

TITLE PAGE

The integration of lessons learned knowledge in Building Information Modelling (BIM)

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Abstract

Lessons learned systems are vital means for integrating construction knowledge into the various phases of the construction project life cycle. Many such systems are tailored towards the owner-organisation's specific needs and workflows to overcome challenges with information collection, documentation and retrieval. Previous works have relied on the development of conventional local and network/cloud-based database management systems to store and retrieve lessons gathered on projects. These lessons learned systems operate independently and have not been developed to take full advantage of the benefits of integration with emerging building information modelling (BIM) technology. As such construction professionals are faced with the shortcomings of the lack in efficient and speedy retrieval of context-focused information on lessons learned for appropriate utilization in projects. To tackle this challenge, we propose the integration of lesson learned knowledge management in BIM in addition to existing 2D-8D modelling of project information. The integration was implemented through the embedding of non –structured query system, NoSQL (MongoDB), in a BIM enabled environment to host lessons learned information linked to model items and 4D modelling project tasks of the digitised model. This is beyond existing conventional text-based queries and is novel. The system is implemented in .NET Frameworks and interfaced with a project management BIM tool, Navisworks Manage. The demonstration with a test case of a federated model from a pre-design school project suggests that lessons learned systems can become an integral part of BIM environments and contribute to enhancing knowledge reuse in projects.

Keywords: *BIM; lessons learned; NoSQL; federated model; Navisworks; project management*

Introduction

The effective and efficient management of processes in project life cycles is vital to construction project managers. One factor that can influence the ease of executing tasks in the project life cycle is the availability of resources in the form of (i) information from knowledge management processes, (ii) software tools to model and manage such information (iii) the learned professional to harness and utilize the information to improve project efficiencies and of course, (iv) novices benefitting from lessons learned experiences on previous projects which they would not otherwise have in making informed project decisions. The challenges in collecting information such as lessons learned to feed into knowledge management systems have been acknowledged (Kamara et al. 2003; Carrillo 2005; Carrillo et al. 2013). Early practices of knowledge management in the construction industry were largely informal and people-centred (Kamara et al. 2003). The most common approach to learning from projects had been through project evaluation without any formal framework for the effective capture and reuse of knowledge when it is most crucial within the relevant project stages of progress (Orange et al. 1999; Kamara et al. 2003). Also mentioned are the difficulties in capturing knowledge without necessarily overloading project participants and the challenges in making such captured knowledge available for reuse when it matters most (Kamara et al. 2003; Carrillo 2005; Carrillo et al. 2013). Ferrada et al. (2014) alleged that companies lose most lessons learned information because of lack of a properly structured collection and collation systems. Nonetheless, this appears to be the easily controllable aspect. With the setting of new targets, rules and work flows, firms can easily improve on the collection of lessons learned information from project activities. Such data eventually grow to become Big Data which comes with the difficulties of timely and content-focused access. Also such enormous amounts of data often face the challenges of making immediate sense out of it as a result of the overwhelming nature. This is where software applications become useful tools to facilitate the management and retrieval of collated information. It is perhaps a more arduous task than the aspect of gathering lesson learned information from project activities. Thus, it is a specialist task and requires the development of software systems that may need to be tailored towards a particular organisation and its existing workflows. Software systems for managing Big Data have often relied

on Relational Database Management Systems (RDBMS) which are now becoming stretched by recent development in the volume, variety and velocity of data streamed across systems (Kossmann et al. 2010). More preferred systems are the schema-free types such as “Not only structured query language (NoSQL)” that can efficiently handle unstructured data with the tendencies for future growth (Hellerstein et al. 2007; Cattell 2011; Kang et al. 2016). An example of NoSQL system is the MongoDB currently gaining ground in construction information technology (IT) applications for element tracking and querying (Jeong et al. 2015; Kang et al. 2016; Kang et al. 2016). We propose exploring the modelling of lessons learned information stored in MongoDB. As suggested by Ferrada et al. (2014), lessons learned systems should take advantage of new technological advances. One of such technological advances is building information modelling (BIM) which is yet to be fully explored in the coupling of nD modelling aspects, including the lessons learned information as an aspect of knowledge management. BIM-enabled systems have been used for the coordination of project management activities including visualisation of models and the detection of clashes resulting from merged models (Abanda et al. 2015). However, aspects of incorporating lessons learned knowledge management functionality in such BIM-enabled project management systems remains to be fully explored.

According to the Project Management Body of Knowledge Guide, lessons learned is the learning gained from performing a project (PMI 2013). Learning gained, whether failure or success, need to be appropriately validated and duly recorded to be of benefit to future projects. Such records will require continuous updating and should be easily accessible through conventional information searching methods which to a large extent, depends on the ever improving advances in information technology applications. However, the innovations in executing construction project tasks have always been in pursuit to catch-up with advances made in information technology developments. In line with this premise, this research aims to enhance the process of storing and accessing lessons learned information that have been captured on projects using BIM capabilities. The intention is to improve the convenience of stakeholder in accessing lessons learned, and therefore contributing to knowledge building and subsequent application in tackling construction challenges. The paper is

presented in 8 main sections; Introduction, Related works, Lessons learned information systems, Methods, System implementation, System demonstration, Discussion and Conclusion.

Related works

A case for BIM-driven knowledge management through lessons learned

Researchers on the 3D to nD modelling project at the University of Salford, UK suggested that measures of time, cost, accessibility, sustainability, maintainability, acoustics, crime and thermal requirement, etc. (to nth measures) can be integrated into the modelling of building information (Lee et al. 2006). With the advent of BIM, the intelligent object-based modelling of construction projects, some individual dimensions (D) of modelling beyond 3D and what they represent are becoming clearer and widely accepted. It is now common to find literature stating modelling dimensions as 4D Schedule, 5D Cost Estimation, 6D Facilities Management, 7D Sustainability and 8D Occupational Safety and Health (Kamardeen 2010; Masood et al. 2014; Harrison and Thurnell 2015; Shetwi et al. 2015; Abanda et al. 2017). A process that cuts across all these dimensions is knowledge management. For example lessons learned, an element of knowledge management, has the potential of being generated in the activities of all the other dimensions. From the stages of project conception, representation of project specifications in 2D and 3D, 4D scheduling to 8D Safety and Occupational Health; learning can be gained and made useful to an ongoing project or in future projects. Just like all other dimensions, knowledge management is not new in the field of construction and does have a significant role in the contemporary modelling of project information targeted at enhancing efficiencies in successful project delivery.

Lessons learned system applications and BIM

Lessons learned are elements of organisational learning and knowledge management (Carrillo 2005) and therefore important for improvements in the productivity of firms and the sectors in which they operate. One of the works portraying the early realisation of this is Kartam (1996) who presented the

development of the Interactive Knowledge Intensive System (IKIS) Constructability prototype in the 1990's. IKIS-Constructability tool, for modelling real-world construction projects, makes use of lessons learned in the construction phase and can be used by a medium to large-sized construction firm. The main features of the tool are its information manageability (organizing, storing, retrieval and updating) format and the adopted knowledge acquisition/engineering (collecting, verifying, categorizing and archiving) approach. The prototype, however, depends on the enthusiastic support and willingness of engineering practitioner to contribute their personal experience to the system developers in order to build a database of lessons learned. The challenge of such arrangement is that user-organisations must find time and resources to review and approve lessons learned that is to be logged onto the system database. Also there is that tendency that the knowledge-base of the lessons learned may be limited to the experiences of the user-organisation and will tend to be restricted from access by outsiders. To tackle such restrictions to free access to acquired knowledge, Lin (2006) proposed Network Knowledge Maps (NKM) hinged on lessons learned. The maps allow users to manage tacit and explicit knowledge through the review of available and missing information through a web browser. NKM have been used by researchers (Wexler 2001; Noll et al. 2002; Woo et al. 2004) to identify intellectual capital to improve organisational learning and entails a diagrammatic/graphical representation of knowledge and knowledge attributes. Feedback from the NKM system flagged challenges that include difficulties associated with acquiring knowledge from management teams, and the lack of willingness and spare/dedicated time to share experiences without some allocated benefits/reward. Eken et al. (2015) mentioned similar challenges as reasons for developing a database structure and information system for capturing lesson learned information from dispersed sources in hypothetical project situations. Lesson learned system have also been explored using mobile system (Ferrada et al. 2014). The preliminary application of the system in a Chilean construction involved the use of a mobile cloud shared workspace which needed improvements in terms of the richness of the knowledge database and the optimization of the system's search engine on the internet (Ferrada et al. 2016).

159 Researchers have also explored the integration of knowledge database with BIM, albeit
160 largely at the concept levels. Charlesraj (2014) proposed a framework to develop a knowledge-based
161 BIM (K-BIM) for the re-use of historical information to support facility management tasks. The
162 underlying concept is centred on developing ontologies for knowledge management and facility
163 management. Also, in the construction phase knowledge management integration with BIM has been
164 suggested. The work referred to here, is the BIM-based Knowledge Sharing Management (BIMKSM)
165 system, connected to a web platform to facilitate information dissemination and exchange among
166 project managers and engineers (Ho et al. 2013; Jan et al. 2013). Other works include that of Bouazza
167 et al. (2015) regarding the re-use of knowledge by sub-contractors and Lui et al. (2014) concerning
168 integrating change management with BIM. The work by Bouazza et al. (2015) produced a
169 conceptual framework for BIM - Knowledge management system (BIM-KM) to coordinate
170 knowledge among sub-contractors along the supply chain based on the mapping of project knowledge
171 database into COBie information. The efforts of Lui et al. (2014) also yielded a framework which is
172 of interest. The framework combines the interpretation of building data from 2D/3D Computer Aided
173 Design (CAD) files into BIM which interacts with Knowledge management system containing a
174 construction knowledge repository. These components combine to yield their proposed building
175 knowledge management system (BKM). The BKM abstracts information through queries from use
176 cases sourced from the Web or locally generated. The abstracted information is transferred to a
177 prototype, called *Knowledge+*, interfaced with Revit through its Application Programming Interface
178 (API). This BKM approach aims to capture, share, reuse and maintain knowledge in communication
179 and collaboration in the building lifecycle (Liu et al. 2014). Finally, aspects of enhancing
180 construction quality management using BIM has also been explored by Chen and Luo (2014). The
181 application is based on using 4D (time sequencing) BIM in relation to construction codes tailored to
182 the product, organisation and process (POP) data definition structure. Chen and Lou (2014) concern
183 was to use BIM to enhance the process of quality control by ensuring consistency between design data
184 and quality control data for monitoring the construction process. Thus, efforts to use design-oriented
185 BIM-enabled tools to improve quality control process and the interpretation of data from CAD files
186 exist. However, there is need to extend research efforts to integrating lessons learned knowledge

management systems to appropriate tasks-oriented BIM tools such as Navisworks for project management purposes as proposed in this paper.

Lessons learned systems require an efficient database management system which should be robust, compatible and easily interoperable with contemporary information modelling or visualisation system used in supporting project tasks (Kartam 1996; Noll et al. 2002; Woo et al. 2004; Lin et al. 2006; Eken et al. 2015). Although SQL-type DBMS that satisfy ACID (Atomicity, Consistency, Isolation and Durability) quality have been useful in managing data, the textual nature of lesson learned information make it best suited for NoSQL systems which need to be fully explored. Also, NoSQL supports the efficient management of unstructured data and it is web ontology compliant which makes it useful in Cloud computing applications. Current needs to cope with storing managing and retrieving heterogeneous online data have led to the deployment of Cloud-based open source file management systems such as Apache Cassandra, Apache H-Base and MongoDB that rely on NoSQL (Grolinger et al. 2013). The advantages of NoSQL systems have been demonstrated in recent research work including the better handling of collected sensor data on Internet of Things (IoT) platform (Le et al. 2014; Kang et al. 2016) and the scaling of traceability systems for smart product ordering in factory supply chains (Kang et al. 2016). Regarding the aspect of information modelling systems, researchers have mostly explored BIM tools such as Revit to demonstrate the integration of knowledge system (Ho et al. 2013; Jan et al. 2013; Liu et al. 2014) leaving out project management tools such as Navisworks. Although Navisworks has featured in a few research albeit not for the management for lessons learned knowledge. For example Navisworks was used as an intermediate tool for model information exchange between Revit and Protégé in developing ontology construction risk knowledge management in Semantic web service (Ding et al. 2016). Also, Revit and Navisworks were combined to produce construction scheduling, 4D models, for integration with quality model to identify quality control criteria and the assignment of responsibilities in the construction process (Chen and Luo 2014). Navisworks is strong in supporting model federation, clash detection, project programming and remains one of the vital BIM tools that supports collaborative working in the construction industry. There is therefore a need to explore how Navisworks, a versatile project

management tool, can be harnessed to manage lessons learned to inform and enhance the processes involved in project delivery.

The role of NoSQL database in lessons learned systems

Relational Database Management Systems have been excellent in managing structured data that rely on static schema (Kossmann et al. 2010). These systems are becoming stretched by recent development in the volume and variety of data, and velocity with which they are required to be streamed across systems. Stevic et al. (2015) argue that the challenges range from difficulties with backup, scaling, recovery and responsiveness of systems relying on RDBMS to handle the analysis of Big Data which is largely unstructured. Schema-free systems such as the Not only SQL (NoSQL) have been suggested to be efficient in handling unstructured data that has the tendencies for future growth (Hellerstein et al. 2007; Cattell 2011; Kang et al. 2016). NoSQL databases are CAP (Consistency, Availability and Partition Tolerance) compliant and offer full text search capabilities as may be applicable to lesson learned systems. Three key advantages of NoSQL databases include a less expensive scale-out architecture that adds low-end resources, consistency in scalability, handling of different data types and formats with high degree of flexibility (Kang et al. 2016). These advantages have made NoSQL data preferable alternative to Relational Database Management System (RDMS) in storing and processing high-volume of data associated with Social Network Services (SNN) and Internet of Things.

NoSQL databases use a number of data structures such as key-value, column, graph and document (Leavitt 2010). The choice of using a given NoSQL database depends on the problem that is intended to be solved. For example NoSQL databases stores may be design to prioritise either or a combination of consistency, partition tolerance, speed or use of low level query languages and as such suitable for different purposes. Some common examples of NoSQL databases include MarkLogic (Document/Graph), MongoDB (Document), Virtuoso (Graph) Apache Cassandra (Column), and Redis (Key-value). A document data model that has featured in the construction and manufacturing domains is the MongoDB. MongoDB was found to perform optimally in the querying

of a traceability system targeted at enhancing decision making in the construction and operation of hardware capacity planning of automobile parts in a smart factory supply chain (Kang et al. 2016). In hybrid architecture to improve e-learning platforms, MongoDB and RDBMS have been combined to handle unstructured data and structured data respectively (Stevic et al. 2015) .

Extending the functions of BIM-based project management systems

Navisworks is one of the common BIM-enabled project management systems (Abanda et al. 2015). Unlike Autodesk Revit, BIM application extensions research (Oti and Tizani 2015; Oti et al. 2016) involving Navisworks is still at infancy and not too common in the construction domain. However, the roles of Navisworks in model visualisation, merging of models, clash detection and scheduling have been widely explored in the industry. Navisworks is known to be compatible with a wide range file formats such as Industry Foundation Classes (IFC), Virtual Reality Modelling Language (VRML), CIMSteel Integration Standards (CIS/2), Design (DGN), Faro, Leica, Alan - Charles - Ian's System (ACIS), Standard ACIS Text (SAT), Stereolithography (STL), American Standard Code for Information Interchange (ASCII) Laser etc. and therefore useful in ameliorating advances in interoperability and integration. Efforts to push the boundaries to which project management systems such as Navisworks can be useful in construction projects alike exist. One of such efforts is demonstrated in tracking objects changes in BIM to assist construction managers in the coordination and management of subcontractors (Giel et al, 2013). The quality control and monitoring in construction can also be carried out by integrating Light Detection and Ranging (LiDAR) and BIM using the Naviswork environment (Wang et al. 2015). In the Asset Management domain, Navisworks has been found useful in hosting applications that explored using Mobile devices for real-time visual facility management (Lin and Su 2013). The visualisation capability in Navisworks in 4D simulations has also been pushed to the limits of immersive virtual reality applications such as CAVE (Cave Audio Video Environment) (Kang and Kuncham 2014). Others include developing a smart controller model of Global Positioning System (GPS) coordinates (Taghaddos and Eslami 2016), optimizing the selection of table structure consisting of beams and slab (Mohammadi et al. 2011), sustainable bridge

information modelling using Building Management System (BMS) features (Marzouk and Hisham 2012a; Marzouk and Hisham 2012b) and BIM navigation incorporated with hand-based gesture on construction sites (Yang and Kang 2014). While all these works are great, BIM-based project management applications centred on easing the accessibility of lessons learned construction knowledge is lacking.

Lessons learned information system

Lessons learned is reliably defined as the learning gained from the process of performing a project (PMI 2013). It is worth mentioning that lessons can be identified at any point of the project life and by any party or stakeholder involved on the project. Since there can be numerous individuals (professionals and tradesmen) and teams involved on a project, it is therefore essential that the process of identifying, documenting and accessing lessons learned be effectively and efficiently managed. There exist various efforts on lesson learned information systems such as the SuperBase based on relational database (Kartam 1996). The work by Eken et al. (2015), also based on relational database, explored leveraging dispersed information retrieval using web services. Mobile applications communicating with Cloud services such as windows Azure hosting Web applications and relational databases have also been proposed (Ferrada et al. 2014; Ferrada et al. 2016) . The main activities common to these lesson learned systems, as also suggested in the literature (Rowe and Sikes 2006) are to (1) identify, (2) document, (3) analyse (4) store and (5) retrieve the lessons learned. Although, the approach to combining these activities may differ in terms of order and structure in companies, we group them into three components; Users; Repositories and Quality assurance (Figure 1). The two main interactions of the users and quality assurance team with the repositories are to store and retrieve lessons learned information. The ease and speed with these actions are executed as and when needed goes a long way to determine the efficient functionality of the system and how knowledge can be diffused and ultimately utilised. Systems that are technological outdated, unfriendly to operate and relatively slow in response will discourage project stakeholders from committing their time and efforts.

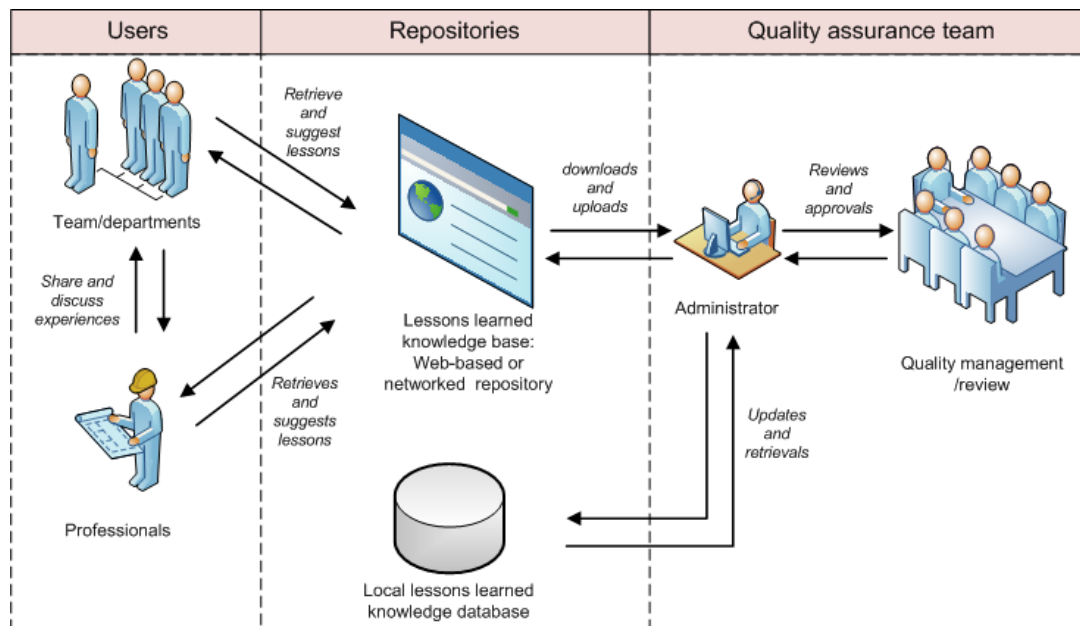


Figure 1 Lessons learned information systems

Methods

This research work builds on a project concerned with the continuous improvement of a pre-designed scheme for schools using BIM, which is delivered as a turnkey project using a framework agreement. The pre-designed scheme presents clear advantage of using lessons learned information and knowledge from the operations phase to continuously improve the design and development of the digitized models. In the sub-sections, further description is given about the approach for utilizing BIM as a learning platform and the methods for improving the process of harnessing lessons learned using emerging BIM technology.

Project description

This study is undertaken as an offshoot of the UK government-funded BIM-enabled low impact school procurement project. The project was about enhancing improvements on the delivery of pre-design schools based on turnkey contract under a national framework arrangement. It entailed

exploring how BIM can be used as a learning platform to increase efficiencies in the processes involved in product delivery. The main concerns are to enhance the collective knowledge and practice of project stakeholders/supply chain members. The products are pre-design school buildings, schemes where buildings of interest are built from an existing design with little or no modifications/variations. This research is of high importance to pre-designed schemes as there is a clear advantage of using lessons learned knowledge from other ongoing or completed projects to continuously improve design and delivery for improvements in the satisfaction of successive clients. The deployment of BIM will assist the Main Contractor to develop and adopt innovative strategies to delivering, refining and optimising the final ‘products’ from the pr-designed models. This has been pursued through focusing on the integration of project data from design, construction and operation stages in a BIM environment. Also, aspects explored include the fostering of enhance BIM-based collaboration among project stakeholders and the testing of research concepts to continuously improve the ‘product’. One key aspect is to utilize feedbacks from downstream to improve project activities that occur upstream and to learn from lessons gained.

Using BIM as a learning platform

The aim of using BIM as learning platform is to reduce gaps in the upstream knowledge-feedback-loop between construction and design. Such feedback concept has been demonstrated in the use of historical energy consumption from BMS in BIM (Oti et al. 2016). The collaborative platform will support integrated collaborative procurement, design, and delivery of low impact pre-designs for turnkey school projects. As illustrated in Figure 2. The building project adopting BIM working method has a federated BIM model tailored to a particular design and a particular site. BIM implementation in the pre-designed schools requires an extra level of generic model development which goes through 5 stages: i) generic BIM model, ii) site specific BIM model (or as-planned BIM model), iii) As-designed BIM model, iv) as-built BIM model and v) live BIM model. The creation of a generic model for a particular pre-designed school type generates significant saving in time and cost for model development for the site-specific BIM models. A site-specific BIM model that fully

represents the actual construction is then developed from the generic model. This takes advantage of the economy-of-scale production logic in generating site-specific BIM model. Efficiency is therefore achieved through data sharing and data reuse. Upon the confirmation of a project proposal, existing drawings, textual information and specifications from a generic digitized model are reproduced and then integrated with various digitized site models and supply chain models. These combinations can then be further tailored as site- specific building information models for construction and operation. These processes produce progressive As-planned BIM, As-built BIM and the live BIM which are used for the actual construction phase and during operations. They also serve as channels to supply feedback to the Model Preparation stage for the refinement of the generic building design model. Such feedback loops drive continuous model or product development. One important process for continuous model development is periodic design reviews that capture the construction issues of the model. In these reviews, one of the areas identified for investigation as feedback channels for improving project delivery is the lesson learned systems. The aspects directly concerned with lessons learned systems have been highlighted by a box in broken (red) lines as shown in Figure 2.

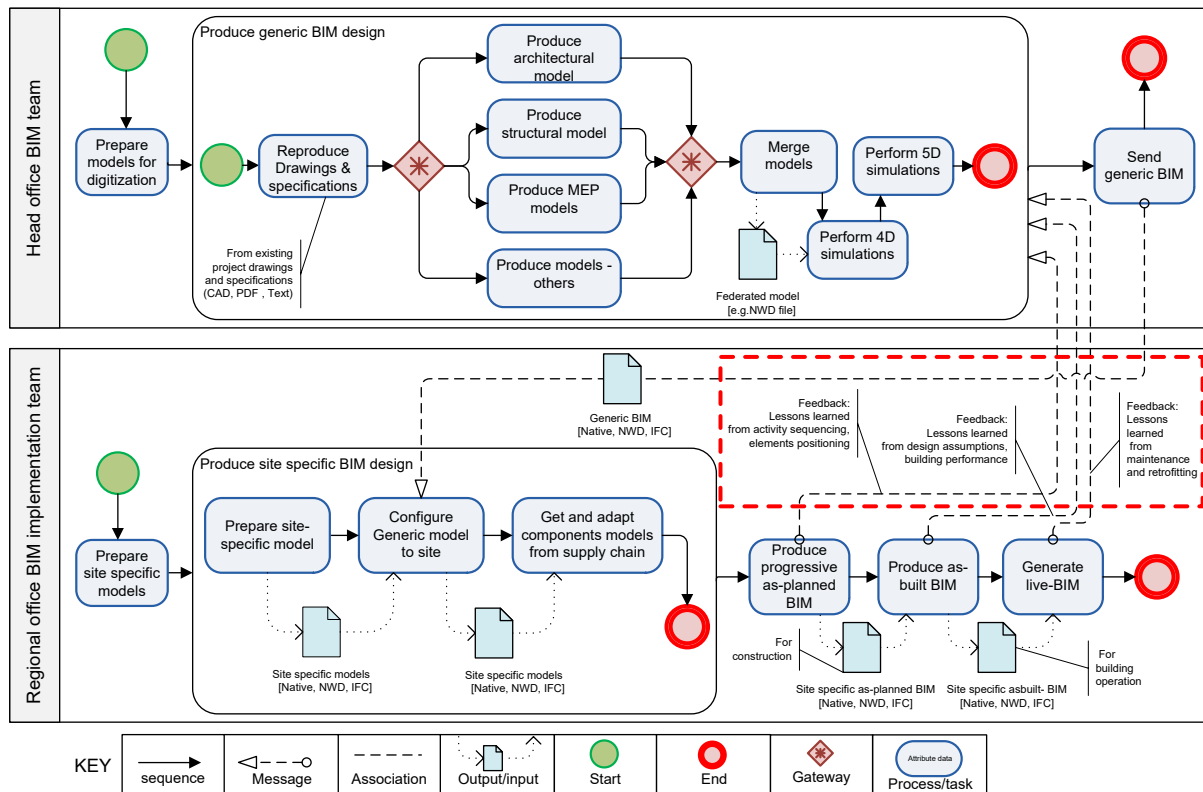


Figure 2 Lessons learned applications in BIM to improve the turnkey process

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350 **Modelling approach for lessons learned systems**

351 There is need for the continuous improvement in the levels of sophistication inherent in design and
352 decision support tools that interoperate with emerging BIM software. This is underpinned by the fact
353 that BIM is ever expanding and is continuously being refined. As Cerovsek (2011) suggests, any
354 BIM schema should never be ‘completed’ but allow for expansion to accommodate evolutionary
355 developments of evolving tools and Architecture, Engineering and Construction (AEC) practices.
356 Lessons learned systems stand as one important aspect of knowledge management (Lin et al. 2006)
357 that need such improvement in harnessing and injection into construction project management. The
358 proposed approach for exploring the enhanced utilization of lessons learned systems in contemporary
359 BIM applications is illustrated in research framework presented in Figure 3. The first part consisting
360 of preliminary activities is aimed at preparing input data (lessons learned), defining approaches to
361 efficiently storing/accessing such data and directly associating sourced data with model items.
362 Associating model items to lessons learned is the process depicted by the second part which involves
363 probing digitized models to identify concepts and structure of model item representation and
364 aggregation for purposes of appropriate lesson to model item mapping. The third part involves the
365 implementation in .Net framework environment and testing how it works with typical knowledge
366 query instances. The implementation which entails aspects of information modelling, concepts and
367 object representation is carried out in C# programming interfaced via API with project management
368 BIM tool such as Navisworks.

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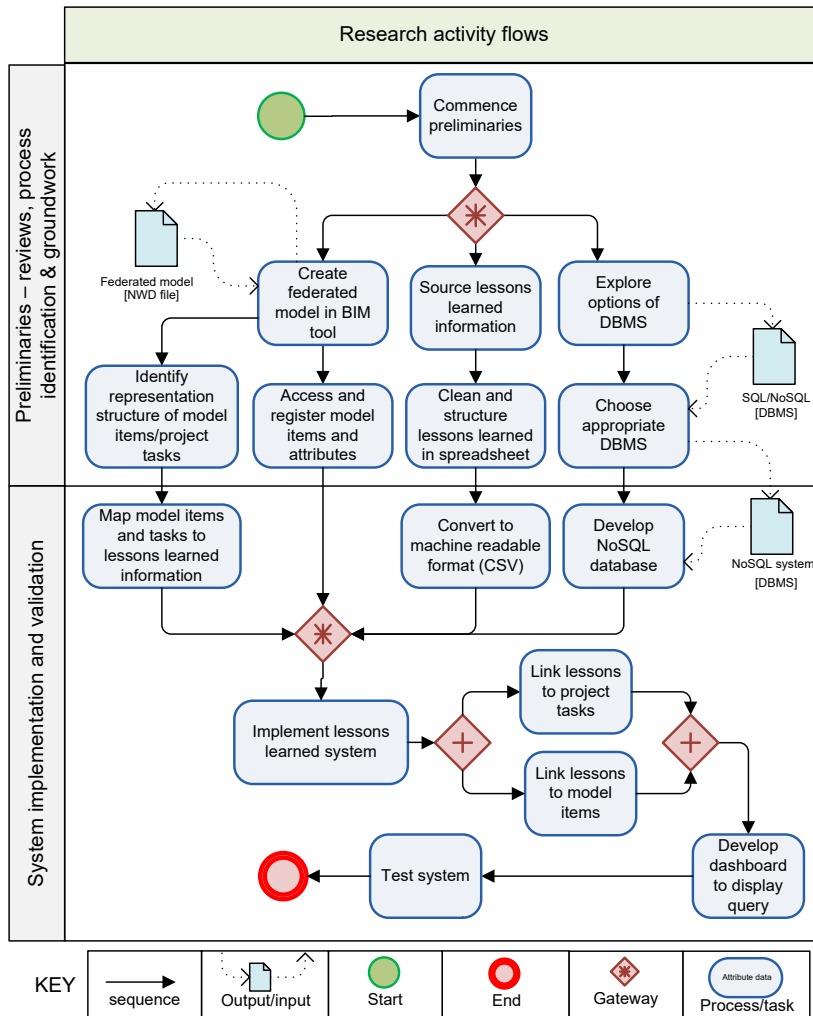


Figure 3 Research framework

The information modelling approach is based on the Rapid Application Development (RAD) principle (Maner 1997) hinged on Icam DEFINITION for Function Modelling 0 (IDEF0) modelling language and Business Management Process Model and Notation (BPNM) used to develop the various relationships and interactions of the system. IDEF0 is combined with BPMN in order to harness their individual strengths in process modelling. While IDEF0 clearly specifies the input and output of a process/task, BPMN provides a compact and comprehensive overview of a whole process that is easily understood in business processes (Tangkawarow and Waworuntu 2016). The simplified IDEF0 Level 0 representation of this research is shown in Figure 4. While the inputs in the research work encompass theoretical research underpinnings, the output remains a validated lesson learned query system that is replicable in terms of the modelling of processes and concepts. The RAD

methodology has been widely used in software development circles and employs cycles of re-specify, re-design and re-evaluate on the prototype system from conception to completion. The advantage of the RAD approach is the increased speed of development and experiences of series of births rather than catching up with deadlines thereby providing opportunities for continuous system refinement.

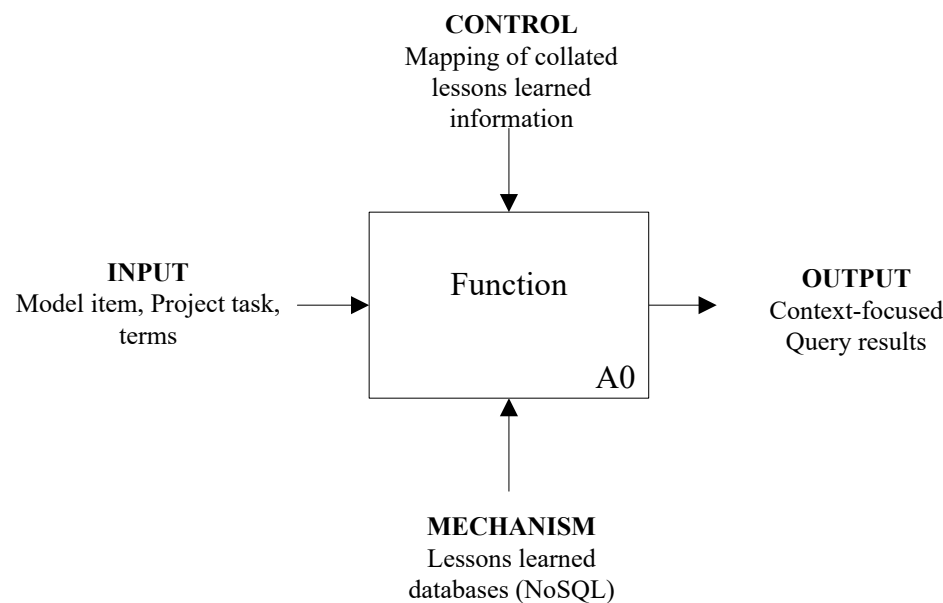
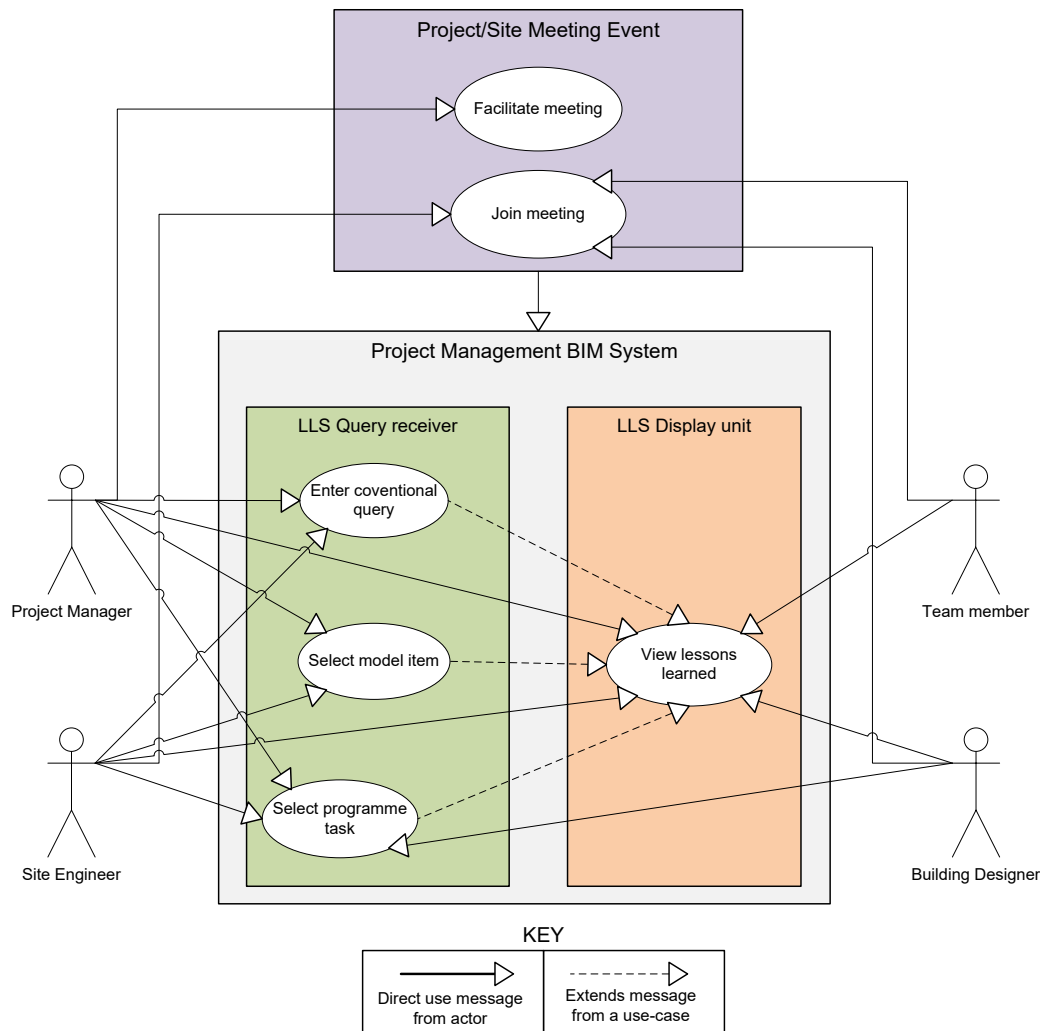


Figure 4 Simplified components of proposed system

System implementation

The focus of this research is to enhance how to ease the access of information about lessons learned on projects to improve stakeholder knowledge and consequently, project efficiencies and delivery. The proposed approach is to link lessons learned information to BIM objects or model items and project tasks. Given that a federated model, as depicted by Level 2 BIM maturity (BIM-IWG 2011), is a coordinated aggregation of digitized models from the various concerned professional domains (architecture and furniture, structural, plumbing, electrical etc.); it presents an opportunity to have a common environment close to the physical building. Such environment provides the possibility of

398 having the varied range of lessons learned issues that may have emanated at the various stages of the
 399 project life cycle to be associated with respective building elements (model item) in a federated model
 400 as well as the schedule of task to execute projects. An example scenario of a use case (Figure 5) for
 401 the proposed system depicts project or site meeting as typical events for which the system can be
 402 utilized. Such meetings will usually have the project manager, site engineers, designers and other
 403 project team members in attendance. The lessons learned system can then be used in the environment
 404 of Project Management BIM-enabled tools such as Navisworks during visualisation of the digitized
 405 models.



407 **Figure 5 Use case for lessons learned system**

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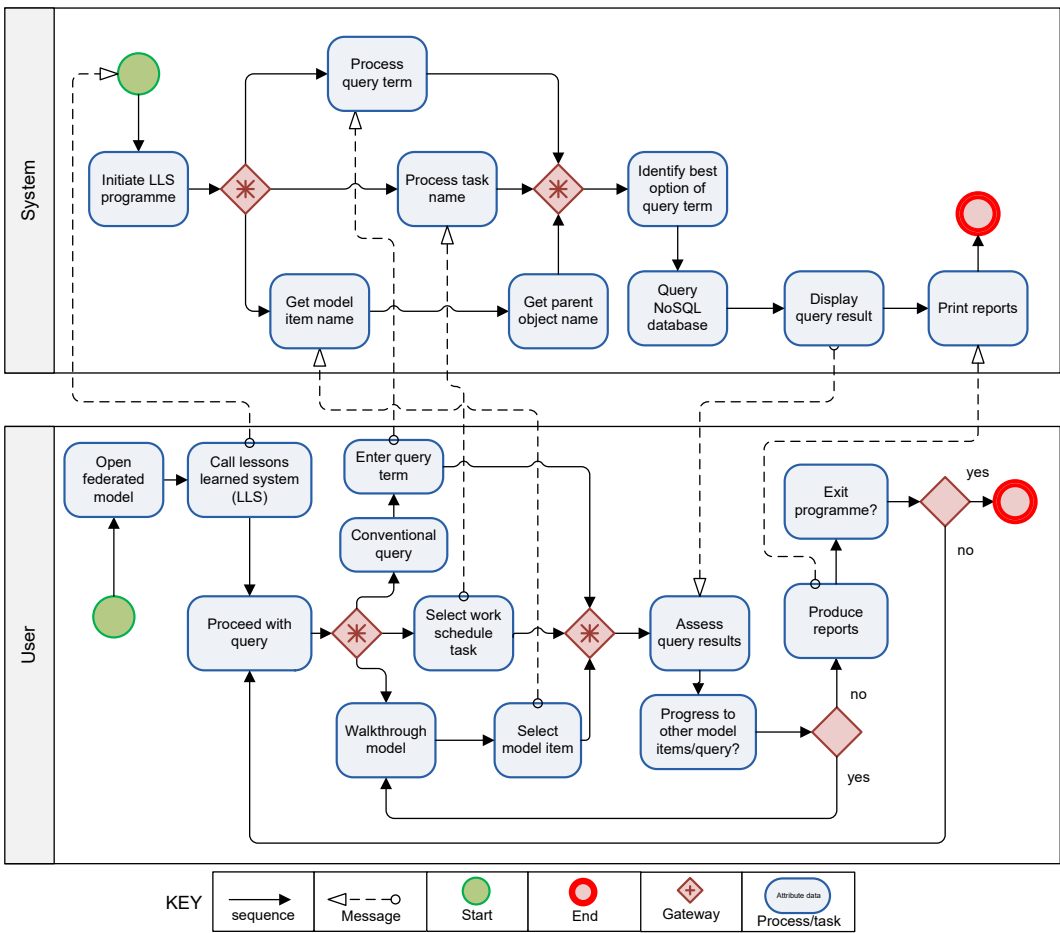
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In line with this premise, a flow chart illustrating the implementation of the system is given in Figure 6. It is made up of ‘user initiated processes’ and the ‘system executed processes’ blocks to respectively capture actions carried out by the user and the corresponding responses of the system. When the programme is called, in addition to conventional database querying, the user has the option to walkthrough the model and see related lessons learned from the selection of interested model items. On the selection of a model item or initiation of a query, information about the parent objects are also checked to identify the most appropriate search criteria to query the NoSQL database. The query results can be consequently assess by the user for subsequent action and recorded accordingly. The flow chart is further discussed by examining the components of the system and its operation.



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Figure 6 System implementation flowchart

System components

The system can be broken into five component modules in line with the simplified representation in Figure 4 which are the Input, Control, Mechanism, Function and Output (Figure 7). These components are characterised by the distinct software environments that have been pooled together in the system implementation. The system can be launched from a BIM-enabled environment (Navisworks) where the Input and Output reside, the lessons learned and associated mappings are from MS Excel environment serving as the Control. The Mechanism is the generated NoSQL database domiciled in MongoDB. The programming instructions, object representations and the manipulation of these data are done in C# (.NET Framework) and constitute the Function.

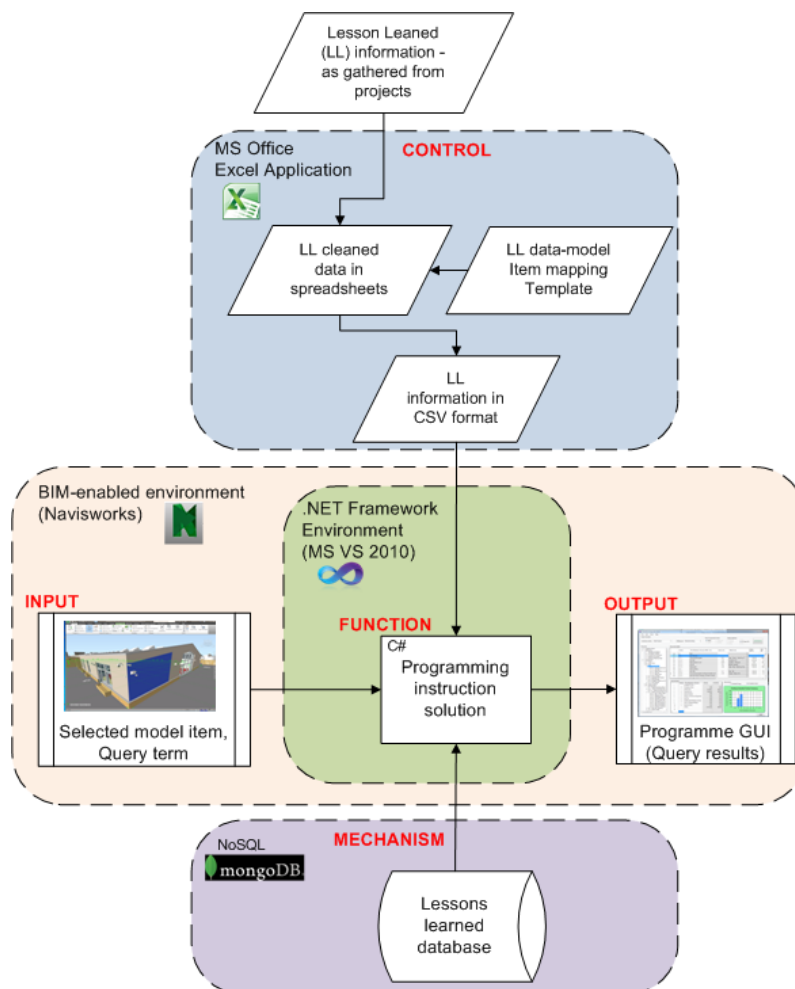
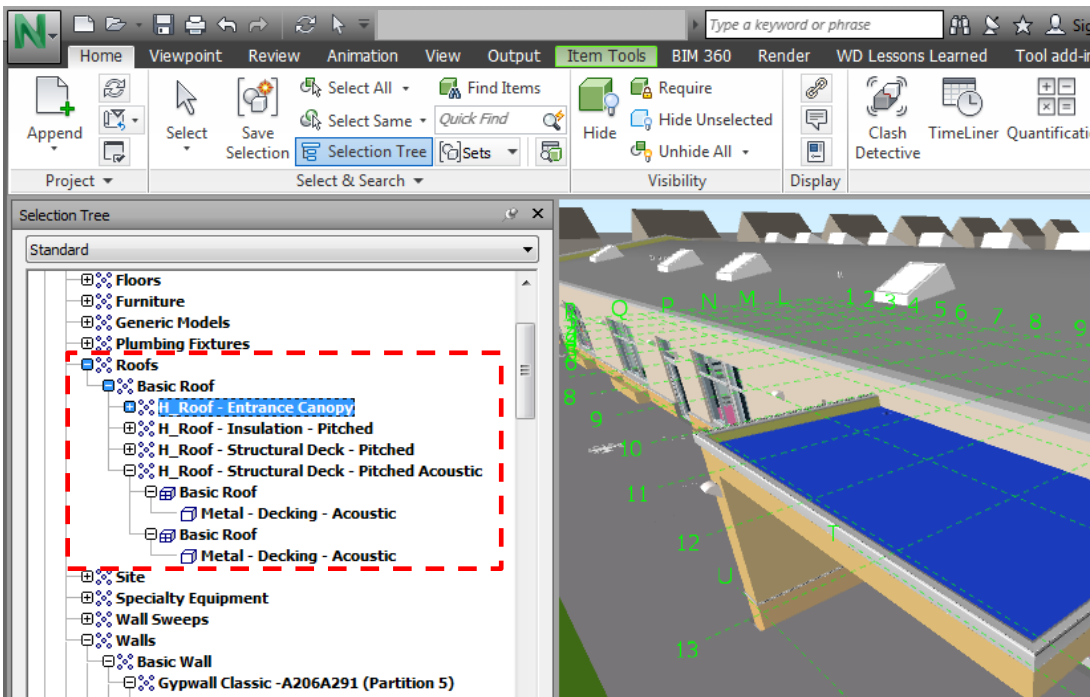


Figure 7 Relationship between system components

Input

Many proposed construction knowledge management systems utilize query systems that require users to type in text-based search terms (Kartam 1996; Lin et al. 2006). With the continuous refining of sophistication in object-based modelling embedded in BIM, the querying of lessons learned can be linked to model items and project tasks. The source of information for the Input is Navisworks environment where federated digitized models can be manipulated to varying degrees. The main action for activating the input into the system is the selection of a model item by double-clicking it with a mouse. Thus, during model walkthrough in sites or project review meetings for example, lessons learned information relating to model items can be automatically accessed. This research therefore proposes model item as direct input into the system. When a model item is selected, the system accesses the properties of the item including those of the parent object. The attributes of the selected item and its parent object are assessed to identify the suitable item name that can be used to interact with the database. For example in the Navisworks environment shown in Figure 8, the Selection Tree displays a detailed hierarchy of model items. The Roofs item is the parent of Basic Roof which in turn has four child objects; H_Roof - Entrance Canopy, H_Roof - Insulation - Pitched, H_Roof - Structural Deck - Pitched and H_Roof - Structural Deck - Pitched Acoustic. In this case, the system will recognise any of these child objects as Basic Roof, by default, when selected during a walkthrough activity. Note that each of these child objects may be a single material, composite material or consist of further child objects.



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454 **Figure 8 Model items hierarchy in Navisworks Selection Tree**

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456 **Control**

457 The Control constitutes a combination of lessons learned (LL) information and mapping information
458 that conforms to model items existing in the federated digitized model in Navisworks environment.

459 The LL information is initially entered into MS Excel spreadsheet by the knowledge management or
460 quality control team of the project/firm. In this form, the information includes series of non-machine
461 readable characters, hence requires cleaning and restructuring to be fit for purpose. Also it is at this
462 stage, the required mapping of model item to LL information can be done (Figure 9). This entails
463 unbundling of the data structure of model items to access the appropriate object type and name to be
464 associated with the respective lessons learned entries (Figure 9 (a)). A field/column

465 (ModelItemAffected), in green dashed-line box (Figure 9 (b)), of typical model item/object names is
466 therefore introduced in the LL spreadsheet to allow for the mapping process. In this example the four
467 groups of roof items (Entrance Canopy, Insulation - Pitched, Structural Deck – pitched and Structural
468 Deck – Pitched Acoustic) are mapped as Basic Roof. All the lesson learned entries that relate to any

of these four groups are tagged as basic roof and will be pulled up during query events. The entries in this field also serve as the search terms used to query the NoSQL database when a model item is selected without the need for developing relational database keys. This is one of the advantages of deploying NoSQL databases such as MongoDB in knowledge management systems.

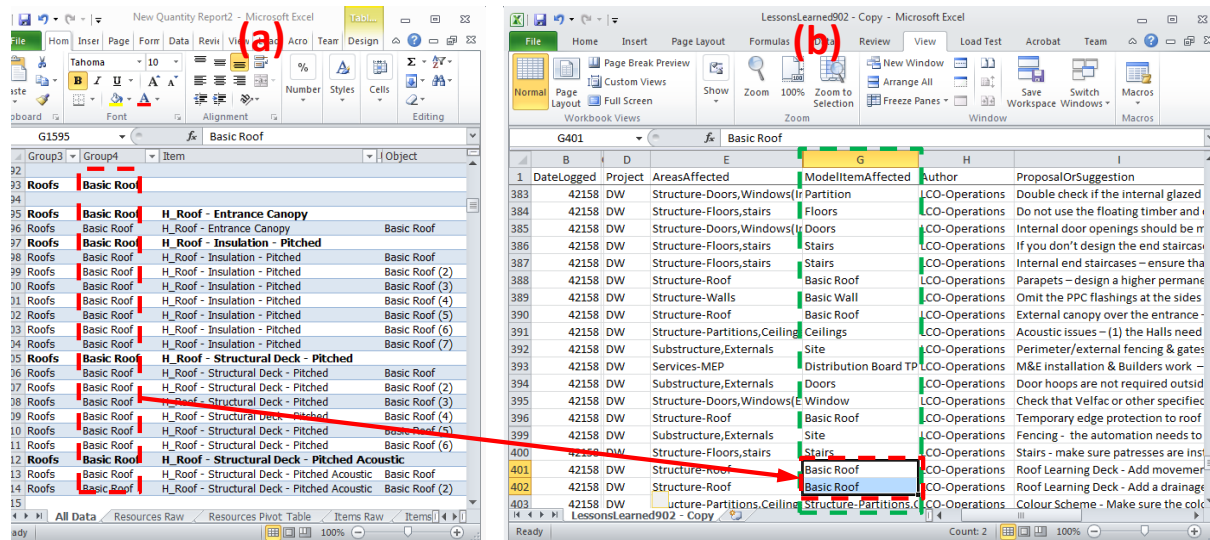


Figure 9 Mapping model item to lessons learned (a) Model item structure from Navisworks (b) LL information with mapping field

Mechanism, Function and Output

The cleaned and mapped lessons learned data is transferred to MongoDB which is the Mechanism environment. MongoDB stores the lessons learned data and provides the environment for data management and manipulation. Data is stored in the form of documents and linked through nodes. MongoDB provides easy access through programming applications such as C# provided the appropriate connection has been established in MS-DOS. C# is the environment where the Function is developed and it is where all the programming instructions are initiated and executed. Figure 10 gives the illustration of an example of the C #snippet that interacts with the NoSQL database as viewed from the MongoDB Compass. MongoDB Compass enables users to probe collections in a cluster of

MongoDB localhost. The interactions with the federated model through Naviswork API to obtain the Input; reading of the Control information (lessons learned) from the cleaned comma-separated values (CSV) file and subsequent insertion into MongoDB are all carried out in the Function. Further, the Function initiates the query according to instructions and sends the results as Output. The Output is the graphical user interface (GUI) displaying the results of the model item query in a Windows form obtained as an external application on Navisworks.

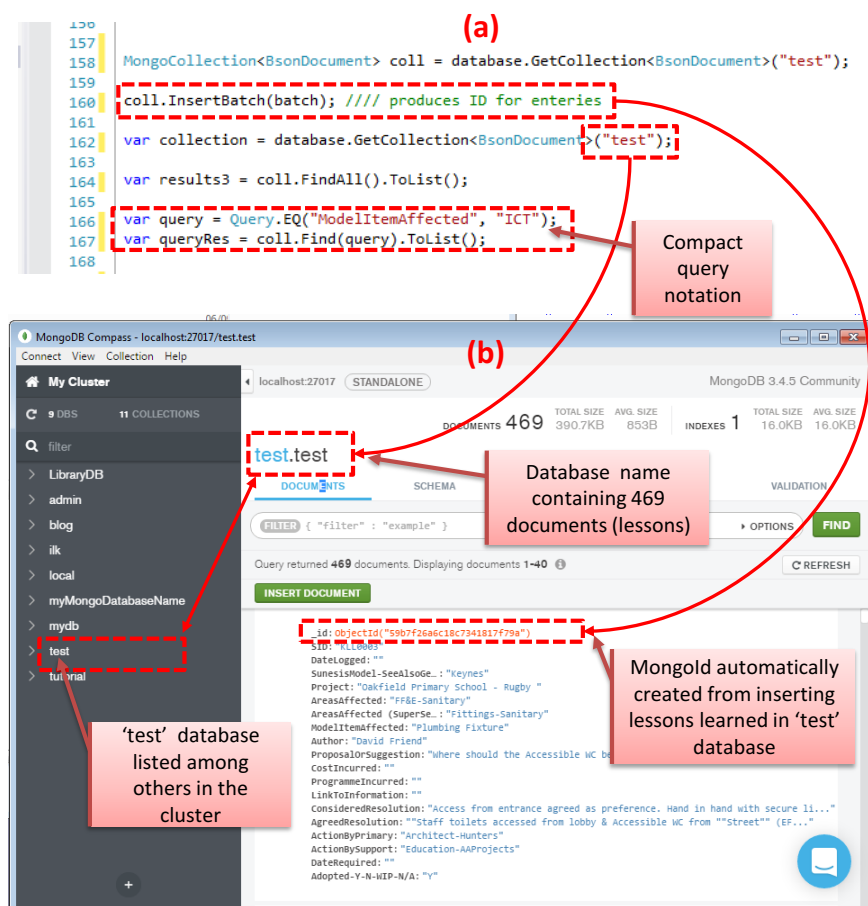


Figure 10 Query and database structure (a) implementation snippet and (b) MongoDB Compass data view

Operation of the system

The system is operated in Naviswork environment implemented through its provided .NET API. The API provides access to objects in a model file or Navisworks application via a combination of various classes, structures, methods, and events contained in different assemblies (Autodesk 2018). Three

frequently used assemblies in the Naviswork.NET API are the Autodesk.Navisworks.Api.dll for Plugins or when working with the Controls API; Autodesk.Navisworks.Automation.dll for working with Automation to drive Navisworks and the Autodesk.Navisworks.Controls.dll – used when requiring GUI Controls or access to Navisworks documents within a third party applications (Autodesk 2018). In this implementation, the proposed system is embedded into Navisworks Ribbon with a resulting window that can blend into the Naviswork GUI. This window allows users to control linking mouse clicks events of object selections to calling the programme.

The scenarios where the proposed system will be most useful are during project review meetings, site meetings, or design processes and reviews. The procedure for operating the programme (Figure 11) commences from when a designer (user) opens a federated model in Navisworks (1). The user can call (activate) the lessons learned programme from the created tile on the Naviswork Ribbon (2). The decision to adopt a conventional text-based query or the selection of model items from walkthrough manipulation is then made by the user (3). Going with the option of selecting models (4), a model item is then selected by double clicking (5). This activates the System to fetch the object properties of the selected items from the model in Navisworks (6). Information about the related objects such as the parents is also acquired (7). The system identifies the appropriate term (object name) from the information attributes of the selected object and its parent (8) which is then used to query the NoSQL database (9). The resulting output is a list of all the related lessons learned shown in GUI (10). It is down to the user to scan through the list and further examine and to note the lessons of interest (11). From here, the walkthrough can continue (12) or be terminated (13).

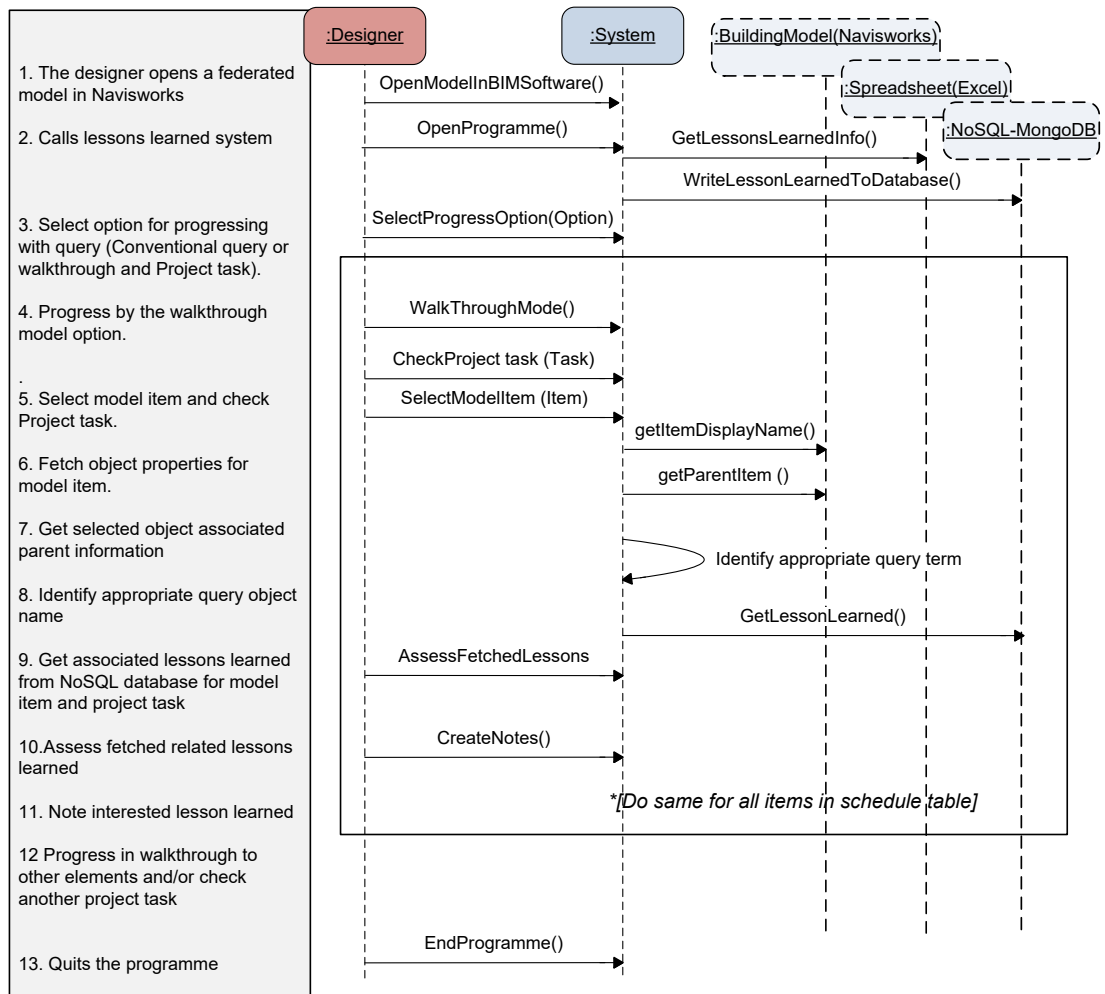


Figure 11 System sequence diagram

System demonstration

This research is a spinoff from the BIM-enabled low impact school procurement project which aimed to use BIM as a learning platform. The idea is to enhance the collective knowledge and practice of project stakeholders in delivering pre-designed school buildings. Pre-design refers to schemes where school buildings, for example, are built from an existing design with some modifications/ variations should they become desirable or necessary. It creates a clear advantage of using lessons learned knowledge from other ongoing or completed projects to continuously improve design and delivery for

improvements in the satisfaction of successive clients. The system is demonstrated using lessons learned that have been collated by the main contractor on various projects.

Lessons learned data

It is recommended that organisations should make a good effort to capture lessons learned and place such in databases that are readily available to stakeholders to learn from (Marlin 2008). Logged lessons learned information should, as much as possible, include both problems and solutions and be easy to access. Although approaches to compiling lessons learned information may differ from firm to firm, as advised by Marlin (2008) , the baseline guide is to ensure that (1) each lesson has been validated appropriately, (2) lessons focus on what (failures or successes) can benefit future projects, (3) recorded lessons learned information should not finger-point or blame anyone and (4) the database is continuously updated and current as well as easily searchable. The lessons learned data available to this research, to a large extent, complies with points 1- 3 above. On the hand and point 4 is subject to continuous improvement depending on technological advancements and the level of sophistication developed in emerging construction information technology tools. It is the aspects of ‘easily searchable’ and efficient ‘database management systems’ in point 4 this research focuses on; taking advantage of emerging BIM capabilities. Figure 9 shows part of the lessons learned information as entered into spreadsheets serving as the lessons learned database for the proposed system. In addition to the fields (areas affected, proposal or suggestion, considered resolution, agreed resolution and adopted affirmation) visible in Figure 12, other important fields in the spreadsheet include the lessons ID, date the lesson was logged, the project name, the primary party to effect action and the supporting party.

| AreasAffected | Autho | ProposalOrSuggestion | ConsideredResolution | AgreedResolution | Adopted |
|---------------|-------------------|---|--|--|---|
| 1 | FF&E-Sanitary | David f | Where should the WC be ent | Access from entrance agreed as prefer | Staff toilets accessed from lobby |
| 2 | Layout-Staff,Ad | David f | Social areas are undersized | Management strategy - to go in CP's / E | Staff room areas as follows |
| 3 | Layout-Staff,Ad | David f | Staff work areas are not shown | Staff / CP's | See also item KLL0006 above |
| 4 | Layout-Staff,Ad | David f | Reprographics is not separated from MEP | to suit volume of copying predicted | Area defined in reception. CP stater |
| 5 | Layout-Staff,Ad | David f | A Senior management office is missing | Community area was reviewed bearing i | Not currently in extension wing due |
| 6 | Layout-Hall,Dinin | David f | The height of the hall does not meet Sp | As low demand (in primaries) will be rett | Not cost effective to raise this secti |
| 7 | Layout-Hall,Dinin | David f | Halls: (Check calculations) Dinin | g requ | Layouts to be loaded with dining furnitur |
| 8 | Layout-Hall,Dinin | David f | The EFA current funding assumes that in | Community room is available. Also help v | Studio of 55m² provided |
| 9 | Layout-Staff,Ad | David f | The chair store size needs checking tha | Check area of store accepts required tal | Final Loaded layout required - Shi |
| 10 | FM | David f | There is no Maintenance store/office | Review as part of opening up above sto | Due to accommodating server & imp |
| 11 | Layout-Staff,Ad | David f | There is no external store for PE equ | As above / previous item. | Storage increased, but no specific |
| 12 | Services-ICT | Sunesi | Server room to be clearly indicated | n This needs to be central same location o | Common except if FE, which is not n |
| 13 | FF&E-Fixed | School | High level classroom cupboards deeper | Consider various forms of storage includ | Improved shelf support as necessa |
| 14 | FF&E-Fixed | School | Full height cupboard for step ladders | In maintenance store - unless agreed oth | Shed as necessary, either external |
| 15 | Layout-Teaching | David f | Current staff / child ratios are 1:13 | who Agreed to accommodate 30 children in 6 | 69m² (to suit 30 pupils) agreed |
| 16 | Layout-Teaching | David f | Sunesis Keynes 1.5FEN only has one Rec | Reorganise to two classes with no Nurs | 1.5FE & not 1.5FENexternal lobby cre |
| 17 | Layout-Teaching | David f | The nursery will need to provide drinks, sna | Needs to be a kitchenette - drinks etc. bu | Adult height kitchenette.Fridge |
| 18 | Layout-Staff,Ad | David f | Bulk storage for Nursery | Resource storage, possibly Christmas et | Sangwin defined on a coloured plar |
| 19 | Layout-Staff,Ad | David f | Storage of buggies and other items is no | Consider external store as cost option | External storage / shelter as abnorm |
| 20 | FF&E-Sanitary | David f | Toilet provision - School Premises Regs an | Ensure age relative provision. | Final check undertaken on conclusi |
| 21 | FF&E-Sanitary | David f | Toilets for Juniors should have full high | Show as required on Model / GA's. This | Make clear on layouts / CP's (cut av |
| 22 | FF&E-Sanitary | David f | Travel distance to Accessible WC | Consideration of adding extra Accessibl | Shortened with revised layout and |
| 23 | Layout-Staff,Ad | David f | The sick bay does need to be on the sch | Two way access | Set across secure line & maintains |
| 24 | Layout-Teaching | David f | SEN room and group rooms are open ar | Consider behavioural element | Interview / SEN room available for s |
| 25 | Layout-Teaching | David f | Classroom sizes. Going back to basics | Originally the classrooms were all the sa | 69m2 for early years & 55m2 for |
| 26 | Layout-Teaching | David f | Classroom Layouts | Demonstrate suitability of design with a | Statement regarding Facilities Out |
| 27 | Services-MEP | PSBP (Priority School Building Programme) | Demonstration over:-- Environmental- Da | This includes uplift to acoustics in tr | |
| 28 | Structure-Doors | School | Cost option for windows into classroom | As Ashcombe this will be an abnormal c | Currently no FF&E on these walls. (Y |
| 29 | FF&E-Fixed | David f | Sinks to classrooms. Child or adult he | Early years (Nursery, Reception & Yea | Single sink at appropriate height.Sei |
| 30 | FF&E-Fixed | David f | All practical in class = 12 * 62 = 744s | All above options reviewed. | Maintain philosophy from original Ke |
| 31 | Layout-Teaching | David f | A technology suite of 68m² would ass | Consider area in Street development. | Note made in CP's.The Food Scienc |
| 32 | FF&E-Fixed | School | Make child safe zone round oven in Foo | Ensure can be closed off after use - H | As noted above moved location. Sa |
| 33 | Structure-Doors | School | Access door for deliveries - narrow (Con' | increase to door & half | Door & half included & over panel o |

Figure 12 Lessons learned extracts

System application and outputs

As depicted by the use-case the proposed system is ideal for supporting construction stakeholders meetings such as project review meetings and site meetings. To use the proposed lesson learned system, the plugin must first be activated through a checkbox accessed from the plugin tab appearing on the Navisworks programme Ribbon. An annotated graphical output of the system is shown in Figure 13. On the background is an example of a federated model in Navisworks to which the lessons learned MongoDB has been linked. It is the model of a completed prototype school building in turnkey offering by the main contractor. At the bottom side of the Naviswork window is the timeline showing typical project tasks such as Foundation construction, Floor construction, Wall construction, Roof construction, Window construction etc. The Roof construction task is checked (1) and therefore made active. This triggers the process of linking corresponding lessons learned to Roof construction tasks when a query is eventually launched. Also in the Navisworks environment background, the roof of the building is selected (2). When the selection of a model item is made by double clicking with the

mouse, the system is automatically called and the lessons learned system window pops up. This event registers the selected model item and the active project task which are simultaneously used to query the database. The query results for the model item and Project task are displayed in data grids, (3) and (4) respectively. Each or any of the relevant listed lessons learned can be explored further by selection triggering a further display of details in the third data grid (5). Reports can be saved and/or printed of for later reference or use. There is also the provision of linking searches to the internet for wider consultation when the need arises.

The screenshot shows the Autodesk Navisworks Manage 2018 (STUDENT VERSION) interface. The 'Lessons Learned' window is open, displaying three data grids:

- (3) Model item or search item - list of relevant lessons learned:** A table with columns: Mongo Id, SID, Date Logged, Sunesis Model, Project, and Areas Affected. It lists five entries related to 'Structure-Roof'.
- (4) Project task - list of relevant lessons learned:** A table with columns: Mongo Id, SID, Date Logged, Sunesis Model, Project, and Areas Affected. It lists five entries related to 'Layout Teacher' and 'Structure-Roof'.
- (5) Details of selected lesson learned:** A table with columns: Project/Sunesis Model, Proposal Or Suggestion, Considered Resolution, and Agreed Resolution. It provides detailed information for a specific lesson learned.

Red dashed boxes and arrows highlight these components and their relationships. A red dashed box labeled (1) highlights the 'Roof construction' task in the timeline. A red dashed box labeled (2) highlights the 'Structure-Roof' model item in the 3D model. A red dashed box labeled (3) highlights the 'Model item or search item' table. A red dashed box labeled (4) highlights the 'Project task' table. A red dashed box labeled (5) highlights the 'Details of selected lesson learned' table. A red dashed box labeled (6) highlights the 'Roof construction' task in the timeline, which is linked to the query result.

Figure 13 System query output

Discussion

A key concern for organisational learning and knowledge management is to improve productivity through lessons learned. The Project Management Body of knowledge Guide sums lessons learned as the learning gained from failures or successes in the experience of performing a project. It is important that learning gained is validated, recorded and continuously updated for futures use.

Regarding lessons learned in the knowledge management circles, the aspect of utilising learning gained to improve the delivery of future projects is even more important as this is where productivity stems from. Suggestions from the literature stipulate that the design of lessons learned systems should generally aim to identify, document, analyse, store and retrieve lessons.

While all the aspects of utilising learning gained and lessons learned system design remain essential, the utilisation of stored lessons learned commences at the point of retrieval from the data store. Conventional text-based information searching systems had sufficed in retrieving lessons learned data but need extending in performance and integration with emerging object-based modelling and visualisation embedded in BIM authoring tools. The ease and speed of the retrieval of lessons learned when needed does influence how knowledge can diffuse and ultimately be used. Such systems need to be technologically up-to-date and user-friendly. This research therefore fulfils the aim of enhancing the process of accessing lessons learned information on projects using BIM capabilities. It contributes to improving project stakeholders' convenience in accessing lessons learned, and therefore contributing to knowledge building and subsequent application in projects. This is achieved by proceeding beyond conventional text-based query to attach relevant lessons learned to (1) appropriate model item connected to the learning gained and (2) appropriate project schedule task where the lessons learned is most beneficial to the project parties responsible for the respective assignments. The lessons learned system was integrated into the Navisworks platform, a project management and coordination BIM-enabled environment useful in model visualisation, clash detection of merged models and simulation of tasks in project schedule

In addition to object-based project information modelling capabilities in BIM, the lessons learned system implementation combined technological advances emerging in database management systems, NoSQL, compliant with contemporary cloud computing services. NoSQL databases support the efficient management of unstructured data and are web ontology compliant. The current needs to cope with storing managing and retrieving heterogeneous online data have lead to the deployment of NoSQL stores for Cloud-based open source file management. MongoDB is sampled in this research as an example of one of such robust, compatible and interoperable NoSQL DBMS. Connections to

MongoDB are established through Microsoft .NET Frameworks applications interfaced with the Naviswork BIM environment. The underlying advantages are (1) it is schema-free structure and flexibility (2) efficiency in handling unstructured data of different formats and (3) the capability to handle future growth of data that will typically characterise lessons learned information.

Activities comprising lessons learned systems have been broadly classified under three groups: Users, Repositories and Quality assurance. The users and quality assurance team generally interact with repositories by means of storing and retrieval of lessons learned. This work focussed on the aspect of retrieval of lessons learned which could have a substantial influence on the response of users in engaging with the system and the subsequent utilisation of learning gained to inform future project tasks. To progress to that point where lessons gained need to be retrieved, lessons must be identified, collected, recorded and stored after due validation. This is a key assumption in the implementation of the lessons learned systems in this research. Hence, the lessons learned data already collated by the main contractor of the project was deployed on the grounds of this assumption. Also, the implementation is a demonstration of concepts and as such limited to verifiable elements in the model and hypothetically generated 4D BIM (schedule) tasks. In this implementation, the executions of queries generated with respect to conventional methods, model items or project tasks are confined within the NoSQL database in the localhost. Search links to the semantic web are out of the scope of this research, having been covered in other studies (Ding et al. 2016; Ferrada et al. 2016).

Conclusion

Although there are studies extending queries of knowledge management systems to semantic web applications, the effective and efficient retrieval of context-focused lessons learned information to aid project delivery still need improvement. In this paper, we proposed improvements relying on BIM technology for the integration of construction knowledge linked to modelled building elements or items and 5D project tasks. This is targeted at helping construction professionals overcome challenges with delays and complications associated with the retrieval of context-focused lessons learned information as elements of knowledge management on projects. In demonstrating this research

concept, the implementation relied on the development of business processes to model and represent concepts, information flows, system components and their relationships. Further, lessons learned information data were hosted in non –structured query system, NoSQL such as MongoDB, linked through .NET Frameworks interfaced with a project management BIM tool, Navisworks Manage. The system was successfully tested with a federated model from a pre-design school project which relies on the reuse of knowledge to improve its product. The approach clearly demonstrated enhancements in the process of storing and accessing lessons learned information that have been captured on projects using BIM capabilities. The proposed system contributes to improving the convenience of stakeholder accessing lessons learned and as such, the enhancement of knowledge building and subsequent application in tackling construction tasks. We therefore conclude that lessons learned systems can become an integral part of BIM environments and contribute to enhancing knowledge reuse in projects.

Data Availability Statement

Data generated or analyzed during the study are available from the corresponding author by request.

Acknowledgement

Some aspects of the research reported in this paper was undertaken as part of the BIM-enabled Collaborative Platform for Innovative Low Impact School Procurement Project funded by Innovate UK (File No: 101343).

References

659 Abanda, F., Kamsu-Foguem, B. and Tah, J. (2017). "BIM—New rules of measurement ontology for
660 construction cost estimation." *Engineering Science and Technology, an International Journal* **20**(2):
661 443-459.

662

663 Abanda, F. H., Vidalakis, C., Oti, A. H. and Tah, J. H. M. (2015). "A critical analysis of Building
664 Information Modelling systems used in construction projects." *Advances in engineering software* **90**:
665 183-201.

666

667 Autodesk (2018). Navisworks API Developers's Guide Autodesk Inc.

668

669 BIM-IWG (2011). BIM Management for value, cost and carbon improvement. *A report for the*
670 *Government Construction Client Group, BIM Working Party Strategy Paper*, BIM Industry Working
671 Group (BIM-IWG).

672

673 Bouazza, T., Udeaja, C. and Greenwood, D. (2015). "The use of building information modelling (BIM)
674 in managing knowledge in construction project delivery: a conceptual model." *Building Information*
675 *Modelling (BIM) in Design, Construction and Operations* **149**: 107.

676

677 Carrillo, P. (2005). "Lessons learned practices in the engineering, procurement and construction
678 sector." *Engineering, Construction and Architectural Management* **12**(3): 236-250.

679

680 Carrillo, P., Ruikar, K. and Fuller, P. (2013). "When will we learn? Improving lessons learned practice
681 in construction." *International Journal of Project Management* **31**(4): 567-578.

682

683 Cattell, R. (2011). "Scalable SQL and NoSQL data stores." *Acm Sigmod Record* **39**(4): 12-27.

684

685 Cerovsek, T. (2011). "A review and outlook for a 'Building Information Model'(BIM): A multi-
686 standpoint framework for technological development." *Advanced Engineering Informatics* **25**(2):
687 224-244.

688

689 Charlesraj, V. P. C. (2014). *Knowledge-based building information modeling (K-BIM) for facilities*
690 *management*. ISARC. Proceedings of the International Symposium on Automation and Robotics in
691 Construction, Vilnius Gediminas Technical University, Department of Construction Economics &
692 Property.

693

694 Chen, L. and Luo, H. (2014). "A BIM-based construction quality management model and its
695 applications." *Automation in Construction* **46**: 64-73.

696

697 Ding, L., Zhong, B., Wu, S. and Luo, H. (2016). "Construction risk knowledge management in BIM
698 using ontology and semantic web technology." *Safety science* **87**: 202-213.

699

700 Eken, G., Bilgin, G., Dikmen, I. and Birgonul, M. T. (2015). "A lessons learned database structure for
701 construction companies." *Procedia Engineering* **123**: 135-144.

702
703 Ferrada, X., Núñez, D., Neyem, A., Serpell, A. and Sepúlveda, M. (2016). "A Cloud-based Mobile
704 System to Manage Lessons-learned in Construction Projects." *Procedia Engineering* **164**: 135-142.

705
706 Ferrada, X., Sepúlveda, M., Serpell, A., Núñez, D. and Neyem, A. (2014). "A lessons-learned mobile
707 system for construction companies: motivation and design." *Procedia Engineering* **85**: 157-165.

708
709 Grolinger, K., Higashino, W. A., Tiwari, A. and Capretz, M. A. (2013). "Data management in cloud
710 environments: NoSQL and NewSQL data stores." *Journal of Cloud Computing: Advances, Systems and*
711 *Applications* **2**(1): 22.

712
713 Harrison, C. and Thurnell, D. (2015). "BIM Implementation in a New Zealand Consulting Quantity
714 Surveying Practice." *Int. J. Constr. Supply Chain Manag* **5**(1): 1-15.

715
716 Hellerstein, J. M., Stonebraker, M. and Hamilton, J. (2007). "Architecture of a database system."
717 *Foundations and Trends® in Databases* **1**(2): 141-259.

718
719 Ho, S.-P., Tserng, H.-P. and Jan, S.-H. (2013). "Enhancing knowledge sharing management using BIM
720 technology in construction." *The Scientific World Journal* **2013**.

721
722 Jan, S.-H., Ho, S.-P. and Tserng, H.-P. (2013). "Applications of building information modeling (BIM) in
723 knowledge sharing and management in construction." *World Academy of Science, Engineering and*
724 *Technology, International Journal of Civil, Environmental, Structural, Construction and Architectural*
725 *Engineering* **7**(11): 828-832.

726
727 Jeong, S., Byun, J., Kim, D., Sohn, H., Bae, I. H. and Law, K. H. (2015). *A data management*
728 *infrastructure for bridge monitoring*. SPIE Smart Structures and Materials+ Nondestructive
729 Evaluation and Health Monitoring, International Society for Optics and Photonics.

730
731 Kamara, J. M., Anumba, C. J., Carrillo, P. M. and Bouchlaghem, N. (2003). "Conceptual framework for
732 live capture and reuse of project knowledge." *CIB REPORT* **284**: 178.

733
734 Kamardeen, I. (2010). *8D BIM modelling tool for accident prevention through design*. 26th Annual
735 ARCOM Conference, Leeds, Association of Researchers in Construction Management.

736
737 Kang, J. and Kuncham, K. (2014). *BIM CAVE for 4D immersive virtual reality*. Creative Construction
738 Conference.

739
740 Kang, Y.-S., Park, I.-H., Rhee, J. and Lee, Y.-H. (2016). "MongoDB-based repository design for IoT-
741 generated RFID/sensor big data." *IEEE Sensors Journal* **16**(2): 485-497.

742
743 Kang, Y.-S., Park, I.-H. and Youm, S. (2016). "Performance Prediction of a MongoDB-Based
744 Traceability System in Smart Factory Supply Chains." *Sensors* **16**(12): 2126.

- Kartam, N. A. (1996). "Making effective use of construction lessons learned in project life cycle." *Journal of Construction Engineering and Management* **122**(1): 14-21.
- Kossmann, D., Kraska, T. and Loesing, S. (2010). *An evaluation of alternative architectures for transaction processing in the cloud*. Proceedings of the 2010 ACM SIGMOD International Conference on Management of data, ACM.
- Le, T. D., Kim, S. H., Nguyen, M. H., Kim, D., Shin, S. Y., Lee, K. E. and da Rosa Righi, R. (2014). *EPC information services with No-SQL datastore for the Internet of Things*. RFID (IEEE RFID), 2014 IEEE International Conference on, IEEE.
- Leavitt, N. (2010). "Will NoSQL databases live up to their promise?" *Computer* **43**(2).
- Lee, A., Wu, S. and Aouad, G. (2006). nD modelling: the background *Constructing the future: nD modelling*. G. Aouad, A. Lee and S. Wu, Taylor and Francis.
- Lin, Y.-C. and Su, Y.-C. (2013). "Developing Mobile-and BIM-based Integrated Visual Maintenance Management System."
- Lin, Y.-C., Wang, L.-C. and Tserng, H. P. (2006). "Enhancing knowledge exchange through web map-based knowledge management system in construction: Lessons learned in Taiwan." *Automation in Construction* **15**(6): 693-705.
- Liu, F., Jallow, A. K., Anumba, C. J. and Wu, D. (2014). A framework for integrating change management with building information modeling. *Computing in Civil and Building Engineering* (2014): 439-446.
- Maner, W. (1997). "Rapid application development using iterative prototyping." Retrieved October, 2012, from <http://csweb.cs.bgsu.edu/maner/domains/RAD.gif>
- Marlin, M. (2008). "Implementing an Effective Lessons Learned Process in a Global Project Environment."
- Marzouk, M. and Hisham, M. (2012a). Bridge information modeling in sustainable bridge management. *ICSDC 2011: Integrating Sustainability Practices in the Construction Industry*: 457-466.
- Marzouk, M. and Hisham, M. (2012b). "Applications of building information modeling in cost estimation of infrastructure bridges." *International Journal of 3-D Information Modeling (IJ3DIM)* **1**(2): 17-29.
- Masood, R., Kharal, M. and Nasir, A. (2014). "Is BIM adoption advantageous for construction industry of Pakistan?" *Procedia Engineering* **77**: 229-238.

- Mohammadi, S., Tavakolan, M., Zahraie, B. and Pourmadadkar, O. (2011). *Optimizing the Selection and Layout of Table Forms with Different Dimensions Using BIM and Integer Programming*. Construction Research Congress 2016.
- Noll, M., Fröhlich, D. and Schiebel, E. (2002). *Knowledge maps of knowledge management tools—Information visualization with BibTechMon*. International Conference on Practical Aspects of Knowledge Management, Springer.
- Orange, G., Burke, A. and Cushman, M. (1999). *An approach to support reflection and organisation learning within the UK construction industry*. BITWorld '99: business information technology management: the global imperative, 30 June – 2 July 1999 Cape Town, South Africa.
- Oti, A., Kurul, E., Cheung, F. and Tah, J. (2016). "A framework for the utilization of Building Management System data in building information models for building design and operation." *Automation in Construction* **72**: 195-210.
- Oti, A. H. and Tizani, W. (2015). "BIM extension for the sustainability appraisal of conceptual steel design." *Advanced Engineering Informatics* **29**(1): 28-46.
- Oti, A. H., Tizani, W., Abanda, F., Jaly-Zada, A. and Tah, J. (2016). "Structural sustainability appraisal in BIM." *Automation in Construction* **69**: 44-58.
- PMI (2013). *A guide to the project management body of knowledge (PMBOK guide)*, Project Management Institute (PMI).
- Rowe, S. and Sikes, S. (2006). *Lessons learned: taking it to the next level*. 2006 PMI Global Congress Proceedings. Seattle, Washington.
- Shetwi, R., Farooq, B. and Popa, C. (2015). *Optimizing Large-scale Transportation Infrastructure Projects using Building Information Modelling*. Canadian Transportation Research Forum 50th Annual Conference-Another 50 Years: Where to From Here?//Un autre 50 ans: qu'en est-il à partir de maintenant? Montreal, Quebec, May 24-26, 2015.
- Stevic, M. P., Milosavljevic, B. and Perisic, B. R. (2015). "Enhancing the management of unstructured data in e-learning systems using MongoDB." *Program* **49**(1): 91-114.
- Taghaddos, H. and Eslami, A. (2016). *Developing a Smart Controller Model Using GPS Coordinates*. Construction Research Congress 2016.
- Tangkawarow, I. and Waworuntu, J. (2016). *A Comparative of business process modelling techniques*. IOP Conference Series: Materials Science and Engineering, IOP Publishing.

831 Wang, J., Sun, W., Shou, W., Wang, X., Wu, C., Chong, H.-Y., Liu, Y. and Sun, C. (2015). "Integrating
832 BIM and LiDAR for real-time construction quality control." *Journal of Intelligent & Robotic Systems*
833 **79**(3-4): 417.

834

835 Wexler, M. N. (2001). "The who, what and why of knowledge mapping." *Journal of knowledge*
836 *management* **5**(3): 249-264.

837

838 Woo, J.-H., Clayton, M. J., Johnson, R. E., Flores, B. E. and Ellis, C. (2004). "Dynamic Knowledge Map:
839 reusing experts' tacit knowledge in the AEC industry." *Automation in Construction* **13**(2): 203-207.

840

841 Yang, C.-C. and Kang, S.-C. (2014). BIM Navigation with Hand-Based Gesture Control on Sites.
842 *Computing in Civil and Building Engineering (2014)*: 785-792.

843

844

845