1   **TITLE PAGE**

2   The integration of lessons learned knowledge in

3   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*

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Introduction

55

56 The effective and efficient management of processes in project life cycles is vital to construction

57 project managers. One factor that can influence the ease of executing tasks in the project life cycle is

58 the availability of resources in the form of (i) information from knowledge management processes, (ii)

59 software tools to model and manage such information (iii) the learned professional to harness and

60 utilize the information to improve project efficiencies and of course, (iv) novices benefitting from

61 lessons learned experiences on previous projects which they would not otherwise have in making

62 informed project decisions. The challenges in collecting information such as lessons learned to feed

63 into knowledge management systems have been acknowledged (Kamara et al. 2003; Carrillo 2005;

64 Carrillo et al. 2013). Early practices of knowledge management in the construction industry were

65 largely informal and people-centred (Kamara et al. 2003). The most common approach to learning

66 from projects had been through project evaluation without any formal framework for the effective

67 capture and reuse of knowledge when it is most crucial within the relevant project stages of progress

68 (Orange et al. 1999; Kamara et al. 2003). Also mentioned are the difficulties in capturing knowledge

69 without necessarily overloading project participants and the challenges in making such captured

70 knowledge available for reuse when it matters most (Kamara et al. 2003; Carrillo 2005; Carrillo et al.

71 2013) . Ferrada et al. (2014) alleged that companies loose most lessons learned information because

72 of lack of a properly structured collection and collation systems. Nonetheless, this appears to be the

73 easily controllable aspect. With the setting of new targets, rules and work flows, firms can easily

74 improve on the collection of lessons learned information from project activities. Such data eventually

75 grow to become Big Data which comes with the difficulties of timely and content-focused access.

76 Also such enormous amounts of data often face the challenges of making immediate sense out of it as

77 a result of the overwhelming nature. This is where software applications become useful tools to

78 facilitate the management and retrieval of collated information. It is perhaps a more arduous task than

79 the aspect of gathering lesson learned information from project activities. Thus, it is a specialist task

80 and requires the development of software systems that may need to be tailored towards a particular

81 organisation and its existing workflows. Software systems for managing Big Data have often relied

82   on Relational Database Management Systems (RDBMS) which are now becoming stretched by recent

83   development in the volume, variety and velocity of data streamed across systems (Kossmann et al.

84   2010). More preferred systems are the schema-free types such as "Not only structured query language

85   (NoSQL)" that can efficiently handle unstructured data with the tendencies for future growth

86   (Hellerstein et al. 2007; Cattell 2011; Kang et al. 2016). An example of NoSQL system is the

87   MongoDB currently gaining ground in construction information technology (IT) applications for

88   element tracking and querying (Jeong et al. 2015; Kang et al. 2016; Kang et al. 2016). We propose

89   exploring the modelling of lessons learned information stored in MongoDB. As suggested by Ferrada

90   et al. (2014), lessons learned systems should take advantage of new technological advances. One of

91   such technological advances is building information modelling (BIM) which is yet to be fully

92   explored in the coupling of nD modelling aspects, including the lessons learned information as an

93   aspect of knowledge management. BIM-enabled systems have been used for the coordination of

94   project management activities including visualisation of models and the detection of clashes resulting

95   from merged models (Abanda et al. 2015). However, aspects of incorporating lessons learned

96   knowledge management functionality in such BIM-enabled project management systems remains to

97   be fully explored.

98   According to the Project Management Body of Knowledge Guide, lessons learned is the learning

99   gained from performing a project (PMI 2013). Learning gained, whether failure or success, need to

100 be appropriately validated and duly recorded to be of benefit to future projects. Such records will

101 require continuous updating and should be easily accessible through conventional information

102 searching methods which to a large extent, depends on the ever improving advances in information

103 technology applications. However, the innovations in executing construction project tasks have

104 always been in pursuit to catch-up with advances made in information technology developments. In

105 line with this premise, this research aims to enhance the process of storing and accessing lessons

106 learned information that have been captured on projects using BIM capabilities. The intention is to

107 improve the convenience of stakeholder in accessing lessons learned, and therefore contributing to

108 knowledge building and subsequent application in tackling construction challenges. The paper is

109   presented in 8 main sections; Introduction, Related works, Lessons learned information systems,

110   Methods, System implementation, System demonstration, Discussion and Conclusion.

Related works

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A case for BIM-driven knowledge management through lessons learned

112

113   Researchers on the3D to nD modelling project at the University of Salford, UK suggested that

114   measures of time, cost, accessibility, sustainability, maintainability, acoustics, crime and thermal

115   requirement, etc. (to n^{th} measures) can be integrated into the modelling of building information (Lee et

116   al. 2006). With the advent of BIM, the intelligent object-based modelling of construction projects,

117   some individual dimensions (D) of modelling beyond 3D and what they represent are becoming

118   clearer and widely accepted. It is now common to find literature stating modelling dimensions as 4D

119   Schedule, 5D Cost Estimation, 6D Facilities Management, 7D Sustainability and 8D Occupational

120   Safety and Health (Kamardeen 2010; Masood et al. 2014; Harrison and Thurnell 2015; Shetwi et al.

121   2015; Abanda et al. 2017). A process that cuts across all these dimensions is knowledge management.

122   For example lessons learned, an element of knowledge management, has the potential of being

123   generated in the activities of all the other dimensions. From the stages of project conception,

124   representation of project specifications in 2D and 3D, 4D scheduling to 8D Safety and Occupational

125   Health; learning can be gained and made useful to an ongoing project or in future projects. Just like all

126   other dimensions, knowledge management is not new in the field of construction and does have a

127   significant role in the contemporary modelling of project information targeted at enhancing

128   efficiencies in successful project delivery.

Lessons learned system applications and BIM

129

130   Lessons learned are elements of organisational learning and knowledge management (Carrillo 2005)

131   and therefore important for improvements in the productivity of firms and the sectors in which they

132   operate. One of the works portraying the early realisation of this is Kartam (1996) who presented the

133   development of the Interactive Knowledge Intensive System (IKIS) Constructability prototype in the

134   1990's. IKIS-Constructability tool, for modelling real-world construction projects, makes use of

135   lessons learned in the construction phase and can be used by a medium to large-sized construction

136   firm. The main features of the tool are its information manageability (organizing, storing, retrieval and

137   updating) format and the adopted knowledge acquisition/engineering (collecting, verifying,

138   categorizing and archiving) approach. The prototype, however, depends on the enthusiastic support

139   and willingness of engineering practitioner to contribute their personal experience to the system

140   developers in order to build a database of lessons learned. The challenge of such arrangement is that

141   user-organisations must find time and resources to review and approve lessons learned that is to be

142   logged onto the system database. Also there is that tendency that the knowledge-base of the lessons

143   learned may be limited to the experiences of the user-organisation and will tend to be restricted from

144   access by outsiders. To tackle such restrictions to free access to acquired knowledge, Lin (2006)

145   proposed Network Knowledge Maps (NKM) hinged on lessons learned. The maps allow users to

146   manage tacit and explicit knowledge through the review of available and missing information through

147   a web browser. NKM have been used by researchers (Wexler 2001; Noll et al. 2002; Woo et al. 2004)

148   to identify intellectual capital to improve organisational learning and entails a diagrammatic/graphical

149   representation of knowledge and knowledge attributes. Feedback from the NKM system flagged

150   challenges that include difficulties associated with acquiring knowledge from management teams, and

151   the lack of willingness and spare/dedicated time to share experiences without some allocated

152   benefits/reward. Eken et al. (2015) mentioned similar challenges as reasons for developing a database

153   structure and information system for capturing lesson learned information from dispersed sources in

154   hypothetical project situations. Lesson learned system have also been explored using mobile system

155   (Ferrada et al. 2014). The preliminary application of the system in a Chilean construction involved the

156   use of a mobile cloud shared workspace which needed improvements in terms of the richness of the

157   knowledge database and the optimization of the system's search engine on the internet (Ferrada et al.

158   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

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187 management systems to appropriate tasks-oriented BIM tools such as Navisworks for project

188 management purposes as proposed in this paper.

189   Lessons learned systems require an efficient database management system which should be

190 robust, compatible and easily interoperable with contemporary information modelling or visualisation

191 system used in supporting project tasks (Kartam 1996; Noll et al. 2002; Woo et al. 2004; Lin et al.

192 2006; Eken et al. 2015). Although SQL-type DBMS that satisfy ACID (Atomicity, Consistency,

193 Isolation and Durability) quality have been useful in managing data, the textual nature of lesson

194 learned information make it best suited for NoSQL systems which need to be fully explored. Also,

195 NoSQL supports the efficient management of unstructured data and it is web ontology compliant

196 which makes it useful in Cloud computing applications. Current needs to cope with storing managing

197 and retrieving heterogeneous online data have led to the deployment of Cloud-based open source file

198 management systems such as Apache Cassandra, Apache H-Base and MongoDB that rely on NoSQL

199 (Grolinger et al. 2013). The advantages of NoSQL systems have been demonstrated in recent research

200 work including the better handling of collected sensor data on Internet of Things (IoT) platform (Le

201 et al. 2014; Kang et al. 2016) and the scaling of traceability systems for smart product ordering in

202 factory supply chains (Kang et al. 2016). Regarding the aspect of information modelling systems,

203 researchers have mostly explored BIM tools such as Revit to demonstrate the integration of

204 knowledge system (Ho et al. 2013; Jan et al. 2013; Liu et al. 2014) leaving out project management

205 tools such as Navisworks. Although Navisworks has featured in a few research albeit not for the

206 management for lessons learned knowledge. For example Navisworks was used as an intermediate

207 tool for model information exchange between Revit and Protégé in developing ontology construction

208 risk knowledge management in Semantic web service (Ding et al. 2016). Also, Revit and Navisworks

209 were combined to produce construction scheduling, 4D models, for integration with quality model to

210 identify quality control criteria and the assignment of responsibilities in the construction process

211 (Chen and Luo 2014). Navisworks is strong in supporting model federation, clash detection, project

212 programming and remains one of the vital BIM tools that supports collaborative working in the

213 construction industry. There is therefore a need to explore how Navisworks, a versatile project

214   management tool, can be harnessed to manage lessons learned to inform and enhance the processes

215   involved in project delivery.

216   **The role of NoSQL database in lessons learned systems**

217   Relational Database Management Systems have been excellent in managing structured data that rely

218   on static schema (Kossmann et al. 2010). These systems are becoming stretched by recent

219   development in the volume and variety of data, and velocity with which they are required to be

220   streamed across systems. Stevic et al. (2015) argue that the challenges range from difficulties with

221   backup, scaling, recovery and responsiveness of systems relying on RDBMS to handle the analysis of

222   Big Data which is largely unstructured. Schema-free systems such as the Not only SQL (NoSQL)

223   have been suggested to be efficient in handling unstructured data that has the tendencies for future

224   growth (Hellerstein et al. 2007; Cattell 2011; Kang et al. 2016). NoSQL databases are CAP

225   (Consistency, Availability and Partition Tolerance) compliant and offer full text search capabilities as

226   may be applicable to lesson learned systems. Three key advantages of NoSQL databases include a

227   less expensive scale-out architecture that adds low-end resources, consistency in scalability, handling

228   of different data types and formats with high degree of flexibility (Kang et al. 2016). These

229   advantages have made NoSQL data preferable alternative to Relational Database Management System

230   (RDMS) in storing and processing high-volume of data associated with Social Network Services

231   (SNN) and Internet of Things.

232   NoSQL databases use a number of data structures such as key-value, column, graph and

233   document (Leavitt 2010). The choice of using a given NoSQL database depends on the problem that

234   is intended to be solved. For example NoSQL databases stores may be design to prioritise either or a

235   combination of consistency, partition tolerance, speed or use of low level query languages and as

236   such suitable for different purposes. Some common examples of NoSQL databases include

237   MarkLogic (Document/Graph), MongoDB (Document), Virtuoso (Graph) Apache Cassandra

238   (Column), and Redis (Key-value). A document data model that has featured in the construction and

239   manufacturing domains is the MongoDB. MongoDB was found to perform optimally in the querying

240   of a traceability system targeted at enhancing decision making in the construction and operation of

241   hardware capacity planning of automobile parts in a smart factory supply chain (Kang et al. 2016). In

242   hybrid architecture to improve e-learning platforms, MongoDB and RDBMS have been combined to

243   handle unstructured data and structured data respectively (Stevic et al. 2015) .

Extending the functions of BIM-based project management systems

244

245   Navisworks is one of the common BIM-enabled project management systems (Abanda et al. 2015).

246   Unlike Autodesk Revit, BIM application extensions research (Oti and Tizani 2015; Oti et al. 2016)

247   involving Navisworks is still at infancy and not too common in the construction domain. However,

248   the roles of Navsiworks in model visualisation, merging of models, clash detection and scheduling

249   have been widely explored in the industry. Navisworks is known to be compatible with a wide range

250   file formats such as Industry Foundation Classes (IFC), Virtual Reality Modelling Language

251   (VRML), CIMSteel Integration Standards (CIS/2), Design (DGN), Faro, Leica, Alan - Charles - Ian's

252   System (ACIS), Standard ACIS Text (SAT), Stereolithography (STL), American Standard Code for

253   Information Interchange (ASCII) Laser etc. and therefore useful in ameliorating advances in

254   interoperability and integration. Efforts to push the boundaries to which project management systems

255   such as Navisworks can be useful in construction projects alike exist. One of such efforts is

256   demonstrated in tracking objects changes in BIM to assist construction managers in the coordination

257   and management of subcontractors (Giel et al, 2013). The quality control and monitoring in

258   construction can also be carried out by integrating Light Detection and Ranging (LiDAR) and BIM

259   using the Naviswork environment (Wang et al. 2015). In the Asset Management domain, Navisworks

260   has been found useful in hosting applications that explored using Mobile devices for real-time visual

261   facility management (Lin and Su 2013). The visualisation capability in Navisworks in 4D simulations

262   has also been pushed to the limits of immersive virtual reality applications such as CAVE (Cave

263   Audio Video Environment) (Kang and Kuncham 2014). Others include developing a smart controller

264   model of Global Positioning System (GPS) coordinates (Taghaddos and Eslami 2016), optimizing the

265   selection of table structure consisting of beams and slab (Mohammadi et al. 2011), sustainable bridge

266 information modelling using Building Management System (BMS) features (Marzouk and Hisham

267 2012a; Marzouk and Hisham 2012b) and BIM navigation incorporated with hand-based gesture on

268 construction sites (Yang and Kang 2014). While all these works are great, BIM-based project

269 management applications centred on easing the accessibility of lessons learned construction

270 knowledge is lacking.

Lessons learned information system

271

272 Lessons learned is reliably defined as the learning gained from the process of performing a project

273 (PMI 2013). It is worth mentioning that lessons can be identified at any point of the project life and by

274 any party or stakeholder involved on the project. Since there can be numerous individuals

275 (professionals and tradesmen) and teams involved on a project, it is therefore essential that the process

276 of identifying, documenting and accessing lessons learned be effectively and efficiently managed.

277 There exist various efforts on lesson learned information systems such as the SuperBase based on

278 relational database (Kartam 1996). The work by Eken et al. (2015), also based on relational database,

279 explored leveraging dispersed information retrieval using web services. Mobile applications

280 communicating with Cloud services such as windows Azure hosting Web applications and relational

281 databases have also been proposed (Ferrada et al. 2014; Ferrada et al. 2016) . The main activities

282 common to these lesson learned systems, as also suggested in the literature (Rowe and Sikes 2006) are

283 to (1) identify, (2) document, (3) analyse (4) store and (5) retrieve the lessons learned. Although, the

284 approach to combining these activities may differ in terms of order and structure in companies, we

285 group them into three components; Users; Repositories and Quality assurance (Figure 1). The two

286 main interactions of the users and quality assurance team with the repositories are to store and retrieve

287 lessons learned information. The ease and speed with these actions are executed as and when needed

288 goes a long way to determine the efficient functionality of the system and how knowledge can be

289 diffused and ultimately utilised. Systems that are technological outdated, unfriendly to operate and

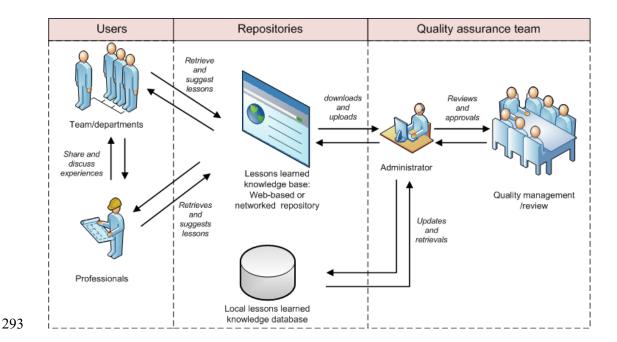290 relatively slow in response will discourage project stakeholders from committing their time and

291 efforts.

292

293

294 **Figure 1 Lessons learned information systems**

Methods

296 This research work builds on a project concerned with the continuous improvement of a pre-designed

297 scheme for schools using BIM, which is delivered as a turnkey project using a framework agreement.

298 The pre-designed scheme presents clear advantage of using lessons learned information and

299 knowledge from the operations phase to continuously improve the design and development of the

300 digitized models. In the sub-sections, further description is given about the approach for utilizing BIM

301 as a learning platform and the methods for improving the process of harnessing lessons learned using

302 emerging BIM technology.

Project description

304 This study is undertaken as an offshoot of the UK government-funded BIM-enabled low impact

305 school procurement project. The project was about enhancing improvements on the delivery of pre-

306 design schools based on turnkey contract under a national framework arrangement. It entailed

307   exploring how BIM can be used as a learning platform to increase efficiencies in the processes

308   involved in product delivery. The main concerns are to enhance the collective knowledge and practice

309   of project stakeholders/supply chain members. The products are pre-design school buildings, schemes

310   where buildings of interest are built from an existing design with little or no modifications/variations.

311   This research is of high importance to pre-designed schemes as there is a clear advantage of using

312   lessons learned knowledge from other ongoing or completed projects to continuously improve design

313   and delivery for improvements in the satisfaction of successive clients. The deployment of BIM will

314   assist the Main Contractor to develop and adopt innovative strategies to delivering, refining and

315   optimising the final 'products' from the pr-designed models. This has been pursued through focusing

316   on the integration of project data from design, construction and operation stages in a BIM

317   environment. Also, aspects explored include the fostering of enhance BIM-based collaboration among

318   project stakeholders and the testing of research concepts to continuously improve the 'product'. One

319   key aspect is to utilize feedbacks from downstream to improve project activities that occur upstream

320   and to learn from lessons gained.

Using BIM as a learning platform

322   The aim of using BIM as learning platform is to reduce gaps in the upstream knowledge-feedback-

323   loop between construction and design. Such feedback concept has been demonstrated in the use of

324   historical energy consumption from BMS in BIM (Oti et al. 2016). The collaborative platform will

325   support integrated collaborative procurement, design, and delivery of low impact pre-designs for

326   turnkey school projects. As illustrated in Figure 2. The building project adopting BIM working

327   method has a federated BIM model tailored to a particular design and a particular site. BIM

328   implementation in the pre-designed schools requires an extra level of generic model development

329   which goes through 5 stages: i) generic BIM model, ii) site specific BIM model (or as-planned BIM

330   model), iii) As-designed BIM model, iv) as-built BIM model and v) live BIM model. The creation of

331   a generic model for a particular pre-designed school type generates significant saving in time and cost

332   for model development for the site-specific BIM models. A site-specific BIM model that fully

333 represents the actual construction is then developed from the generic model. This takes advantage of

334 the economy-of-scale production logic in generating site-specific BIM model. Efficiency is therefore

335 achieved through data sharing and data reuse. Upon the confirmation of a project proposal, existing

336 drawings, textual information and specifications from a generic digitized model are reproduced and

337 then integrated with various digitized site models and supply chain models. These combinations can

338 then be further tailored as site- specific building information models for construction and operation.

339 These processes produce progressive As-planned BIM, As-built BIM and the live BIM which are used

340 for the actual construction phase and during operations. They also serve as channels to supply

341 feedback to the Model Preparation stage for the refinement of the generic building design model.

342 Such feedback loops drive continuous model or product development. One important process for

343 continuous model development is periodic design reviews that capture the construction issues of the

344 model. In these reviews, one of the areas identified for investigation as feedback channels for

345 improving project delivery is the lesson learned systems. The aspects directly concerned with lessons

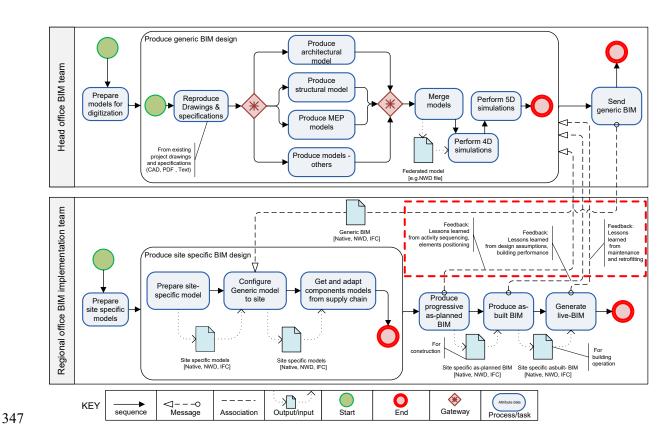346 learned systems have been highlighted by a box in broken (red) lines as shown in Figure 2.

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

349

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

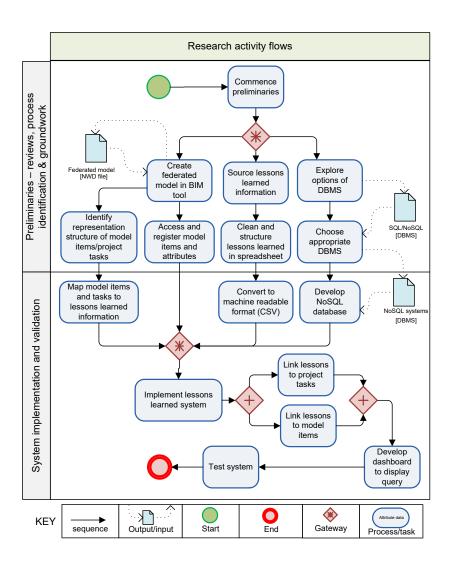368   BIM tool such as Navisworks.

369

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

382   methodology has been widely used in software development circles and employs cycles of re-specify,

383   re-design and re-evaluate on the prototype system from conception to completion. The advantage of

384   the RAD approach is the increased speed of development and experiences of series of births rather

385   than catching up with deadlines thereby providing opportunities for continuous system refinement.
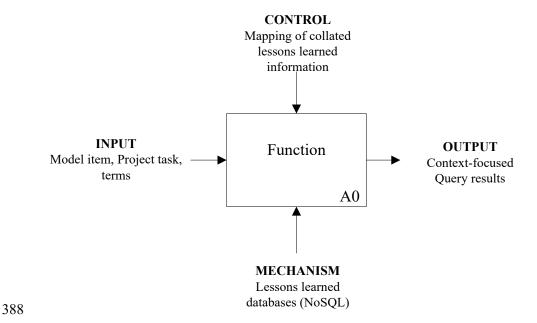
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387

CONTROL
Mapping of collated
lessons learned
information

| **INPUT**
Model item, Project task,
terms | → | Function

A0 | → | **OUTPUT**
Context-focused
Query results |

MECHANISM
Lessons learned
databases (NoSQL)

388

389   **Figure 4 Simplified components of proposed system**

System implementation

391   The focus of this research is to enhance how to ease the access of information about lessons learned

392   on projects to improve stakeholder knowledge and consequently, project efficiencies and delivery.

393   The proposed approach is to link lessons learned information to BIM objects or model items and

394   project tasks. Given that a federated model, as depicted by Level 2 BIM maturity (BIM-IWG 2011),

395   is a coordinated aggregation of digitized models from the various concerned professional domains

396   (architecture and furniture, structural, plumbing, electrical etc.); it presents an opportunity to have a

397   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

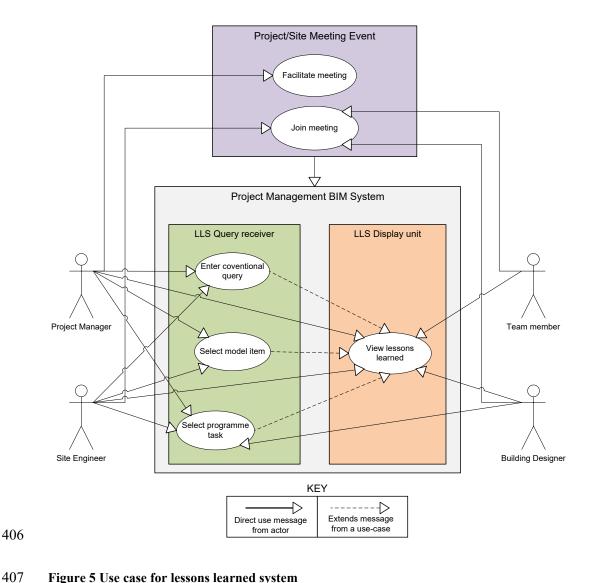404   of Project Management BIM-enabled tools such as Navisworks during visualisation of the digitized

405   models.

406

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

408

409

410   In line with this premise, a flow chart illustrating the implementation of the system is given in

411   Figure 6. It is made up of 'user initiated processes' and the 'system executed processes' blocks to

412   respectively capture actions carried out by the user and the corresponding responses of the system.

413   When the programme is called, in addition to conventional database querying, the user has the option

414   to walkthrough the model and see related lessons learned from the selection of interested model items.

415   On the selection of a model item or initiation of a query, information about the parent objects are also

416   checked to identify the most appropriate search criteria to query the NoSQL database. The query

417   results can be consequently assess by the user for subsequent action and recorded accordingly. The

418   flow chart is further discussed by examining the components of the system and its operation.
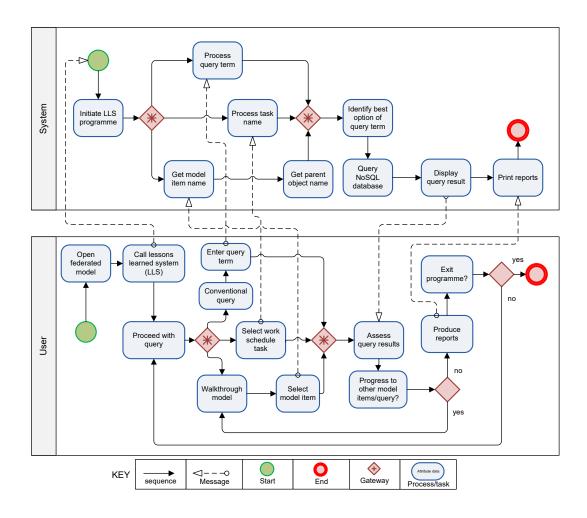

419

420   **Figure 6 System implementation flowchart**

System components

422   The system can be broken into five component modules in line with the simplified representation in

423   Figure 4 which are the Input, Control, Mechanism, Function and Output (Figure 7). These

424   components are characterised by the distinct software environments that have been pooled together in

425   the system implementation. The system can be launched from a BIM-enabled environment

426   (Navisworks) where the Input and Output reside, the lessons learned and associated mappings are

427   from MS Excel environment serving as the Control. The Mechanism is the generated NoSQL

428   database domiciled in MongoDB. The programming instructions, object representations and the

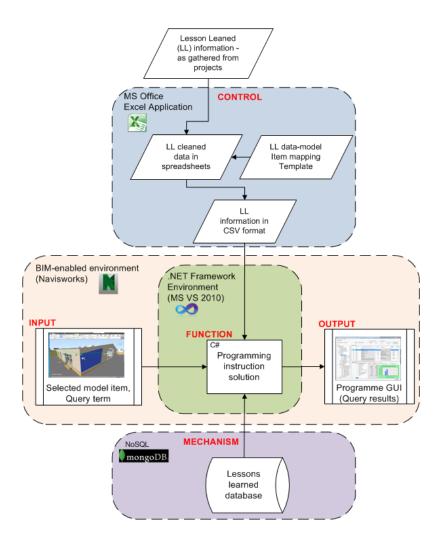429   manipulation of these data are done in C# (.NET Framework) and constitute the Function.

430

431   **Figure 7 Relationship between system components**

432

433   *Input*

434   Many proposed construction knowledge management systems utilize query systems that require users

435   to type in text-based search terms (Kartam 1996; Lin et al. 2006). With the continuous refining of

436   sophistication in object-based modelling embedded in BIM, the querying of lessons learned can be

437   linked to model items and project tasks. The source of information for the Input is Navisworks

438   environment where federated digitized models can be manipulated to varying degrees. The main

439   action for activating the input into the system is the selection of a model item by double-clicking it

440   with a mouse. Thus, during model walkthrough in sites or project review meetings for example,

441   lessons learned information relating to model items can be automatically accessed. This research

442   therefore proposes model item as direct input into the system. When a model item is selected, the

443   system accesses the properties of the item including those of the parent object. The attributes of the

444   selected item and its parent object are assessed to identify the suitable item name that can be used to

445   interact with the database. For example in the Navisworks environment shown in Figure 8, the

446   Selection Tree displays a detailed hierarchy of model items. The Roofs item is the parent of Basic

447   Roof which in turn has four child objects; H_Roof - Entrance Canopy, H_Roof - Insulation - Pitched,

448   H_Roof - Structural Deck - Pitched and H_Roof - Structural Deck - Pitched Acoustic. In this case, the

449   system will recognise any of these child objects as Basic Roof, by default, when selected during a

450   walkthrough activity. Note that each of these child objects may be a single material, composite
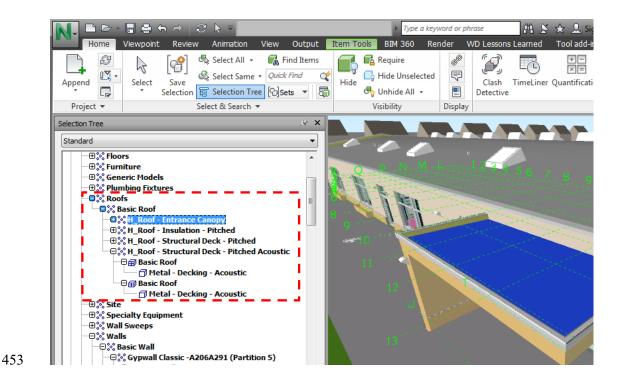
451   material or consist of further child objects.

452

453

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

455

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

469   of these four groups are tagged as basic roof and will be pulled up during query events. The entries in

470   this field also serve as the search terms used to query the NoSQL database when a model item is

471   selected without the need for developing relational database keys. This is one of the advantages of

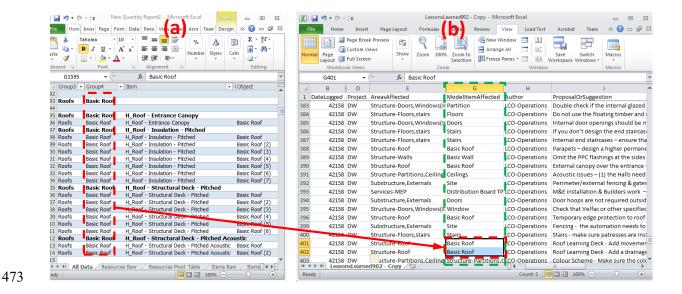472   deploying NoSQL databases such as MongoDB in knowledge management systems.

473

474   **Figure 9 Mapping model item to lessons learned (a) Model item structure from Navisworks (b) LL**

475   **information with mapping field**

476

477

478   *Mechanism, Function and Output*

479   The cleaned and mapped lessons learned data is transferred to MongoDB which is the Mechanism

480   environment. MongoDB stores the lessons learned data and provides the environment for data

481   management and manipulation. Data is stored in the form of documents and linked through nodes.

482   MongoDB provides easy access through programming applications such as C# provided the

483   appropriate connection has been established in MS-DOS. C# is the environment where the Function is

484   developed and it is where all the programming instructions are initiated and executed. Figure 10 gives

485   the illustration of an example of the C #snippet that interacts with the NoSQL database as viewed

486   from the MongDB Compass. MongoDB Compass enables users to probe collections in a cluster of

487   MongoDB localhost. The interactions with the federated model through Naviswork API to obtain the

488   Input; reading of the Control information (lessons learned) from the cleaned comma-separated values

489   (CSV) file and subsequent insertion into MongoDB are all carried out in the Function. Further, the

490   Function initiates the query according to instructions and sends the results as Output. The Output is

491   the graphical user interface (GUI) displaying the results of the model item query in a Windows form

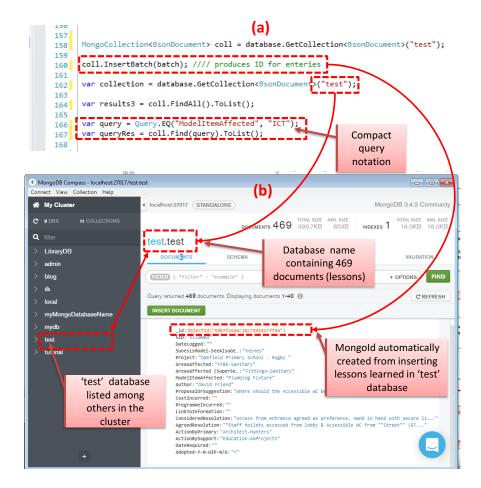492   obtained as an external application on Navisworks.

493

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

495   **view**

496   **Operation of the system**

497   The system is operated in Naviswork environment implemented through its provided .NET API. The

498   API provides access to objects in a model file or Navisworks application via a combination of various

499   classes, structures, methods, and events contained in different assemblies (Autodesk 2018). Three

24

500   frequently used assemblies in the Naviswork.NET API are the Autodesk.Navisworks.Api.dll for Plug-

501   ins or when working with the Controls API; Autodesk.Navisworks.Automation.dll for working with

502   Automation to drive Navisworks and the Autodesk.Navisworks.Controls.dll – used when requiring

503   GUI Controls or access to Navisworks documents within a third party applications (Autodesk 2018).

504   In this implementation, the proposed system is embedded into Navisworks Ribbon with a resulting

505   window that can blend into the Naviswork GUI. This window allows users to control linking mouse

506   clicks events of object selections to calling the programme.

507   The scenarios where the proposed system will be most useful are during project review

508   meetings, site meetings, or design processes and reviews. The procedure for operating the programme

509   (Figure 11) commences from when a designer (user) opens a federated model in Navisworks (1). The

510   user can call (activate) the lessons learned programme from the created tile on the Naviswork Ribbon

511   (2). The decision to adopt a conventional text-based query or the selection of model items from

512   walkthrough manipulation is then made by the user (3). Going with the option of selecting models (4),

513   a model item is then selected by double clicking (5). This activates the System to fetch the object

514   properties of the selected items from the model in Navisworks (6). Information about the related

515   objects such as the parents is also acquired (7). The system identifies the appropriate term (object

516   name) from the information attributes of the selected object and its parent (8) which is then used to

517   query the NoSQL database (9). The resulting output is a list of all the related lessons learned shown in

518   GUI (10). It is down to the user to scan through the list and further examine and to note the lessons of

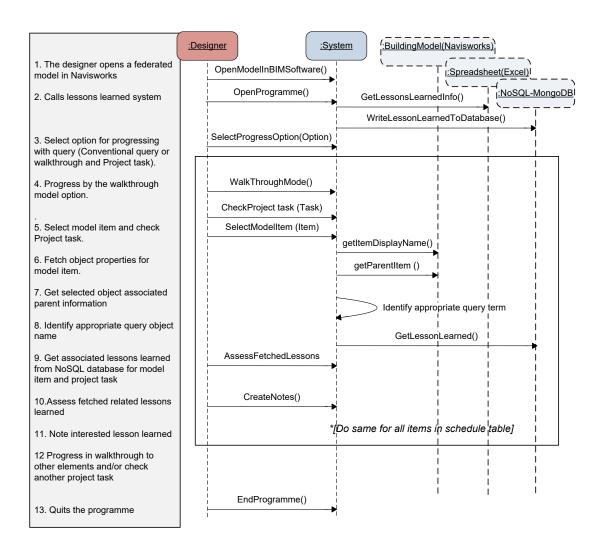519   interest (11). From here, the walkthrough can continue (12) or be terminated (13).

520

521

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

533 improvements in the satisfaction of successive clients. The system is demonstrated using lessons

534 learned that have been collated by the main contractor on various projects.

535 **Lessons learned data**

536 It is recommended that organisations should make a good effort to capture lessons learned and place

537 such in databases that are readily available to stakeholders to learn from (Marlin 2008). Logged

538 lessons learned information should, as much as possible, include both problems and solutions and be

539 easy to access. Although approaches to compiling lessons learned information may differ from firm to

540 firm, as advised by Marlin (2008) , the baseline guide is to ensure that (1) each lesson has been

541 validated appropriately, (2) lessons focus on what (failures or successes) can benefit future projects,

542 (3) recorded lessons learned information should not finger-point or blame anyone and (4) the database

543 is continuously updated and current as well as easily searchable. The lessons learned data available to

544 this research, to a large extent, complies with points 1- 3 above. On the hand and point 4 is subject to

545 continuous improvement depending on technological advancements and the level of sophistication

546 developed in emerging construction information technology tools. It is the aspects of 'easily

547 searchable' and efficient 'database management systems' in point 4 this research focuses on; taking

548 advantage of emerging BIM capabilities. Figure 9 shows part of the lessons learned information as

549 entered into spreadsheets serving as the lessons learned database for the proposed system. In addition

550 to the fields (areas affected, proposal or suggestion, considered resolution, agreed resolution and

551 adopted affirmation) visible in Figure 12, other important fields in the spreadsheet include the lessons

552 ID, date the lesson was logged, the project name, the primary party to effect action and the supporting
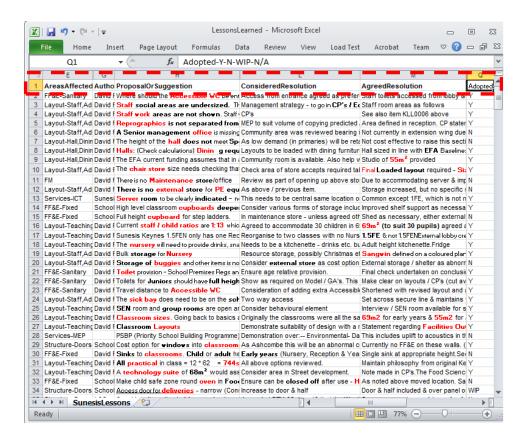
553 party.

554

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

570   mouse, the system is automatically called and the lessons learned system window pops up. This event

571   registers the selected model item and the active project task which are simultaneously used to query

572   the database. The query results for the model item and Project task are displayed in data grids, (3) and

573   (4) respectively. Each or any of the relevant listed lessons learned can be explored further by selection

574   triggering a further display of details in the third data grid (5). Reports can be saved and/or printed of

575   for later reference or use. There is also the provision of linking searches to the internet for wider
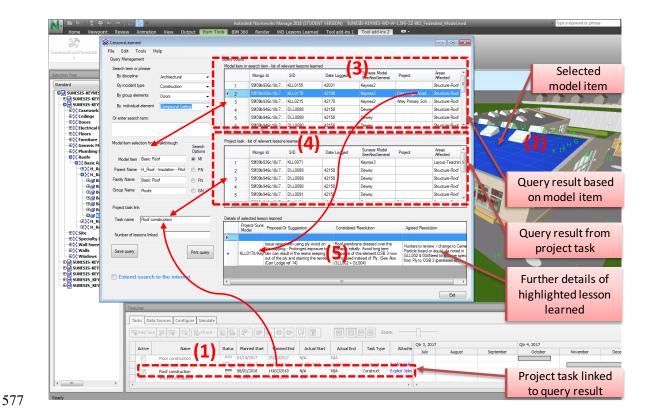
576   consultation when the need arises.

577

578   **Figure 13 System query output**

579   # Discussion

580   A key concern for organisational learning and knowledge management is to improve productivity

581   through lessons learned. The Project Management Body of knowledge Guide sums lessons learned as

582   the learning gained from failures or successes in the experience of performing a project. It is

583   important that learning gained is validated, recorded and continuously updated for futures use.

584   Regarding lessons learned in the knowledge management circles, the aspect of utilising learning

585   gained to improve the delivery of future projects is even more important as this is where productivity

586   stems from. Suggestions from the literature stipulate that the design of lessons learned systems should

587   generally aim to identify, document, analyse, store and retrieve lessons.

588   While all the aspects of utilising learning gained and lessons learned system design remain

589   essential, the utilisation of stored lessons learned commences at the point of retrieval from the data

590   store. Conventional text-based information searching systems had sufficed in retrieving lessons

591   learned data but need extending in performance and integration with emerging object-based modelling

592   and visualisation embedded in BIM authoring tools. The ease and speed of the retrieval of lessons

593   learned when needed does influences how knowledge can diffuse and ultimately be used. Such

594   systems need to be technologically up-to-date and user-friendly. This research therefore fulfils the aim

595   of enhancing the process of accessing lessons learned information on projects using BIM capabilities.

596   It contributes to improving project stakeholders' convenience in accessing lessons learned, and

597   therefore contributing to knowledge building and subsequent application in projects. This is achieved

598   by proceeding beyond conventional text-based query to attach relevant lessons learned to (1)

599   appropriate model item connected to the learning gained and (2) appropriate project schedule task

600   where the lessons learned is most beneficial to the project parties responsible for the respective

601   assignments. The lessons learned system was integrated into the Navisworks platform, a project

602   management and coordination BIM-enabled environment useful in model visualisation, clash

603   detection of merged models and simulation of tasks in project schedule

604   In addition to object-based project information modelling capabilities in BIM, the lessons

605   learned system implementation combined technological advances emerging in database management

606   systems, NoSQL, compliant with contemporary cloud computing services. NoSQL databases support

607   the efficient management of unstructured data and are web ontology compliant. The current needs to

608   cope with storing managing and retrieving heterogeneous online data have lead to the deployment of

609   NoSQL stores for Cloud-based open source file management. MongoDB is sampled in this research

610   as an example of one of such robust, compatible and interoperable NoSQL DBMS. Connections to

611 MongoDB are established through Microsoft .NET Frameworks applications interfaced with the

612 Naviswork BIM environment. The underlying advantages are (1) it is schema-free structure and

613 flexibility (2) efficiency in handling unstructured data of different formats and (3) the capability to

614 handle future growth of data that will typically characterise lessons learned information.

615   Activities comprising lessons learned systems have been broadly classified under three groups:

616 Users, Repositories and Quality assurance. The users and quality assurance team generally interact

617 with repositories by means of storing and retrieval of lessons learned. This work focussed on the

618 aspect of retrieval of lessons learned which could have a substantial influence on the response of users

619 in engaging with the system and the subsequent utilisation of learning gained to inform future project

620 tasks. To progress to that point where lessons gained need to be retrieved, lessons must be identified,

621 collected, recorded and stored after due validation. This is a key assumption in the implementation of

622 the lessons learned systems in this research. Hence, the lessons learned data already collated by the

623 main contractor of the project was deployed on the grounds of this assumption. Also, the

624 implementation is a demonstration of concepts and as such limited to verifiable elements in the model

625 and hypothetically generated 4D BIM (schedule) tasks. In this implementation, the executions of

626 queries generated with respect to conventional methods, model items or project tasks are confined

627 within the NoSQL database in the localhost. Search links to the semantic web are out of the scope of

628 this research, having been covered in other studies (Ding et al. 2016; Ferrada et al. 2016).

Conclusion

630 Although there are studies extending queries of knowledge management systems to semantic web

631 applications, the effective and efficient retrieval of context-focused lessons learned information to aid

632 project delivery still need improvement. In this paper, we proposed improvements relying on BIM

633 technology for the integration of construction knowledge linked to modelled building elements or

634 items and 5D project tasks. This is targeted at helping construction professionals overcome challenges

635 with delays and complications associated with the retrieval of context-focused lessons learned

636 information as elements of knowledge management on projects. In demonstrating this research

637 concept, the implementation relied on the development of business processes to model and represent

638 concepts, information flows, system components and their relationships. Further, lessons learned

639 information data were hosted in non –structured query system, NoSQL such as MongoDB, linked

640 through .NET Frameworks interfaced with a project management BIM tool, Navisworks Manage. The

641 system was successfully tested with a federated model from a pre-design school project which relies

642 on the reuse of knowledge to improve its product. The approach clearly demonstrated enhancements

643 in the process of storing and accessing lessons learned information that have been captured on

644 projects using BIM capabilities. The proposed system contributes to improving the convenience of

645 stakeholder accessing lessons learned and as such, the enhancement of knowledge building and

646 subsequent application in tackling construction tasks. We therefore conclude that lessons learned

647 systems can become an integral part of BIM environments and contribute to enhancing knowledge

648 reuse in projects.

649

650 Data Availability Statement

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

652

653 Acknowledgement

657

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