Implementation of Computerized Maintenance Management System (CMMS) in Upgraded Pillar Point Sewage Treatment Works

Henry K.M. Chau[1], Ricky C.L. Li[2], Tim S.T. Lee[3], Bill S.M. Cheung[4] and Teck Suan Loy[5].

Abstract In the past, monitoring and scheduling the operation and maintenance activities of physical assets in Sewage Treatment Works (STWs) of Drainage Services Department (DSD) follow a traditional risk based approach with due consideration to the financial as well as the state of the assets. This approach relied heavily on a labour intensive data logging, tracking and analysis exercise by experienced staff. There is an increasing trend that a more systematic management of such assets (hereon referred to as Asset Management) is desirable to achieve a more efficient and effective operation of the STWs. DSD adopts the strategy and philosophy of Asset Management System for optimization of life cycle cost, finance, system reliability, work force, inventory & resources in the Upgraded Pillar Point Sewage Treatment Works. A key part of Asset Management System, known as Computerized Maintenance Management System (CMMS), was integrated with the Supervisory Control and Data Acquisition (SCADA) system to realize and implement various functions such as creating, linking, triggering & maintaining corrective maintenance and preventive maintenance tasks. Each entity

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[1] Henry K.M. Chau
Chief Engineer, the Drainage Services Department of the Government of the Hong Kong Special Administrative Region
Email: henrykmchau@dsd.gov.hk

[2] Ricky C.L. Li
Chief Engineer, the Drainage Services Department of the Government of the Hong Kong Special Administrative Region
Email: rickyli@dsd.gov.hk

[3] Tim S.T. Lee
Technical Director, AECOM Asia Company Limited
Email: tim.lee@aecom.com

[4] Bill S.M. Cheung (✉)
Senior Resident Engineer, AECOM Asia Company Limited
Email: sre@dc200803.com

[5] Teck Suan Loy
Board Member, ATAL- Degrémont-China State Joint Venture
Email: teck.suan.loy@degremont.com

is condition-monitored with rule-based philosophy. Traditionally, the rules are usually based on typical settings recommended by experienced staff and/or manufacturers that apply to similar equipment regardless of the equipment's lifetime variation due to manufacture quality, installation workmanship, operating conditions and environment, etc. For Upgraded Pillar Point Sewage Treatment Works (PPSTW), Recursive Auto-Regression (RAR) modelling[1] technique is adopted to automatically predict specific equipment's remaining useful life (RUL) and compare the lead time of components' delivery and process time of overhaul sub-contracting so as to establish an optimum preventive maintenance schedule with delivery, resources and cost optimization. Prediction accuracy of the developed RAR model is verified by numerical simulation with inputs to CMMS condition monitoring engine. A pilot study on the integration of CMMS with the SCADA system has been implemented on the outfall screw pump shaft bearings for experimental validation of the RUL model and investigating the feasibility of its application.

Keywords CMMS · Recursive Auto-regression · Condition Based Monitoring · Remaining Useful Life

1. Introduction

Traditional risk based approach of a labour intensive data logging, tracking and analysis exercise by experienced staff is currently adopted for monitoring and scheduling the operation and maintenance activities of physical assets in sewage treatment facilities of DSD. With the development of information technology, there is an increasing trend that a more systematic management of such assets, i.e. asset management is desirable to achieve an efficient and effective operation of the STWs. For the "Design, Build and Operate Pillar Point Sewage Treatment Works" project, DSD has implemented seamlessly asset management strategy and philosophy with integration of SCADA system and CMMS system for optimization of life cycle cost, finance, system reliability, work force, inventory, resources, etc.

2. Asset Management

As defined (PAS 55, 2004), Asset Management is "systematic and coordinated activities and practices through which an organization optimally manages its assets, and their associated performance, risks and expenditure over their lifecycle for the purpose of achieving its organizational strategic plan."[2] which is of growing importance to contribute better services with enhanced performance and efficiency. Asset management combines management, finance, economic, engineering, risk & reliability, and other factors that are to be applied to physical assets in providing required level of services throughout an asset's service. It is a systematic process of managing the asset's entire life cycle in most cost-effective and optimized manner, including its design, construction, commissioning, operation, maintenance, repair, modification, replacement and ultimate disposal.[3] Normally asset would remain in working for a substantial period of time when best practices in proper operation and maintenance are adopted. Subject to the assets usage, nature, quality and its operation environment, it is of vital importance that well-timed maintenance and routine inspection for achieving an optimum service life of an asset with the aims of expert knowledge before catastrophic failure occurs.[4]

Asset management philosophy and strategy for Upgraded PPSTW are developed based on the following objectives:

- Failure prediction and prevention
- Equipment redundancy and availability
- Condition-based maintenance with continuous monitoring and assessment
- Asset performance benchmarking
- Optimization of capital expenses (Capex) and operation expenses (Opex)

Capex is the cost of developing or providing non-consumable parts for the product or system while Opex is an ongoing cost for running a product, business or system[5]. In other words, Capex and Opex constitute all costs that are allocated to an asset throughout its entire life cycle. The asset management strategy integrates Capex and Opex optimization to deliver maximum cost saving by extending the useful life of the equipment with predictive and preventive maintenance approach while corrective maintenance is minimized.

All in all, integrated control, information and database system, i.e. Asset Management Package, CMMS Package & SCADA Package, plays an important role for the implementation of a sound meaningful asset management system. In modern sewage treatment works, Supervisory Control and Data Acquisition (SCADA) system, as its name implies, is the key element for process automation and data gathering by a computerized and centralized industrial control system that monitors and facilitates control of the whole works. Majority of the control actions are performed by remote terminal unit (RTU) or programmable logic controller (PLC) which control functions are normally limited to supervisory level intervention and override, that is, RTU/PLC processes the feedback control loop and the SCADA supervises overall performance of the loops. Another function of SCADA system is data acquisition which initiates inputs at field side such as meter readings, equipment status, etc. that are connected to SCADA. Data is then transferred and visualized at the plant control room via Human-Machine Interface (HMI) for subsequent plant operation and decision making.[6] However, the SCADA system alone does not possess any planning, scheduling, monitoring, etc. of asset management and maintenance functionality.

Proper maintenance and appropriate renewal of parts, equipment and plant are considered as one of the best practices to extend the service life of an asset in order to arrive at the lowest lifelong cost. For implementing Design, Build and Operate contract in Upgraded PPSTW, asset renewal cost forms an important element of the overall cost and must be properly accounted for so that the planned maintenance and renewal can be undertaken. CMMS is typically adopted and widely used to keep the track record of all entities within the Works which is a proprietary software package that maintains database of an organization's maintenance operations and facilitates the management of plant's system and equipment, daily operation work, correction and preventive maintenance works. The CMMS, which is capable in creating, linking, triggering and maintaining Corrective Maintenance (CM) and Preventive Maintenance (PM) tasks, is therefore implemented with Maintenance, Inventory and Procurement Modules to facilitate the management of assets for Upgraded PPSTW.

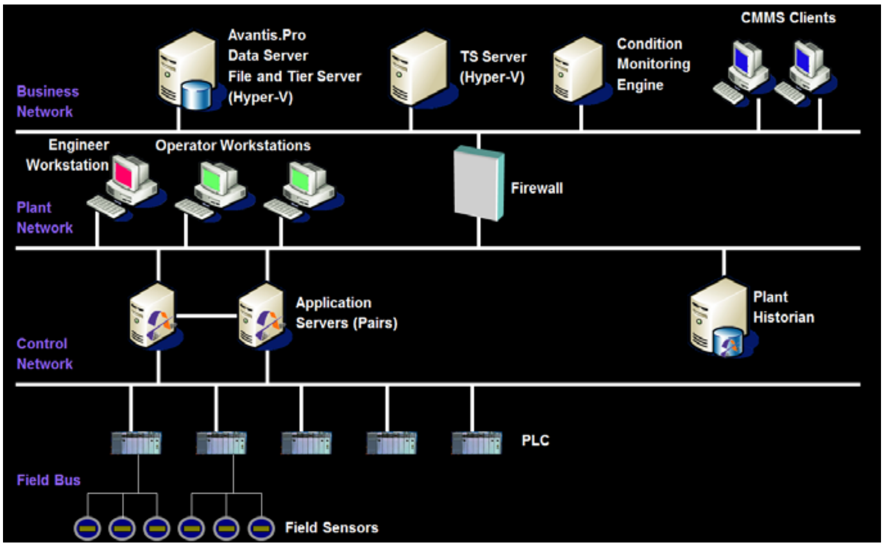

Fig. 1 Asset management system network architecture

The architecture of Upgraded PPSTW's asset management system is presented in Fig. 1. It is a third-generation networked architecture of four layers, namely, field bus, control network, plant network and business network. Field bus refers to all available field sensors, instrument readings, equipment status, running information etc. that connected to the PLC of each treatment process unit with various types of contacts (dry contacts, hardwires, etc.) and buses (Modbus, Profibus, etc.). The PLCs are then configured to form a complete control network of the Works in accordance with developed system control philosophy. The SCADA system connects the control network for overall plant control, monitoring and data logging and visualizes the plant operation with HMI. The business network consists of CMMS server and condition monitoring engine to form the business network that is attached to the plant network and integrates with the SCADA system. It utilizes standard communication protocols and security techniques when implementing the integration of SCADA, CMMS and Condition Monitoring Engine. To reduce the potential vulnerability of the Asset Management System from remote attack, accessibility over internet is denied. To restrict un-authorized access or tackle an attack, hardware-based firewall is also installed which controls incoming and outgoing traffic between CMMS and SCADA networks and secures the network with trust.

Condition based monitoring engine integrates real time plant information and assesses equipment status accurately and timely. It relies on rule-based condition monitoring engine for creating work orders automatically that minimize human and capital resource. The CMMS database file server, tier server and remote desktop services server (Hyper-V) utilize Microsoft virtualization environment to achieve central administration tasks which host CMMS database, middle tier and transaction services components via integrated CMMS operation environment with computer. Data Flow of Condition Based Monitoring System is illustrated in Fig. 2.

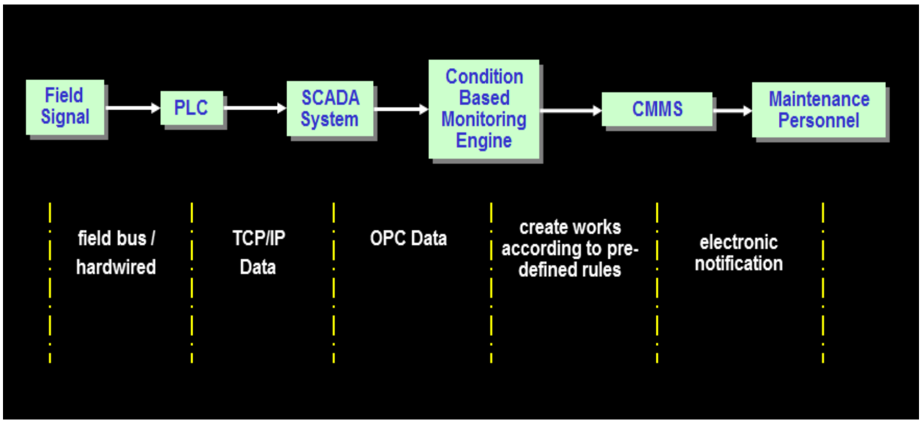

Fig. 2 Data flow of condition based monitoring system

3. Computerized Maintenance Management System

The core of the CMMS of Upgraded PPSTW consists of Maintenance, Inventory and Procurement module which aims to facilitate the management of plant's system and equipment, daily operation work, correction & preventive maintenance works and generation of various analysis and management reports. The CMMS creates, links, triggers and maintains CM and PM activities and also keeps track of status of Work Order.

The CMMS features the following Maintenance Management functions:

- Entity Management (Equipment Costs & History tracking)
- Work Planning (Work Order creation, planning, printing, tracking and closing)
- PM Jobs (Creating PM jobs, assigning frequency of PM to Equipment, triggering and executing PM Work Orders)
- Maintenance, Repairs, and Operations (MRO) Inventory Management

Entity management is incorporated in the CMMS to maximize the flexibility of equipment database, which supports the management of both maintainable and organizational entities, as well as tracking capital projects and related tasks and expenditures. Maintainable assets include anything that needs to be repaired such as a piece of equipment whilst organizational entities refer to any arrangement of the system that is used to collect cost, statistical, budget or backlog information such as a cost centre. For Upgraded PPSTW, the CMMS is capable to keep track of all the spare parts that are being used in those maintainable entities and organizational entities created within the CMMS.

The Work Management of CMMS is purposed to ensure that maintenance personnel can manage and plan incoming work requests as well as automatically generated work from preventive maintenance programs. Work Planning is essential to ensure that labour, materials, tools, drawings and subcontractor requirements, as well as safety information, can be identified on work orders to support proactive maintenance activities. For Upgraded PPSTW, the CMMS enables operator staff to use the work request as a simple electronic tool to communicate a need for service to the maintenance department by creating Work Orders from pre-planned Work Order Templates. Work Orders are created in several ways, namely, Simple Work Orders that contain only one task for a single entity while Multi-Task Work Orders are adopted when multiple entities are affected or multiple task are required. The CMMS identifies the entity to be repaired, overhauled, replaced or maintained on the Work Request and Work Order with condition monitoring features incorporated. In addition, to ensure the safety of maintenance personnel, the CMMS generates and provides safety instruction of any potential hazardous or dangerous condition associated with a job, the entity on which the works is to be performed, or the materials or tools involved with the work. The CMMS also provides with the material transactions functionality which consists of issues and returns from the warehouse for inventoried items and procurement for non-inventoried material. When closing a work order, the CMMS records the entry of allocated costs with descriptions for future historical analysis.

The CMMS also features with Planned Preventive Maintenance (PM) function which is based on user defined activities to be performed with essential resources input such as labour requirements, material requirements, safety information, etc. The CMMS triggers PM Works Orders depending on user defined frequency criteria. Multiple triggering is possible. Subsequent PM based Work Orders are created automatically and placed in the Work Order Backlog for execution purpose. The CMMS is equipped with statistical function by maintaining a number of inputs for each entity in a database for analytical use.

A Maintenance, Repair and Operation (MRO) Inventory module is specifically assigned to enable the control of a large number of unique and low-unit value items. The MRO Inventory module automates the reorder process in the CMMS by recognizing calculated safety stock levels, replenishment lead times and sophisticated "available-to-promise" logic based on expected receipts and issues. The MRO Inventory module provides the ability to uniquely identify and track repairable items and critical parts through serialization so that operation staff have ready access to the inventory information and management decision such as inventory status, location, quantity in stock, supply lead time, etc.

The CMMS also generates reports to facilitate operation staff on plant performance monitoring and statistics review by automatic reports generation mode to be scheduled by time of day, day of week, hour of day, or at the end of a shift, or on demand by operation staff. Typical CMMS report contains information on plant influent, plant effluent and dewatering system, their duty/ standby train/ units status, actual retention time of the units, chemical inventory as well as their summaries on alarms and maintenance activities including corrective and preventive maintenance work orders cleared and not yet cleared. Operation staff can add snapshots of trends, histograms using graphic templates in their CMMS reports.

4. Condition-Based Maintenance Approach

Condition-based maintenance (CBM) has been widely adopted in the industry due to its maintenance efficiency and flexibility[7]. CBM is based on using real-time data to prioritize and optimize maintenance resources. However, modelling, maintaining and using the required data from asset management to implementation of CBM is complex and intensive in nature. Data acquired must be accurate because it forms the basis for the decision support tools. In fact, CBM is usually performed based on an assessment or prediction of the equipment health instead of its service time so as to reduce down time and enhance operational safety.

Modern diagnostic practice in industry is the combination of human expert knowledge and experience of equipment status and failure with continuously monitoring and analyzing its condition. An effective prognostic model requires performance assessment, development of real-time condition monitoring information and degradation signals, failure analysis, health management and prediction, feature extraction and historical knowledge of faults[8] which necessitate tremendous effort, resources and expertise with every data acquisition. For Upgraded PPSTW, extensive instrumentation of equipment together with computer tools for analyzing and predicting equipment’s remaining useful life (RUL) are used in the process of CBM implementation. Online condition monitoring is adopted for applicable equipment to estimate the RUL and achieve maintenance optimization. Accurate prediction of equipment’s RUL is somehow critical for its operation and productivity.

For demonstration, taking sewage pump as an example, the first condition is the running hour of the pump with triggering condition referred to the equipment O&M manual. The second condition is operating current of the pump. These conditions are very useful for assessing general loading status of the pump. The CMMS monitors all the duty and standby pumps to record their running conditions. Operation sequence is assigned with priority to the loading conditions and health status of each pump instead of traditional averaging running hour approach. The last condition is the establishment of Degrading Index for equipment with RAR model for the forecast of RUL of the equipment. Above mentioned three conditions are implemented simultaneously in the CMMS in determining maintenance schedule and works planning. In order to facilitate the operation of SCADA and CMMS, CMMS client desktop is integrated into the SCADA system as shown in Fig. 3. In the CMMS, operation staffs are able to monitor, operate and schedule maintenance with single screen user interface and review all particulars of the equipment, Work Request details, Work Order details and generation, resources allocation & scheduling, etc.

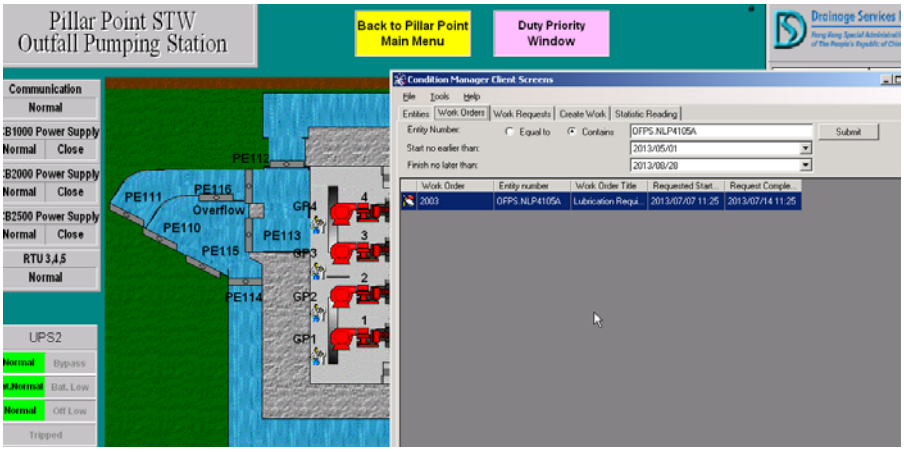

Fig. 3 SCADA interface with CMMS desktop integrated

5. Case Study – RUL Estimation of the Existing Outfall Screw Pump Bearing

The accuracy of the RUL estimation plays a critical role for the CMMS. As part of testing and commissioning program for the CMMS, a case study has been carried out to examine the work flow for optimal time in generating work request using Degrading Index and Recursive Auto-Regression (RAR) model.

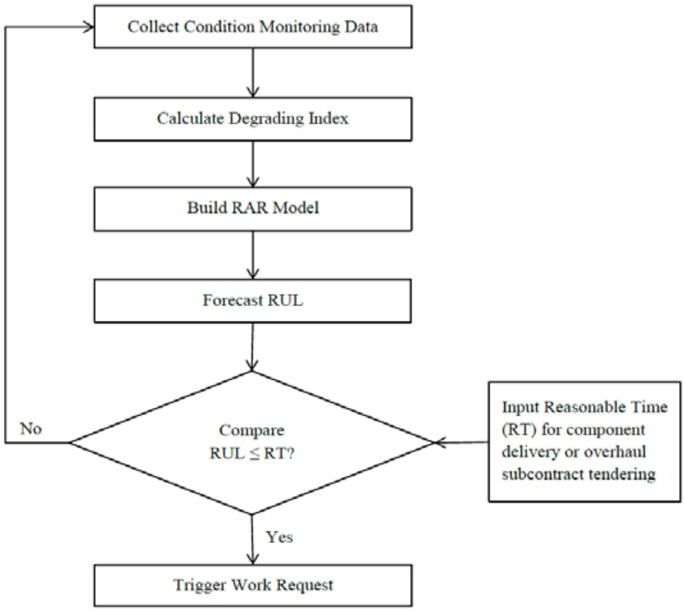

Fig. 4 Work flow of the RUL modelling

In this case study, the RUL of the existing Outfall Screw Pump bearing is used to compare the Reasonable Time for component delivery or overhaul subcontract tendering in the Upgraded PPSTW. Work flow of the RUL modelling is shown in Fig. 4 while schematic and photo of the experimental setup is shown in Fig. 5.

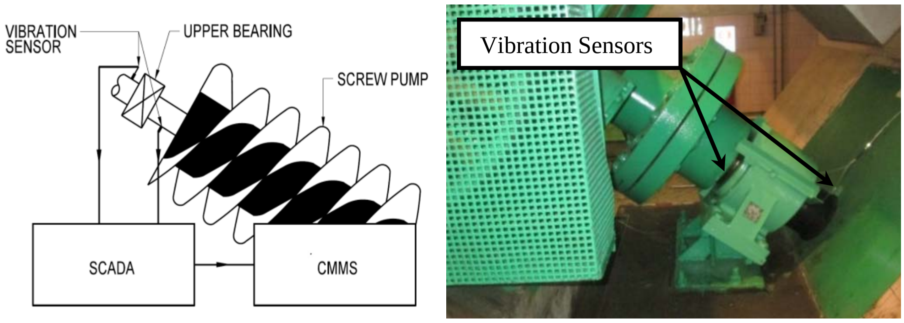

Fig. 5 Schematic and photo of the experimental setup

5.1 Collect Condition Monitoring Data

This is the first stage of the Case Study. Three sets of vibration sensors are mounted to the pump shaft of Outfall Screw Pump No.4 so as to measure the pattern and magnitude of linear and angular vibration when in operation. The measured field data is fed to the SCADA system. The condition monitoring data is then retrieved by the condition monitoring engine of the CMMS for subsequent manipulation and processing.

5.2 Calculate the Degrading Index (DI)

This is the second stage of the Case Study. For each set of condition monitoring data, Degrading Index is calculated with root-mean-square (RMS) of vibration magnitude.

5.3 Build RAR Model

This is the third stage of the Case Study. The Recursive auto-regression (RAR) model comprises of a time series stochastic autoregressive (AR) model and recursive parameter estimation with an established algorithm based on model order determination with Akaike's Information Criterion (AIC) [9] and the parameters estimate with Recursive Least Square method [10]. The RAR model is then integrated to the condition monitoring engine of the CMMS as one of the rules in the decision support tool.

5.4 RUL estimation – Degrading index forecasting

This is the fourth and the last stage of the Case Study. When the future degrading index forecasted in the time series equation is equal to or more than the threshold degrading index, the time step ahead corresponding to this forecasted degrading index is considered to be RUL of the machine. The RUL is compared with Reasonable Time (RT) for component ordering & delivery or subcontracting overhaul works. If RUL is still longer than RT, then the condition monitoring process will continue and proceed as no follow-up action is anticipated. However, when the RUL is equal to or less than RT, a Work Request for Standard Overhaul Procedure will have to be initiated.

6. RUL Modelling System Test

Before the implementation of RUL prediction in practical application, a numerical simulation of the model is performed to assess its accuracy and triggering function. In this practical application, the senor and transducer will take vibration measurement and send the measured signals to SCADA system and CMMS one by one in time sequence. In the system test, a signal generator is employed to play the role of sensor and transducer. It generates a series of signals to SCADA system and CMMS according to a preset governing equation plus±1% random part. The series of signals simulates vibration data and the degrading indexes.

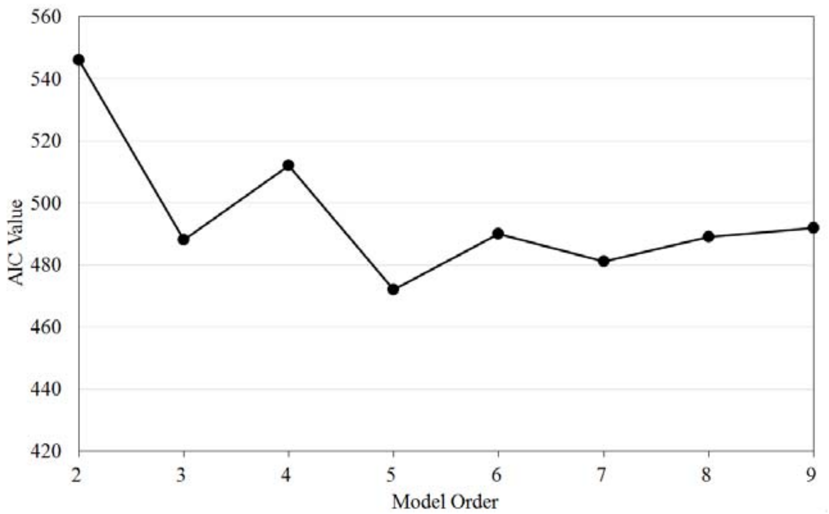

Fig. 6 AIC value with different order of model

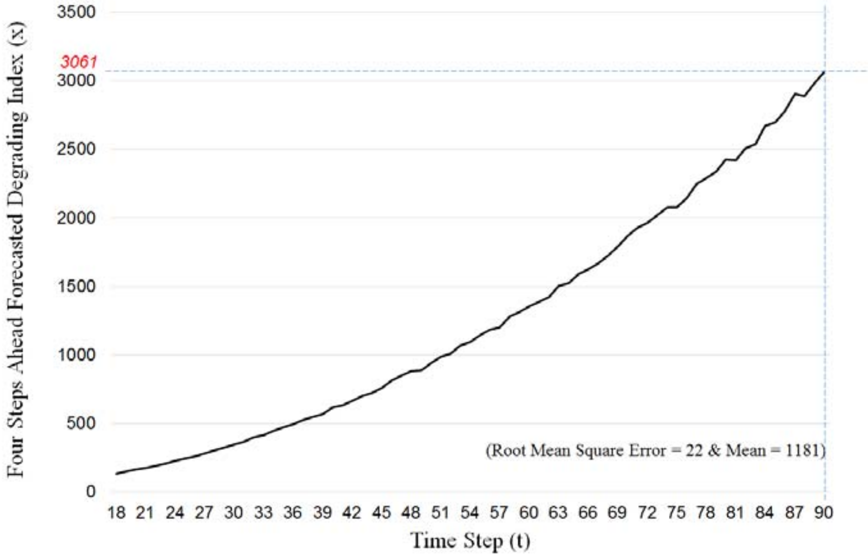

Fig. 7 Four Steps Ahead Forecasted Degrading Index

During the test, the CMMS system automatically built a RAR(5) degrading index model according to the received data from the signal generator while 5th order model had a minimum AIC value shown in the Fig.6. RAR(5) model was adopted to predict when the future degrading index was equal or nearest to preset threshold degrading index of 3,000. For the result shown in Fig. 7, the degrading index of 3061 was reached at 90th step which was forecasted at the 86th step. Time for four steps ahead forecasting (90th - 86th) was 8 weeks as 2 weeks was for each sampling time step. RUL was considered as 8 weeks which was equal to the preset RT of 8 weeks. As such, work requested was triggered automatically at 86th step to allow 8 weeks for component delivery and overhaul subcontracting. Also, the root mean square error of 22 and the mean of 1181 were found based on the following equation (6.1). The error-to-mean ratio of 1.86% (i.e. 22÷1181) comprised of two parts with one part an accumulated inaccuracy of multiple forecasting steps and the other part of ±1% pure random and uncorrelated in each raw signal is considered acceptable.

$$Root\ Mean\ Square\ Error = \sqrt{\frac{\sum_{i=t}^{N}(X_i - \bar{X})^2}{N}} \quad (6.1)$$

where X_i is the ith set of actual degrading index originated from the signal generator, X is the forecasted degrading index from RAR(5) model built in CMMS and N is number of signal.

Using the equation (6.2), the forecasting accuracy for degrading index of 99.18% was found at the time step of 90. In this case, the degrading index is vibration magnitude that is likely possible to indirectly represent the wearing of pump shaft's bottom bush which is submersed in sewage during operation. The inaccuracy of 0.82% for predicting the bush's wearing is acceptable in industry.

$$\text{Forecasting Accuracy \%} = \left(1 - \frac{\sqrt{(X_i - \bar{X})^2}}{X_i}\right) \times 100\% \quad (6.2)$$

$$= \left(1 - \frac{\sqrt{(3036 - 3061)^2}}{3036}\right) \times 100\% = 99.18\%$$

7. Conclusion

Though SCADA and CMMS has been adopted in various sewage treatment works and pumping stations of DSD, in this study, condition monitoring with the methodology of RAR for assessing RUL of the equipment is performed and integrated to the Plant's CMMS and SCADA as a part of equipment diagnostic program for the optimization of asset management system. Plant operation, maintenance and resource management is utilized seamlessly under this platform integration. Meanwhile, the proposed RUL forecasting modelling is verified and proved with high accuracy by numerical simulation. This equipment life forecasting model will be further validated by field experimental test and to be implemented for various equipment.

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