quality in Maintenance Engineering, 15(1), 92-105.

FIATECH. (2009) URL: http://fiatech.org/tech-roadmap/roadmap-overview.html

Hao, Q., Wang, S., Xue, Y., Shen, W. (2009a) An interactive decision support method for multi-project schedule coordination. Proc. CSCE 2009, ICS-214.

Hao, Q., Xue, Y., Wang, S., Shen, W. (2009b) A dynamic scheduling algorithm for time- and resource-constrained task networks. Proc. IEEE Int. Conf. on SMC, pp. 4512-4517.

Hassanain, M.A., Froese, T.M., Vanier, D.J. (2003) Framework model for asset maintenance management. Journal of Performance of Constructed Facilities, 17(1), 51-64.

Hoke, J., Craig, L. (2008) Leadership and the SAP Plant Maintenance Tools. URL: http://www.cmmscity.com/articles/leadersip_sap_pm.htm

Hosseini, M. (2009) Condition Based Maintenance and Performance. URL: http://www.plant-maintenance.com/articles/CBM_Performance.shtml

iUI. (2009) URL: http://code.google.com/p/iui/

Luan, Q., Siew, C.K., Losfin, H. (2006) Asset health index method for diesel generation unit replacement planning. IEEE Power Engineering Society General Meeting.

MAXIMO, IBM. (2009) URL: http://www-01.ibm.com/software/tivoli/products/maximo-asset-mgmt/

MIMOSA. (2009) URL: http://www.mimosa.org/

Motamedi, A., Hammad, A. (2009) Lifecycle management of facilities components using radio frequency identification and building information model. ITCON, 14, 238-262.

Narasimhan, V.L. (2008) A risk management toolkit for integrated engineering asset maintenance. Australian Journal of Mechanical Engineering, 5(2), 105-114.

Narayanamurthy, G., Arora, S. (2008) An integrated maintenance and asset management system (IMAMS). Proc. Integrated Communications, Navigation and Surveillance Conference.

Pathak, J., Li, Y., Honavar, V., McCalley, J. (2007) A service-oriented architecture for electric power transmission system asset management. LNCS, Vol. 4652, pp. 26-37.

SAP Library - Plant Maintenance Online. (2009) http://www.sap.com/

Shen, W., Hao, Q., Mak, H., Neelamkavil, J., Xie, H., et al., Systems integration and collaboration in architecture, engineering, construction, and facilities management: A review. Advanced Engineering Informatics, doi:10.1016/j.aei.2009.09.001.

Su, C.J. (2009) Effective mobile assets management system using RFID and ERP technology. Proc. 2009 WRI Int. Conf. on Communication and Mobile Computing, Vol.3, pp.147-151.

Sun, Y., Ma, L., Mathew, J. (2008) Determination of optimal preventive maintenance strategy for serial production lines. Australian J. of Mechanical Engineering, 5(2), 97-103.

Valentine, E., Zyskowski, P. (2009) Models (BIM): How it has changed FM, FMJ. URL: http://www.fmlink.com/ProfResources/Magazines/article.cgi?FMJ:fmj051409-1.html

Zhang, L., Mathew, A., Zhang, S., Lin, M. (2006) Implementation of asset health assessment system with pattern-oriented design and practice. Proc. IEEE Int. Conf. on Intel. Sys., pp. 666-671.

Zhu, J., Li, X., Hao, Q., Shen, W. (2010) A new approach for resource-constrained multi-project scheduling. Proc. Construction Research Congress 2010.