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# Challenges of Adopting Knowledge-based Building Information Modeling for E & M Asset Management Supplemented with Mobile Solutions–A Case Study in Public Sewage Pumping Facilities

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**Abstract:** Digital innovations in connection with the Building Information Modeling (BIM) enable better integration and interaction of various forms of building information and data created throughout the lifecycle of the facilities concerned. However, without widely accepted role model or practical framework on BIM-integrated building maintenance, many maintenance professionals might consider BIM implementation and asset management as isolated practices and would find it difficult to retrieve and use relevant BIM-derived information for asset-related decision making and monitoring when taking over the as-constructed BIM model in project completion stage, resulting in significant reduction in efficiency and productivity in asset management (AM). The purposes of this paper were (i) to summarize the major obstacles in use of BIM as far as maintenance personnel are concerned; (ii) propose steps in setting up AM-customized BIM requirements in early modeling stage to avoid information loss when going through different life cycle stages and (iii) develop a practical methodology with work practices to use BIM in maintenance phase. A case study of BIM deployment in asset management of electrical & mechanical (E&M) facilities in a typical public sewage pumping station serves as an example showing how challenges are experienced and overcome. The findings of the study indicate that there is a high potential for BIM benefits in asset management provided that an over-arching BIM corporate strategy, interoperability of BIM model integrated with in-service maintenance management system, and customized user applications in work routines are implemented.

**Keywords:** BIM, COBie, Asset Management, Fault Tree Analysis, Paperless Workflow, Color-Code Asset Health Index

## 1. Introduction

Accumulated historical data is essential for maintenance professionals in asset-related planning, monitoring and decision. However, for existing buildings, incomplete, outdated or fragmented information in as-built documentation are commonplace, resulting in time loss and increased start-up cost in addition, alteration and maintenance works, as well as ineffective life-cycle management for building elements. Those data in the form of drawings, testing reports, maintenance records, and etc are normally text based and are not systematically connected, making the correlation of building performance with various systems and components time consuming and less efficiency. In nowaday practice, maintenance personnel often use Computerized Maintenance Management System (CMMS) together with Supervisory Control & Data Acquisition System (SCADA) to monitor asset operating conditions; issue work orders for preventive and predictive maintenance; record and track equipment; add inspection & maintenance data; maintain replacement parts inventory and arrange maintenance labour scheduling. But, such IT systems are mainly for information sharing, with less emphasis on interactive knowledge-based capture techniques (i.e. case-based reasoning) and parent-child interrelations between various building systems and components [1]. In addition, information has not been captured from the maintenance operations managed by CCMS and SCADA systems to analyze how a building has deteriorated or plan proactive maintenance actions.

The emergence of Building Information Modeling (BIM) provides digital representation of the physical and functional characteristics of an asset and serves as one of the new information and communication technology (ICT) approaches for creating, exchanging and managing asset lifecycle data across all planning, construction, operation and maintenance functions [2]. It is well proven in previous studies [3-5] that the adoption of BIM had concentrated in design and construction stages, with different functionality such as crash analysis, simulation, scheduling, space management, risk scenario planning etc, is beneficial to the project works, by virtue of improved productivity, better coordination, reduced error as well as rework and better time-cost trade-off balance. Recently, the research focus of BIM has shifted to knowledge-based asset management stage covering maintenance, refurbishment, de-construction (i.e. end-of-life consideration [4] covering the longest life span of buildings [4]). The goal of asset management is to optimize asset use and manage all maintenance efforts involved in making assets as reliable, accurate, and efficient as possible. However, there is no well accepted model or work routines based on BIM principle to provide a generic IT solution provided or collaborated by the principles of BIM to facilitate capturing, retrieving and analyzing knowledge from all related building elements in maintenance operations in response to failures. Therefore, BIM in asset management is not widely used in maintenance industry yet. In view of this, some studies have proposed that BIM comprising ICT frameworks and tools could support maintenance operations to manage accurate building information over a whole building life cycle for all related asset elements in terms of data management.

Several BIM applications in asset management have therefore been developed. For instance, Motawa and Almarshad [1] have developed BIM-integrated Case-Based Reasoning module to capture and model knowledge learnt from previous incidents to diagnose failure causes and suggest solutions of various reactive maintenance actions in buildings; Eastman and Teicholz [6] have introduced the use of Construction Operation Building Exchange (COBie) standard to store the BIM-derived asset information in a structured way, enabling an automatic transfer of information to asset management system with the most minimal manual data entry; Motamedi et al [7] has investigated the BIM-based visual automated analytics for visualizing the possible failure root-cause detection; Mohandes et al [8] has identified different applicable areas in facility management such as locating building elements, creating digital asset-related information, managing space utilization, planning emergency events, monitoring energy utilization etc.

The above literatures focus on integration of BIM in building facilities management. Very few studies have focused on the feasibility of integration between BIM and AM in sewage handling facilities as well as the practicable protocols for BIM-AM implementation in the wastewater industry. In the form of a case study, this paper aims to summarize and discuss the challenges, applicable areas and practical solutions of the trial application of BIM in managing electrical & mechanical assets in a typical public sewage pumping station.

# 2. Methodology

## *2.1. General*

Drainage Services Department (DSD) of the Government of the Hong Kong Special Administrative Region manages over 230 nos. of public sewage pumping stations in Hong Kong. An ISO55001-recognized asset management (AM) system has been implemented in DSD since 2014 to optimize the long-term operation and maintenance of electrical & mechanical (E&M) assets. A typical 3-storey Ma On Shan Area 108 Sewage Pumping Station, with a total sewage handling capacity of 42,100 $m^3$/day, is selected the trial implementation of BIM-AM integration works in DSD. The schematic diagram and layout of the public sewage pumping station are shown in Figure 1.

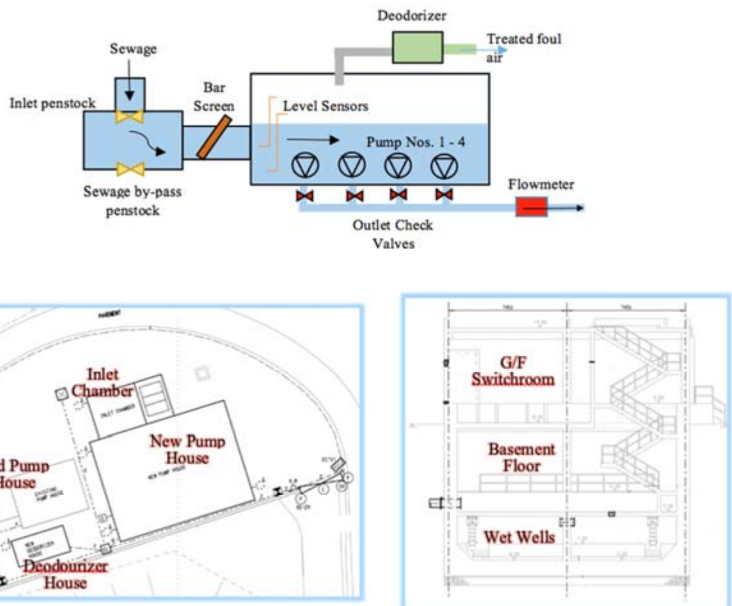



***Figure 1.*** *Schematic diagram and layout of the Ma On Shan Area 108 Sewage Pumping Station.*

### *2.2. Coordination Tools Used*

At present, the construction industry mostly uses Auto CAD platform with ".dwg" file format for creation of 2D drawings. In our case study, Autodesk BIM platform is used to ease of exchange of data among 2D drawings, BIM model, commercial BIM visual analytics and commercial mobile platform. Table 1 shows the coordination tools used under the case study.

***Table 1.*** *Coordination tools used.*

| Coordination tools | Products |
|---|---|
| BIM modeling | Autodesk Building Design Suite Ultimate 2015 |
| BIM visual analytic | Autodesk BIM 360 Glue; Autodesk A360; Fuzor |
| Mobile platform | Autodesk BIM 360 field; SnagR |

### *2.3. Procedures*

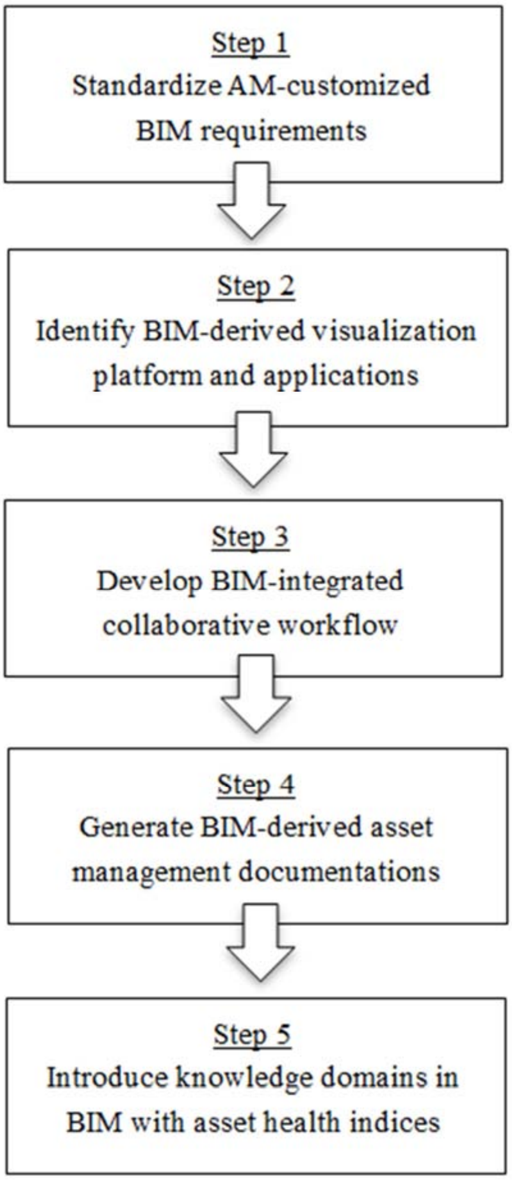



***Figure 2.*** *Workflow of the trial implementation.*

The trial implementation of BIM-AM integration is divided into 5 steps illustrated in Figure 2. Step 1 involves the standardization of AM-customized BIM requirements before the start of BIM modeling, which involves asset inventory, AM-customized model hierarchy, asset data and data-related process. Step 2 is to identify the platforms and applications for BIM-derived visualization in terms of walkthrough and navigation. Step 3 is to develop a framework on BIM collaborative paperless workflow, supplemented with a mobile platform for site management tracking, site safety & environmental planning and defect management. Step 4 involves creation of workflow for generating BIM-derived asset management documentations. Lastly, Step 5 introduces knowledge domains in BIM by creating color-coded asset health indices generated by fault tree analysis.

## 3. Obstacles of BIM Implementation in Asset Maintenance

In this section, some common challenges faced by the asset maintenance industry and specific problems encountered in our case study while adopting BIM in maintenance stage are discussed. Assets include buildings and equipment.

### *3.1. Overlooking Asset Maintenance Requirements*

The rate of BIM adoption in asset maintenance industry is considered very low. The most dominant factor may be that BIM designers are generally lack of asset operational knowledge and maintenance experience. As a result, a typical BIM model is normally developed for design and construction functionalities only, overlooking essential asset-related information and documents required for the subsequent asset operation and maintenance phase [4]. Such a model may only meet part or even none of the organizational asset maintenance needs. On the other hands, asset maintenance personnel do not always know how to use the as-constructed BIM model. They may also have no idea as to what BIM-derived information they may possibly get for making maintenance-related decisions and what BIM applicable areas they could use to facilitate their work routines. Consequently, they may not want to pay for the maintenance, update and use of the as-constructed BIM models in their maintenance activities even though the models are the basic products of every project after construction, leading to wastage of previous efforts/resources in modeling as well as information in the models. The lesson learnt in our case study is that early involvement of maintenance personnel in the modeling stage is essential for creating agreed model fundamentals and proof-of-concept framework. In that way, it is easier to eliminate any barrier between BIM modelers and asset maintenance personnel, and introduce BIM to plant management as new tools to facilitate their work.

### *3.2. Non-compatible Data Standard and Quality*

Data standard and quality are crucial to the functionality of BIM applications [4]. However, the model fundaments on geometric and non-geometric attributes may not be well defined and standardized in design stage. Consequently, large amounts of data collected in BIM model during design and construction stages cannot be migrated automatically into the databases of existing maintenance management system, resulting in large time and cost implications for re-entry of BIM-derived data and documentations. Therefore, AM-customized BIM requirements on data standard and quality in early modeling stage is essential to avoid information loss during information progressing between different life cycle stages. To avoid re-work, the lesson learnt in our case is that the required attributes under different levels of details, model hierarchy for asset information, compatible database export format from BIM model and other model definitions should be carefully studied through discussions and interviews with plant management before the start of modeling work. These aims to ascertain and agree on information needs, data fields and compatible data transfer format for smooth introduction of BIM process in the existing asset maintenance management system.

### *3.3. Diversity and Interoperability of BIM and AM Software*

The high initial cost of BIM software is always a main issue when deciding on investment in BIM. In addition, there are not many software programs capable of doing all tasks in a cost-efficient manner. Organizations are therefore reluctant to or incapable of forcing BIM use based on proprietary standards and software [3]. To enhance data exchange between different BIM software and AM systems, there is a need to unify the information content of BIM with open and non-proprietary standards, where BIM and AM software packages are able to communicate with each other for current and future needs. In our trial BIM-AM integration, graphical model was stored in open Industry Foundation Class file (IFC) format for data management. The project numerical/textual data was categorized under ISO-derived OmniClass Construction Classification (OmniClass) and organizational specific classifications in an object-oriented manner. Parent-child relationships were established among different model elements. Eventually, the project data and documentations were stored in non-proprietary Construction Operations Building Information Exchange (COBie) standard to allow open data exchange in a structured way.

### *3.4. Immature Competency of In-House Skillsets*

Without adequate skillsets and knowledge, new BIM tools can hardly be introduced. This may lead to a situation where the project team does not know what they need in a BIM-implemented project work. As a result, no essential tools can be identified to satisfy the current and future needs. Consequently, BIM, if any, has to be implemented in a rush or the BIM implementation job has to be outsourced. In any case, the outcome could still be satisfactory but the organization cannot be self-sustainable in in-house skillset development [2]. Regarding the high demand of advanced features required by the highest level of BIM, full implementation will take lots of time. Our trial concentrates on developing a proof-of-concept framework for integration between BIM and AM. Three fundamental skillsets that have been developed for starting BIM-AM integration are (i) to create common shared parameters in BIM for maintaining E&M systems in various projects in meeting current and future needs; (ii) to establish automatic database linkage between BIM and AM software; and (iii) to capture knowledge or intelligence from BIM to enhance maintenance.

### *3.5. Absence of Real Cases Demonstrating Return of Investment*

The high cost of BIM implementation, which includes the costs for hardware, software, programs and supporting mobile applications, always deters asset maintenance personnel from using BIM. If data on the possible cost savings of BIM implementation on maintenance process is collected and analyzed, maintenance personnel would be more convinced to pay the associated BIM costs [8]. However, the determination of what to measure to justify use of BIM in maintenance stage are challenging and in lack of consistency.

## 4. AM-Customized BIM Requirements

To facilitate the automatic transfer of asset data captured in design and construction stages for future operational use, the standardization of asset data should be properly defined under the framework of ISO 55001-recognized asset management at the start of modeling work. To ensure smooth data transfer to the in-service maintenance & management system, the required attributes, level of details, level of development, model hierarchy and compatible file transfer format for asset data can be determined by taking the following 5 steps.

### *4.1. Step 1-identify Asset Inventory*

Good quality of asset data is essential for creating “asset health index” and “identifiable criteria” for BIM-aid decision marking of implementing knowledge domains in BIM. To capture good asset data in BIM, the existing mechanism under the in-service asset management system governing the types of assets, associated attributes and documentations should be followed in the BIM modeling work. For the sewage pumping station under our trial, 15 nos. E & M assets listed in Table 2 were modeled. 8 out of the 15 nos. E&M equipment were considered as critical assets, as they would adversely affect the normal operation of the sewage pumping stations if they were accidentally out of service.

***Table 2.*** *E&M asset inventory for typical sewage pumping station.*

| Item | Name of E&M assets | Asset location | Criticality |
|---|---|---|---|
| 1. | Penstocks | Inlet Chamber | Critical asset |
| 2. | Screenings | Inlet Chamber | Critical asset |
| 3. | Pumps | Wet Well | Critical asset |
| 4. | Pipeworks and valves | Dry Well | Critical asset |
| 5. | Deodourizers | Deodourizer Room | Critical asset |
| 6. | Lightings | Pump House | Non-critical asset |
| 7. | Switchboards | Switchroom | Critical asset |
| 8. | Building services installation | Pump House | Non-critical asset |
| 9. | Fire services installation | Pump House | Non-critical asset |
| 10. | Lifting appliances | Pump House | Non-critical asset |
| 11. | Emergency generator | Pump House | Non-critical asset |
| 12. | Flowmeter | Dry Well | Non-critical asset |
| 13. | Level sensor | Wet Well | Critical asset |
| 14. | Supervisory Control & Data Acquisition System | Pump House | Critical asset |
| 15. | Closed Circuit Television & Access Control | Pump House | Non-critical asset |

### *4.2. Step 2-AM-customized Model Hierarchy*

The BIM model elements for assets should be grouped in accordance with the organizational ISO 55001 specific classification, such that they fulfill the parent-child relationships of different model elements and storing project data in COBie structured format. Table 3 shows the typical mapping table of model hierarchy and COBie sheets for one critical asset (i.e. screenings in the sewage pumping station) in our trial.

***Table 3.*** *Mapping table of model hierarchy and COBie sheets against ISO55001 asset hierarchy.*

| ISO 55001 | | BIM Model Element | | Example |
|---|---|---|---|---|
| Asset hierarchy | Asset Entity | Model Hierarchy | COBie Sheets | |
| 1st level | Plant | --- | Facility | Ma On Shan 108 SPS |
| 2nd level | Location | --- | Floor, Space, Zone | Inlet Chamber |
| 3rd level | Area/System | Tier 1–Sub process | System | Screenings |
| 4th level | Main equipment | Tier 2–Asset group | Component, Attribute, Type | Bar Screen |
| 5th level | Parent-child relationship (optional) | Tier 3–Component group | Assembly | Chain, motor, drive shaft, rakes, gripper |

### *4.3. Step 3-define Asset Data*

The appearance of a BIM model is only one piece of information about an E&M asset and is usually the least important. The information richness of a BIM model is represented by Level of Development and Level of Details, defining the level of clarity and amount of information about the attributes respectively. Each E&M asset in a BIM model should be designed, defined and updated with specific attributes according to certain Level of Detail at different Level of Development. It shall come from three sources: (1) specific project attributes; (2) current attributes stored and managed in in-service maintenance & management system (MMS); and (3) additional attributes as and when required by O&M team, which may not be stored and managed in MMS. Table 4 summarizes all of the designed attributes of the assets while Table 5 shows an example of designed attributes and documentations at different Level of Development for one critical asset (i.e. a pump) in a typical sewage pumping station.

***Table 4.*** *Designed attributes of E & M assets in a sewage pumping station.*

| | | | |
|---|---|---|---|
| Common attributes: | | • Entity name<br>• Entity location<br>• Entity number<br>• Entity type<br>• Entity classification<br>• Entity manufacturer<br>• Place of origin<br>• Entity model / serial number<br>• Manufacturer contacts | • Expected lifetime<br>• Installed date<br>• Entity status<br>• Service date<br>• Defect liability end date<br>• Original price amount<br>• Preventive maintenance job type<br>• Spare parts details |
| Specific attributes : | Penstocks | • Dimension of opening<br>• On and off seat head<br>• Weight<br>• Material frame | • Spindle material<br>• Seating face / wedge face<br>• Door nuts |
| | Screenings | • Overall dimensions<br>• Screen bar cross-sectional dimension<br>• Bar spacing<br>• Flow rate<br>• Voltage | • Material<br>• Weight<br>• Speed<br>• Torque<br>• Efficiency |
| | Pumps | • Application media<br>• Solid handling capacity<br>• Material<br>• Flow rate<br>• Head<br>• Diameter | • Pump speed<br>• Motor rating<br>• Direct on line / full load current<br>• Power factor / efficiency<br>• Weight |
| | Pipeworks & valves | • Test standard<br>• Class / thickness<br>• Diameter<br>• Pressure rating | • Test pressure<br>• Working pressure<br>• Material<br>• Weight |
| | Deodourizers | • Type<br>• Overall dimensions<br>• Air flow capacity<br>• Retention time<br>• Pressure drop | • Material<br>• Impregnated material<br>• Power rating<br>• Weight |
| | Lightings | • Application (Indoor/outdoor)<br>• Quantity | • Insulation class<br>• Power rating |
| | Switchboards | • Test standard<br>• Application (Indoor/outdoor)<br>• Insulation class<br>• Overall dimensions<br>• Rated operational voltage | • Rated current<br>• Busbar cross-section area<br>• Busbar short-time/fused short-circuit current<br>• Battery mode / life<br>• Weight |
| | Building services installation | • Test standard<br>• Application (Indoor/outdoor)<br>• Cooling capacity (if applicable) | • Overall dimensions<br>• Rated current<br>• Weight |
| | Fire services installation | • Test standard<br>• Application (Indoor/outdoor) | • Overall dimensions<br>• Weight |
| | Lifting appliances | • Safe working load<br>• Span gantry rail<br>• Traveling speed | • Total lift for hoist<br>• Motor rating<br>• Weight |
| | Emergency generator | • Rated power<br>• Frequency<br>• Output power | • Maximum continuous rating<br>• Weight |
| | Flowmeter & level sensors | • Nominal diameter<br>• Measurement range | • Insulation class<br>• Weight |
| | Supervisory control & data acquisition system | • Maximum memory<br>• Memory type<br>• Battery model / life<br>• Total I/O maximum | • Analog I/O<br>• Humidity range<br>• Mean time between failure<br>• Weight |
| | Closed circuit television and access control | • Len size<br>• Len resolution<br>• Insulation class<br>• Optic / electronic zoom<br>• Material<br>• Hard disk capacity | • Numbers of channel<br>• Video monitor output<br>• Video capturing speed<br>• Capacity<br>• Weight |

***Table 5.*** *Designed attribute table for a critical asset (i. e. pump) in sewage pumping station.*

| LOD | Proposed attributes | Level of Details ( Example) | Supplementary documentation |
|---|---|---|---|
| LOD 100 | Entity name | Ma On Shan Area 108 SPS | Design COBie spreadsheet. |
| LOD 200 | Entity location | Main Pumping Station | |
| LOD 300 | Entity number | 14273 | |
| LOD 300 | Entity type | Sewage pump | |
| LOD 300 | Entity classification | Submersible Pump No. 1 | |
| LOD 400 | Entity manufacturer | ABC | Construction COBie spreadsheet.<br>Approved equipment letters and product catalogue.<br>Approved civil work requirement & general arrangement drawings.<br>Mill certificate.<br>RFI inspection reports.<br>Material-on-site reports.<br>T&C reports<br>Site photos/video clips.<br>Incident reports |
| LOD 400 | Place of origin | Switzerland | |
| LOD 400 | Entity model/serial number | H08K-H03R | |
| LOD 400 | Application media/Solid handling capacity | Sewage / 145 mm | |
| LOD 400 | Material | Cast iron grade 260 | |
| LOD 400 | Flow rate | 162 l/sec | |
| LOD 400 | Head | 33.7m | |
| LOD 400 | Diameter | Impeller : 410mm<br>Inlet : 250 mm<br>Discharge : 200 mm | |
| LOD 400 | Pump speed | 1485 RPM | |
| LOD 400 | Motor rating | 110 kW | |
| LOD 400 | DOL/full load current | 1431 / 202 | |
| LOD 400 | Power factor/efficiency at full load | 0.88 / 93% | |
| LOD 400 | Weight | 318 kg | |
| LOD 400 | Expected life time | 20 years | |
| LOD 400 | Installed date | 1/5/2008 | |
| LOD 400 | Manufacturer contacts | ABC website | |
| LOD 500 | Entity status | Operating | As-built COBie spreadsheet<br>As-fitted drawings.<br>Final O&M manual.<br>Spare part list<br>Training manual |
| LOD 500 | Service date | 12/6/2009 | |
| LOD 500 | DLP end date | 12/6/2010 | |
| LOD 500 | Original price amount | $ 150,000 | |
| LOD 500 | PM job type | 1) Oil check after first 1000 hrs and once a year thereafter.<br>2) Replace oil if oil is contaminated. | |
| LOD 500 | Additional spare part name | 2 sets of stainless steel impellers | |

### *4.4. Step 4-fix and Execute the Data-Related Process*

Microsoft Excel file has been used for collecting data on equipment from respective equipment designers, contractors and suppliers. The file is for feeding information onto in-service maintenance & management system over the past decades [8]. The import of project data was already not a problem as per the perspective of current various maintenance & management system. The ways of adopting an open file data transfer in which Excel file from BIM model for importing the project data automatically to the in-service maintenance & management system was one of the main focus of this case study. Worksheets to COBie standard are in form of Excel format. They serve to classify project data in different information categories and relationships in different sheets. Those data should be updated consistently throughout various project stages to keep the underlying asset-related information embedded in the model updated, while the model may not change visually in appearance if dimension-related information is not amended. The timing of COBie data transfer from design BIM model in design stage to as-operated BIM model in handover stage could be determined based on the specific requirement of project office. Table 6 shows that the framework of COBie data drop could be determined in 4 steps from Data Drop 1 to Data Drop 4.

***Table 6.*** *COBie data drop approach.*

| Item | Project Stage | COBie Approach | COBie Sheet Name | COBie Sheet Contents |
|---|---|---|---|---|
| 1. | Early design | Data Drop 1 (30% of asset-related information contained) | Contact | People and companies |
| | | | Facility | Project, Site, and Facility |
| | | | Floor | Vertical levels and exterior areas |
| | | | Space | Spaces |
| | | | Zone | Sets of spaces sharing a specific attributes |
| | | | Type | Sets of spaces sharing a specific attribute |
| | | | Attribute | Properties of referenced item |
| | | | Coordinate | Spatial locations in box, line, or point format |
| 2. | Detailed design | Data Drop 2 (50% of asset-related information contained) | Contact | People and companies |
| | | | Component | Individually named or schedule items |
| | | | System | Sets of components providing services |
| | | | Type | Sets of spaces sharing a specific attribute |
| | | | Assembly | Constituents for Types, Components and others |
| | | | Connection | Logical connections between components |
| | | | Impact (if any) | Economic, Environmental and Social Impacts at various stages in the life cycle |
| | | | Attribute | Properties of referenced item |
| | | | Coordinate | Spatial locations in box, line, or point format |
| | | | Issue (if any) | Other issues remaining at design |
| 3. | Construction | Data Drop 3 (90% of asset-related information contained) | Contact | People and companies |
| | | | Type | Types of equipment, products, and materials |
| | | | Component | Individually named or schedule items |
| | | | Document | All applicable document references |
| | | | Attribute | Properties of referenced item |
| | | | Coordinate | Spatial locations in box, line, or point format |
| | | | Issue (if any) | Other issues remaining at construction. |
| 4. | O&M | Data Drop 4 (100% of asset-related information contained) | Contact | People and companies |
| | | | Spare | Onsite and replacement parts |
| | | | Resource | Required materials, tools, and training |
| | | | Job | PM, Safety, and other job plans |
| | | | Document | All applicable document references |
| | | | Attribute | Properties of referenced item |
| | | | Coordinate | Spatial locations in box, line, or point format |
| | | | Issue | Other issues remaining at handover (defect lists) |

### *4.5. Step 5-introduce Knowledge Domain in BIM*

The availability of reliable asset-related information such as details of spare part is vital for effective asset management, as it supports decision making, planning and execution of work in operation and maintenance phase. Although maintenance personnel may have an on-line supervisory control & data acquisition system (SCADA) overseeing the asset operating status, it cannot provide early warnings on any fault symptoms or deteriorating status if those monitoring parameters or sensors are not condition-based type as well as the SCADA control philosophy is not based on fault tree concept. As a result, traditional regular on-site inspection and maintenance still involve survey of asset condition to find out any pre-mature fault symptoms. Despite of this, unexpected equipment outage still cannot be easily identified in early stage.

Intelligence management may be realized in future, but to date, decision making during the asset life cycle still relies on the experience of maintenance personnel. Introduction of BIM would supplement the in-service maintenance & management system on asset health monitoring if a knowledge domain is embedded in BIM, which establishes relationships between assets and knowledge related to the possible causes of critical failures of asset elements. So, this trial implementation tries to set up a proof-of-concept framework to convert the asset risk register and failure causes for the assets in a typical sewage pumping station. Based on a fault tree concept, data related to identifiable major fault symptoms of critical assets could be consistently recorded, stored and analyzed through BIM-integrated mobile applications using predefined electronic asset inspection forms.

#### *4.5.1. Fault Tree Analysis for Critical Incident*

In a typical sewage pumping station, one of the most critical incidents to be avoided is sewage by-pass (overflow), probably due to outage of critical assets. By using a fault tree analysis, probabilistic risk assessment can be made to model the sequences of such incident, including various events leading to the incident and associated symptoms. Figure 3 shows the fault tree for a sewage by-pass incident. It sets out the possible causes of failures and identifiable major fault symptoms according to maintenance records. The incident, its immediate cause and root cause are defined as top, immediate and basic events respectively.

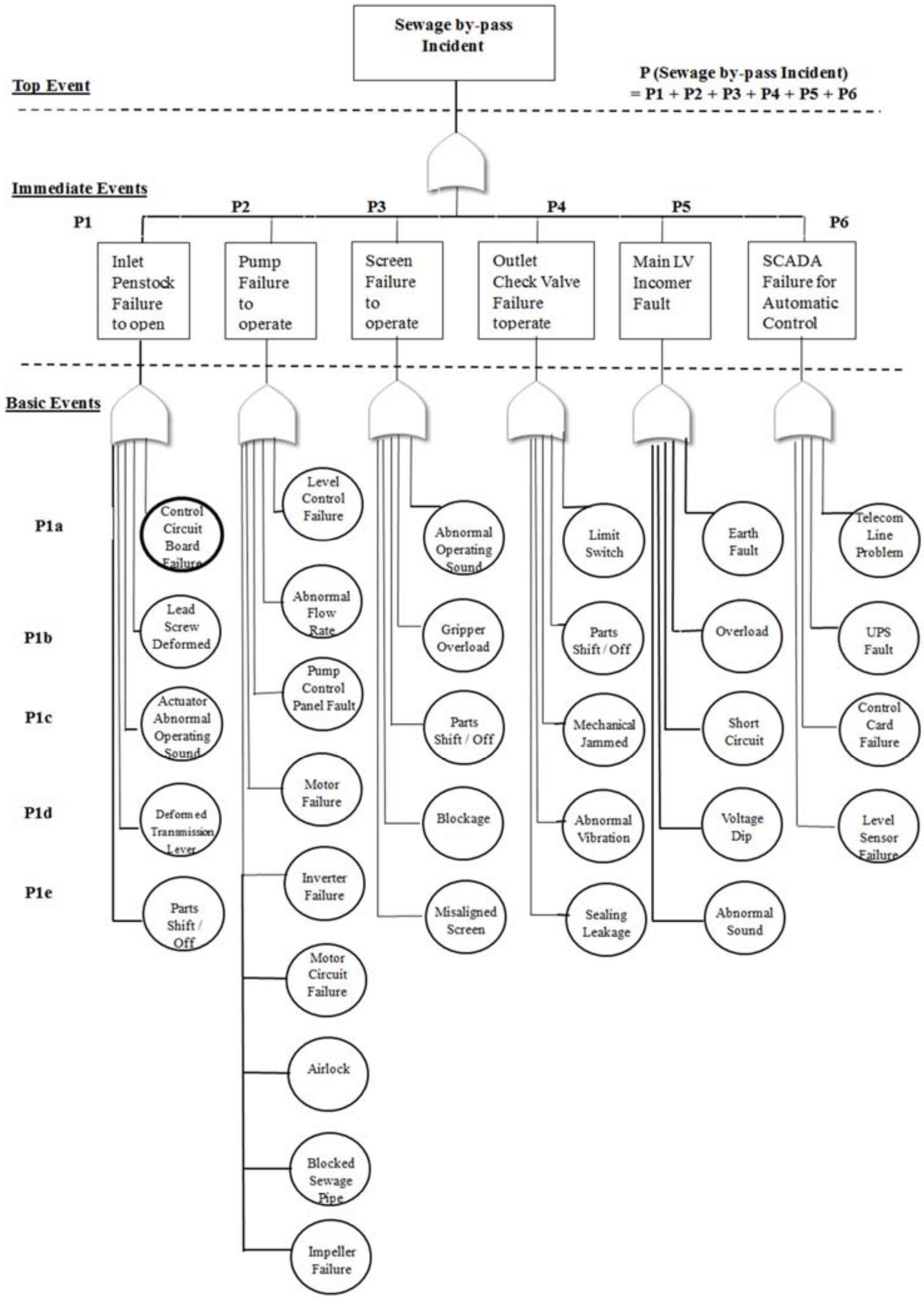



***Figure 3.*** *Fault tree for a sewage by-pass incident of sewage pumping station.*

### *4.5.2. Quantitative Analysis of Fault Tree*

The main events contributing to the sewage by-pass incident can be ranked quantitatively by the fault tree analysis. The occurrence of either immediate or basic failure events can be regarded as a Poisson Process. The process assumes that the probability of a failure event occurring in any specified short-time period is approximately proportional to the length of the time period. The occurrences of failure events in disjoint time periods are statistically independent and events do not occur in the same time [11]. The occurrence of failure events (x) in some fixed period of times is a Poisson distributed variable as follows:-

$$p_x(\mathrm{x}) = \frac{(\mathrm{ht})^x \mathrm{e}^{-ht}}{\mathrm{x}!} \quad (1)$$

Where $p_x$ (x): Probability of x occurrences in a period of time, t

h: Average failure rate per time unit

The failure probability can be calculated from:

$$\mathrm{P}\ (\mathrm{X} > 1) = 1 - p_x(0) = 1 - e^{-ht} \quad (2)$$

Where P (X>1): Probability of one or more failure events

P (0): Probability of no failure events

In case of a sewage by-pass, such incident might occur once in several years and the outage duration of pumping station due to breakdown of critical assets may be in the order of a few days under the worst scenario. A time period of 1 year can be chosen for the fault tree analysis of sewage by-pass incident. The actual incident rate of each fault associated with different critical assets could be statistically calculated according to the monthly data collected from the predefined fault-tree-derived "Monthly Asset Inspection Form" through the mobile solutions by maintenance personnel during their on-site inspection work.

Referring to Figure 3, the failure probability of a sewage by-pass incident can be calculated by adding the probability of all immediate events (P1 + P2 + P3 + P4 + P5 + P6 ), in which the main contribution to the incident can be identified easily. Likewise, the failure probability of immediate failure events can be calculated by summing up all identifiable fault symptoms (Px = Pxa + Pxb + Pxc + Pxd + Pxe, where x = 1 to 6).

#### *4.5.3. Asset Health Index*

The asset condition represented from bad to good can be mapped with an asset condition rating from 1 to 4 respectively through a qualitative analysis of a database integrated with asset inspection results through mobile solutions. Eventually, an asset health index in terms of either "Good Condition in orange color", "Satisfactory Condition in green color", "Alarming Condition in yellow color" or "Bad Condition in red color" could be visualized in a BIM model with predefined color coding, modified from the concepts by A. Motamedi et al [7] and Kyle et al [10]. The proof-of-concept algorithm of the proposed database, for converting the actual accident rate of each identified fault symptoms from the basic failure events in mobile solutions to the visualized asset health index to represent operating condition of an asset in BIM are based on the asset risk register shown in Table 7.

***Table 7.*** *Asset risk register for mapping the failure rate with color-coded asset health index.*

| Likelihood of occurrence of fault symptoms | Failure Rate (Numbers / hour) | | Annual Failure Probability, P (time = 1 year) | |
|---|---|---|---|---|
| Rare (More than 1 per 12 months) | 0.00012 | | 0.630 | |
| Unlikely (More than 1 per 9 months) | 0.00015 | | 0.736 | |
| Possible (More than 1 per 6 months) | 0.00023 | | 0.863 | |
| Likely (More than 1 per 3 months) | 0.00046 | | 0.981 | |
| Almost certain (More than 1 per month) | 0.00138 | | 1.000 | |
| Consequence of failure | | | Rating | |
| Asset still in operation | | | 1 | |
| Asset still in operation but site attendance required | | | 2 | |
| Asset in partial operation | | | 3 | |
| Asset not in operation | | | 4 | |
| Asset Risk Rating (Consequence x Failure Probability) [ α ] | Asset Condition | Asset Condition Rating | | Asset Health Index (Predefined with color code) |
| ≤ 1 | Good | 1 | | Orange |
| 1 < α ≤ 2 | Satisfactory | 2 | | Green |
| 2 < α ≤ 3 | Alarming | 3 | | Yellow |
| 3 < α ≤ 4 | Bad | 4 | | Red |

The visualization color coding in the BIM aims to provide a more user-friendly human-machine interface in plant management. An early warning signal on critical assets' health condition can improve operational efficiency and prioritize asset replacement, without the need of repeatedly analyzing too much maintenance data in in-services MMS and SCADA system.

# 5. BIM-Integrated Maintenance Work Routines

There are many potential maintenance applications of BIM during an asset life cycle. Yet, lots of time would be required if full implementation is needed. To integrate BIM with the existing asset management system, some BIM applicable areas have been identified, tried and tested with a view to meeting current and future operational and maintenance needs. They are discussed as follows.

### *5.1. Creation of Digital Asset Data*

The implementation of BIM in design and construction stages provides a chance for digitalizing asset data in electronic forms to get prepared for future asset handover (from work contractors to asset owner) and to minimize manual import of data to in-service MMS. According to the requirements of maintenance personnel, those AM-customized asset data includes the following, which was embedded in the BIM model shown in Figure 4.

a) Numerical/textual data: Include information on project team, site condition and coordinates, spaces, zone, equipment, materials, attributes, manufacturer/supplier details, historic event/impact logs, spare parts, resource required, safety procedures, maintenance procedures etc under different levels of development.

b) Documentation: Include design reports, equipment submission, product catalogues, drawings, test certificates, inspection/test forms, incident reports, commissioning reports, site photos, video clips, training manuals, O&M manuals, spare part list, inventory list etc under different level of development.

***Figure 4.*** *The digital asset information embedded in each model element.*

Upon completion of project commissioning, the above BIM data structured in COBie sheets could be uploaded and transferred to in-services MMS for supporting work order management, repair and maintenance management, traceable and retrievable data management, as well as efficient distribution of documents and drawings. In case the in-service MMS is not compatible with COBie sheets (as in this trial), a mapping template with customized application program interface should be developed. Figure 5 shows the import of Excel format of MMS to ensure smooth data migration and uploading.

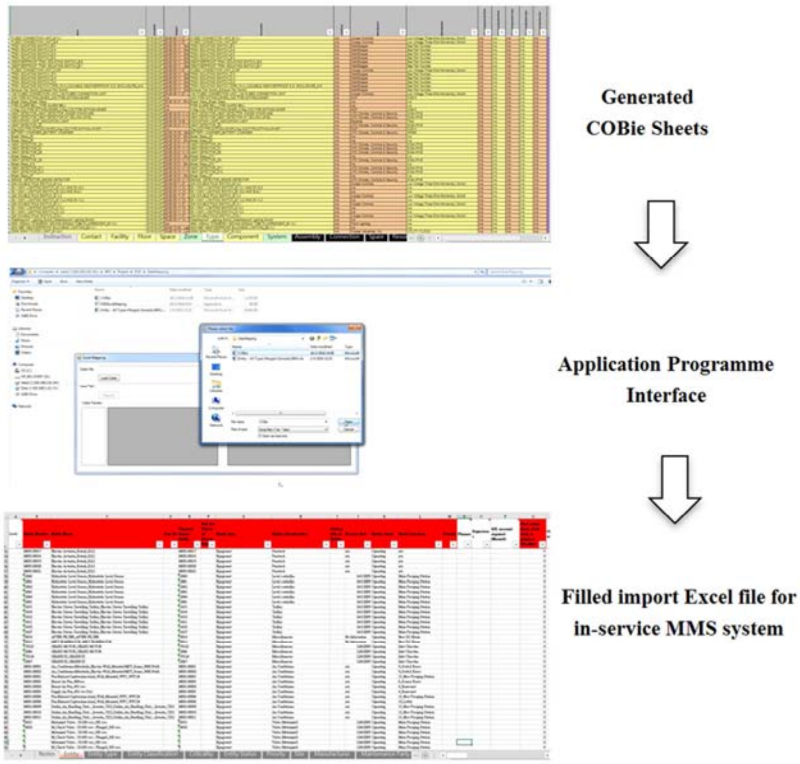



***Figure 5.*** *Application program interface for data migration to the MMS of the case study.*

### *5.2. Visualization of Space and Virtual Asset*

The 3D graphical model of BIM provides a user-friendly human-machine interface (HMI) for improved visualization on walkthrough, navigation, virtual modeling with different settings and animation. This enables a much quicker and cost-effective approach to check the site condition and maintainability of equipment, identification of parts to be repaired or replaced, and enhancement of site safety. This 3D HMI is particularly useful for inspecting those areas in building facades, confined wet well, cable drawpits, trenches, sump pits, emergency tank and sewage piping network in sewage pumping station where normal inspection in person may not be always feasible. This is particularly relevant under certain situation such as lack of access. Figure 6 shows some such situation.

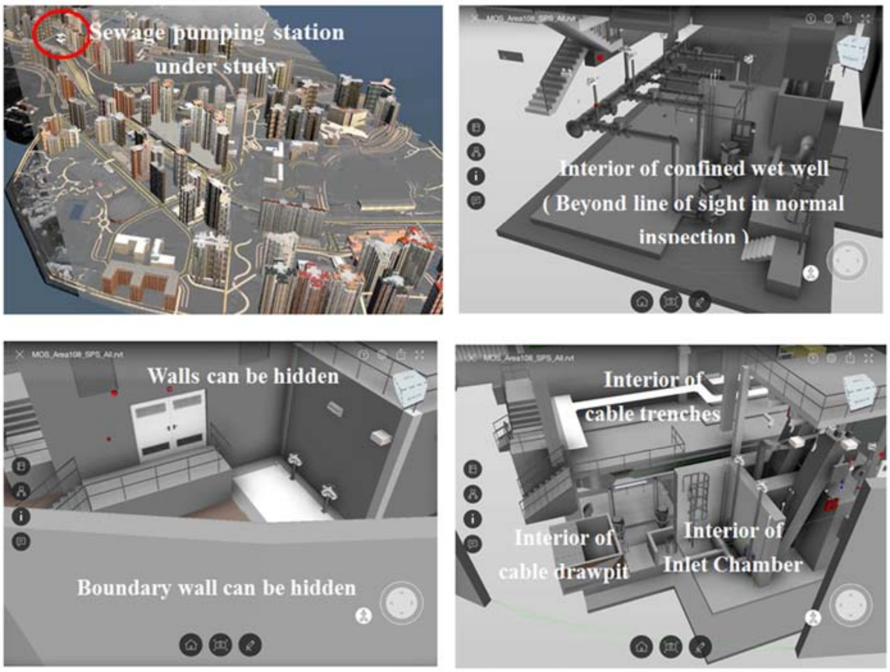



***Figure 6.*** *Real-time access for LIDAR-integrated surrounding environment and interior views for confined space areas for the sewage pumping station under study.*

### *5.3. Adoption of Electronic Paperless Workflow*

BIM could come with 2D field drawings, project data and asset data. With the implementation of the customized application programme interface in BIM model, different predefined layout plans and electronic forms with BIM data could be updated in BIM-mobile applications automatically. This could serve a business intelligence tool to support field maintenance works in a common electronic platform in a paperless manner.

#### *5.3.1. Site Management Tracking*

The potential BIM-integrated mobile application to work routines related to site management are shown in Figure 7. They include:

- Electronic site daily reporting (including site photos, video clip etc) to record daily construction activities in different work areas and get feedback and agreement from contractor timely.
- Electronic Site Early Warning Notice to contractor.
- Electronic Site Staff Instruction Form.
- Electronic material-on-site/T&C inspection system recording the inspection findings together with signature and site photos, and BIM-connected document history such as mill certificate, approved submission, supplier supplementary information etc.

#### *5.3.2. Site Safety/Environmental Planning*

The potential BIM-integrated mobile application to work routines related to site safety and environmental planning are shown in Figure 8. They include:

- Electronic weekly site safety and environmental inspection checklist.
- Electronic confined space operation assessment checklist.
- Electronic monthly mosquito checklist.

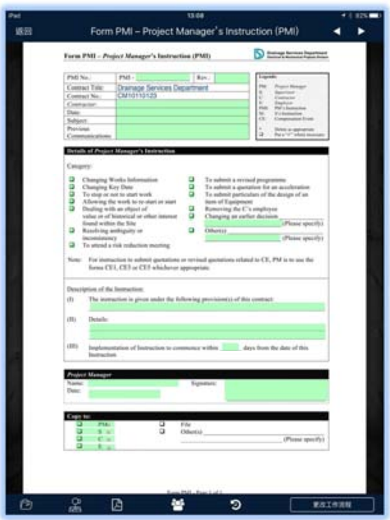
#### *5.3.3. Defect Reporting and Management*

The potential BIM-integrated mobile application to work routine related to defect reporting and management are shown in Figure 9. They include:

- Electronic list of defects with site photos linked to BIM model during routine inspection walks.
- Electronic notification of defects (including equipment breakdown incident)
- Electronic summary on defect rectification statistics and due date alert to get timely feedback from the contractor.

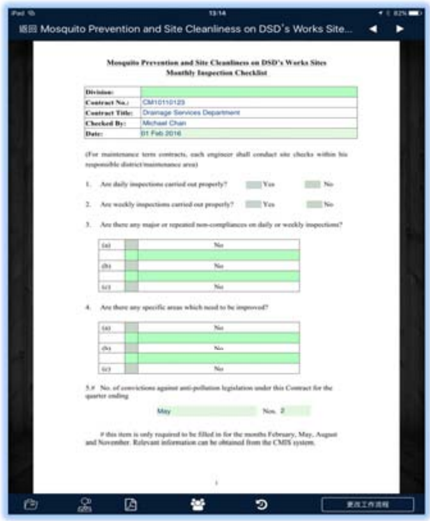
(a) Electronic site daily reporting.


(b) Electronic site diary.

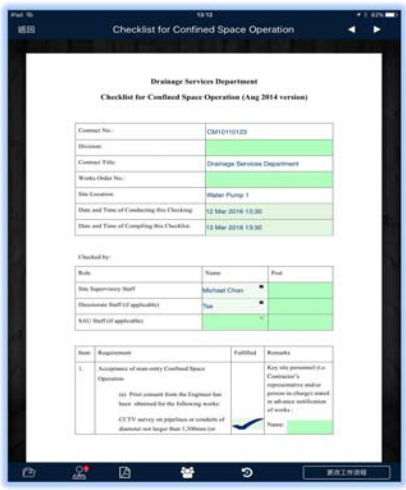



(c) Electronic site staff instruction form.

*Figure 7. BIM-integrated electronic work routines on site management tracking.*



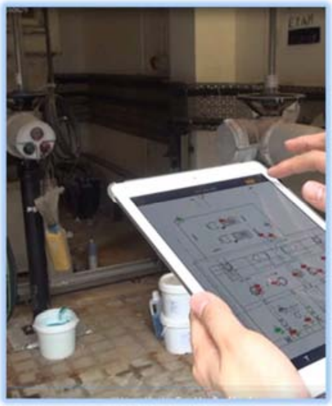

(a) Electronic monthly mosquito checklist.



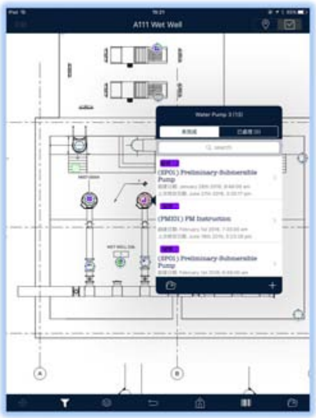

(b) Electronic confined space assessment checklist.


(c) Electronic weekly site safety and environmental inspection checklist.

*Figure 8. BIM-integrated electronic work routines on site safety & environmental planning.*



(a) Electronic notification of defects.




(b) Electronic list of issued defects.


(c) Electronic summary of defect rectification statistics.

***Figure 9.*** *BIM-integrated electronic work routines on defect reporting and management.*

Immediate capturing, recording and analysing of actionable information could be displayed in the dashboards either in web-based portal or mobile solutions for more informed maintenance decisions. It is shown in Figure 10.

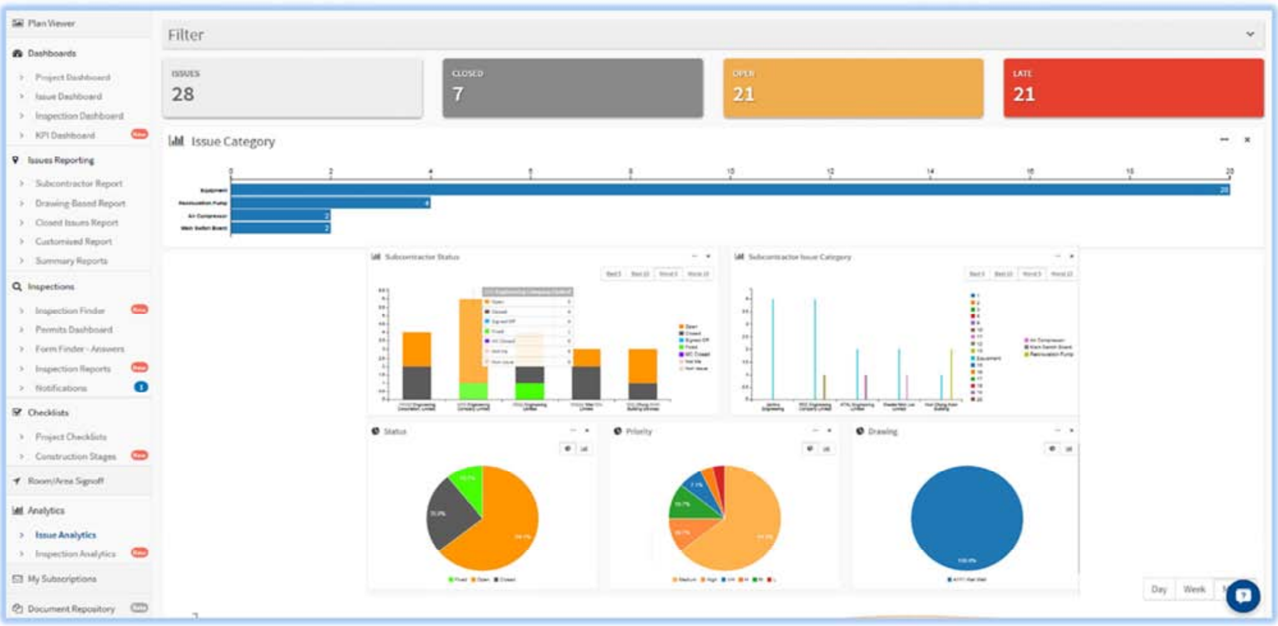


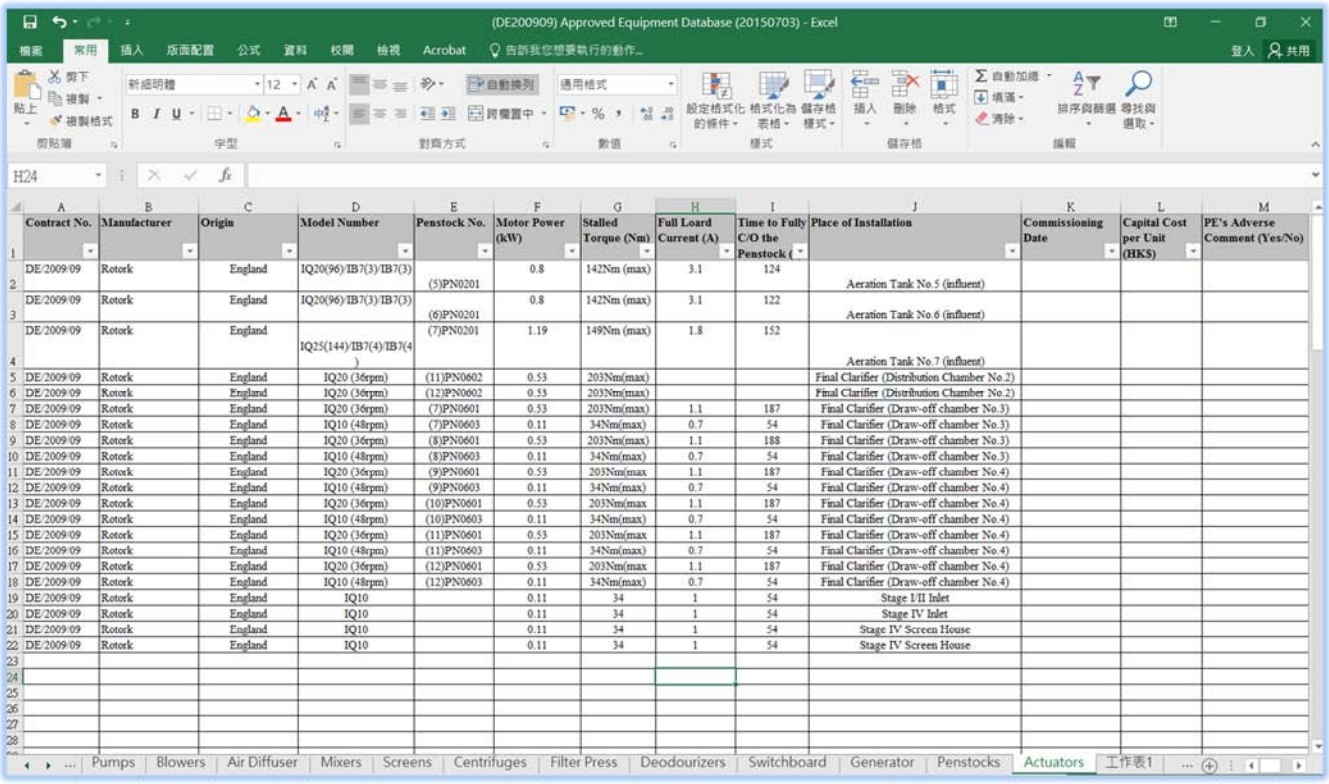

***Figure 10.*** *Dashboards for issue reporting, inspections, checklists and analysis.*

### *5.4. Creation of Asset Management Documentation*

The BIM data in COBie worksheets could be used for generating some initial asset management documents automatically using customized application programme interface at the start, especially the asset is handed over for plant operation and maintenance. The documents may include (i) asset maintenance plan shown in Table 8 and (ii) list of equipment inventory and spare parts as shown in Figure 11.

***Table 8.** Asset maintenance plan for one of the critical assets on pump installation.*

| Asset (Parent) | Critical Parts (Child) | PM frequency | Expected lifetime (years) | Acceptable range | Planned actions |
|---|---|---|---|---|---|
| Pump | Motor | Bi-monthly | 13 | Within service life | Replace bearings within 4 to 6 yrs. Vibration analysis every 5 years. |
| | Pump | Bi-monthly | 60% of full flow rate | Within service life | Record pump flow rate after each PM work. Replace impeller if flow rate below acceptable range of 60%. |
| | PLC | Bi-monthly | 5 | Within service life | Battery discharge test quarterly. |
| | Shaft | Bi-monthly | 18 | Within service life | Alignment check after annual overhaul. |


(DE200909) Approved Equipment Database (20150703) - Excel

| | Contract No. | Manufacturer | Origin | Model Number | Penstock No. | Motor Power (kW) | Stalled Torque (Nm) | Full Loard Current (A) | Time to Fully C/O the Penstock ( | Place of Installation | Commissioning Date | Capital Cost per Unit (HK$) | PE's Adverse Comment (Yes/No) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2 | DE/2009/09 | Rotork | England | IQ20(96)/IB7(3)/IB7(3) | (5)PN0201 | 0.8 | 142Nm (max) | 3.1 | 124 | Aeration Tank No.5 (influent) | | | |
| 3 | DE/2009/09 | Rotork | England | IQ20(96)/IB7(3)/IB7(3) | (6)PN0201 | 0.8 | 142Nm (max) | 3.1 | 122 | Aeration Tank No.6 (influent) | | | |
| 4 | DE/2009/09 | Rotork | England | IQ25(144)/IB7(4)/IB7(4) | (7)PN0201 | 1.19 | 149Nm (max) | 1.8 | 152 | Aeration Tank No.7 (influent) | | | |
| 5 | DE/2009/09 | Rotork | England | IQ20 (36rpm) | (11)PN0602 | 0.53 | 203Nm(max) | | | Final Clarifier (Distribution Chamber No.2) | | | |
| 6 | DE/2009/09 | Rotork | England | IQ20 (36rpm) | (12)PN0602 | 0.53 | 203Nm(max) | | | Final Clarifier (Distribution Chamber No.2) | | | |
| 7 | DE/2009/09 | Rotork | England | IQ20 (36rpm) | (7)PN0601 | 0.53 | 203Nm(max) | 1.1 | 187 | Final Clarifier (Draw-off chamber No.3) | | | |
| 8 | DE/2009/09 | Rotork | England | IQ10 (48rpm) | (7)PN0603 | 0.11 | 34Nm(max) | 0.7 | 54 | Final Clarifier (Draw-off chamber No.3) | | | |
| 9 | DE/2009/09 | Rotork | England | IQ20 (36rpm) | (8)PN0601 | 0.53 | 203Nm(max) | 1.1 | 188 | Final Clarifier (Draw-off chamber No.3) | | | |
| 10 | DE/2009/09 | Rotork | England | IQ10 (48rpm) | (8)PN0603 | 0.11 | 34Nm(max) | 0.7 | 54 | Final Clarifier (Draw-off chamber No.3) | | | |
| 11 | DE/2009/09 | Rotork | England | IQ20 (36rpm) | (9)PN0601 | 0.53 | 203Nm(max | 1.1 | 187 | Final Clarifier (Draw-off chamber No.4) | | | |
| 12 | DE/2009/09 | Rotork | England | IQ10 (48rpm) | (9)PN0603 | 0.11 | 34Nm(max) | 0.7 | 54 | Final Clarifier (Draw-off chamber No.4) | | | |
| 13 | DE/2009/09 | Rotork | England | IQ20 (36rpm) | (10)PN0601 | 0.53 | 203Nm(max | 1.1 | 187 | Final Clarifier (Draw-off chamber No.4) | | | |
| 14 | DE/2009/09 | Rotork | England | IQ10 (48rpm) | (10)PN0603 | 0.11 | 34Nm(max) | 0.7 | 54 | Final Clarifier (Draw-off chamber No.4) | | | |
| 15 | DE/2009/09 | Rotork | England | IQ20 (36rpm) | (11)PN0601 | 0.53 | 203Nm(max | 1.1 | 187 | Final Clarifier (Draw-off chamber No.4) | | | |
| 16 | DE/2009/09 | Rotork | England | IQ10 (48rpm) | (11)PN0603 | 0.11 | 34Nm(max) | 0.7 | 54 | Final Clarifier (Draw-off chamber No.4) | | | |
| 17 | DE/2009/09 | Rotork | England | IQ20 (36rpm) | (12)PN0601 | 0.53 | 203Nm(max | 1.1 | 187 | Final Clarifier (Draw-off chamber No.4) | | | |
| 18 | DE/2009/09 | Rotork | England | IQ10 (48rpm) | (12)PN0603 | 0.11 | 34Nm(max) | 0.7 | 54 | Final Clarifier (Draw-off chamber No.4) | | | |
| 19 | DE/2009/09 | Rotork | England | IQ10 | | 0.11 | 34 | 1 | 54 | Stage I/II Inlet | | | |
| 20 | DE/2009/09 | Rotork | England | IQ10 | | 0.11 | 34 | 1 | 54 | Stage IV Inlet | | | |
| 21 | DE/2009/09 | Rotork | England | IQ10 | | 0.11 | 34 | 1 | 54 | Stage IV Screen House | | | |
| 22 | DE/2009/09 | Rotork | England | IQ10 | | 0.11 | 34 | 1 | 54 | Stage IV Screen House | | | |

Pumps | Blowers | Air Diffuser | Mixers | Screens | Centrifuges | Filter Press | Deodourizers | Switchboard | Generator | Penstocks | Actuators | 工作表1

***Figure 11.** Equipment inventory and spare parts list.*

### *5.5. Adoption of Knowledge-Based Asset Health Index*

Asset health index, represented by color-coding visualization, could provide a 3D human-machine interface in BIM to facilitate visualization in a user-friendly format. The index is developed based on analysed knowledge-based asset data stored in in-services MMS, mobile applications or other backend databases. This trial implementation presents a proof-of-concept demonstration of such visualized asset health index under the framework of ISO 55001 asset management of DSD and according to the fault tree analysis on sewage by-pass failure mode defined in Section 4.5. A specific monthly asset inspection form was drawn up as shown in Figure 12 under asset management to assist plant management in keeping track of a set of identifiable major fault symptoms in 8 nos. critical assets as defined in Table 2. The plant operator is required to record those fault symptoms in the above-mentioned electronic form via mobile applications during their regular monthly on-site inspections. Those field data collected via mobile applications are stored in standalone SQL-based relational database. The actual asset failure rates of fault symptoms as collected through monthly asset inspections by mobile applications, against the predefined threshold limits on asset risk rating for a particular critical asset could be analysed in a backend relational database. The database could then generate the SQL files on the following 4 sets of visualized asset types to be imported to AutoDesk Revit software as filtering criteria values, with required color patterns as shown in Figure 13. Figure 14 shows the color-coded asset health index in BIM model for the quick reference by plant management.

- Critical assets with "Good Condition" in orange color.
- Critical assets with "Satisfactory Condition" in green color.
- Critical assets with "Alarming Condition" in yellow color.
- Critical assets with "Bad Condition" in red color.


***Figure 12.*** *Chinese-version asset inspection form used by front-line staff through BIM-integrated mobile applications.*

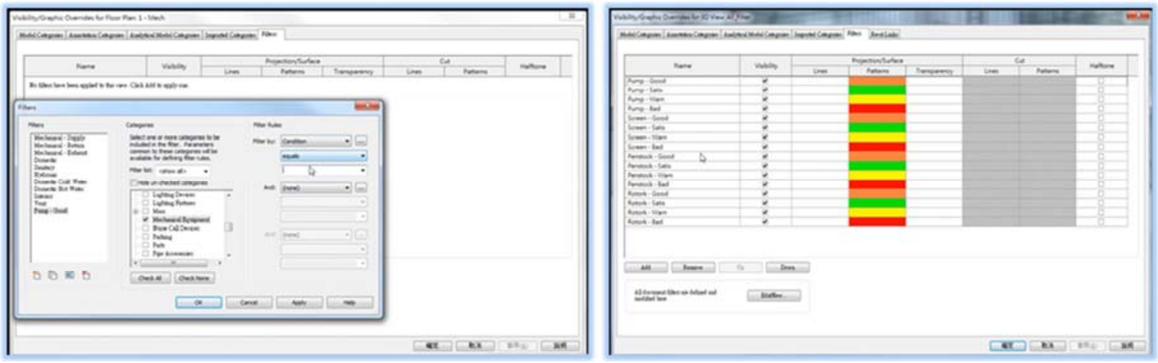


***Figure 13.*** *Filtering criteria values with required color patterns in AutoDesk Revit software.*


***Figure 14.*** *Color-coded asset health index in BIM model.*

## 6. Conclusions

This paper discusses the trial application of BIM technology to E&M asset management of a typical sewage pumping station. It is noticed that many challenges have been encountered. To succeed in BIM application, plant management should be involved at the start of BIM modeling as well as in implementation process and functionality development in different stages. This could help incorporate maintenance requirements and AM-compatible BIM data, develop BIM skillset, and demonstrate practicable BIM-integrated work routines that could enhance maintenance process. The study serve to bridge some adoption gaps between BIM and AM by setting out AM-customized BIM requirements on model fundamentals and hierarchy, as well as knowledge-based BIM applications in maintenance work routines in the context of wastewater industry.

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