Case-based reasoning and BIM systems for asset management

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Abstract

Purpose – The next generation of Building Information Modelling (BIM) seeks to establish the concept of Building Knowledge Modelling (BKM). The current BIM applications in construction, including those for asset management, have been mainly used to ensure consistent information exchange among the stakeholders. However, BKM needs to utilise knowledge management (KM) techniques into building models to advance the use of these systems. The purpose of this paper is to develop an integrated system to capture, retrieve, and manage information/knowledge for one of the key operations of asset management: building maintenance (BM).

Design/methodology/approach – The proposed system consists of two modules; BIM module to capture relevant information and case-based reasoning (CBR) module to capture the operational knowledge of maintenance activities. The structure of the CBR module was based on analysis of a number of interviews and case studies conducted with professionals working in public BM departments. This paper discusses the development of the CBR module and its integration with the BIM module. The case retaining function of the developed system identifies the information/knowledge relevant to maintenance cases and pursues the related affected building elements by these cases.

Findings – The paper concludes that CBR as a tool for KM can improve the performance of BIM models.

Originality/value – As the research in BKM is still relatively immature, this research takes an advanced step by incorporating the intelligent functions of knowledge systems into BIM-based systems which helps the transformation from the conventional BIM to BKM.

Keywords BIM, Building maintenance, Asset management, Building knowledge modelling, Case-based reasoning, Knowledge systems

Paper type Research paper

Introduction

During the whole lifecycle of a building and for asset management purposes, different stakeholders handle different working stages. The information exchanged among the teams of each stage is generally limited in the format of spreadsheets, word documents, and 2D drawings (Vanlande *et al.*, 2008). Therefore, history, decisions made, and insights realised may be fully or partially lost during the life span of a building. Until recently, the construction industry has been generally revolved around 2D systems as digital drafting tools with limited use of 3D models for sharing information, visualisation, and design development (Singh *et al.*, 2011). After the recent development in Building Information Modelling (BIM) technology, the use of intelligent building systems supersedes the use of 3D models to cope with the rising complexity in constructing and maintaining buildings. 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

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(Dzambazova *et al.*, 2009). Therefore, BIM functions can be utilised as an efficient means in reducing and mitigating difficulties when managing activities during the building lifecycle. Furthermore, as asset management operations for buildings can last for decades, its key activities for building maintenance (BM) evolve with time to maintain the delivery of satisfactory service when products and technologies become absolute. In this respect, a system that utilises the features of BIM technology can considerably improve BM operations.

Several BIM applications have been developed with various design/construction/operational focuses, such as: sustainability (Arayici *et al.*, 2011; Barnes and Castro-Lacouture, 2009), energy analysis (Motawa and Carter, 2013; Cho *et al.*, 2010; Stumpf *et al.*, 2009), maintainability checking (Leite *et al.*, 2009; Dehlin and Olofsson, 2008), visualisation (Sacks *et al.*, 2010; Babic *et al.*, 2010; Eastman *et al.*, 2008), cost estimation (Kiziltas and Akinci, 2010), and BIM-enabled design (Khanzode *et al.*, 2008). There are also several BIM-focused studies aimed at improving facility management (FM) practices for the functions of locating components, facilitating access of real-time data, checking maintainability, automatic creation of digital assets, quality control and assurance, energy management, and space management (Becerik-Gerber *et al.*, 2012). Among these applications there are: BIM based package for the FM Exemplar project of Sydney Opera House (Akhurst and Gillespie, 2006), AROMA-FF which is developed to utilise data including BIM databases to obtain information and geometric representation of facilities and equipment (Lee and Akin, 2011), and the web-based Facilities Maintenance Management prototype decision support system (Hao *et al.*, 2010). Whereas BIM related systems mainly focus on utilising technical information and allowing the access to multiple databases, they generally do not consider the knowledge gained during the stage of maintenance and operation of buildings. This is mainly because the application of knowledge management (KM) needs different technical and structured ontologies from what is typically utilised when developing BIM databases; i.e. ontologies related to specific knowledge domain such as design knowledge, asset management knowledge, etc. Therefore, this research aims to integrate BIM models with a knowledge management tool to capture and retain knowledge of the particular operation of asset management "Building Maintenance".

On the other hand, KM refers to the tasks of capturing, sharing, storing, and retrieving knowledge of experts about certain domain. The concept of KM has been utilised to improve performance, reduce cost, increase efficiency, and quality (Nonaka and Takeuchi, 1995). For BM operations, capturing, and sharing knowledge follows the practices of KM as for other construction operations. Practitioners usually gain and share knowledge via several methods, such as: mentoring and learning from each other, attending training courses, and via formal and informal meetings. However, for storing (codifying) and retrieving knowledge, specific BM knowledge ontology should be designed as has been conducted for this research. In literature, several KM systems have been revolving around managing knowledge in BM. Ali *et al.* (2002, 2004) introduced a prototype system to improve the management of Reactive Maintenance projects. Other examples include: "Building Maintenance Community of Practice" by Fong and Wong (2009), and the web-based system "Consulting Knowledge System" by Lepkova and Bigelis (2007). The chief objective of such applications is the improvement of knowledge sharing and communication between stakeholders in BM. However, linking this knowledge with building models is always missing. Therefore, this research aims to bridge this gap.

Based on the identified aim of this research as above, the research will achieve new levels of efficiency in sharing information and knowledge by integrating KM and BIM technologies. 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. This development has led to the establishment of the concept of Building Knowledge Modelling (BKM) as proposed by Motawa and Almarshad (2013). As shown in Figure 1, the proposed system integrates a case-based reasoning (CBR) module to capture/retrieve the knowledge gained of BM operations with a BIM module to capture/retrieve the information of the maintained elements.

The advancement of BKM over the conventional KM systems can be shown by the intelligent capabilities of searching through all affected building elements when retrieving a knowledge case of a maintained element. 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. Several examples have shown the need for additional maintenance/replacement to other affected building elements because of the failure of a specific element, which may become a major maintenance operation. On the other hand, the advancement of BKM over the current BIM systems can be shown in representing, capturing, retrieving, and most importantly learning over time from the several solutions adopted for building problems during the whole life cycle.

In addition to the conventional features of BIM models, the proposed system will also allow users to navigate maintenance cases and utilises the principles of CBR in retrieval of similar maintenance cases. The system uses an IFC protocol to integrate the BIM module with the CBR module. This paper discusses the development stages and the algorithm adopted for the CBR module and how the module is integrated with the BIM module. The adopted taxonomy for the knowledge cases of maintenance operations is based on the findings of the interviews and case studies conducted with professionals working in public BM departments, as illustrated in Almarshad *et al.* (2011).

The methodology of developing the CBR module

Two approaches are usually used in the development of CBR models, problem solving, and interpretive (Kolodner, 1992). In the first approach, similar old problems are used as a direct and definitive guide to provide an almost right solution to a new problem. The other approach is about evaluating a new case in the context of old cases to justify certain solution when there is ambiguity about the new case. Both approaches can be utilised at the same time for a CBR model and they both need a case retrieval

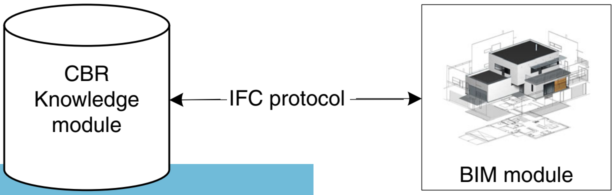

Figure 1.
Integrating case-based reasoning (CBR) with BIM system

mechanism to recall useful stored cases which allows learning from experience. This is done through retrieving and then ranking cases based on their similarity to a new problem. The user has then the option of either selecting and applying a solution from the most similar retrieved old problems or deriving a solution by evaluating several similar retrieved solutions. The methodology followed to develop the CBR module is shown in Figure 2.

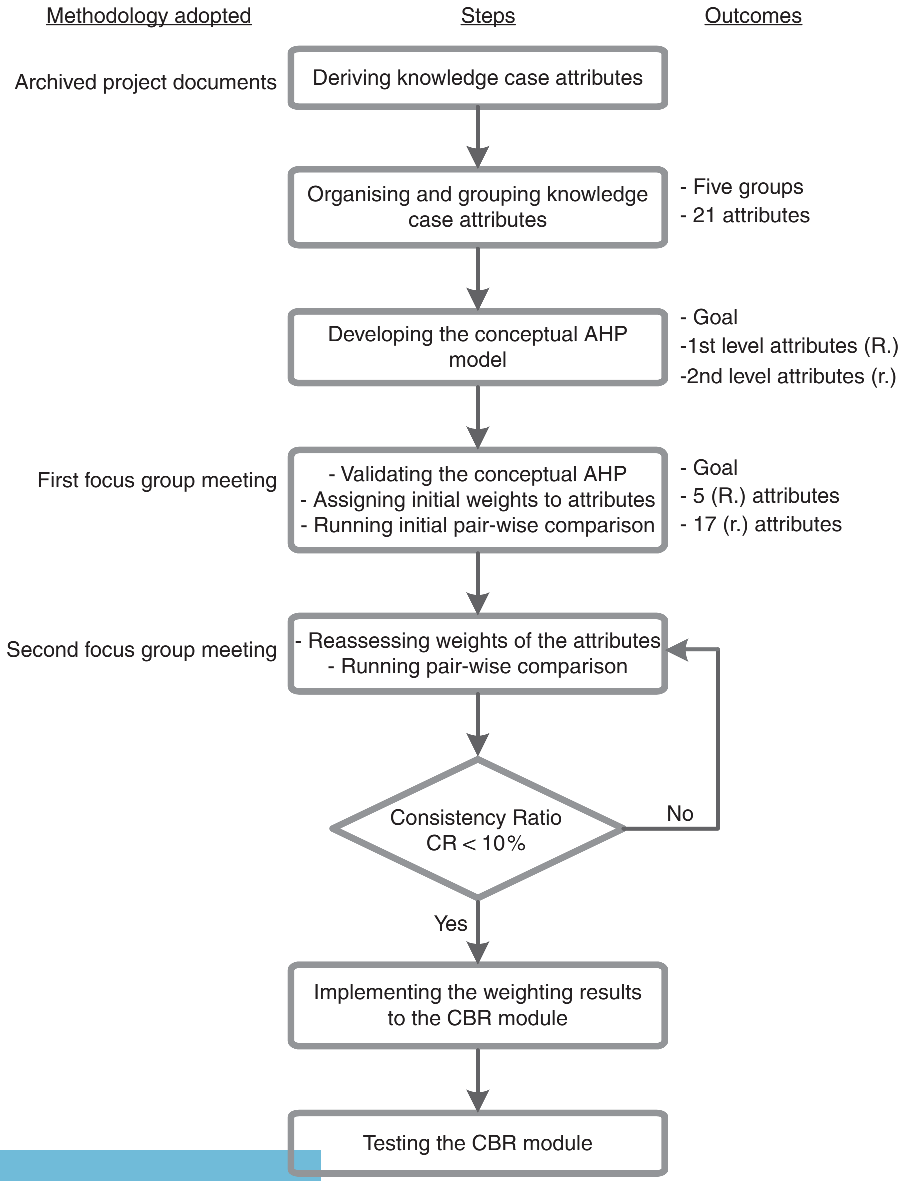

Figure 2.
The methodology of developing the CBR module

In order to distinguish between cases in the CBR module, certain attributes were assigned to the knowledge cases in order to query solutions of similar cases from the stored cases in the system. Dissimilarities between such attributes will lead to matching differences between the knowledge cases. Nearest-neighbour technique is implemented to retrieve the most similar case to a query by identifying and ranking the cases with the highest score of matching attributes to the query.

As shown in Figure 2, the process of developing the knowledge case attributes started with deriving them from documents used in BM works. In total, 21 attributes were initially identified to describe knowledge cases. The ten public BM departments participated in the study have provided examples of documents used in their BM activities which include:

(1) maintenance request forms;
(2) site hand-in forms;
(3) formal letters of communication between parties;
(4) written memos;
(5) daily maintenance reports;
(6) approval forms;
(7) permit forms;
(8) payment forms;
(9) progress meetings minutes; and
(10) final completion forms.

The identified attributes are then organised into five groups to classify knowledge cases, as shown in Table I.

In order to use CBR in problem solving, a weighting score should be assigned to each attribute of a knowledge case. Assigning these scores is based on the influence of an attribute on the retrieving process. An attribute with high influence on distinguishing between cases in the CBR module should have a higher weighting score than the score of an attribute with a low influence. The scores should normally be agreed by professionals in the field of application (BM in this case) to identify the level of influence. Those professionals should follow a methodological technique to help them develop the scores for all attributes. For this research, the analytical hierarchy process (AHP) has been considered to derive weights to the identified attributes through the mechanism of pair-wise comparison. The following section illustrates the methodology adopted to conduct the AHP exercise.

The methodology to apply AHP for the proposed CBR module

AHP is a mathematical concept developed by Saaty (1980) to aid in decision making. This concept is an analysis tool that depends on judgments of experts to develop ratio scales of decision criteria though pairwise comparisons. According to Saaty (1980), the essence of the AHP process is the breakdown of a complex problem into hierarchal model that contains decision goal, criterions, and alternatives. Based on the complexity of the problem, the AHP model can have sub-levels of sub-criteria. On this hierarchal model, matrices of pair-wise comparisons to the elements of this hierarchy level are to be constructed. Weighting the elements of each hierarchy levels is based on their

Table I.
Proposed attributes of knowledge cases used in CBR module

Group name	Attribute name	Description
BM Project details	1. Date	Date of the knowledge case
	2. Client name	Name of beneficiary unit
	3. Contractor name	Name of contractor undertaking maintenance works
	4. Address	Location of the building
	5. Governorate	Name of province
	6. Project name	Name of the maintenance project
Building details	7. Building type	Usage of the building (school, office building, police station)
	8. Structure type	Concrete, wood, steel, combined, etc.
Knowledge case indexing	9. Category	Legal, technical, administrative
	10. Section	Which section within each category
	11. Sub-section	Which sub-section within each section
Particular knowledge case details	12. Topic	General topic of a knowledge case
	13. Issue/problem	Particular issue/problem of a particular case
	14. Reaction/solution	The reaction/solution to a particular case
	15. Keywords	Keywords that identify a particular case
	16. Related elements	The closest element affected by the case
Author details	17. Author name	Name of the case's author
	18. Author position	Working title of the case's author
	19. Knowledge interest	Building maintenance category that captures author's interest
	20. Phone	Contact number
	21. e-mail	Contact e-mail

relative preference to elements of the next higher level. The concept uses eigenvector and eigenvalue properties of these matrices to produce the ratio scales. AHP allows tangible and intangible parameters to be compared against each other for priority weighting (Wedley, 1990). Saaty (1980) proposed a scale technique for weighting the elements when pair-wise comparison is implemented, as shown in Table II. Assignment

Table II.
AHP fundamental rating scale

Intensity of importance	Definition	Explanation
1	Equal importance	Two elements contribute equally to the objective
3	Moderate importance	Experience and judgement slightly favour one element over the other
5	Strong importance	Experience and judgement strongly favour one element over the other
7	Very strong or demonstrated importance	An element is favoured very strongly over the other; its supremacy demonstrated in practice
9	Extreme importance	The evidence favouring one element over the other is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate importance of values listed above	When a compromise is needed for a difficult value of dominance
1/2, 1/3, 1/4, 1/5, 1/6, 1/7, 1/8, 1/9	Reciprocals of the above	If element *x* has one of the above values assigned to it when compared with element *y*, then *y* has the reciprocal value when compared with *x*

Source: Saaty (1980)

of a weighting score from the scale is based on the importance or dominance of an element over other elements at the same hierarchal level to achieve the goal in the next higher level.

AHP has been widely used in construction related research. For example, Lai *et al.* (2008) implemented AHP to develop a budget determination model for public building construction projects. An *et al.* (2007) utilised AHP to determine the weight of attributes for a CBR-based construction cost estimating model. To evaluated FM services in residential buildings, Lai and Yik (2011) used AHP to isolate responses with inconsistency of judgments. Furthermore, Das *et al.* (2009) implemented AHP to develop a standard method for acquisition of tacit knowledge in FM. Within the area of BM and restoration, Wang *et al.* (2008) utilised AHP in developing a CBR-based cost estimation model for restoration of buildings.

The AHP model developed for the proposed CBR module has the goal of retrieving the most similar knowledge case when a CBR inquiry is made. Therefore, the importance of an attribute in distinguishing between knowledge cases has been set as the goal by which attributes are weighted against. The attributes and their groups illustrated in Table I were reorganised as first and second level criteria in the conceptual AHP model. The attributes were set as second-level criteria (r.), and their groups were set as first-level criteria (R.). The adopted methodology to develop the CBR module has a major task to validate the identified hierarchy and to assign weights to these attributes, as explained in Figure 2. This will be illustrated next.

Validating the AHP hierarchy model

Two focus group meetings have been conducted with professionals working in public BM departments. Eight experts have participated in the focus group meetings who were a mix of relatively experienced and inexperienced professionals working in BM departments of various sizes to reflect the different BM practices. The participants possess various roles in their departments: managers, team leaders, engineers, and architects. The aim of the first meeting was to validate the knowledge case attributes and identify the AHP weights of the validated attributes. Expert Choice and Excel software were employed to analyse the results of the meetings. The validated hierarchy is shown in Figure 3 with a total of 17 second-level criteria (r.). Among the changes to the initial list of attributes was the removal of attribute (r.14). The participants argued that users would describe problems in order to retrieve a solution, and therefore it would be ineffective to consider the solution fields in searching the knowledge-base.

The participants also added attribute (r.7) "Number of stories" of "Building details". The reason for that was some maintenance problems may be affected by the number of stories of a building. Such problems include electricity, elevators, water leaking, and HVAC. Moreover, in the group of "Case details" (R4), attribute (r.15) "cause of a problem" was also added as a distinguishing attribute. The participants have acknowledged that a problem caused by different sources may lead to different approaches of resolution. For example, a leaking problem from an air conditioning system needs different solution if compared with a leaking problem from toilets.

In the second part of this meeting, the weights of the case attributes based on the AHP pair-wise comparisons principles were allocated. Each participant was asked to weigh the attribute using the pair-wise comparison tables. The overall judgments were then aggregated. According to the AHP methodology, results from the pair-wise comparison should be rejected if the consistency ratio (CR) for an attributes priority matrix exceeds 0.10 (10 per cent). The priority matrices and the inconsistency test have

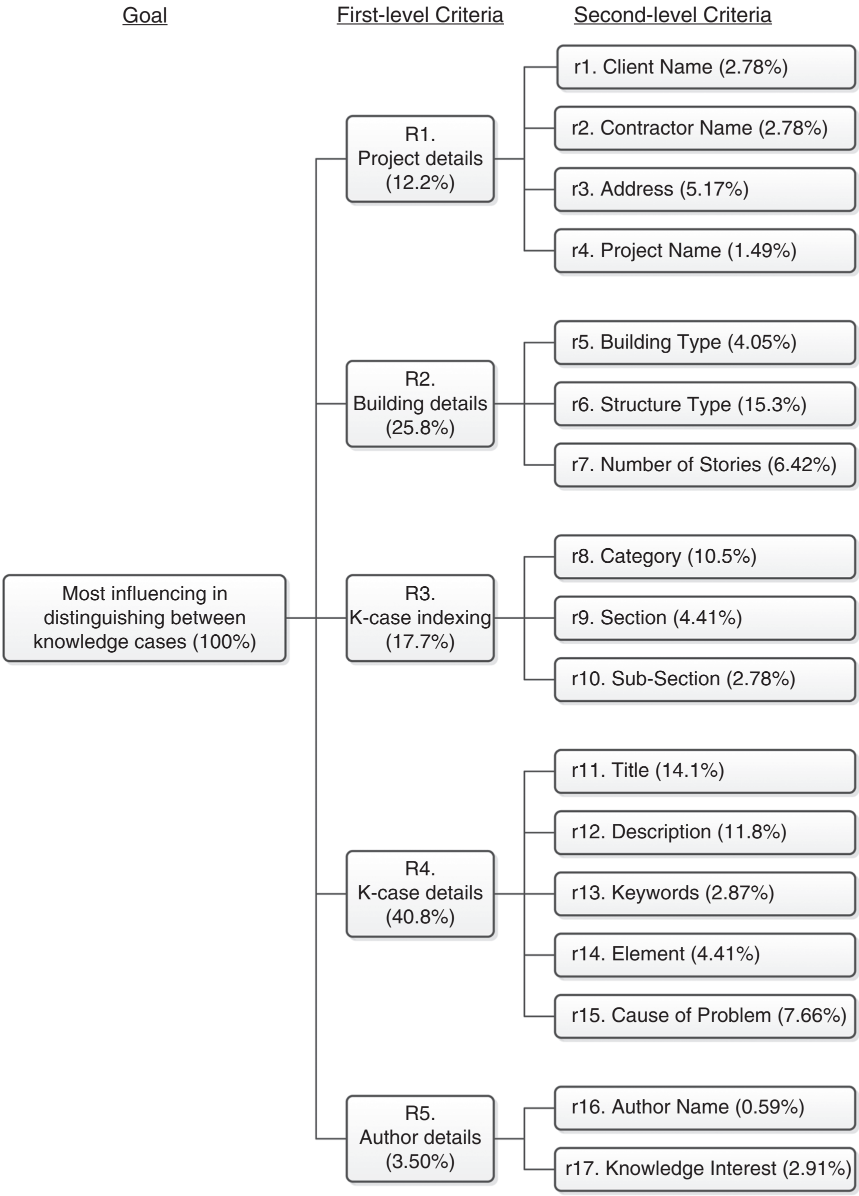

Figure 3.
Knowledge case attributes for the CBR module (hierarchy levels and attributes weights)

been conducted according to the consistency index (CI) and the CR equations developed by Saaty (1977) as shown the following equations. Table III illustrates the CR results obtained in the first meeting:

$$CI = \frac{\lambda_{max} - n}{n-1} \tag{1}$$

$$CR = \frac{CI}{RI} \qquad (2)$$

where n is the dimension of a matrix, λ_{max} the maximal eigenvalue, RI the random index.

As shown in Table III, the CR exceeds the 10 per cent consistency limit for matrices of the first-level criteria, building details, and knowledge case details. Therefore, a second focus group meeting was conducted to allow participants to reassess their views expressed in the first meeting. The CR values based on the reassessment have been recalculated and approved within the acceptable limits as shown in Table III. After confirming the CR for all matrices, the weighting scores were identified for all attributes, as shown in Table IV.

The last step in developing the AHP model was to adjust the weightings of the second-level criteria (r.) according to the weight of their corresponding first-level criteria (R.), as calculated by Equation (3). Figure 3 shows these adjusted values which will be the default weights of the knowledge case attributes in the proposed CBR module:

$$W_i = W_{i(r.)} \times W_{i(R.)} \qquad (3)$$

where W_i is the adjusted criteria weight, $W_{i(r.)}$ the weight of second-level criteria, $W_{i(R.)}$ the weight of corresponding first-level criteria.

CBR and BIM modules integration

The virtual building models developed in BIM-based environment comprise elements such as wall, door, footing, etc. (element-based models). However, retrieving maintenance case details is based on knowledge cases that may include one or more building elements. Therefore, in order to deal with this discrepancy and to integrate the CBR module with the BIM module of the proposed system, additional parameters are used for the elements in the BIM model to represent the knowledge case attributes identified previously (Autodesk Revit is the BIM environment used for this research).

Two forms of parameters are used to represent building elements in Revit; instance and type parameters. For the proposed system, custom instance parameters are added to manage the discrepancy between the knowledge attributes and the BIM models. Figure 4 illustrates the process of identifying these parameters which include the creation of parameters and then specifying their properties. Defining the properties of each parameter involves selecting the type, data format, and categorisation.

	CR	
Matrix name	Results from the 1st meeting	Results from the 2nd meeting
First-level criteria	0.17	0.06
Project details	0.03	0.03
Building details	0.13	0.05
Knowledge case indexing	0.05	0.05
Knowledge case details	0.21	0.07
Author details	0.00	0.00

Table III. Consistency ratio for the attributes priority matrices

Table IV.
The weighting scores for the first-level criteria and the second-level attributes

Code		Priorities with respect to: most influencing on distinguishing between knowledge cases
	First-level criteria	
R1.	Project details	0.122
R2.	Building details	0.258
R3.	*K*-case indexing	0.177
R4.	*K*-case details	0.408
R5.	Author details	0.035
	Second-level criteria	
	Project details attributes	
r1.	Client name	0.261
r2.	Contractor name	0.169
r3.	Address	0.451
r4.	Project name	0.119
	Building details attributes	
r5.	Building type	0.157
r6.	Structure type	0.594
r7.	Number of stories	0.249
	Knowledge case indexing attributes	
r8.	Category	0.594
r9.	Section	0.249
r10.	Sub-section	0.157
	Knowledge case details attributes	
r11.	Title	0.346
r12.	Description	0.288
r13.	Keywords	0.071
r14.	Element	0.108
r15.	Cause of problem	0.188
	Author details attributes	
r16.	Author name	0.167
r17.	Knowledge interest	0.833

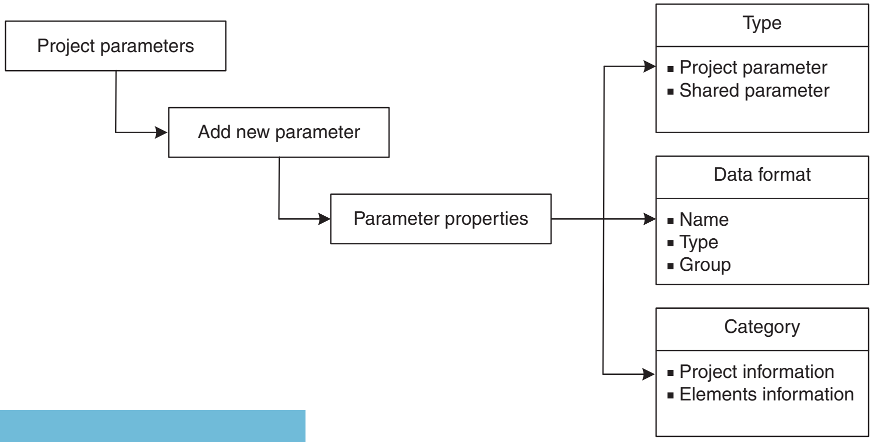

Figure 4.
Parameter settings in the BIM environment of "Revit"

Sets of parameters are added for project information and building elements in a way to be consistent with what should be read and retained by the proposed system. The parameters represent the generic project information to be extracted from a maintenance project and the parameters associated to building elements comprises knowledge case details and categorisation, as shown in Table IV. These parameters become part of the building model when uploaded by the BIM environment. An application example will be discussed later in this paper to illustrate how users of the proposed system can enter these parameters into the system. Figure 5 shows how the CBR and the BIM modules are integrated through the knowledge-based library. Retaining of a knowledge case and processing the added parameters can run through two routes either using the designed user interface of the CBR module or by uploading the BIM model of the building, as shown in Figure 5.

System application

The CBR module permits users to create knowledge cases. In this process, users can add maintenance cases to either stored or newly created projects. Users can either submit a project number to retrieve the details of a stored project or insert the details of a new project (project details as illustrated in Table IV). The details of a new knowledge case can then be inserted (case details as illustrated in Table IV). Upon storing, unique project and case IDs are assigned to distinguish between projects and to link knowledge cases to a particular project. This method can maintain the organisation of cases when updates are made, and allow multiple and simultaneous storing of cases to a particular project.

The other route to insert knowledge cases is by uploading the BIM model. When uploading a BIM model for a particular building, 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 capturing of knowledge/information cases involves users filling the fields of parameters with case details. For example, when an insight has been acknowledged during the works of a maintenance project and believed to be worth capturing as a knowledge case, users can fill in the designated element parameter fields in the BIM-based environment, as illustrated earlier in Table IV. The designated attributes include case's topic, problem, solution, keywords, and element name. Users then insert category, section, and sub-section in which the case to be stored later in the system.

The IFC file format includes information related to project elements, their hierarchy, relationships, geometry, and properties. The project details are shown in the right box and the captured cases are shown in the left box. Each identified maintenance case stored in the system database is assigned a unique case ID. This will allow each project having multiple cases described. This is due to the fact that professionals may face several problems in a single maintenance case that need to be addressed. As a result, multiple insights could be captured in separate cases.

Case relationships

It is common that several building elements may be affected by the breakdown of one element and the maintenance team should investigate the ripple effects of maintaining certain elements on other elements. Therefore, the proposed system has been developed to have the ability to seek relationships between maintenance cases of several elements. By tracing history of work and identifying related problems, this feature can provide

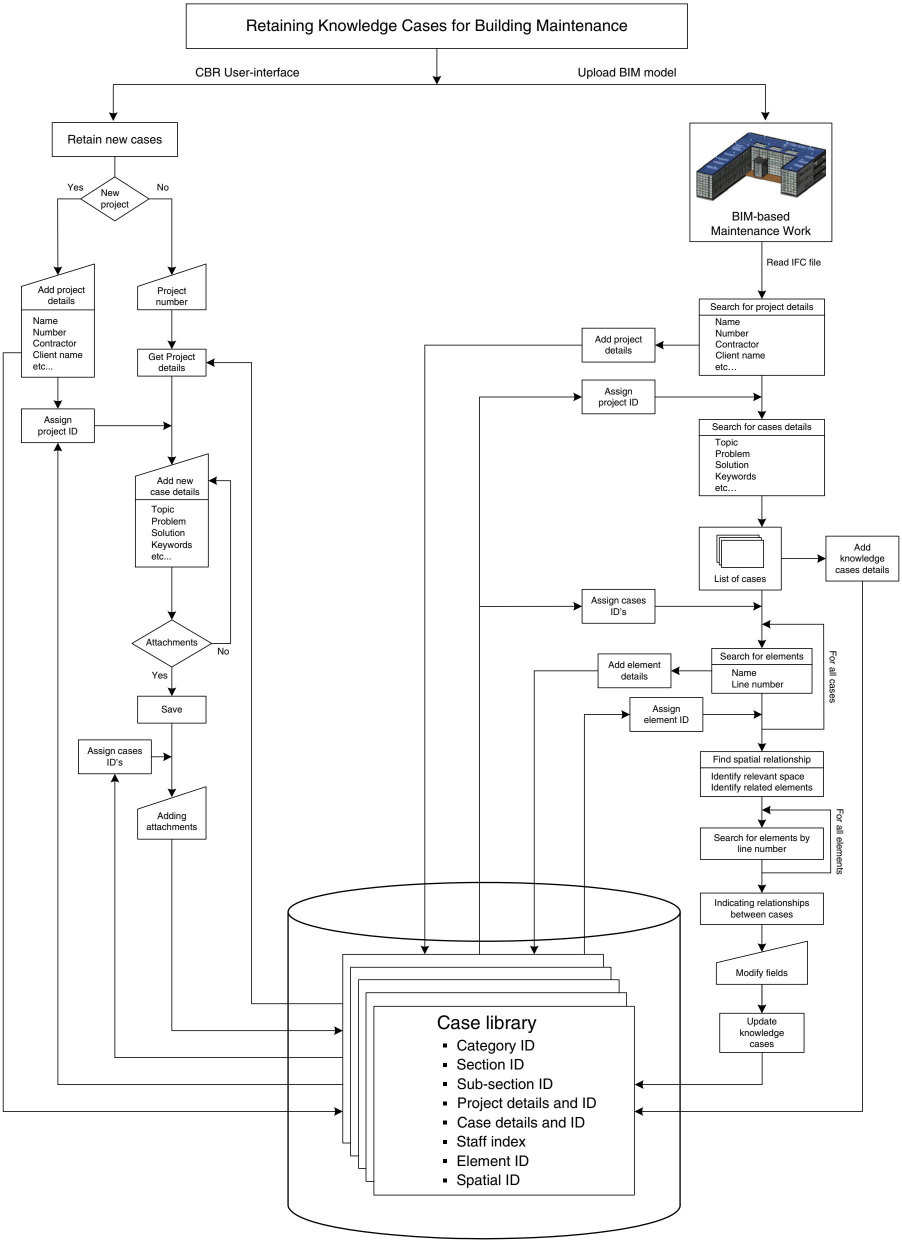

Figure 5.
CBR and BIM modules integration

professionals with a comprehensive understanding of issues related to their maintenance works. The notion of process adopted by the system for identifying relationship between cases is based on the intelligent features of BIM objects.

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.

Conclusion

Several systems have been developed to facilitate either information or knowledge sharing for asset management and building maintenance. However, the efficient practice requires a system that can handle both information and knowledge in an integrated way. This paper presented a methodology to integrate CBR and BIM modules to capture, manage, and retain accumulated information and knowledge of maintenance projects as key operations of asset management. The case-retaining function, along with other functions and modules of the system, makes use of the intelligent objects capability of BIM models to retain knowledge cases for building maintenance and to identify related cases. The system can assist in tracing back the history of maintenance cases of a building and providing comprehensive understanding to support the process of decision making for new maintenance cases. In order to validate the developed CBR module, the AHP methodology has been utilised to rank and weigh the knowledge case attributes based on the principles of the AHP pair-wise comparisons. It is concluded that the integration of CBR and BIM facilities will enhance the practices of sharing information and knowledge. In addition, the integration of the principles of KM into BIM-based systems is a way forward towards the transformation from the conventional BIM to BKM. BKM can help professionals make informative decisions supported by previous learnt experiences. BKM can archive the full history of building operations that is valuable to buildings' owners and facility managers in an easy searchable format to be used for future purposes. While the proposed system was developed for public building maintenance, the process of development can be adopted for other KM domains; such as for other operations of asset management and for design and construction stages. In addition to the adopted BIM spatial relationships, there are also other forms of case relationships that can be utilised to cluster building elements along with the associated knowledge cases.

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