Abstract: Building operations and maintenance require comprehensive systems that facilitate capturing and retrieving information/knowledge about all related building components to better plan and analyse how a building has been designed, constructed, operated or deteriorated. By incorporating Knowledge and Information Management principles, the transformation from ‘Building Information Modelling’ (BIM) to ‘Building Knowledge Modelling’ (BKM) can be better recognized. BKM enables the integration and exchange of the 3-D data for building models and the knowledge gained from operations on all related elements. BKM systems in this respect can represent, capture and retrieve the working solutions conducted for the operation and maintenance activities. This paper aims to introduce a BKM system to capture, retrieve and manage information/knowledge for building operation and maintenance. The main function of the developed system is to capture the information/knowledge relevant to operation/maintenance cases and pursue the related affected building elements by these cases. The paper concludes that BKM improves the functions provided by BIM models and the proposed BIM-knowledge system can improve the performance of the building operation activities.

Keywords: BIM, Building operations, Knowledge systems

1 Introduction

BIM technologies are used across all stages of building’s lifecycle and have a great impact on buildings performance. Currently, BIM technologies focus on the manipulation of data and information of projects which helps the generation and collection of building information created over the building’s lifecycle by different teams with different objectives and stored in different systems. In this respect, various studies have been conducted to develop ontological frameworks for the different types of information that can be used during the design, construction, and operation phases of buildings lifecycle for projects’ design and construction. With the recent development in BIM technologies, BIM-based frameworks have been developed using the installed digital systems in buildings to monitor performance.

Based on these additional features, there is a need to bring the technology of Knowledge Systems to the BIM technology. Knowledge systems usually capture the experiences of professionals/users and store previous operational cases with all lessons learned and solutions adopted. The stored knowledge can be used later to guide solutions to new problems and sustain the building’s integrity. Therefore, the concept of “Building Knowledge Modelling” (BKM or the 7D-BIM model) has been established to develop further the traditional BIM systems [21].

As knowledge systems should be domain specific, certain knowledge domain should be identified to apply with BIM models. The concept of BKM can be applied on any knowledge domain with knowledge ontology adaptation. For this research, maintenance of public buildings has been identified for the knowledge domain. Public Buildings always vary in shape, type, size, complexity and purpose. Building Maintenance (BM) services usually extend from minor repair works to bespoke renovation and reconstruction projects. Such diversity in categories of buildings and services make the process of maintenance complex. This requires public departments to seek means to improve their business performance in maintaining public buildings.
Decisions in BM are mostly based on professionals’ accumulated knowledge and available information about building elements and technologies. Building Maintenance (BM) is defined as “work, other than daily and routine cleaning, necessary to maintain the performance of the building fabric and its services” [8]. Furthermore, the significance of BM can be well acknowledged as its core business is maintaining the “nation’s most valuable asset” [10]. However, BM is yet recognised as part of the Facilities Management (FM) sector [6] and simultaneously part of the construction sector [4, 12]. This probably promoted the recognition of BM as a non-core business in organisations [26] which consequently has limited the attention towards “free thinking” and improvements for delivery of services [23]. However, skills and knowledge in refurbishment management are more significant than those in general construction management [14]. In literature, KM systems have been used for BM. However, much of the literature on KM has been directed towards the private sector when compared to what has been addressed for KM in public sector [9, 11]. Therefore, this research aims to investigate the adoption of KM within public sector, particularly for BM, and to develop a Building Knowledge Modelling (BKM) system that captures/retrieves the knowledge of maintenance teams utilising the intelligent features of BIM systems.

2 Building maintenance in public departments

The starting point for this research was to investigate the maintenance process in public departments and identify the opportunities of knowledge capture and exchange [5]. To sustain their services, maintenance departments responsible for maintaining public buildings can range from small sections working within larger facilities departments to distinguished large departments with headquarters and branches. Teams working within the departments comprise in-house personnel and out-sourced contractors. The contract used by the surveyed public maintenance departments to fulfil their maintenance duties includes different sections on the specification of different maintenance work such as: earth works, concrete works, wood works and masonry works. Figure 1 illustrates an outline of the maintenance process adopted by the surveyed departments; further details about the process can be found elsewhere [5]. Upon receiving requests and reports for maintenance works from a business unit or by maintenance teams, technical teams visit the site to assess works needed and issue estimated job description to the management team for approval. The approximation of quantities, items, types of works and project total cost included in the job description are based on the contract signed between the public department and the maintenance contractor. When the proposed project is approved, detailed lists of items with its quantities are then issued to the contractors or to in-house teams. The technical teams will then supervise the works being carried out. Upon finishing the project, the contractor/in-house teams and the supervising group issue a re-measured and modified total cost with detailed list of quantities for items and works that were carried out for the maintenance work to be ready for payment. The outlined process helped identifying the opportunities available for sharing knowledge among the maintenance teams, as indicated in Figure 1 by the dotted boxes. The role of the proposed BKM system to improve the BM process has also been identified. Next sections will review the use of BIM and KM in BM, and then the function of BKM will be illustrated.
3 BIM for Building Maintenance

BIM systems not only create 3D virtual models, but also facilitate the collaboration between stakeholders. The principal aim of BIM is the management of stakeholder input throughout the entire lifecycle of a project [13]. Furthermore, as operational stages of buildings can last for decades, BM activities evolve with time to maintain the delivery of satisfactory service when products and technologies become absolute. Therefore, having accessible and sufficient information is a key challenge before commencing maintenance operations. There are several BIM-focused studies aimed at improving BM practices which are sometimes considered parts of Facility Management (FM) applications. Application areas include locating components, facilitating access of real-time data, checking maintainability, automatic creation of digital assets, quality control and assurance, energy management, and space management [7]. Examples of applications include: BIM based package for the FM Exemplar project of Sydney Opera House which is developed to manage digital data generated by procurement and benchmark sections of the project [1], AROMA-FF which is developed to utilise data including BIM databases to obtain information and geometric representation of facilities and equipment [18], and the web-based Facilities Maintenance Management (FMM) prototype decision support.
system proposed [17]. FMM is based on basic processes for Asset Management, Corrective Maintenance, Preventive Maintenance, and Condition-based Maintenance. Whereas BIM related systems mainly focus on utilising technical information and allowing the access to multiple databases, they generally do not target the knowledge gained during the stage of maintenance and operation of buildings that can also be captured and be transferable through a BIM model. Therefore, incorporating Knowledge Management (KM) principles can help in achieving new levels of efficiency in BM performance. This will enable further development of the BIM systems from the focus on technical and geometric data to incorporate non-technical and non-geometric knowledge associated with building practices. The proposed BKM aims to capture both information and knowledge of BM which will be illustrated later in this paper, but the adoption of KM for BM will be presented first in the next section.

4 Knowledge management (KM) applications in Building maintenance

The concept of KM has been implemented by organisations to gain better market share and competitive advantage [22]. While it has been acknowledged that individuals possess their tacit knowledge, genuine potential benefits reside in transforming individual knowledge into institutional knowledge [15]. BM and construction organisations implement the concept of Knowledge Management (KM) to improve performance, reduce cost, increase efficiency and quality [20, 24, 25]. Regarding KM studies in the public sector, Yao et al. [27] discovered that public employees acquire information and knowledge through informal channels due to the absence of formal knowledge networks. Their research also revealed that barriers to knowledge sharing in public organisations include lack of time, lack of incentives/rewards and poor culture for knowledge sharing.

Through mapping the process in reactive maintenance projects, Ali et al. [2] revealed several major problems including selecting the right contractor for the right problem, double handling of data entry and transfusing of information. Such issues were due to lack of communication and knowledge sharing. BM activities are extended to buildings’ life span and involve multiple stakeholders that are replaced over time. Fong and Wong [16] provided examples of knowledge sharing opportunities in building maintenance that cover project location and proximity, type of repair work, reaction time, functioning of materials and products, details of contractors and suppliers and health and safety issues. Several KM systems have been revolving around utilising and managing of knowledge in BM, for example: Ali et al. [2, 3], Fong and Wong [16], and Lepkova and Bigelis [19]. The chief objective of such applications is the improvement of knowledge sharing and communication between stakeholders in BM.

Despite the useful functions provided by these applications, they are lacking the intelligent capabilities of searching through all affected building elements when retrieving a knowledge case of a maintained element. For BM, buildings behave as one unit and several elements can be affected by a cause of failure or defect. Therefore, additional maintenance/replacement to affected elements of a building can be caused by the failure of another element. In this respect, KM systems for BM should not only facilitate communicating knowledge among the stakeholders in reporting and describing the problem, or between the BM manager and the contractor in quotes estimation, price negotiations and payment processes. KM systems should be integrated enough to enable maintenance team to manage and share all details about knowledge cases over the building life time for all related elements of a building.

Therefore, BM requires a comprehensive system that facilitates capturing/retrieving information/knowledge about all related components to better plan and analyse how a building has been served or deteriorated. By incorporating Knowledge Management principles with Information Management principles, the transformation from ‘Building Information Modelling’ (BIM) to ‘Building Knowledge Modelling’ (BKM) can be better recognised. BKM enables the integration and exchange of 3D models data with its embedded intelligence and the knowledge gained from BM operations on all
related elements. BKM systems in this respect can represent, capture, retrieve solutions, and most importantly learn over time.

This research proposes a BIM-based knowledge management system that facilitates not only the capturing and retrieval of information and knowledge but also the ability to trace and associate maintenance cases of a building. The proposed BKM system will take advantage of the opportunities in the maintenance process (shown in Figure 1) to capture, reuse and share knowledge of employees. This paper specifically illustrates how the adopted BKM system retains knowledge in a BIM environment.

5 Building Knowledge Modelling System for Building Maintenance

The proposed system integrates a knowledge-based module to capture/retrieve the knowledge gained of BM operations, and a BIM-module to capture/retrieve the information about the maintained elements and identify to the knowledge-based module what other related elements are affected by a maintenance operation.

In addition to the conventional features of BIM models, the proposed system provides additional functions for building maintenance cases, namely; case browsing, case retrieving, and case retaining. The case browsing function allows users to navigate and browse maintenance cases based on criteria set by the users when searching for a particular case. The case retrieving function utilises the principles of Case-Based Reasoning (CBR) in retrieval of similar maintenance cases and uses an IFC protocol to integrate building models with the knowledge system. Details on the algorithm adopted for the CBR are beyond the scope of this paper. The following section discusses how knowledge cases are retained by the BIM environment.

6 BIM and case parameters

BIM applications produce element-based building models as virtual projects comprise of elements such as wall, door, footing, etc. However, retrieving maintenance case details is based on knowledge cases utilised by professionals that may include one or more building elements. Therefore, in order to deal with this discrepancy, additional parameters are used for the elements in the BIM model (Autodesk Revit is the BIM environment used for this research).

A set of parameters associated to building elements have been added to BIM models which comprises of knowledge case details and categorisation, as shown in Table 1. The categorisation used in the system is based on the BM contracts used within the surveyed public departments. This approach to implement the categories of work packages which are well known to the potential users may assist the system to be reached by wider professionals while requiring minimal training. The overall taxonomy adopted for the system consists of three categories: legal, technical and administrative. The legal category includes sections related to contract law, regulations, legal conditions, and health and safety. The Technical category comprises of sections organised based on work packages used in BM contracts. The administrative category contains sections related to BM processes and staff details. The default taxonomy adopted for the system can be easily modified to suite any other particular BM organisations.

The developed system includes a Case-Based Reasoning (CBR) module to store and retrieve similar knowledge cases. When uploading a BIM model for a particular building into the developed system, the used IFC protocol extracts the building details from the BIM environment including the classified knowledge for maintenance cases which are then organised and stored in the database to be later searched for solutions. The IFC file format includes also information related to project elements, their hierarchy, relationships, geometry and properties. The proposed system identifies the spatial relationships between elements that are provided by the IFC schema. The system then clusters elements
along with the associated cases into groups. Each group is then assigned with a unique ID to indicate the relationship between an element and its related spatial group. By the end of this process, related cases in single spatial group are linked to each other. Whenever a case has been searched and demonstrated, related cases of the same spatial group are presented.

<table>
<thead>
<tr>
<th>Parameter name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2. Section</td>
<td>Sections within each category.</td>
</tr>
<tr>
<td>3. Sub-Section</td>
<td>Sub-sections within each section.</td>
</tr>
<tr>
<td>4. Topic</td>
<td>General topic of a captured case.</td>
</tr>
<tr>
<td>5. Issue/Problem</td>
<td>Particular issue/problem of the case.</td>
</tr>
<tr>
<td>6. Reaction/Solution</td>
<td>The reaction/solution to the case.</td>
</tr>
<tr>
<td>7. Keywords</td>
<td>Keywords that identify the case.</td>
</tr>
<tr>
<td>8. Element</td>
<td>The element affected by the case.</td>
</tr>
</tbody>
</table>

Table 1: Parameters of the knowledge case in the BIM model

When searching the CBR library for a new case of maintenance, the taxonomy of maintenance work will be searched to retrieve the associated information that lists the Legal and administrative information of the case/element. The system also retrieves the technical contextual information in relation to this specific element and its related ones from the context-based BIM. The system allows users to browse all similar cases and select the closest solution. The selected solution with any modification added by users, if needed, is then retained as a new case in the CBR library, which represents how the system learns from new cases.

7 System application
The typical scenario for the system application starts by having the building information stored on BIM application as for any conventional BIM model (Autodesk Revit is the BIM application used for this system). This building information is to be updated after construction to enter maintenance data for building elements. Additional fields have been designed and added to the original Revit BIM model to accommodate the required maintenance data. These additional fields are part of the developed system; therefore once the BIM module is uploaded within the system, these fields will be populated automatically in the BIM application. The system will need users to fill these fields in order to identify the maintenance case. Each case description includes mainly: the maintenance problem and the solution adopted. An example is shown in Figure 2, which is about the maintenance solution adopted for fixing a leaking window. The BIM application includes all other information of this specified building element, i.e. “window1”.

When the maintenance team gets a new maintenance problem and needs to search the system library for any similar cases, the system interface allows users to describe the new case, as shown in Figure 3, for this example it was by writing this statement “window leaking problem in the building”. In addition to the description, the system will use the default weights assigned to the case attributes. The users are allowed to modify these weights, as shown on the left hand side in Figure 3, to best represent his/her assessment on these attributes. The system then starts searching the CBR library, retrieves all similar cases, and ranks them according to the similarity index, as shown in Figure 4 for this example. When
users select a case from this searching result, further details will be shown including all maintenance work for affected building elements to the retrieved case which gives more rich information about further possible maintenance work to other related building elements, as shown in Figure 5 where three other elements were affected by the identified maintenance case. The output on the left hand side in Figure 4 allows users to browse all related information about the stored maintenance cases in terms of the identified BM taxonomy. The system allows the information about a whole building elements and maintenance cases to be shown from any interface the users are on. This means when an element is selected via BIM module, all information including maintenance information will be retrieved. As well as, when a maintenance case is searched for via CBR module, the information about the maintained element and any other affected elements by this maintenance case will be retrieved.

Figure 2: Data for maintenance cases in BIM application (output from Autodesk Revit)
Figure 3: Enquiry about similar cases in the CBR library

Figure 4: System output
8 Conclusion

The system presented in this paper shows how a BIM model can capture building maintenance knowledge. It can assist in tracing back the history of maintenance cases of a building and help maintenance teams find solutions for the new BM problems based on the previous stored experiences. It can also help clients to archive all buildings history with all reasons behind making BM decisions.

9 References