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A knowledge-based BIM system for building maintenance

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ABSTRACT

Decisions for building maintenance require integration of various types of information and knowledge created by different members of construction teams such as: maintenance records, work orders, causes and knock-on effects of failures, etc. Failing to capture and use this information/knowledge results in significant costs due to ineffective decisions. Majority of the current building maintenance systems mainly focus on capturing either information or knowledge. This research aims to develop an integrated system to capture information and knowledge of building maintenance operations when/after maintenance is carried out to understand how a building is deteriorating and to support preventive/corrective maintenance decisions. To develop the system, a number of case studies were investigated and interviews were conducted with professionals from different building maintenance departments in public organisations. This methodology helped identify the building maintenance process and the opportunities for knowledge capture and exchange. A taxonomy for building maintenance was then identified which enabled a formal approach for knowledge capture. The proposed system utilises the functions of information modelling techniques and knowledge systems to facilitate full retrieval of information and knowledge for maintenance work. The system consists of two modules; BIM module to capture relevant information and Case-Based Reasoning (CBR) module to capture knowledge. The system can help maintenance teams learn from previous experience and trace the full history of a building element and all affected elements by previous maintenance operations. It is concluded that the integrated knowledge-based BIM systems can provide advanced useful functions for construction operations. On the other hand, incorporating Knowledge Management principles embedded in CBR systems with Information Management principles embedded in BIM systems is a way forward for the transformation from 'Building Information Modelling' to 'Building Knowledge Modelling'.

1. Introduction

Building maintenance (BM) is seen as an activity in the larger context of facilities management (FM) [1] and simultaneously is considered as part of the construction sector [2,3]. However, little considerations were offered to improvement and "free thinking" in the delivery of services of building maintenance [4]. This is perhaps because BM and FM are seen as "non-core" functions that provide "supportive" services in organisations [5]. With the rapid development of the business environment in both private and public sectors, practical relevance of FM is increasingly being recognised by organisations [6]. Within the area of public sector, Barrett and Baldry [1] stated that decisions, policies and processes of FM are largely influenced by: non-financial aspects related to standards of public service terms, public accountability and probity to meet needs, and expectations/interests of various and authoritative stakeholders. Such issues put increasing pressure on the FM and BM practitioners to improve the delivery of services.

Generally, maintenance can be either preventive or corrective. The preventive maintenance concerns about the routine maintenance plan. However, the corrective maintenance concerns about the reactive maintenance in response to a cause of failure or break down. In the current practice, the information required for implementing preventive maintenance can be easily prepared ahead of actions if compared with the information required for corrective maintenance. One of the key challenges in projects is always the need to have sufficient information on products ready available for any maintenance operation, such as: specifications, previous maintenance work, list of specialist professionals to conduct work, etc. As BM activities cover the longest life span of buildings and involve multiple stakeholders that may be replaced over time, detailed data of used products are needed to be tracked by authorities and clients [7]. Therefore, BM requires a comprehensive information system that captures/retrieves information on BM components and all its related building components.

Various studies have proposed integrated IT solutions for the various project life cycle phases, including BM. The development of these IT solutions was based on different principles, such as 'software fixing' by Syal et al. [8] and blackboard architecture by Yau et al. [9]. These principles have problems with the information flow between various functions and also problems with expandability and maintainability with other packages. Later on the principle of integrated databases such as the solutions developed by Aouad et al. [10] and Underwood

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and Alshawi [11] were adopted in a way to overcome these problems. However, these integrated IT solutions were mainly for information sharing with little emphasis on knowledge capture and sharing. In another approach to improve the capability of these IT solutions in terms of data management, several technologies were integrated with these solutions such as Radio Frequency Identification (RFID) by Legner and Thiesse [12] and Chien-Ho Ko [13] to collect and share maintenance data with the most minimal manual data entry. These efforts, in addition to others, drove to the development of the generic IT solution provided by the principles of Building Information Modelling (BIM).

BIM can provide the facilities of these integrated solutions and overcome such problems in a comprehensive manner. BIM can enhance collaboration between team members and facilitate further the mutual channel for information. BIM comprises ICT frameworks and tools that can support stakeholders' collaboration over projects life-cycle. While BIM is thought to transform the way the built environment is working [14], studies related to BIM have often been focusing on storing and sharing technical information. BIM capabilities can be enhanced by knowledge-based techniques, such as Case-Based Reasoning (CBR), to enable both information and knowledge-sharing that will benefit stakeholders. By incorporating Knowledge Management principles embedded in CBR systems with Information Management principles embedded in BIM systems, the transformation from 'Building Information Modelling' to 'Building Knowledge Modelling' can be better recognised.

While many of the current FM applications adopt BIM technology and provide functions for BM (such as: assisting in helpdesk call centres and managing assets, spaces, costs and utilities), Knowledge Management

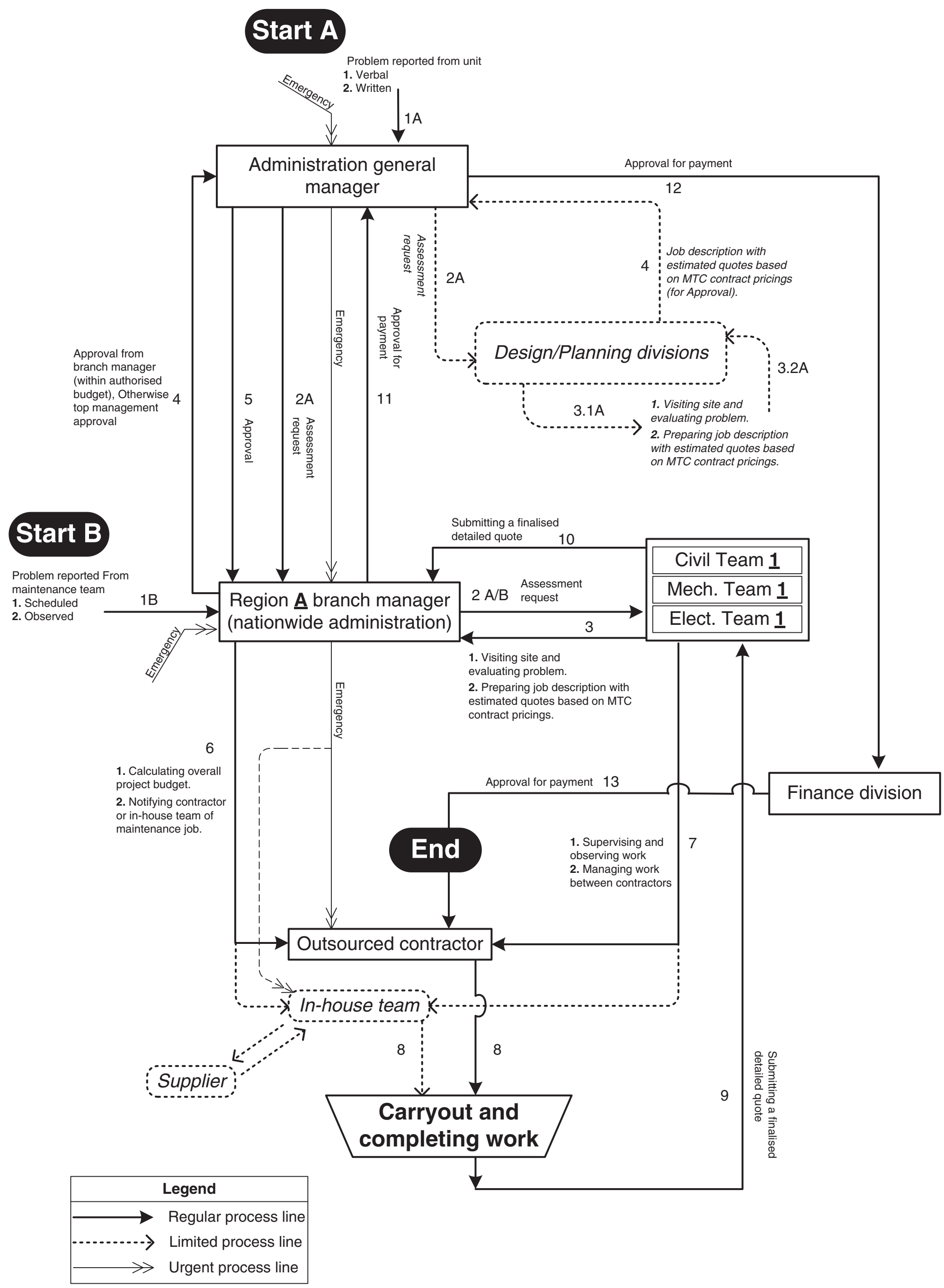

Fig. 1. Building maintenance process in public organisations.

(KM) facilities are not normally provided by these applications. In addition to information, knowledge created from maintenance operations such as: lessons learnt from the investigation of causes of failure, reasons of selecting specific method of maintenance, selection of specialist contractors, ripple effects on the other building elements, should also be captured/retrieved in sufficient details. Several examples have shown the need for additional maintenance/replacement to affected elements of a building because of the failure of another element, which becomes essential in updating information and knowledge when managing BM. 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. Lack of information/knowledge may lead to ineffective maintenance, repeating mistakes, and inefficient maintenance plan for other building elements.

On the other hand, several KM applications for BM have been developed to improve the performance of BM process, such as those of: Ali et al. [15], Lepkova and Bigelis [16], and Fong and Wong [17]. The main functions of these applications are capturing, sharing, and reusing knowledge by stakeholders. They can help facilitate the communication between parties, identifying problems, selecting the appropriate contractor and allowing feedback on completed work. 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. The new development in BIM technology can change the way these applications work. 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, this research will develop an integrated knowledge-based BIM system that enables capturing/retrieving information and knowledge on BM considering all affected building components for any maintenance operation. This paper will first develop the BM process model, initially proposed by Almarshad et al. [18] to identify opportunities and mechanisms of capturing knowledge for BM in public organisations. The paper then introduces the architecture of the developed system. The system is automated to capture and retrieve information and knowledge on BM operations via a developed web-based application that integrates a case-based reasoning module with BIM application. The following section presents first the developed BM process followed by the system architecture.

2. Building maintenance process

The process developed for this research is mainly for BM in public organisations that use annual maintenance contracts with specialist contractors. BM in public organisations was investigated in ten case studies (three small, four medium, and three large organisations) [19]. While all the investigated cases were based in Kuwait, the procedures can be adopted in any public organisation that has similar hierarchy organisational structure and comprises several branches where no formal communication links exist between the different maintenance teams across these branches. In this BM process, there are many common problems identified which are relevant to KM, such as: the difficulty of searching and finding old problem/solution records since no methodology is currently used. However, in very few cases, records on problems and solutions were only documented when the case is large enough to be presented and discussed in face-to-face meetings. However, for this type of organisations where channels of communication are limited, knowledge can only be shared within the same team.

The developed BM process, as shown in Fig. 1, consists of the main team members (in boxes) and the type of activities and processes that might be conducted (arrows linking these boxes). The objective of adopting a KM methodology is to introduce as few as possible of extra activities and to make use of the current processes, as additional work load may hinder the introduction of any new concept [19]. For KM practices in BM, several KM models have been reviewed such as Nonaka and Takeuchi [20], Wiig et al. [21], Davenport and Prusak [22], and Alavi and Leidner [23]. From the analysis of these models with regard to the developed BM process, four opportunities for knowledge capture, reuse

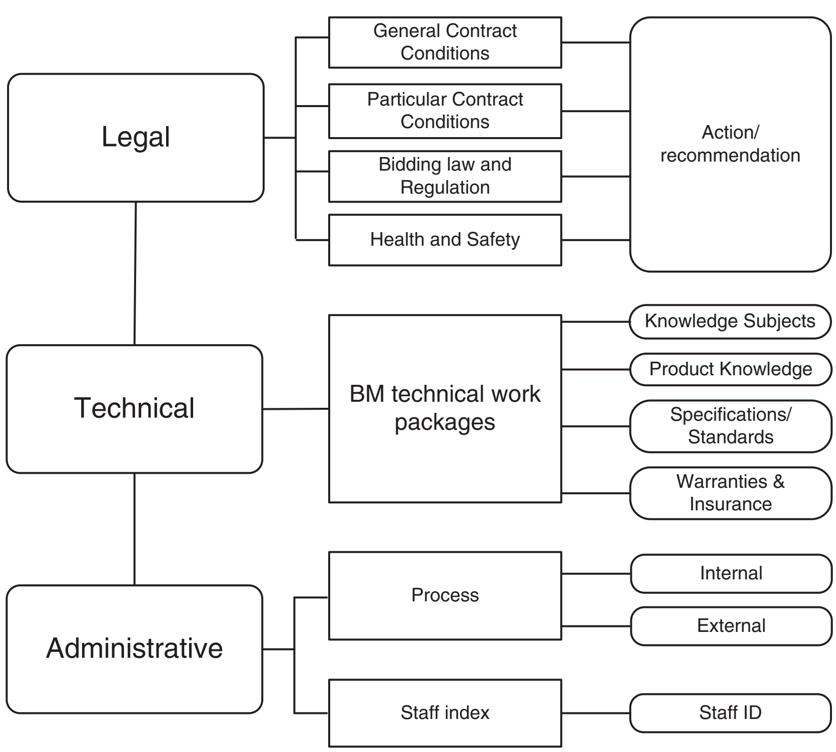

Fig. 2. Taxonomy for building maintenance.

and sharing were identified. The first opportunity exists in "Process 3" where a team member visits the site for evaluating and submitting needed repairs, estimating quotes and quantities. The second opportunity is found in "Process 6" when a team member supervises and/or manages the work of projects. The third opportunity exists in "Processes 8 and 9" where finalised paperwork is submitted. Lessons learnt are to be documented in these processes. The fourth opportunity can take place in the "Process 1B" where a team member conducts routine visits to sites; as his/her comments are to be recorded in this stage. Furthermore, the process shows that communication lines of teams are limited to managers, contractors and in-house workforce. This leads to maintenance teams be isolated within repair projects located in their jurisdiction. Therefore, there is a need for a supportive system to connect all team members, their thoughts, experiences, decisions and knowledge which can have a significant impact on performance. The adopted BM process helped identify the requirements of the proposed Knowledge-base BIM system. The proposed system integrates a case-based reasoning module and BIM module to capture, codify, and retrieve information/knowledge cases for BM. The following section presents the system architecture and the functions of its components.

3. Knowledge-base BIM system for building maintenance

The proposed system aims to utilise the functions of information modelling techniques and knowledge capture to provide full retrieval for information and knowledge of BM activities in order to understand how a building is deteriorating and to support proactive maintenance decisions. The development of this system needs first the identification of taxonomy for maintenance tasks based on the classification of work identified for this research. The taxonomy will enable a formal approach for knowledge capture by providing customised templates for each type of work. The taxonomy will also help in developing the case representation required for the case-based reasoning methodology adopted for the developed KM system.

3.1. Building maintenance taxonomy

Several taxonomy schemes have been identified for construction projects in general. The main purpose of these schemes is to facilitate information flow and knowledge sharing. Examples of these schemes include: Construction Index/SFB (CI/SFB), RIBA Uniclass (Unified Classification for the Construction Industry), ISO 12006-2:2001, and the American Construction Specifiers Institute (CSI). For BM taxonomy, the Royal Institution for Chartered Surveyors (RICS) has published

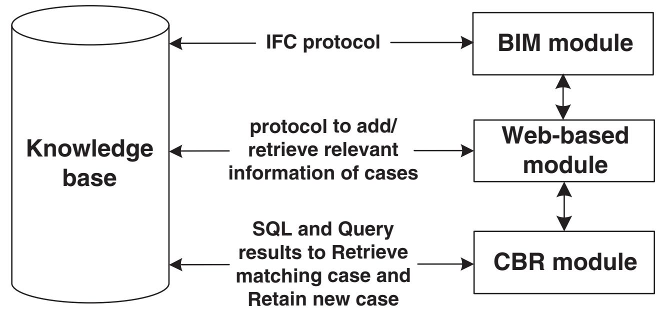

Fig. 3. Modules of the Knowledge-base BIM system for building maintenance.

the Building Maintenance Price Book (BMPB). Several other research studies have proposed special taxonomies for BM to organise and manage knowledge in certain context to be easily utilised by users. For example, Ali et al. [15] classified knowledge for reactive building maintenance into three major classes: building maintenance, equipment maintenance and services. Fong and Wong [17] categorised BM knowledge based on 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.

For this research, the taxonomy adopted for BM was designed based on the currently used contracts of BM in the public sector in Kuwait. Capturing and clustering knowledge cases should be indexed in a familiar manner to users to be easily searched and retrieved by the professionals when needed. This will facilitate the use of the system to wide users and organisations while requiring minimal training. The adopted taxonomy was verified by interviews with professionals

Table 1
BM technical work packages.

Section One:	**17** Paints Works
1 Demolition, Dismantling and Removal	**18** Glass and Plastic Works
2 Assembly and Installation	**19** Construction, Design and Landscaping Works
Section Two:	**Section Three:**
3 Earth works	**20** Labour and Technicians
4 Concrete Works	**Section Four:**
5 Masonry Works	**21** Machinery and Equipment
6 Plaster Works	**Section Five:**
7 Steel Works	**22** Air Conditioning Works
8 Aluminium Works	**23** Mechanical Works
9 False Ceiling Works	**24** Lifts
10 Roof Covering Works	**Section Six:**
11 Flooring and Cladding Works	**25** Fire Alarm and Extinguishing Works
12 Bathroom Hardware and Sanitary Works	**26** Phone and Service Bells Works
13 Water Supply Works	**27** Electrical Works:
14 Sewage Works	**Section Seven:**
15 Insulation layers for Wetness, Humidity and Heat	**28** Roads, external areas and Related Works
16 Wood Works	**29** Miscellaneous Works

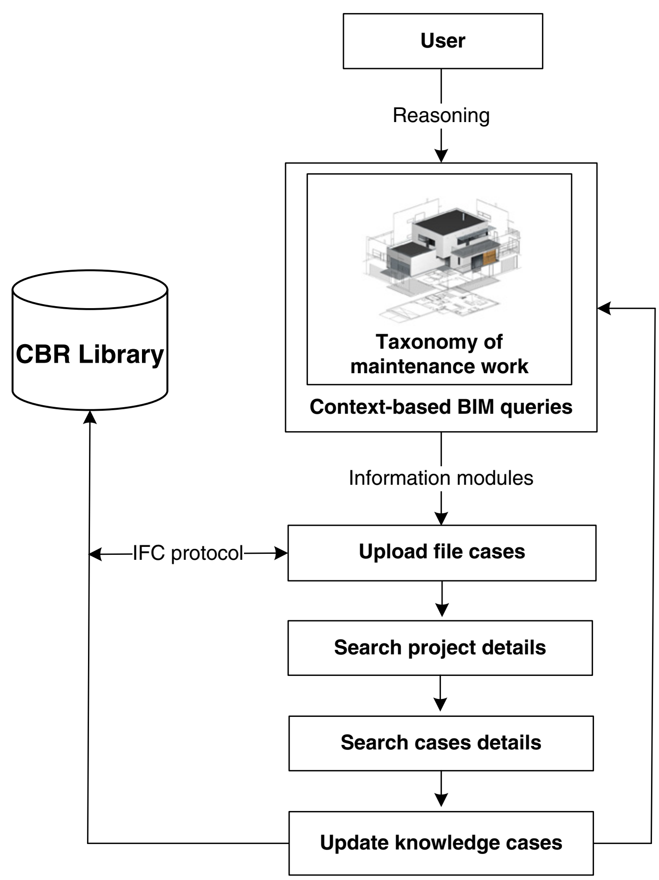

Fig. 4. BIM module.

working in the investigated case-studies to identify the most suitable format for work categories [18]. Fig. 2 shows the adopted taxonomy which includes: legal, technical, and administrative categories. The legal category has four related sections to classify the knowledge based on contract type, contract conditions, bidding regulations, and Health and Safety related issues. For the BM technical work packages, there are 29 work packages as shown in Table 1. Each work package includes details on the technical specification of each type of work, durability, frequency of use, method of construction, components/materials quantity and costs, maintenance data and responsibilities, etc. The administrative category covers the administration processes such as: maintenance task database, the replacement period of a component, approval procedures, recruitment plans, general financial processes, in addition to knowledge relevant to the human resource department. The taxonomy is set to be the default formatting for work classification. However, other classifications can also be followed in the proposed system, if required. This taxonomy is used to design the proposed case-based reasoning module, to be presented later. The following section illustrates the system architecture.

4. System architecture

Fig. 3 illustrates the main modules of the proposed system which were developed to capture and model BM information and knowledge. The CBR-module will help capture/retrieve the knowledge about BM cases, and the BIM-module will capture/retrieve the information of the maintained components and identify to the CBR-module what related components are affected by a maintenance operation. The web-based module is mainly to integrate the CBR and the BIM modules in a user-friendly interface. It also works as the data–entry interface for knowledge cases when the potential users of the system do not have BIM environment. But the system, in this case, will lose the intelligent function provided by the BIM environment. The following sections discuss the system modules.

4.1. BIM module

The high initial cost of BIM is always a main issue when deciding on investment in this technology, especially if BIM is only to be used during design and construction stages of projects. The use of the integrated Knowledge-base BIM system to monitor post-construction stage for maintenance management could justify better the investment in BIM technology and also improve processing the lifecycle-data that is created/maintained by BIM (e.g. requirements, operational, and maintenance information).

The basic block in BIM is the building/structure element (e.g. wall, column, etc.), so all attributes and properties of BIM modules represent elements. However, the basic block of KM is a case which may include

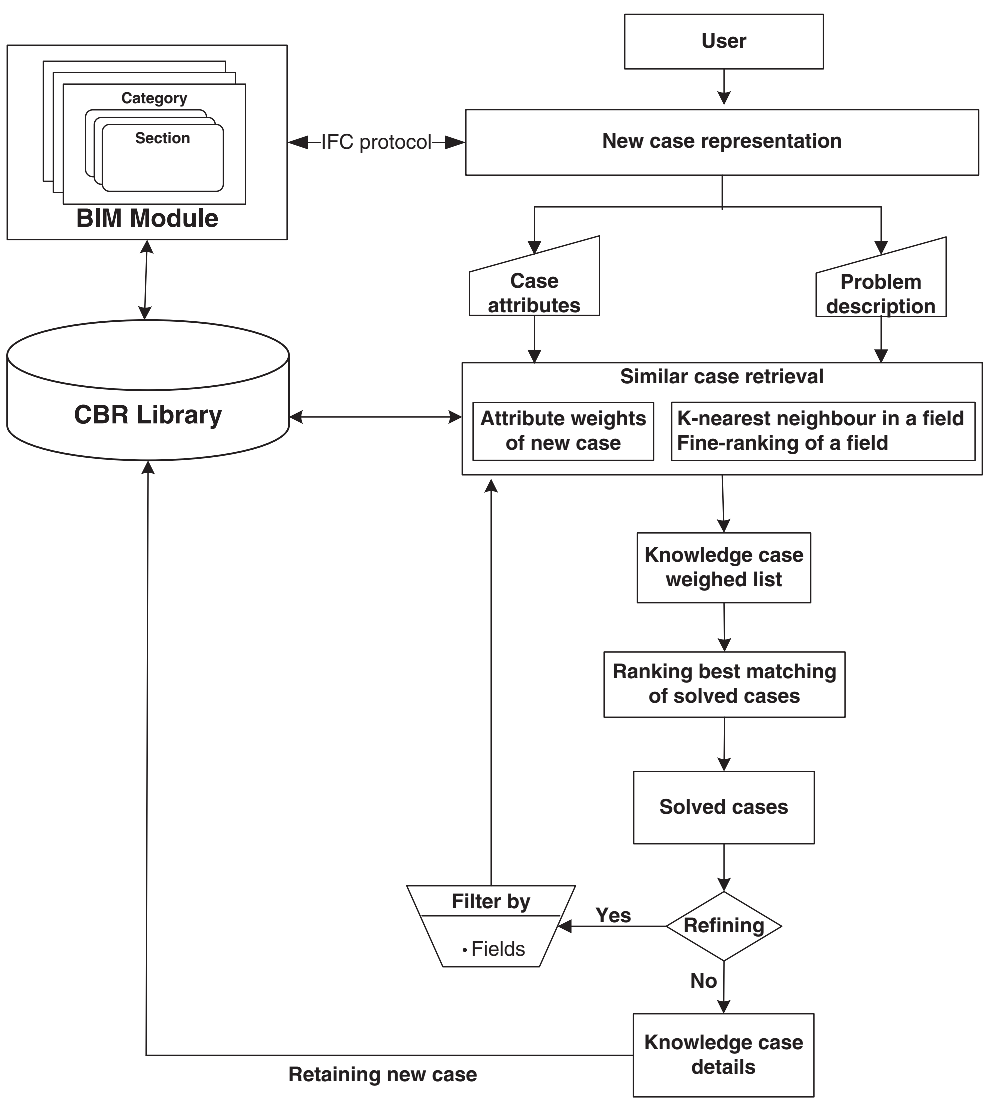

Fig. 5. Case-Based Reasoning (CBR) module.

Table 2
Case attributes for BM.

Attribute category	Attributes	Description
Building details	(1) Building type	Usage of the building (school, office building, police station)
	(2) Structure type	Concrete, wood, steel, combined, etc.
Knowledge case Indexing	(3) Category	Legal, technical, administrative
	(4) Section	Which section within each category
	(5) Sub-Section	Which sub-section within each section
Particular knowledge case details	(6) Topic	General topic of a knowledge case
	(7) Issue/Problem	Particular issue/problem of a particular case
	(8) Reaction/Solution	The reaction/solution to a particular case
	(9) Keywords	Keywords that identify a particular case
	(10) Affected Elements	The closest element affected by the case

one or more building elements. The question is how a KM system can capture knowledge of multiple elements or how BIM can accommodate a knowledge case. Therefore, the proposed system utilises BIM to reason about a maintenance history and to identify the changes to the contextual information that may need to be captured for maintenance work for one or more elements.

Fig. 4 shows how BIM module is used to retrieve the information of the targeted building element for maintenance and all its related elements. For a new case of maintenance, the taxonomy of maintenance work will be searched to retrieve the associated information module that lists the Legal and administrative information of the case/element. The module also queries and retrieves the technical contextual information in relation to this specific element and its related ones from the context-based BIM. This information will be used later with the knowledge cases stored in the CBR library to search for a solution for a new maintenance case. All retrieved information will be presented with the output of the CBR module to provide a full maintenance history for the targeted elements and its related ones.

4.2. Case-based reasoning (CBR) module

Many IT solutions have been developed to model knowledge in KM systems. These solutions are designed based on different techniques and ontologies to model the knowledge of certain domain, such as: Expert Systems (ES), Case-Based Reasoning (CBR), Artificial Neural Network (ANN), etc. In construction, KM systems use these techniques to model certain practices, e.g. construction planning and productivity analysis [24], estimating construction technology acceptability [25], and Construction Cost Estimation [26]. For BM, several KM systems were developed to diagnose the causes and suggest solutions of various maintenance operations in buildings; such as the REPCON system [27], civil infrastructure preservation [28], and determining life cycle costs of facilities including maintenance [29]. The advantages and disadvantages capabilities associated with these techniques help select the most suitable one for certain practice based on the nature of knowledge to be captured and modelled.

From the case studies undertaken as part of this research, maintenance operations need to benefit from previous experience in terms

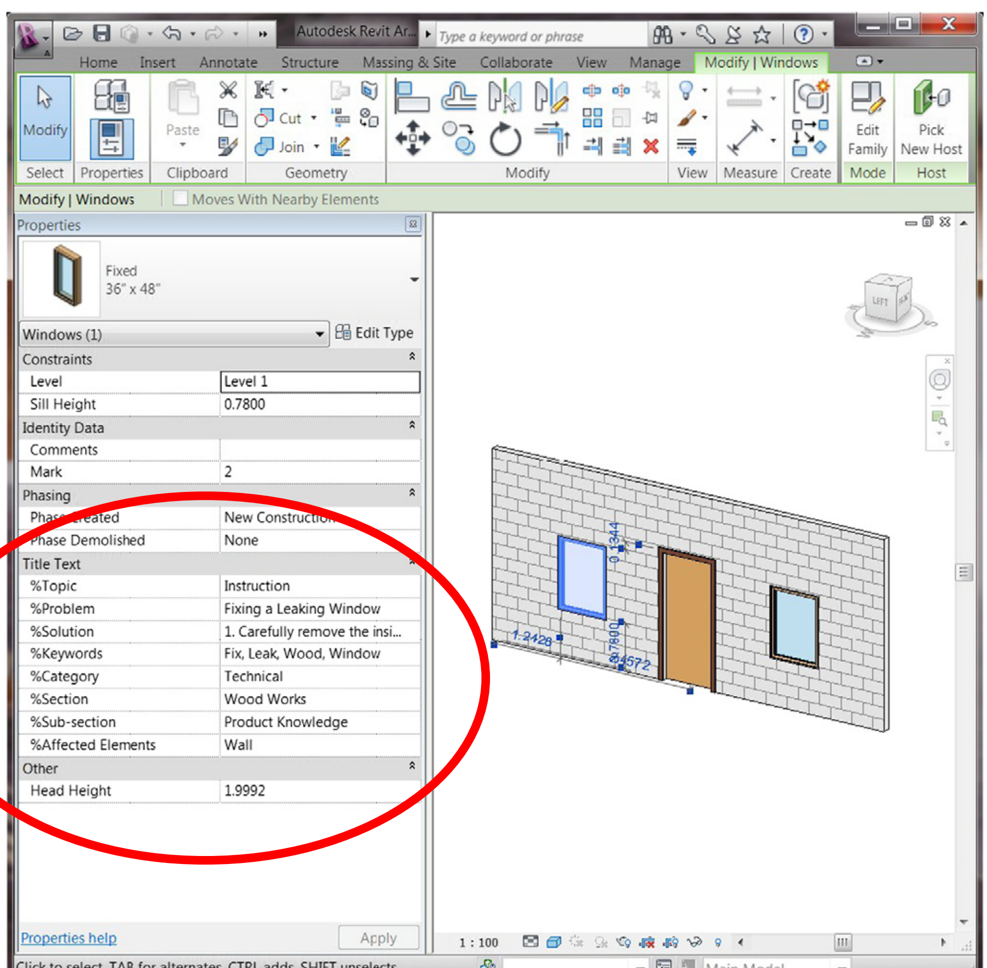

Fig. 6. Data for maintenance cases in BIM application (output from Autodesk Revit [32]).

of avoiding same mistakes and adopting successful solutions from previous cases. There are also cases when dispute arises between different stakeholders regarding the kind of remedy actions for certain maintenance operations. Therefore, detailed analysis and investigation of the causes and effects in addition to detailed knowledge of building defects are required.

These reasons make approaches such as ES and ANN inappropriate for modelling knowledge of BM. ES need to represent knowledge in the form of well-defined rules with limited domains of knowledge. This is not always appropriate in BM because the available knowledge on the recorded maintenance events cannot be encapsulated in rules explicitly and it is difficult to formulate a complete and accurate set of rules to capture the expertise required for a generic KM system for BM. In addition, ES cannot normally learn over time which is a key aspect of BM as new solutions always come to the industry and ES is based on prior knowledge of a few known alternatives. On the other hand, ANN systems were found inappropriate, as they neither provide details of variable manipulations nor the rationale for the conclusions drawn, which is needed in cases of dispute. While ANN can learn from new cases, it needs huge data to train and develop. From this brief discussion, CBR systems were found the most suitable approach for modelling the knowledge domain of BM.

The psychological plausibility of CBR makes it fundamentally different from other major AI approaches as a problem solving paradigm in the form of intra-domain analogy [30]. Cognitive psychology research considers reasoning by reusing past cases as a powerful and frequently applied way to solve problems for human. Instead of relying solely on the general knowledge of a problem domain or making relationships between problem descriptors and conclusions, CBR is able to utilise the specific knowledge of previously experienced problem cases in order to identify a solution for new problems. CBR is also an approach to incremental, sustained learning, since a new experience is retained each time a problem has been solved making it immediately available for future problems. A typical CBR system operates according to the following steps: 1) identify the current problem situation, 2) search past cases similar to the new one, 3) retrieve the most similar case to solve the current problem, 4) evaluate the proposed solution, and 5) update the system by learning from this experience. The structure of the CBR module developed for the proposed BM system is shown in Fig. 5. The following sections discuss the main components of this structure.

4.2.1. Case representation

BM knowledge cases can be represented in a variety of forms using a range of AI representational formalisms such as: frames, objects, predicates, semantic nets and rules [31]. For the proposed system, the information of projects and elements already stored by the BIM module will be retrieved to identify all technical and maintenance information of the BM case, including any information of the related building elements to the maintained element. Common attributes of the cases should be identified in a way to simplify entering case description and to enable the retrieval of the most suitable cases. From the interviews conducted to develop the adopted BM process, a number of case attributes for BM were defined as shown in Table 2. These attributes have been ranked and given weights to distinguish the importance of each attribute to a knowledge case. These attributes in addition to "Problem description" will discriminate BM cases, so useful cases can be retrieved using the adopted evaluation functions in the "Similar case retrieval" step.

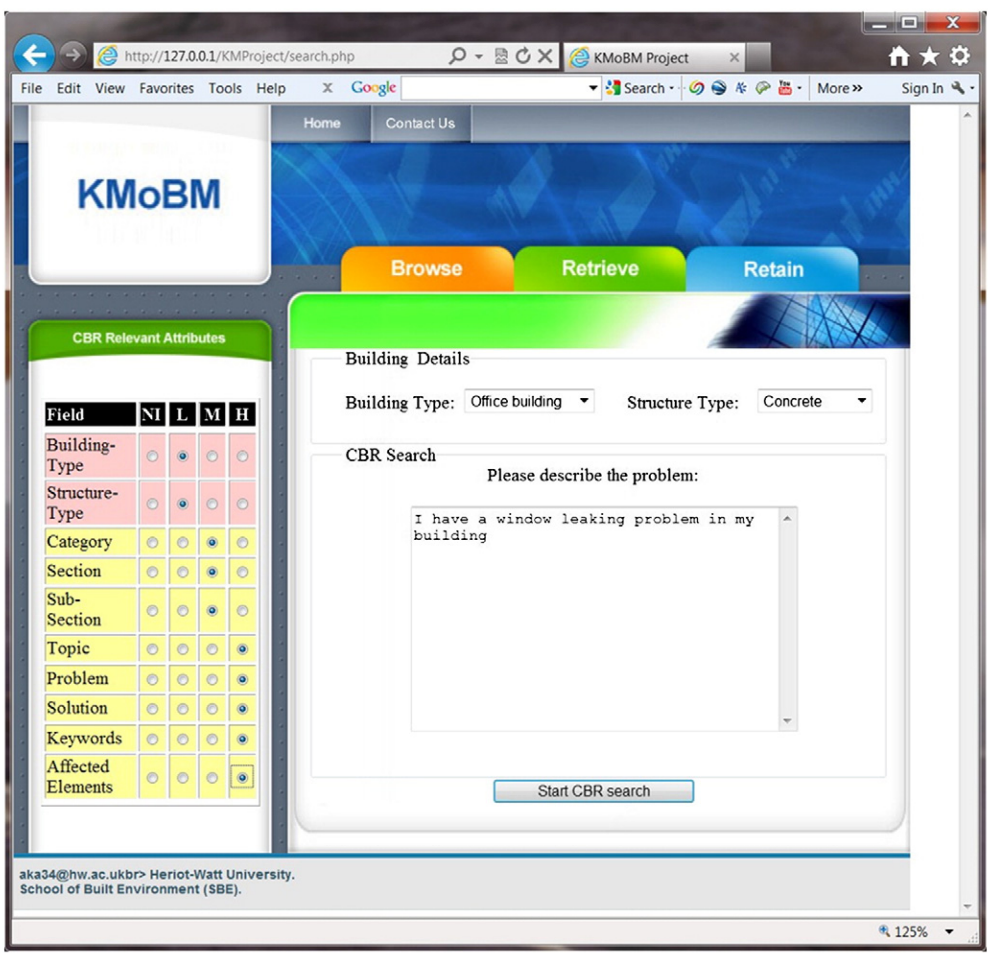

Fig. 7. Enquiry about similar cases in the CBR library.

4.2.2. CBR Library

An efficient CBR system should include a library of rich data that stores enough historical cases for an effective retrieval of similar cases. In this study, information about BM cases was collected from the interviewees including various reports on previous projects available in the investigated public departments. In these departments, the majority of the interviewees have experienced problems such as repeated mistakes on the selection of maintenance methods or repaired components. The information stored in this library is structured according to the identified taxonomy for BM, as shown in Fig. 2 (Section 3.1 above).

4.2.3. CBR module for similar case retrieval

Cases can be retrieved from the CBR library based on a number of techniques. Nearest neighbour technique is one of the most widely used techniques in this process. The best match case is retrieved using similarity scores. Details on the evaluation functions used for the CBR module is beyond the scope of this paper. The solution goes through iterative procedure to filter and rank similar cases from the CBR library which may also need refining the case representation until the most similar case is identified. The solution is then retained as a new case in the CBR library, which represents how the system learns from new cases.

5. 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 [32] 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 which could be relevant to any category of the adopted taxonomy identified earlier. Each case description includes mainly: the maintenance problem and the solution adopted. An example is shown in Fig. 6, which is about the maintenance solution adopted for fixing a leaking window.

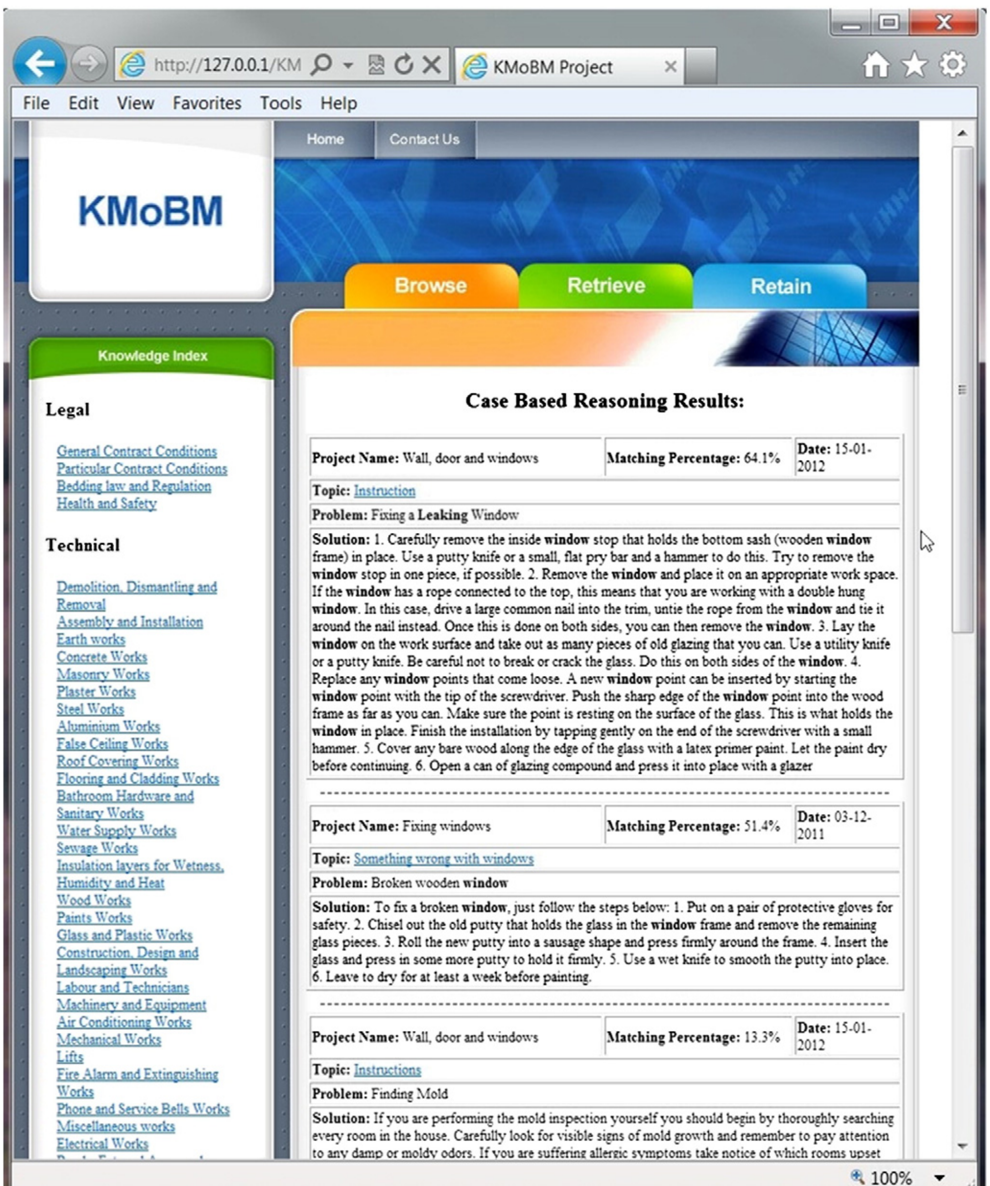

Fig. 8. System output.

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 Fig. 7, 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, as illustrated above. The users are allowed to modify these weights, as shown on the left hand side in Fig. 7, 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 Fig. 8 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 Fig. 9 where three other elements were affected by the identified maintenance case. The output on the left hand side in Fig. 8 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.

6. Conclusions

Improving the operations of building maintenance requires many supportive facilities for both management and technology aspects. This research aimed to provide maintenance teams in public organisations with an integrated information/knowledge system that helps capture/retrieve all relevant information/knowledge on maintenance operations. The system uses the facilities provided by the BIM technology to capture/retrieve the information for the design/construction/operation of buildings. This is in addition to using the features of the intelligent BIM objects which are capable of representing their relationship to each other. Capturing these relationships helped improve the knowledge retrieved by the typical knowledge systems for building maintenance. On the other hand, the current BIM applications cannot fully utilise the capabilities of knowledge systems in capturing various forms of professional knowledge on various construction operations such as building maintenance. This research developed an integrated case-based reasoning BIM system for building maintenance, as an approach to establish the transformation from 'Building Information

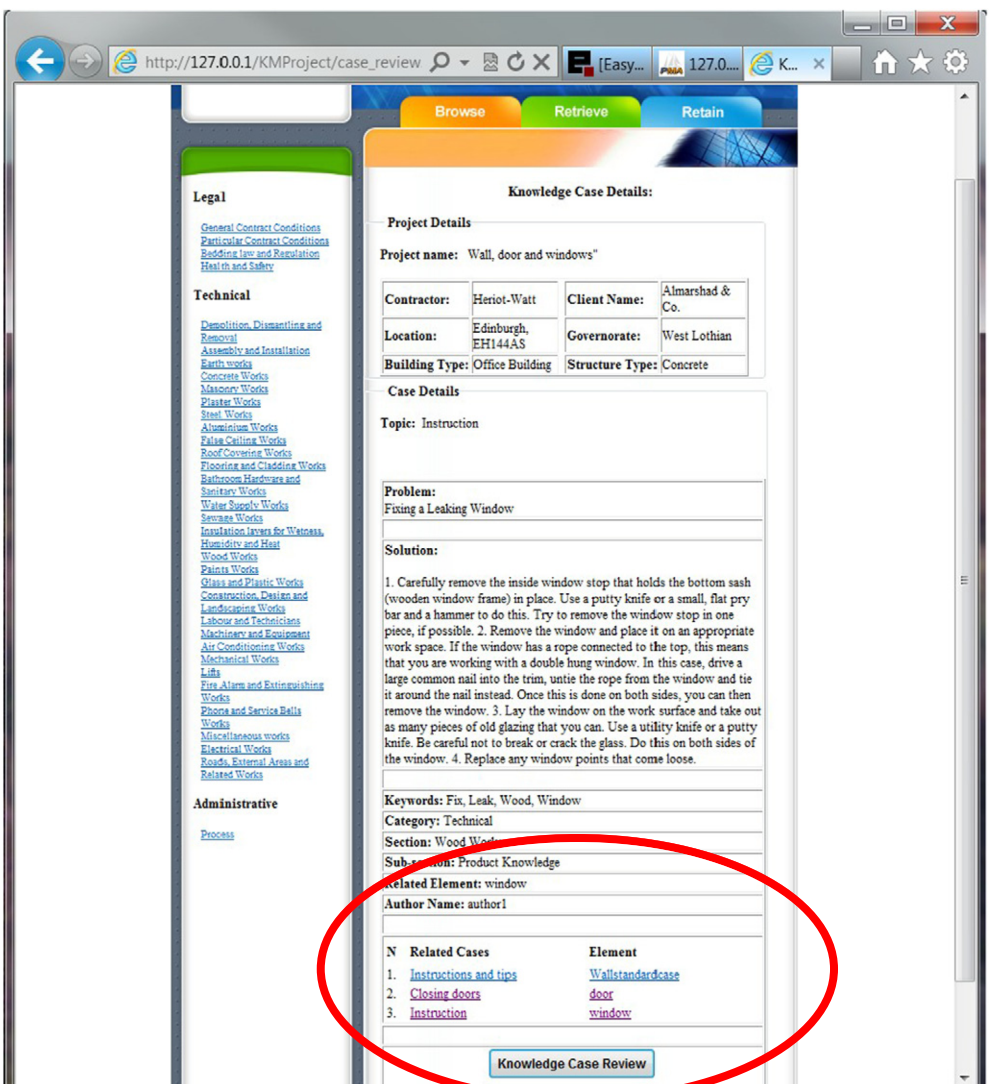

Fig. 9. System output-related elements.

Modelling' to 'Building Knowledge Modelling'. For any maintenance case, the system can help maintenance teams learn from previous experience and trace the full history of a building element and all affected elements by previous maintenance operations. While the developed system concerns more about information/knowledge capture and retrieval, the efficiency of the system can be improved by the automation of data capture using technologies such as RFID, which is part of the current development of this system. With further development in knowledge-based BIM systems, further improvements to the management of other construction operations can also be provided.

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