

AUTOMATING CONSTRUCTION MANUFACTURING PROCEDURES USING BIM DIGITAL OBJECTS (BDO): CASE STUDY OF KNOWLEDGE TRANSFER PARTNERSHIP PROJECT IN UK

ABSTRACT

Purpose: This paper presents a novel proof of concept framework for implementing BIM Digital Objects (BDO) to automate construction product manufacturers' processes and augment lean manufacturing.

Design/methodology/approach: A mixed interpretivist and post-positivist epistemological lens is adopted to pursue the proof of concept's development. From an operational perspective, a synthesis of literature using interpretivism provides the foundation for deductive research enquiry implemented within a case study approach. Within the case study, participatory action research (PAR) is implemented to test the proof of concept via three 'waterfall' research phases, viz: i) literature diagnosis and BIM package selection; ii) BDO development; and iii) validation and evaluation.

Findings: The findings illustrate that a BDO (which represents the digital twin of manufacturing products) can augment and drive automation processes and workflows for construction product manufacturers within a contractor's supply chain. The developed framework illustrates the benefits of a BDO, by reducing the number of manufacturing processes to effectively eliminate early errors in the model, generate financial savings and reduce material wastage.

Originality: This research provides a seminal case study that implements BDO to automate construction product manufacturing processes and moreover, demonstrates the utilisation of BDO at an operational (vis-à-vis theoretical) level. Future research is proposed to implement a longitudinal approach to measure and report upon the success (or otherwise) of the proof of concept when implemented on fabrications and shop floor procedures.

KEYWORDS

BIM digital objects, construction supply chain, IoT, Industry 4.0, manufacturer and case study

INTRODUCTION

Contemporary construction activities have progressively shifted towards implementing digital information to circumvent excessive material waste generation (Woodhead et al., 2018),

whilst simultaneously augmenting operational procedures (Schwabe et al., 2018) and optimising the flow of information handling during a project's lifecycle (Marzouk et al., 2018). Perhaps driven by Brexit (GOV, 2019) and the desire to intensify national productivity rates (Mohamed et al., 2017), the UK government mandated BIM level 2 for public funded projects as a panacea to construction project performance issues that doggedly persist (Edwards et al., 2017; Binesmael et al., 2018; Jallow et al., 2019). This political intervention has ensured that architects and contractors increasingly adopt (or demand from members of their supply chain) federated BIM digital objects (BDO) (HM Government, 2013). Moreover, a recent industrial survey led by National Building Standards (NBS) reports that 69% of specifiers, including architects and contractors, request BIM product data from product manufacturers (NBS, 2019). However, 61% of architects and contractors have noted that BIM manufacturing product information is often supplied as needed for the project vis-à-vis in an instantly configurable format (ibid). According to Abanda et al. (2017) and UKBIMALLIANCE (2019), the main challenges associated with BDO are:: 1) the majority of manufacturing BDO are outsourced by the BIM hosting company; 2) not all hosting companies allow manufacturers to own their product information, forcing them to pay for regulated subscription fees; 3) some contractors and architects force their supply chain manufacturers to generate their BDO using a hosting company; 4) BDO generated by a hosting company are often generic and lack the logic that allows for various alternative configurations of product design; and 5) the generation of BDO are often utilised as a crude marketing tool rather than an accurate object of manufacturing product data. Yet, against this problematic contextual setting (coupled with a rapidly developing technological landscape), innovations at the forefront of developments such as Industry 4.0 offer manufacturers an opportunity to improve users' services, augment data interactions between stakeholders and enhance automation of products' development and manufacturing (Qi and Tao, 2018). Furthermore, there is a significant dearth of studies, that have been undertaken in this area (Tang et al., 2019).

Given the prevailing context of challenges and innovative opportunities, a Knowledge Transfer Partnership (KTP) provided the perfect antidote to overcome many conundrums represented by BIM within a manufacturing context . The KTP is a partnering project funded by (innovate UK), a business partner (small-to-medium enterprise (SME)) and managed by knowledge base partner embodied by a University. Hitherto, the KTP project is established, if there is a clear demonstration of a problem, which if tackled by the KTP, will provide

significant benefits to the business partner such as: service improvements; turnover increases; design and manufacturing processes improvements; and culminating in demonstrable evidence that the research achieves a substantial impact upon society and the wider community. The KTP started in 1975, with an average contribution of: 700% for the return of investment by; £5.2 of turnover; and an overall of £117 million for the UK economy over the last 30 years (Warwick Economics and Development, 2015). Thus, the current case study presented in this paper, underpinned by the KTP and its findings, are manifested to improve the business procedures within the construction manufacturing SME. The overarching aim of this paper, is to provide a proof of concept and conceptual workflow that guides manufacturers through their automation processes using BDO. Concomitant objectives realised through achieving this aim are: automating manual processes; facilitating operational information; improving user experience; automating the generation of BDO manufacturing reports; and subsequently, increasing productivity.

RESEARCH METHODOLOGY

The research utilised a mixed philosophical design to position the work within both pertinent theory and practice. An overarching post-positivist (Gefen and David, 2019; Kankam, 2019; Moon, 2019) epistemological design was predominantly adopted using a deductive approach to test a conceptual proof of concept framework previously proposed by Al-Saeed et al. (2019). To adequately contextualise the research within the existing body of knowledge, an interpretivist epistemological lens was also adopted to synthesise pertinent literature (Research Methodology, 2016). Diagnostic software (such as R Studio (RStudio, 2019) and Bibliometrix (Bibliometrix, 2019)) were used to review current theories and existing frameworks in order to determine potential applications of knowledge transfer to the specific phenomena under investigation in this work. A case study research strategy was implemented within a construction product manufacturer SME located in the Black Country conurbation – a geographic area (situated North-West of Birmingham) that constitutes the UK's industrial heartland and is widely acclaimed as being the birthplace of the first industrial revolution (Hammond and Hammond, 2005). The SME manufactures a range of 24 washroom products for new and refurbished buildings, including vanity units, toilet cubicles and integrated duct systems. Currently, the company employs 53 staff, generates a turnover of £6 million per annum and has an organisational structure that includes a senior management team (ST – frequency (f) = 2); design team (DT – f = 5); estimation team (ET – f = 4); and fabrication team (FT – f = 42).

From an operational perspective (refer to Figure 1), participatory action research (PAR) was implemented because this research instrument enables collaboration, augments internal validity and ultimately provides a justification for research inquiry (Anderson and Herr, 2007). The PAR consisted of a three-stage iterative and dirigible ‘waterfall’ process (with four phases) (Gillis and Jackson, 2002; Siew et al., 2013; Tüzün et al., 2019) comprising of: 1) review, evaluation and selection of an optimal BIM package that delivers company requirements, through the use of a qualitative componential matrix (Chapman et al., 2019; Davtalab et al., 2018; Pärn and Edwards, 2017a). This matrix provided an insightful cross comparison between alternative BIM software applications that could be utilised within the proof of concept framework; 2) development of BDO to demonstrate their inherent benefits within this case study using hierarchal and relational diagrams that illustrate the relationships between various oriented BIM objects and semantic ontologies; and 3) validation and evaluation of BDO by comparing the new implemented workflow within the conceptual workflow previously developed (cf. Al-Saeed *et al.*, 2019). Each cycle built upon the findings emanating from the previous cycle until a satisfactory solution was reached (Baum et al., 2006).

<Insert Figure 1 about here>

For this seminal research, only one product range (namely: cubicle washroom unit) was analysed as a control group to ensure that any variations in process (between product groups) could be avoided within the proof of concept. In addition, participants’ opinions were gathered and analysed quantitatively to determine areas that required further improvement but also to determine the feasibility of rolling out the proof of concept across the entire range of 24 products.

PHASE ONE - LITERATURE DIAGNOSIS AND SOFTWARE SELECTION

The literature review conducted utilised the Web of Science (WOS) database repository due to its superior coverage of extant literature (Wang and Waltman, 2016). As demonstrated in many database-comparisons (Chadegani, 2013; Iowa State University, 2019; Aksnes and Sivertsen, 2019), WOS was favoured for the bibliometric analysis for the following reasons, namely, the database focuses upon: 1) journals with high impact and influential journals in the literature; 2) journals that specialise in technology, social science, science, arts and

humanities; when compared with Scopus, which focused on journals associated with physical, life, health social science. Because the premise of this research was to develop a proof of concept model, search terms focused upon the conceptualisation and design stages of manufacturing processes only and within this context, used four search query strings, viz: 1) ‘*BIM*’ and ‘*object*’ and ‘*design*’; 2) ‘*BIM*’ and either ‘*software*’ or ‘*computer aided design*’; 3) ‘*Industry 4.0*’ and ‘*construction*’; and 4) ‘*BIM*’ and ‘*data*’ and ‘*design*’. Given the rapid pace of technological developments in this area of study, and to limit the evaluation of literature discourse to only the most recent and up-to date studies in the field, only published research papers and conference proceedings from 2015 to 2019 were only chosen for the bibliometric analysis. A total of 750 publications were initially identified but this sample was reduced to 450 publications following a manual filtering of abstracts which sought to remove superfluous or irrelevant materials that associated with agriculture, industrial engineering, aerospace and historical buildings This filtration process, ensures the inclusion of relevant literature, which focused mainly on the use of BIM, IoT and Industry 4.0 within the manufacturing and construction context only. Additionally, it allows for the development of conclusions that add a practical value to this case study research.

Research themes and clustering

Descriptive ‘keywords co-occurrences’ data mining analysis was utilised to identify words and titles contained within the sample frame of publications, where each publication constituted a unit of analysis (La Paz et al., 2019; Roberts et al., 2019). The R Studio programming language within the Bibliometrix software package was utilised because of its inherent ability to visualise relationships within the literature (Aria and Cuccurullo, 2017). The bibliometric text file of sample literature was first loaded to R Studio then converted into a data frame using the function `convert2df` viz: `{M <- convert2df(D, dbsource = "isi", format = "bibtex")}`. A matrix was then generated with two bipartite networks to represent the keywords and their co-occurrences or frequency alongside their level of association with each other. A rectangle matrix was generated using the `cocMatrix` function viz: `{A <- cocMatrix(M, Field = "AU", sep = ";")}`. The matrix was then used to generate the bibliometric keyword co-occurrences analysis viz: `{NetMatrix <- biblioNetwork {M, analysis = "co-occurrences", network = "keywords", sep = ";"}}`, where the number of keywords was set to 30 and the ‘fruchterman’ network analysis style was used viz: `{net=networkPlot(NetMatrix, n = 30, Title = "Keywords Co-occurrences", type =`

"fruchterman", size=T, remove.multiple=FALSE, labels=0.7, edgesize = 5)}. For a more complete description of the codification used, interested readers should consult with (*ibid*)

The analysis in Figure 2 revealed two distinct clusters, namely: 1) the design stage (coloured red) which encapsulates simulation, optimisation and waste minimisation through sustainability; and 2) the conceptual stage (coloured blue) which emphasises information, management and knowledge.

<Insert Figure 2 about here>

Additional text mining analysis was required to interpret further the analysis of the keywords. Therefore, a bibliometric conceptual structure mapping was conducted to contextualise the main concepts of *titles*, *abstracts* and *keywords* within sample literature based on their corresponding themes. The conceptualStructure function was used in R Studio with the following parameters viz: {CS <-conceptualStructure(M,field="ID", method="MCA", minDegree=3, k.max=8, stemming=TRUE, labels=10, documents=10)}. The corresponding results were plotted on a two dimensional map which used the natural language processing routines and Porter's stemming algorithms to assign terms to their respective cluster (Porter, 2001). Figure 3 shows four highlighted clusters, namely: 1) internet of things or industry 4.0; 2) BIM, CAD, ontology, documentation design and management; 3) adopting innovative solutions and strategies; and 4) algorithms generation and code checking. The emerging clusters reveal that 'information processing' and 'query retrieval' have become prominent topics within contemporary BIM literature – thus signifying a further expansion of BIM data management applications within the workplace. This finding also suggests that BIM data management tools increasingly coalesce with the internet of things and advanced algorithms to improve error and clash detections earlier in the conceptual and design stages of a product's manufacturing lifecycle (Pärn et al., 2019).

<Insert Figure 3 about here>

Prominent countries, authors and the chronological order of literature

To determine the predominant countries at the forefront of collaborative research into BIM applied to manufacturing, bespoke code lines were adopted viz: {NetMatrix <- biblioNetwork(M, analysis = "collaboration", network = "countries", sep = ";")},

net=networkPlot(NetMatrix, n = dim(NetMatrix)[1], Title = "Country Collaboration", type = "sphere", size=TRUE, remove.multiple=FALSE, labelsize=0.7, cluster="none"). Results revealed that China is the most productive and collaborated country followed by USA, UK and Germany (refer to Figures 4 and 5).

<Insert Figure 4 about here>

<Insert Figure 5 about here>

Co-citation analysis was then employed to examine the most prominent references in the field (Trujillo and Long, 2018), where the analysis was determined when two publications were cited by a third paper, the `biblioNetwork` function was used to plot the co-citation network for the total studies referenced in sampled articles viz: `{NetMatrix <- biblioNetwork (M, analysis = "co-citation", network = "references", sep = ";")}`. Figure 6 illustrates two dichotomous clusters of references from co-citation. The first cluster focuses on reviewing the benefits of using BIM for the commercial environment and how it can be used to leverage cost, time and production improvements (Azhar, 2011; Eastman et al., 2011). The second cluster emphasises the role of using algorithms to leverage the BIM technology in order to generate technical reports (such as quantity schedules and cost estimations) and overcome potential issues associated with applications interoperability while using BDO.

<Insert Figure 6>

In a similar vein, the `hiscite` bibliometric web analysis tool was utilised to classify the most prominent authors based upon classification criteria to filter the sample result. These criteria were: 1) a minimum of two local citation score (LCS), where the LCS is based upon an accumulated number of citations received from the 420 chosen for bibliometric analysis; and 2) the global citation score (GCS), where the GCS is based upon the article's total citation including the 420 sample of bibliometric studies (Garfield et al., 2006). Based on `Hiscite` analysis, 30 prominent authors were identified and listed in Table 1. In addition, `Hiscite` was used to generate a chronological literature map from the list of top authors and suggests that the origin of the research themes for this paper emerged from the study of no 17 (Kassem et al., 2015) which focused on sharing knowledge and collaborations for BIM. Other studies debated the use of ontological query retrievals, algorithms, task automations and data

management. The analysis also revealed that internet of things was discussed separately without being linked to other studies in literature.

<Insert Figure 7>

Most articles revealed a fragmented and diverse body of knowledge that could be categorised into multiple thematic clusters. However, there was no comprehensive framework that included the main themes of sharing knowledge and collaborations; query retrieval; tasks automations; internet of things; and data management. Therefore, this paper applies and tests the four identified themes within BDO in manufacturing product development.

BIM package selection

A plethora of commercially and alternative BIM software packages are available within the market, each with attractive individual technical features and attributes (LodPlanner, 2019). Choosing the optimal software to ensure the BDO are utilised by clients is therefore a fundamental concern for the case study SME. This is because such a decision could have major ramifications for future business growth and prosperity should IT conflicts occur. To mitigate this financial risk, a list of prominent, widely used software packages was drawn up by the lead researcher (LR) in conjunction with the SME's CAD lead (CL), operational director (OD) and managing director (MD). These personnel were invited to contribute because they were directly responsible for procurement decisions and had in-depth knowledge regarding: 1) company requirements; and 2) software capabilities. Prior to this case study, the participating SME had tried to create their own BDO using the Microvellum software (Microvellum, 2019). However, Microvellum is not classified as a CAM-CAD solution and not as a BIM tool; presently, it is not well integrated with other AEC software applications nor widely used within the 'upstream' manufacturing process (which predominantly involves architects and designers). Therefore, Microvellum was discarded as a viable software solution at the outset of the case study. Six other potentially viable software applications were identified by LR and CL. A list of twenty-six evaluation criteria was developed, dictated by three aspects: ease of use; interoperability and data handling. Thereafter, these evaluation criteria were re-evaluated for each of the six software packages and individual scores were summed to give a total score for each package. Based upon the results of evaluation, Autodesk Revit was selected as the most efficient tool to augment the generation of BIM for the SME (refer to Table 2). It should however be noted that a major

limitation of a case study is that inference cannot be drawn to other similar SMEs – however, whilst the analysis results presented here are very specific to the participating company, the methods adopted could be used in other similar studies.

PHASE TWO – BDO OBJECT DEVELOPMENT

Once the BIM package had been selected, the LR and CL arbitrarily decided that three manufacturing product ranges was a manageable workload for developing the proof of concept. The products chosen were: the integrated panelling systems (IPS); vanity unit; and toilet cubicle range (refer to Appendix 1). Design and production maps were then developed to depict the current process of geometrical and semantic data requirements across all members of staff in the SME. This depiction provided a better understanding of the products' parameters at each stage of product development.

Early trials using Autodesk Revit revealed that the software was capable of constructing the 3D model with a sufficient level of semantic information including the product's parameters embedded within the model. The trials also uncovered several issues viz: 1) difficulties in querying the model's parameters via the software interface, particularly when the model was constructed by other nested family components; 2) difficulties in exporting the information in various formats with the right level of information (interoperability issues); and 3) issues related to managing the constraints of BDO parameters as too many constraints can cause breaking of the geometrical object's logic. A potential solution to these issues was to integrate Revit with Dynamo (as an application programming interface (API) 'plugin') to process and manage the information complexity involved.

Geometrical configurations of BDO

To generate representative parameters for the chosen three product ranges, five thematic multiple categorisations were developed viz:

- 1 - *Dimensional parameters* that control the geometrical shaping of BDO in three dimensional space (using co-ordinates x,y,z);
- 2 - *Associated parameters* that represent nested values from nested family objects. Nested families are modelled objects grouped and placed in the final family object that represents the BDO. For example, a BDO of toilet cubicle may consist of multiple modelled families (i.e. ironmongery, doors, panels). These parameters' values within the nested families will be referred to as nested values. The dimensional parameters (as

nested values), generated from nested families of the ironmongeries, are part of the holistic BDO for the cubicle product - these can include anything from height to number of screws;

- 3 - *Dynamic Parameters* control dimensional and associated parameters and are dedicated solely for the purpose of constructing multiple BDO configurations. These dynamic parameters are constructed using formulas and algorithms in Dynamo and can hide and unhide BDO elements to fit a specific design configuration defined by the end user (architect).
- 4 - *Semantic information* or *data parameters* are used to generate product information reports such as asset information management and COBie sheets.
- 5 - *Identification parameters* that are used for tracking components and families of BDO. These are normally in image information exchange format and used in common data environment (CDE).

Following the delineation of product parameters in Revit, the geometrical model was generated in Revit and its parameters were assigned accordingly.

Quantity report generation in Dynamo

The LR, CL, OD and production manager (PMR) developed a list of fabrication requirements from the BDO to enable the facilitation of information between the CAD departments, architects and shop floor. This information was broken down based on products' assemblies and fabrications' processes. For example, some manufacturing components within the nested families needed to be exported as geometrical dimensions and, in some instances, they also needed to be exported as drawing eXchange format (DXF) to determine the tool pathing for the computer numerical control (CNC) machines. The information was identified for each BDO prototype and taken into consideration during the development of the logic's workflow in visual programming software Dynamo. Following the identification of relevant BDO, the generation of quantity sheets was broken down into six stages of an iterative waterfall quality process (McCormick, 2012): 1) selecting the BDO nested families before exporting the nested values related from cost parameters ; 2) checking any errors in the model - these were developed via the generation of text parameters in Revit to ensure that users abide by the current manufacturing procedures set by the SME; 3) filtering the information from these elements and components by retrieving the relevant parameters (or the required information) via the `Element.GetParameterValueByName` method in Dynamo (refer to Figure 8). These

parameters were sent to Revit in the form of queries and their data structure could be anything from Boolean (0,1), text and length, with numerical value depending on the parameter type set in the native Revit file; 4) sorting out the relevant information in Dynamo's workflow into lists before exporting to comma separated values (CSV) files. Each list was filtered by testing its Boolean condition in Dynamo such that once the condition was true, all its relevant information was retrieved. For example, a cubicle contains various structural elements such as a wall, door and ironmongery; these were indexed and sorted in the same list if they required the same manufacturing procedures; 5) translating all information into strings so as to enable the counting of similar occurrences and elements. Following the counting, the information list was re-structured again and indexed into a new list that associated each element with its counting number; 6) converting the numerical counted string values into integer values before exporting them to a CSV file. The CSV file was then imported into Microsoft (MS) Excel and sent to members of the fabrication team with all the identified elements from the model. Each row in the data frame represented the item type, quantity, type of materials and type of finish.

<Insert Figure 8>

Automating the cost calculations (5D)

The SME sought to develop an automated costing sheet at the outset of the research project vis-a-vis determining this information from antiquated manual procedures. This was mainly because the manual system is prone to costly human errors and omissions so automating the cost directly from BDO ensured that information was accurately translated from the project parameters (geometry, materials, finishes and fabrication procedures) to the accumulated scheduled list. Cumulatively, an enormous 90% in time savings are estimated over the product design to manufacturing production process when compared to the existing manual system. In order to generate the costing sheet, all relevant information from the estimation manager (EM) was first collated in a back-end database held on a MS Excel spreadsheet. Information held included: product component sizes; materials; finishes; and the estimated cost. All the back-end calculations were then coded and mirrored in the BDO using Dynamo's workflow.

< Insert Figure 9>

The costing information was automated by categorising into a list all BDO elements that shared similar attributes. For example, a BDO of washroom cubicle contains multiple elements of partitions, ironmongery and doors, so to facilitate the translation of the information embedded in these elements it was important to arrange all the similar elements into a list. These lists were then retrieved separately and factored based on their associated quantities and costs. The final costing price was accumulated according to the BDO geometrical and semantic information specified in Revit. The calculations for similar components were exported as CSV data and viewed in MS Excel. Information provided included: materials items (e.g. door or walls); material dimensions; finish; counting number; and the cost per item.

Generation of COBie MS Excel sheet

Construction Operations Building Information Exchange (COBie) was identified as a model view definition (MVD) of the industry foundation class (IFC), where COBie provided a subset of information for the BIM native model that included product information such as type, instance, colour, material and other attributes. Currently, the UK's National Building Standards (NBS) explains the relevant information that must be specified and included within the COBie sheet for manufacturers (NBS, 2018). Therefore, NBS guidance was used to generate the parameters for each range of the SME's BDO. NBS COBie classifications restructure the information into two types: 1) IFC parameters; and 2) COBie parameters that must be created in Revit as shared parameters. Shared parameters constitute groups of parameters that are created in Revit as text (txt.) files. The generation of these parameters is a time-consuming task because each parameter must be assigned to the right group and its data structure must be declared (e.g. text, Boolean, length, integer etc.) prior to assigning it in Revit. To overcome these issues an algorithm was developed to generate the BDO parameters for each different type of product range prototype. This approach increases productivity and reduces human prone errors while simultaneously ensuring these parameters are assigned to their corresponding property sets in Revit. Notably, not all information was listed in NBS shared parameters because prevailing NBS standards failed to specify what type of attributes were normally requested for each product type. Similarly, when generating the components sheet of the model, these same issues were found. Namely, the shared parameters did not classify the sort of components that needed to be exported to COBie. A further problem identified during the development of COBie information was the need for regular/ periodic information updates and some fields (for example, the space in the components sheet) were

not to be completed in earlier stages of the project. The developed workflow for COBie provided a viable solution to these aforementioned issues once all manufacturing parameters on the COBie sheet were identified, namely: *contact, type, component, system and attribute*. These parameters were exported to the COBie MS Excel sheet in order to facilitate the delivery of product information to facility managers and building owners.

User workflow and IoT

While developing parametric tools for the Revit BDO, it was observed that user manipulation of parameters in Revit (to secure the ‘right configuration’) was a time-consuming activity; in some cases, up to 250 parameters could be contained in one object in a BDO. Furthermore, the ability to copy the parameter’s value from one nested family to another within the same BDO proved to be problematic. In addition, the CL highlighted that some users do not have accessibility to BIM native software and instead rely solely on sketches and descriptive specifications. It was important therefore to filter these parameters so that users could manipulate them easily, without becoming inadvertently overwhelmed by the sheer amount of information or the complexity of the user interface. In response to this another algorithm was developed that enabled users to manipulate the BDO configuration from their mobile and tablet devices. The workflow’s algorithm was developed by: 1) extracting the value of the parameters in each BDO; 2) grouping all the relevant values into one group; and 3) exporting the parameters’ names and corresponding values to CSV format. The chosen parameters were mapped to CSV format with the following titles: ID - the numerical order of objects within the BDO from 1-8 letters; Parameter Functioning Group - representing the break down structure of components and elements related to the objects; Revit Parameter Name - a description providing brief information about the parameter in Revit; Input Type - stating the type of input in Revit; Value Type – a description of the type of data structure for the parameter’s input such as text, real, length or integer input value; and Example of Values - providing default value types for the BDO configuration. Cumulatively, this information allowed the user to have an insight into the range of values that could be used as a default

To extend the workflow and enable integration with the Internet of Things (IoT), it was important to extend the logic in Dynamo to enable such functionality. Following consultation with CL and OD, it was decided to integrate the current workflow with Google Sheets by allowing bi-directional connection through Google’s API. Consequently, the workflow was built using custom packages (e.g. Raindrops) in Dynamo’s library; Raindrops aims to enable

integration with Google Sheets (Dynamo, 2019). The workflow was built through: 1) establishing the connection with Google Sheets via its API service, with the user being prompted to enter access tokens in order to activate the connection; 2) creating a Google Sheet with similar data output to the (.CSV) workflow to act as an alternative accessible cloud data; 3) filtering the Google Sheets files and choosing the right one from a list of available sheets on Google Drive - accomplished by using the `Find.FindSpreadsheets` node in Dynamo. The workflow required that the existing spreadsheets developed in MS Excel were copied to Google Sheets using the `write.writesheet` node in Dynamo; 4) after copying the logic it was important to re-enforce the data again from Google Sheets rather than using MS Excel spreadsheets. The `Read.ReadSheet` node allows users to read all inputs in Google Sheets; 5) filtering the data input from Google Sheets and writing the data back to Revit using `Element.SetParameterByName` node in Dynamo. Google Sheets can be accessed via mobile phone and the app was installed and tested via an operating system (IOS) device (refer to Figure 10). Overall, the testing illustrated that the information was changing instantly in the model when it was set to automatic, which allowed for any changes made via mobile app to be applied instantly into the BDO.

< Insert Figure 10 >

Exporting the data to database

Retrieving design and manufacturing information when necessary through the product's manufacturing lifecycle represented a significant problem for the SMEs. To solve this fundamental data management issue, a logical understanding of all information and processes can be transformed into a light structured data through using SQLite. SQLite was chosen as a database because it has a module that integrates with Python which can be retrieved from the Dynamo interface. The benefits of following such an approach are: information can be retrieved efficiently; writing and reading of information can be done with simple steps; files are light and consume very small computational processing powers compared with other type of database formats; the database is well-integrated with multiple programming languages which enable it to be called within particular arbitrary logic. More importantly, linking BDO data with an SQLite database improves the quality of information and also enables tracking of BDO manufacturing procedures. The SQLite logic was embedded and tested as demo for the developed BDO by: 1) creating a Python node in Dynamo embedded with the previous scripts created earlier including quantity, cost and the user workflow from Google Sheets; 2)

creating a database table in SQLite with an X number of rows that correspond to the order of data in Dynamo file. For instance, a cost sheet would have the following rows: item, description, number and cost. Hence, the developed node in Python needed to reflect the number of data inputs, in order to re-enter these rows as headers in the SQLite database. After creating the database table and initiating the number of headers in the first row, the developed logic in Python looped through the list of input values and re-assigned them according to their index value (refer to Appendix 2). The data was saved on a database file.db which could be viewed via a web browser or mobile application linked to the IoT (refer to Figure 11).

<Insert Figure 11 >

Once the result was saved into the database, logic\scripts were developed to query the output and instantly retrieve the information requested. To fulfil this premise, a SELECT SQL method was used to query the model and retrieve any requested information at any given time. A query was developed based on specific filtering criteria, such as price and project name

User notification

The CL, MD and OP also discussed the need to keep track of not just the components of the BDO through product lifecycle manufacturing, but also their need to track the flow of information. Mobile notification provided a solution to this requirement by informing relevant users of the delivery of information as soon as such was released or updated. The senior management's MD and OD suggested developing a script that shared the quote with users as soon as the total cost of the product was produced. Hence, a Python script node inside the Dynamo environment was developed to export automated cost sheets directly into a text message sent to the client. The developed script used Twilio API web service which provides a module in Python that enables communication by sending text messages through Python code. The code was developed through a number of steps: 1) importing Twilio's modules; 2) providing the account ID and authentication; and 3) inserting the text message with a link to view the data. Python code was developed to import the external Python file and run it inside Dynamo.

The CL and SM were also interested in sending notifications to the users via emails. Therefore, further code was developed to add notifications for each pivotal phase of the information delivery. For example, the cost sheet notification informed the user that the cost sheet for the BDO was ready to be viewed and checked (refer to Appendix 3 and 4). Such functionality ensured that information was accessible to authorised parties and facilitated better collaboration and sharing of information. Apart from enhancing the communication between different parties within the project, the developed script to generate user's notifications optimised productivity and reduced the lead time of the product delivery.

Evaluation

A workshop session was arranged by the LR with participants from the SME (namely: OD, MD, EM, PRM) to evaluate the developed workflow. At the start of the session, a demo was run to explain the outcome from the workflow. Thereafter the LR instructed the participants to write down a suggested characteristic that best represented the workflow. After deciding on the main characteristics, the participants were asked to evaluate each characteristic based on its desirability from 1 (not desirable) to 10 (most desirable). Following the evaluation, final ranking was assigned to each characteristic (refer to Figure 12). It was apparent that multiple gains were achieved by piloting the workflow. For instance, improving the model's flexibility achieved the highest ranking from the evaluation. The MD emphasised the importance of this attribute:

“The workflow will improve the model's flexibility internally for the company and externally for the client; it will allow the clients to modify the drawings rapidly.”

It was also noted that the workflow would have a high impact on improving the cost efficiency. The OD emphasised this attribute:

“People can do more in the office and in the factory. Becoming more efficient we can generate more quotes, we can do more drawings with the same amount of body counts with high levels of accuracy.”

Improving efficiency will automate the manual procedures and subsequently empower the business to make better decisions. As such, the EM commented that using the workflow would enable unskilled business employers to make faster and better decisions.

“The fact that less trained people will be able to make decision faster.”

Similar views were echoed by the (PRM):

“The person who is making the decision is better informed and comfortable with the decisions that they are making with no detriment to the company.”

At the end of the session, the ST demonstrated that the developed workflow would better inform the company with regards to their margin knowledge, and would allow the ST to better manage the business processes by embedding and sharing knowledge through the BDO. The ST also agreed that workflow would contribute to many other benefits that are yet to come in the future and are subject to emerging technologies and customer usability.

CONCLUSION

The research in this paper explained various approaches to improving the functionality of BDO for an SME supply chain manufacturer working within the AECO industry. Albeit the paper focused on improving the functionality of BDO through the use of scripting and automation, it is also worth mentioning that such a solution needs to be well-integrated with various parties across all manufacturing stakeholders in order to: 1) ensure that stakeholders' knowledge and engagement are enhanced by the new workflow; and 2) enable solutions that eliminate the current issues that doggedly persist with manual manufacturing processes.

The implementation of BDO within manufacturing is an inclusive process that relies on engaging and allowing people to take ownership of the developed workflow. In addition, these new process improvements can be measured and recorded too. The SME has very limited knowledge in adopting BIM technology, apart from the top management view of pushing the BIM agenda to improve their workflow and build a stronger corporate profile as an innovative company - this exemplar shows senior management support is critical to implementing any change within the business. Pivotal to this success is the senior management's firm commitment to: upskilling staff members; technology adoption; and lean improvement in data and information management, which is critical to company success. This research will sustainably improve the company's capacity for continuous learning and improvement via the ongoing use of BIM technological tools. The BDO will work as a real

utility to transfer knowledge and improve collaboration across the product's whole-lifecycle. It is envisaged that the developed workflow for BDO will provide further benefits to the business in the future, particularly on the fabrication and assembly side. Given the growing need to utilise and implement BIM in the construction manufacturing environment, the developed proof of concept proffers a cohesive blueprint to streamline the manufacturing BDO from the upstream (product's query) to downstream (fabrication and asset management). In the context of the case study, the proof of concept, shows that BDO can be exploited as a decision-making tool, more so than an artefact to satisfy the buildings' mandates and standards. By the same token, and from a practical perspective, each concomitant solution developed in phase (3) of the proof of concept can be incorporated, developed and tested in a wider digital business service such as cloud computing, standalone software and mobile application(s) for construction manufacturers.

This research used empirical inquiry to investigate a unique case study in an SME. However, there are limitations for using such a methodological approach, for example the validity of the results and the generalisation are considered subjective. Future research will therefore test the implemented improvements in the case study by analysing feedback from BDO users (e.g. architects, building owners and facility managers) and non-conformance reports (NCR), as well as the IoT sensors embedded in products.

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Figure 1- Phases and methods implemented within a waterfall design

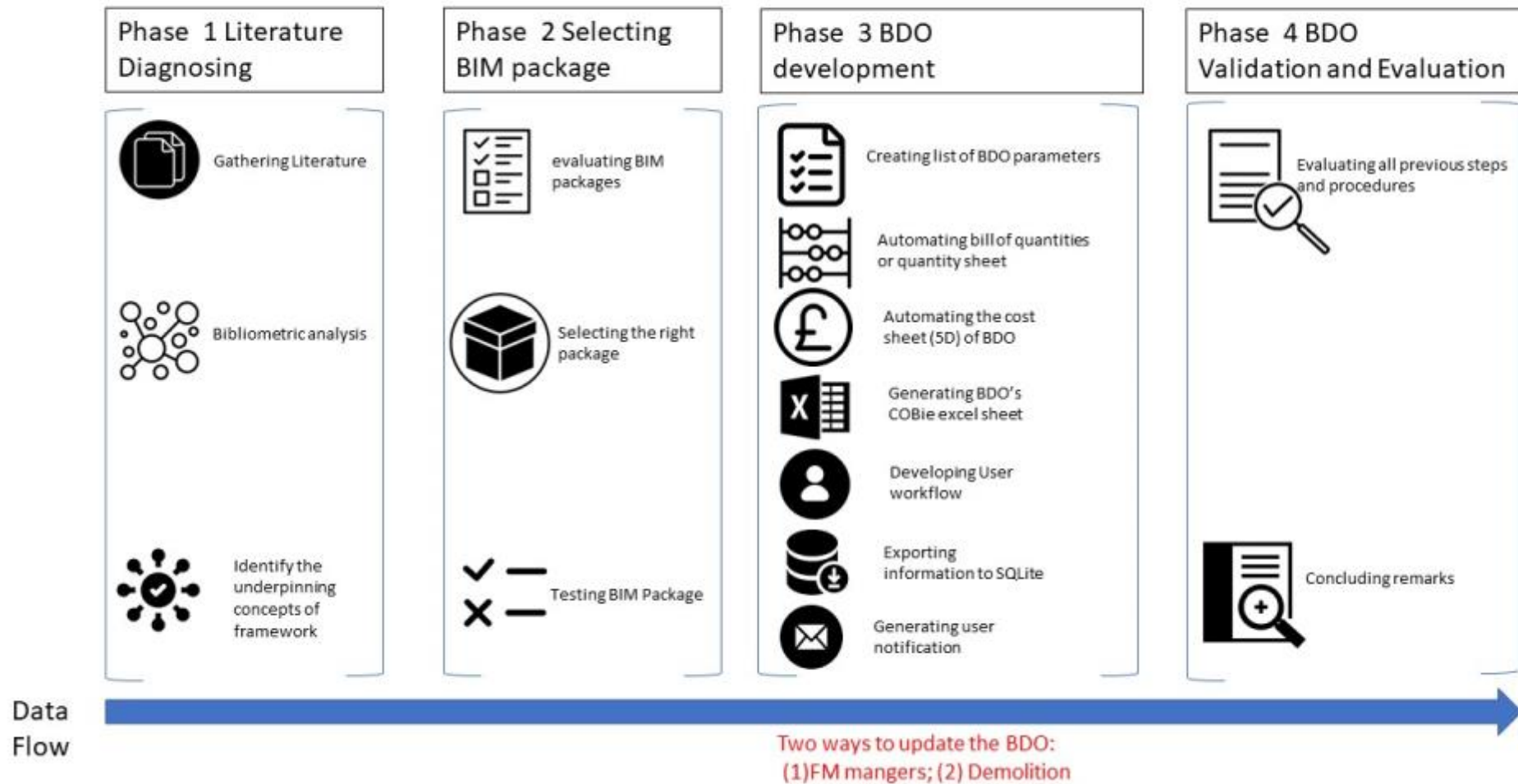


Figure 2 - Keyword co-occurrences analysis generated in R studio

Keyword Co-occurrences

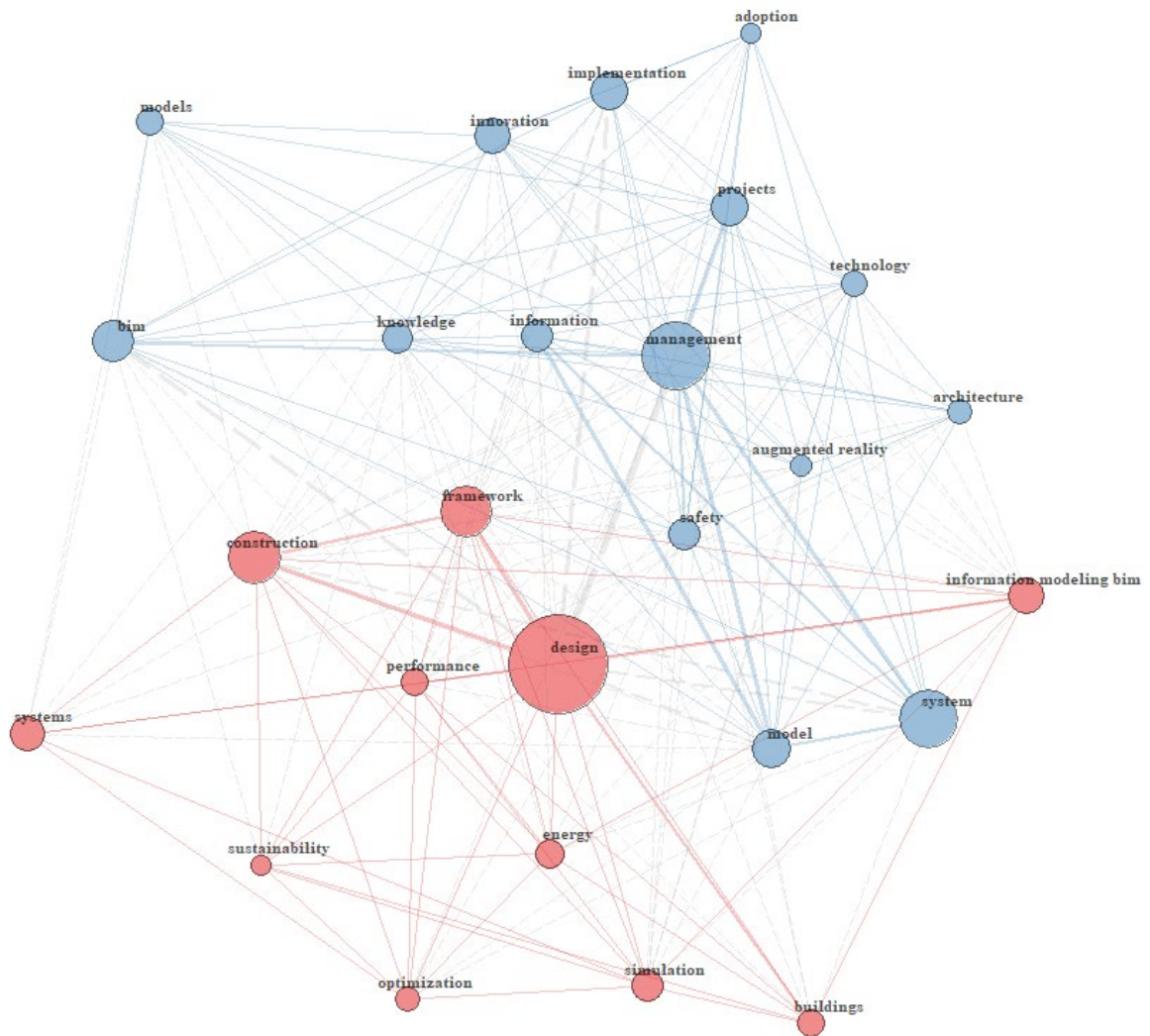


Figure 3 - Conceptual structural map

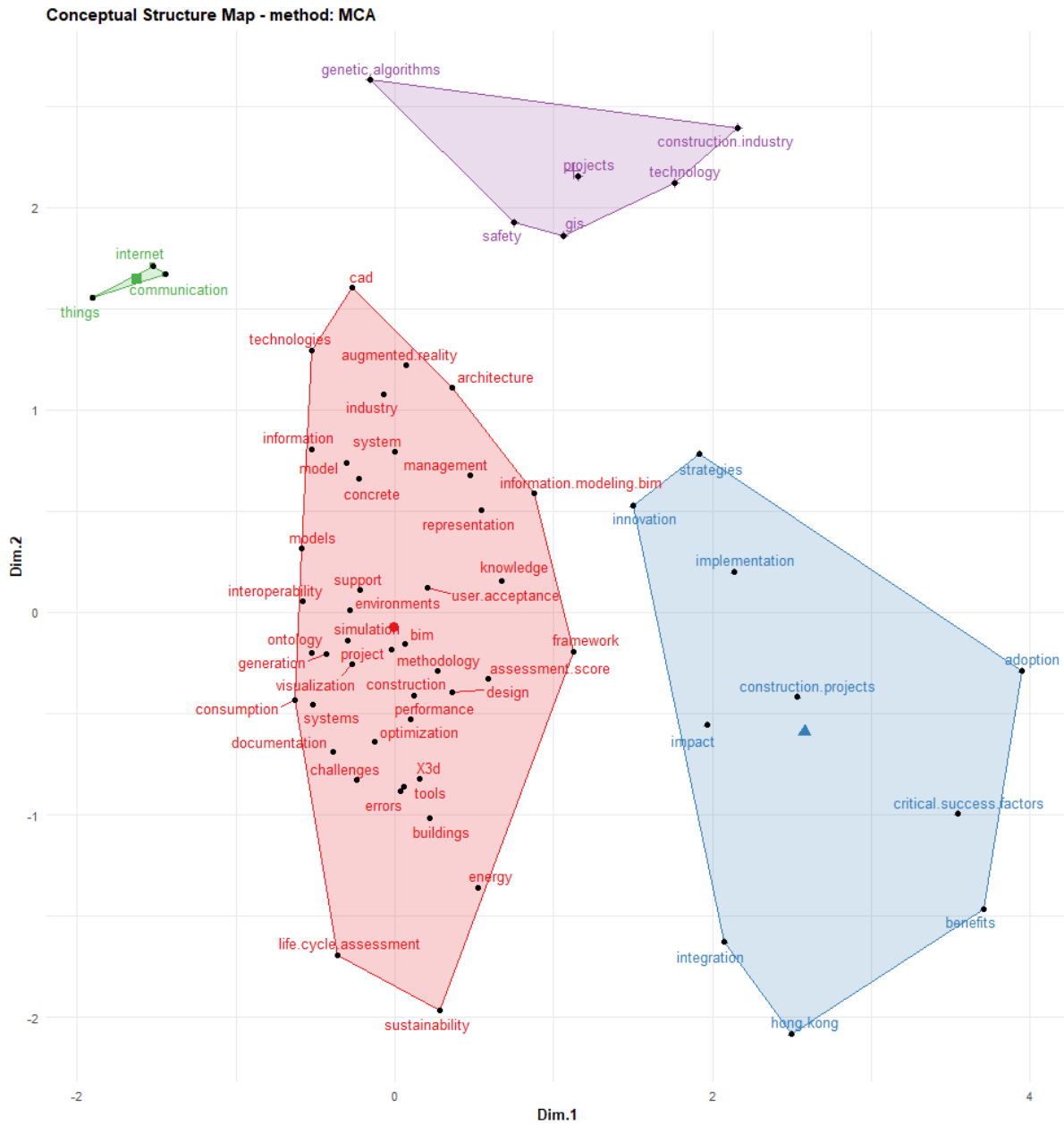


Figure 4 - Most productive countries in literature

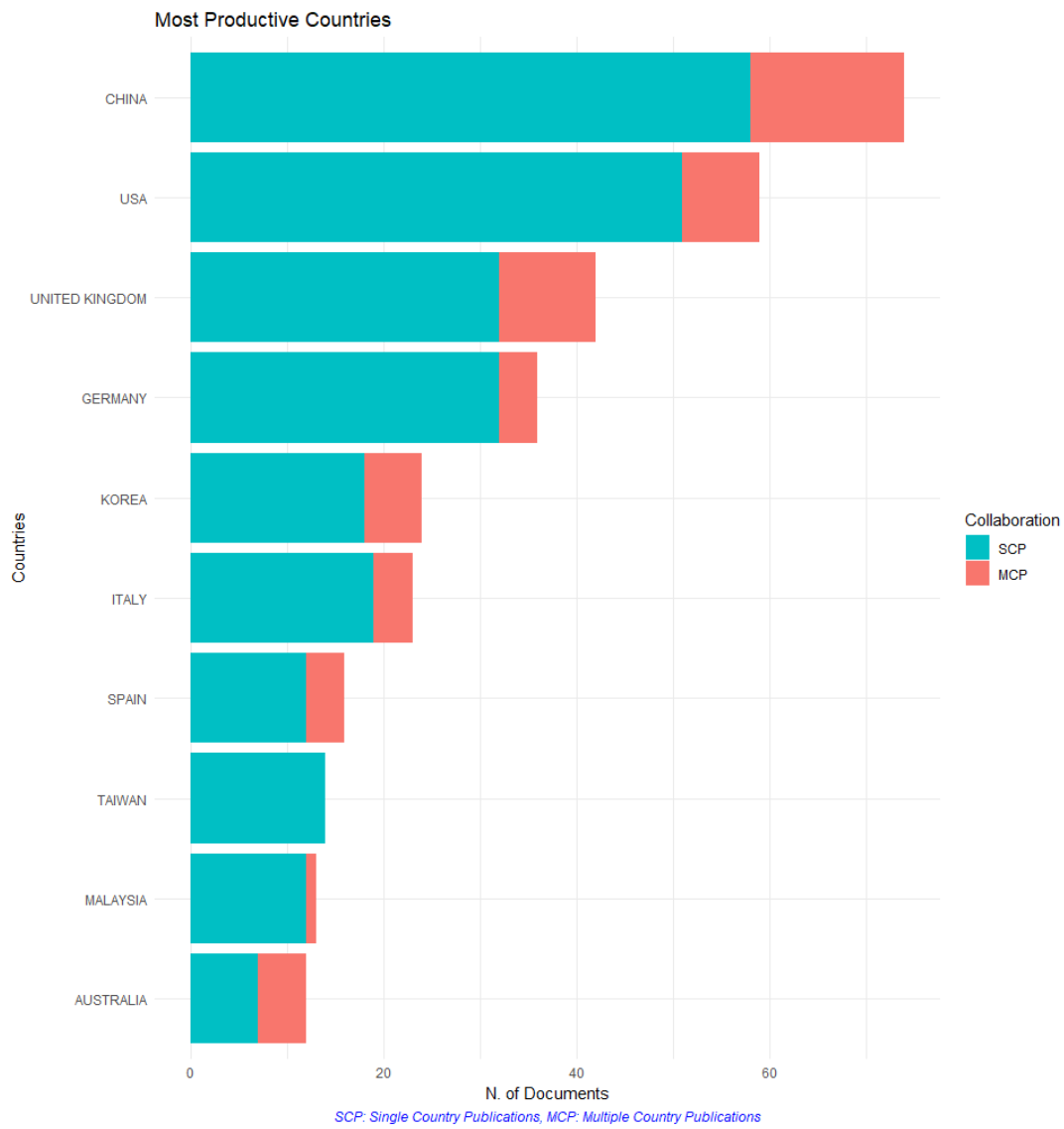


Figure 6 - Co-citation network

Co-Citation Network

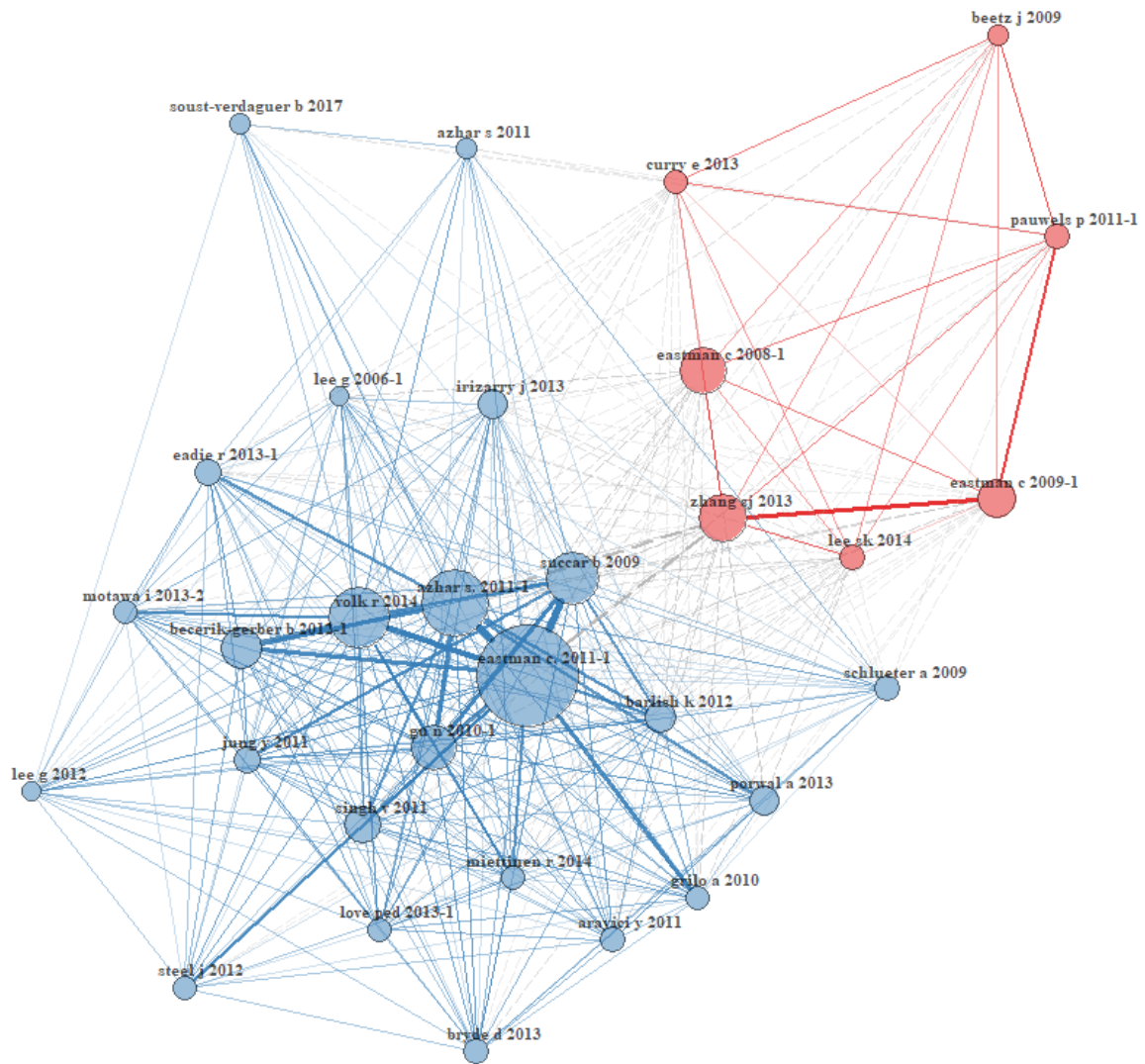


Figure 7 - Chronological map of literature

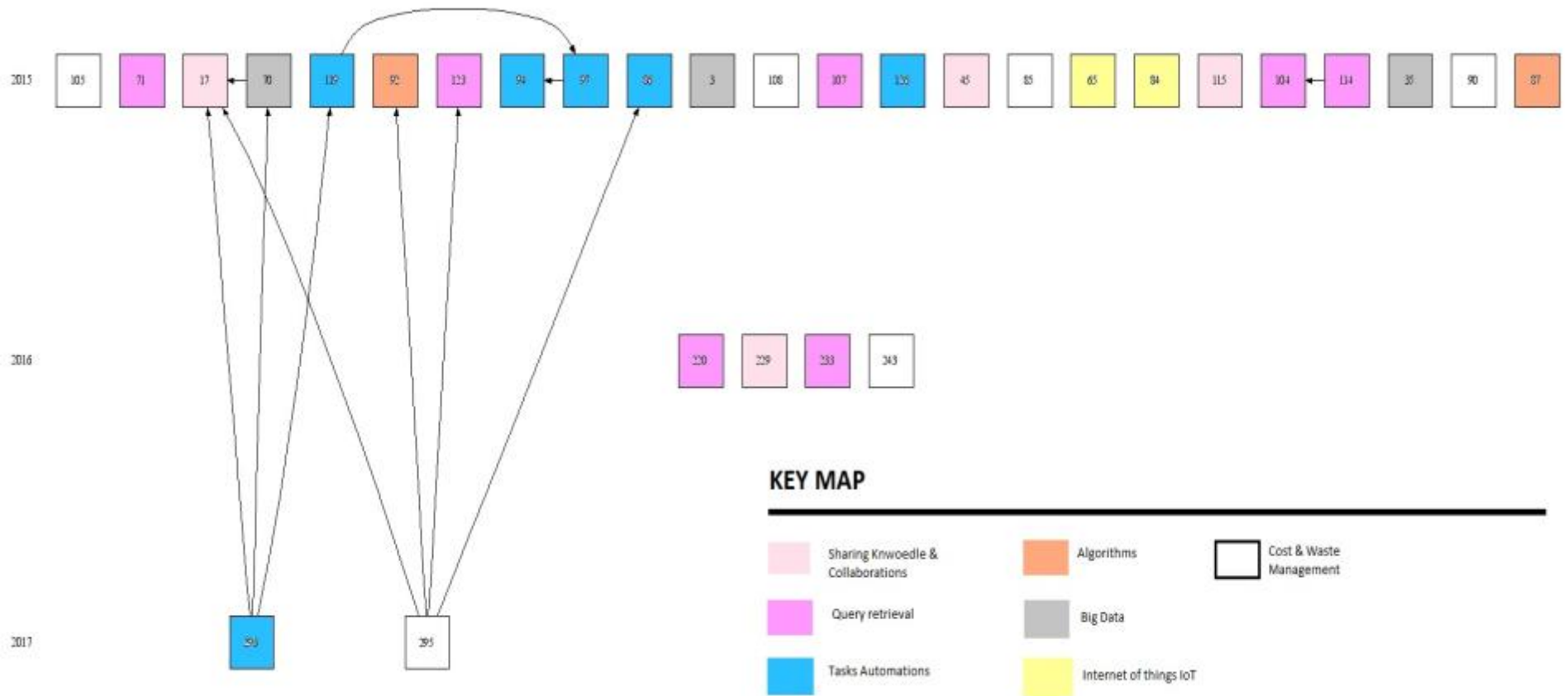


Figure 9 - Cost Script Developed in Dynamo

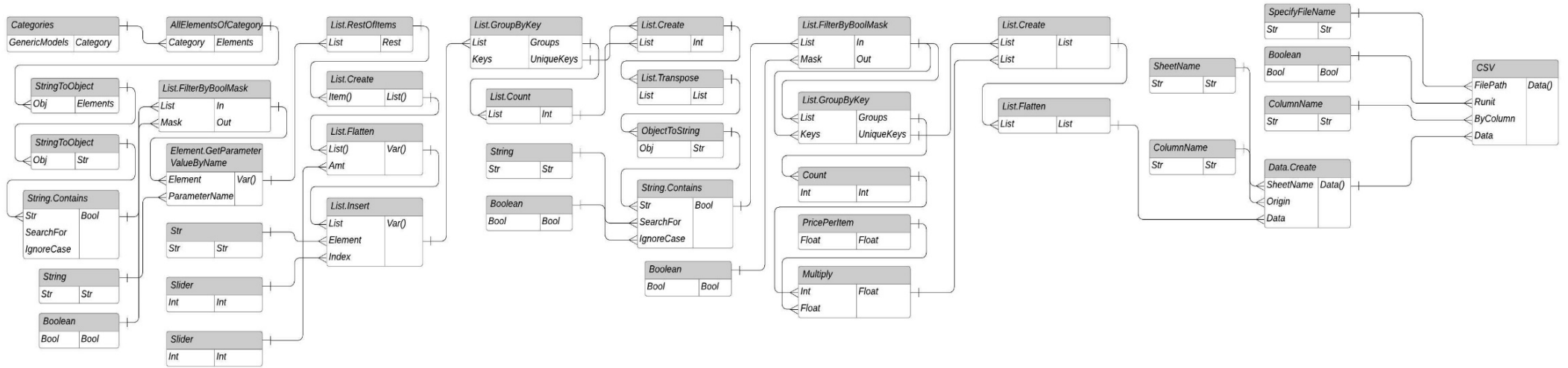


Figure 10 - Google Sheets accessed from IOS

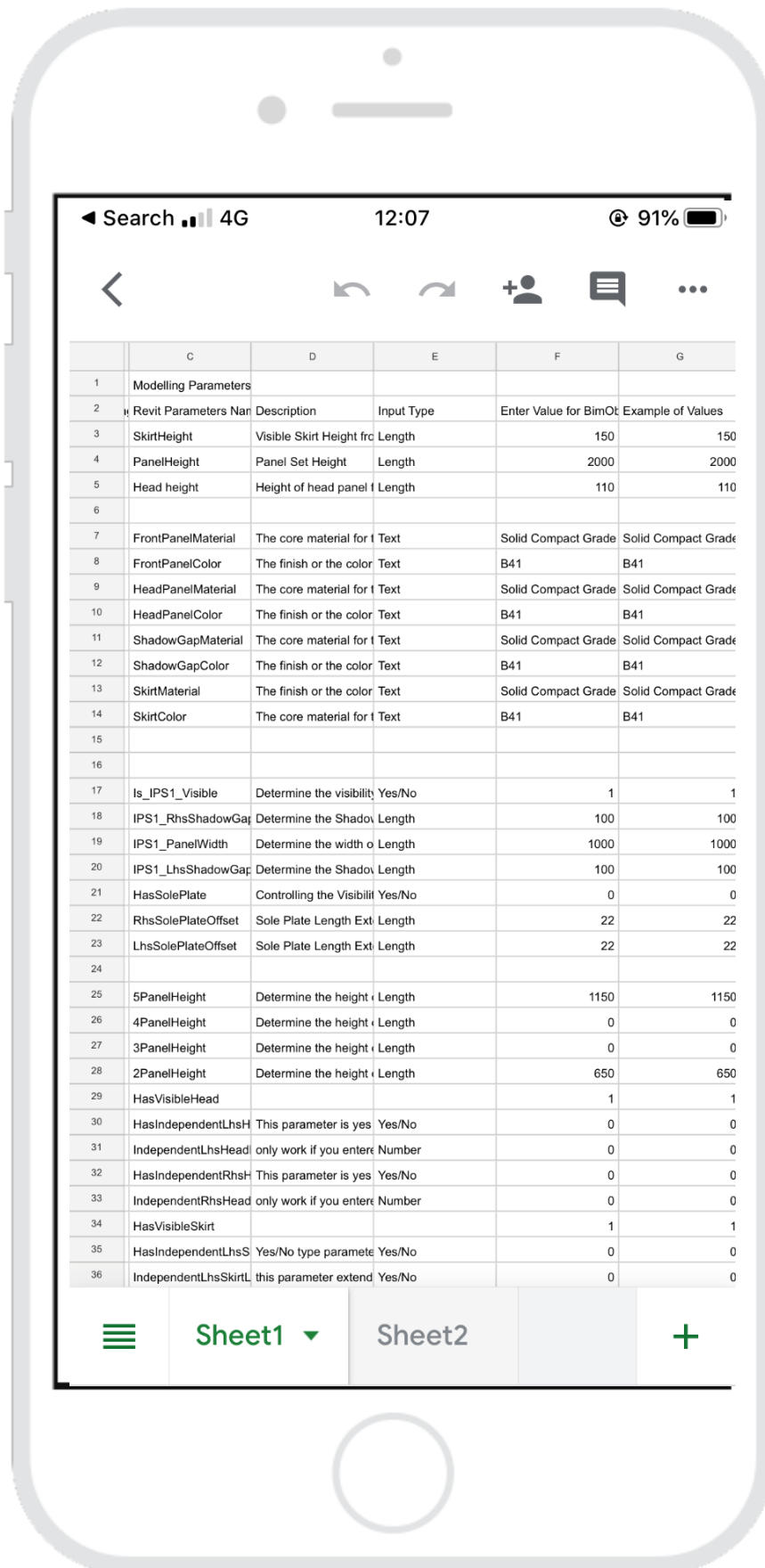


Figure 11- SQLite viewer via IOS device

Description	Quantity	£Price
x 2000	1.000000	227.800000
x 700	2.000000	204.000000
7m x 500mm	1.000000	56.100000
7m x 100mm	1.000000	16.150000
7m x 300mm	1.000000	38.250000
.13	2.000000	67.960000
.13L	2.000000	34.480000
/A150	3.000000	51.180000
per cubicle	1.000000	15.000000
	2.000000	9.600000
_A13	2.000000	4.560000
n wall pack (3/pk)	4.000000	26.480000

Filter 12 records LIMIT 1000

Figure 12 - Code Snippet for Using Mobile Text Notifications

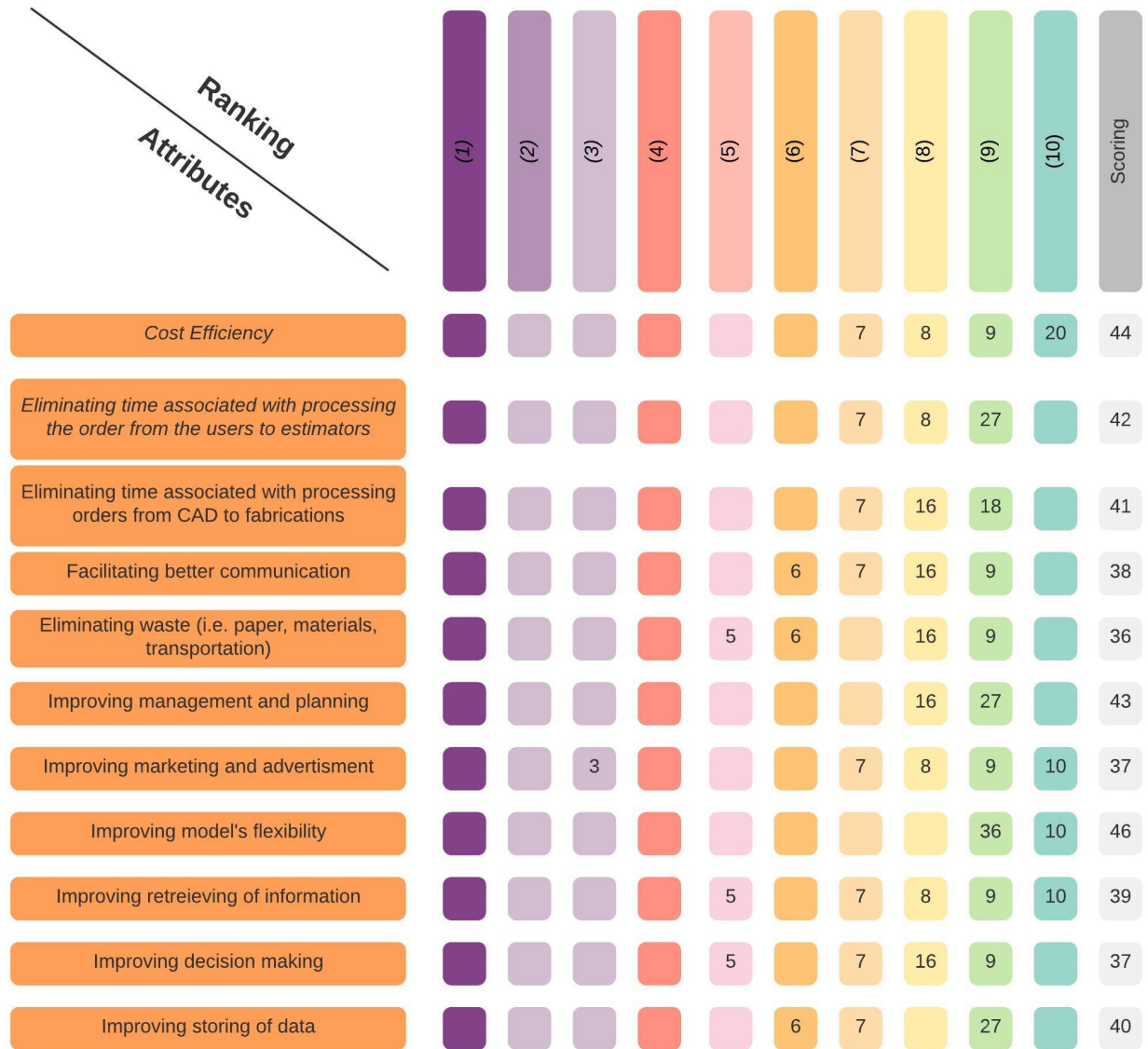


Table 1 - Most Prominent Authors in Literature

Ranking of authors based on their total citations	<u>Histcite classification number</u>	Author	Focus of the study	LCS	GCS
1	3	(Zhou et al., 2016)	Big data analytics and its impact on cost in buildings	2%	7%
2	17	(Kassem et al., 2015)	BIM and information management for FM, case study	5%	5%
3	35	(McArthur, 2015)	Data processing and management for asset management	3%	3%
4	45	(Ding et al., 2015)	Knowledge sharing and collaboration	3%	3%
5	65	(Isikdag, 2015)	Internet of things and BIM	2%	1%
6	70	(J et al., 2015)	Data processing and management for asset management	2%	2%
7	71	(Jiang et al., 2015)	Query retrieval and ontologies	2%	1%
8	84	(Chi et al., 2015)	Use of sensors and tracking to reduce the waste in fabrications process	3%	2%
9	85	(Malsane et al., 2015)	Task automation	4%	2%
10	86	(Wang et al., 2015)	Waste management	3%	4%
11	87	(Jun et al., 2015)	Task automation	2%	1%
12	90	(Korpela et al., 2015)	Data management and processing for asset management	2%	2%
13	92	(Lee, Oh, et al., 2015)	Warning for BIM, code checking, validations	2%	1%
14	94	(Borrmann et al., 2015)	Task automation through optimising semantic and geometric data	4%	5%
15	97	(Karan and Irizarry, 2015)	Task automation	5%	5%
16	104	(Oh et al., 2015)	Code checking and validations	4%	3%
17	105	(Wong and Zhou, 2015)	Cost improvements through intelligent buildings and automation	6%	11%
18	107	(Costa and Madrazo, 2015)	Query retrieval and ontologies	2%	2%
19	108	(Kensek, 2015)	Environmental sensors integrated with buildings	2%	2%

			through dynamo and scripting BIM		
20	114	(Lee, Eastman, et al., 2015)	Query retrieval and semantic ontologies	4%	2%
21	115	(Oh et al., 2015)	Knowledge sharing and collaboration	3%	3%
22	119	(Kumar and Cheng, 2015)	Task automation through optimising semantic and geometric data	3%	5%
23	123	(Wetzel and Thabet, 2015)	Query retrieval and ontologies	3%	4%
24	126	(Lee, Tae, et al., 2015)	Task automation through optimising semantic and geometric data	2%	3%
25	220	(Belsky et al., 2016)	Semantic ontologies and interop ability	5%	3%
26	229	(Lee et al., 2016)	Code checking and validations	3%	2%
27	233	(Kim et al., 2016)	Query retrieval and semantic ontologies	5%	2%
28	243	(Oesterreich and Teuteberg, 2016)	Industry 4.0 and automation	3%	7%
29	293	(Pärn and Edwards, 2017b)	Task automation	3%	2%
30	295	(Ghaffarianhoseini et al., 2017)	Waste management	3%	4%

Table 2 - Evaluation of BIM Packages

Factors Evaluated	BIM Packages					
	Revit	Sketchup	Microstatio	ArchiCad	Rhinoceros	Vectorwork
Usability	7	9	8	8	4	9
Integration with BIM hosting cloud services (NBS, BIMobject, Bimstore)	9	7	8	9	6	6
Exportability & integration with various BIM software in the market	8	6	7	7	6	6
Market share	9	6	4	7	5	6
Parametric design capabilities	8	5	6	7	6	6
Scripting, API support, integration with multiple programming languages	9	7	7		9	8
Scheduling & drafting capabilities	7	7	7	6	5	7
Support network & multiple users	8	4	5	8	5	6
Virtual reality support	10	10	10	10	8	9
Augmented reality support	10	10	10	10	8	9
Parametric function capabilities	9	5	9	9	7	7
Friendly user interface	8	10	9	9	6	9
Ease of access and retrieval to commands	8	10	8	9	6	9
Support model's query	8	4	6	9	9	7
Linked with cost data	6	3	6	5	4	5
Clash detection	8	4	8	8	6	8

support						
Photorealistic rendering support	10	10	10	10	8	10
Various printing formats support	9	9	9	9	9	9
Size of files	6	8	8	6	7	7
Database integration support	9	6	9	8	6	7
Price & subscription cost	5	6	6	7	7	7
Project planning tools support	8	4	8	7	5	7
Import of various file formats	8	8	8	8	7	7
Education and tutorial accessibility	10	9	8	8	7	7
Cloud viewing support	10	10	8	8	6	8
Managing IFC BIM files	6	7	6	6	4	6
Total	213	184	198	198	166	192

Appendix 1 (Panelling manufacturing procedures for IPS, Toilet Cubicles and Vanity Unit)



Appendix 2 (Exporting BDO data to SQL database)

Enable Python support and load DesignScript library

```
import clr
clr.AddReference('ProtoGeometry')
from Autodesk.DesignScript.Geometry import *
# The inputs to this node will be stored as a list in the IN variables.
lst1=IN[0]
lst2=IN[1]
lst3=IN[2]
lst4=IN[3]
lst5=IN[4]
lst6=IN[5]
import sys
sys.path.append('C:\\Program Files (x86)\\IronPython 2.7\\Lib')
sys.path.append('C:\\Program Files (x86)\\IronPython 2.7\\DLLs')
clr.AddReference("IronPython.SQLite.dll")
import sqlite3
conn=sqlite3.connect('C:\\Users\\YahyaAS\\Documents\\database_files\\{}'.format(lst6))
c=conn.cursor()
c.execute('CREATE TABLE IF NOT EXISTS {} (id TEXT, name TEXT, description TEXT,item
TEXT)'.format(lst5))
#cursor.execute('CREATE TABLE names (id INTEGER PRIMARY KEY, name TEXT)')
for i in range(len(lst1)):
    c.execute('INSERT INTO {} VALUES(?, ?, ?, ?)'.format(lst5), (lst1[i],lst2[i],lst3[i],lst4[i]))
#connection.commit()
# Place your code below this line
# Assign your output to the OUT variable.
conn.commit()
OUT = lst6
```

APPENDIX 3 (Mobile notification for the user)

```
# Enable Python support and load DesignScript library
import clr
clr. AddReference('ProtoGeometry')
from Autodesk.DesignScript.Geometry import *
# The inputs to this node will be stored as a list in the IN variables.
lst1= IN[0]
# Place your code below this line
import sys
sys.path. Add('C:\\Program Files (x86)\\IronPython 2.7\\Lib')
from System.Diagnostics import Process

path = r"C:\ProgramData\Anaconda3\Lib\site-packages"
myfile = "Text_sms.py"
command = "%s\\%s"% (path,myfile)
proc = Process()
proc.StartInfo.FileName = command
proc. Start()
proc. Wait()

# Assign your output to the OUT variable.
OUT =lst1

#from Text_sms.py file
from twilio.rest import Client

# Your Account Sid and Auth Token from twilio.com/console
account_sid = '#####'
auth_token = '#####'
client = Client(account_sid, auth_token)

message = client.messages \
    .create(
        body="this an automated SMS to notify you {} with current changes on {}
api".format("a","b"),
        from_='+44#####',
        to='+44#####'
    )
print(message.sid)
```

Appendix 4 (Email notification for the user)

```
# Enable Python support and load DesignScript library
import clr
clr.          ('ProtoGeometry')
from Autodesk.DesignScript.Geometry import *
# The inputs to this node will be stored as a list in the IN variables.
dataEnteringNode = IN
# Place your code below this line
clr.          ("Microsoft.Office.Interop.Outlook")
from System.Runtime.InteropServices import Marshal

mail= Marshal.          ("Outlook.Application").          (0)
mail.Recipients.      ("userxxxxxxx@gmail.com")
mail.Subject = "Cost Sheet for IPS_Mariner_875345"
mail.Body ="this is an autmoated email to inform you that the cost sheet for IPS_Mariner_875345 is
ready to be viewed"
mail.      ();
# Assign your output to the OUT variable.
OUT = 0
```