A CONCEPTUAL FRAMEWORK FOR UTILISING BIM DIGITAL OBJECTS (BDO) IN MANUFACTURING DESIGN AND PRODUCTION: A CASE STUDY

ABSTRACT

Purpose: Construction manufacturers predominantly rely upon antiquated manual design and production processes and procedures because they lack technical skills needed to automate working practices. This paper seeks to automate manufacturing processes by optimising the utilisation of BIM Digital Objects (BDO) via the development of a conceptual model. Concomitant objectives seek to: reduce design errors; eliminate unnecessary costs; automate the generation of quantity bills; and maximise productivity performance.

Design/methodology/approach: An inductive approach was adopted through a post positivist epistemological lens set within the context of a case study of a small-to-medium enterprise (SME). From an operational perspective, both qualitative and quantitative data was collected and analysed via a novel four phase waterfall design viz: i) literature diagnosis; ii) recording contemporary practice; iii) mapping manufacturing workflow and procedures; iiii) evaluation and proof of concept development.

Findings: The work illustrates that BDO enhances manufacturing workflow, reduces product manufacturing lead time and augments quality assurance throughout the whole life cycle of a manufactured product. The conceptual model developed provides a pragmatic and comprehensive solution to automate construction manufacturing procedures and improve the facilitation of information exchanged between all stakeholders involved.

Originality/value: This study presents the first comprehensive case study of BDO application within a manufacturing context. Future research is however, needed to test and validate the conceptual model presented in practice. In doing so, the model can be further refined using practitioner input and real-life manufacturing processes and procedures.

KEYWORDS

BIM, construction supply chain, BIM objects, conceptual framework, information management

INTRODUCTION

"Computers have lots of memory but no imagination (Anon)."

The architectural, engineering, construction and operations (AECO) sector has steadily shifted towards adopting disruptive digital technologies throughout its entire supply chain (from building component manufacture through to the building's facilities management team) (Caneparo *et al.,* 2014). Throughout this transition, building information modelling (BIM) has resided at the vanguard of advancements made (Alvarez-Anton *et al.,* 2016; Herr and Fischer, 2018; Succar and Kassem, 2015). In the UK, the government has mandated the implementation of BIM level 2 for all public funded contracts thus requiring architects, contractors, supply chain manufacturers to work on individual 3D models to generate a unified or federated BIM model (HM Government, 2013); where this federated model facilitates the exchange of geometric and semantic data among construction project stakeholders (HM Government, 2013). An associated objective being to ease the processing of data and establish intelligent relationships between product components and their functionalities (Eastman *et al.,* 2011; Reddy, 2012).

Within the manufacturing sector of the AECO supply chain, early adopters of innovation actively seek to synergise their manufacturing production processes with architects and construction practitioners by seamlessly integrating their products into BIM digital objects (BDO) (Alwisy *et al.,* 2018). This enables manufacturers to supply a comprehensive package of rich semantic and geometric information directly to their customers thus: augmenting user satisfaction (Joblot *et al.,* 2017); improving productivity (Park and Lee, 2017); enhancing accuracy (Garagnani and Manferdini, 2013); providing real time feedback and analysis (*ibid*); and minimising human prone errors (Gigante-Barrera *et al.,* 2017). Reddy (2012) proffers that using manufacturer's BDO will increase product sales and the likelihood product specification by designers (i.e. architects) and future clients (Reddy, 2012). However, the exchange of information between the supply chain manufacturers and architects has hitherto proven both problematic and costly. This is because additional cost is incurred by not using an engineering-to-order strategy which enables manufacturers to customise the product in response to customer needs vis-à-vis producing an 'off-the-shelf' product with fixed dimensions (Ghaffarianhoseini *et al.,* 2017; Vass and Gustavsson, 2017). The technological capacity of supply chain partners (often small-to-medium enterprises (SMEs)) also represents a major issue because they lack core skills and competencies needed to participate within a multi-collaborative digital design process (Wang *et al.,* 2017). For example, creation of parametric BDO content is often prevented by a lack of relevant software skills (Ghaffarianhoseini *et al.,* 2017). Consequently, manufacturers create superficial BDOs that lack sufficient graphical and non-graphical data in order avoid BIM wash - namely a phenomena where SME manufacturers deceptively claim to use BIM services to garner new business (cf. Holzer, 2016) without understanding the full functionality of these services nor how such can benefit the client or the project (Eastman 2011).

In a supply chain manufacturing context, the use of BDOs range from fixed to dynamic BDO design (Tadeuz and Maruf, 2016). Holzer (2016) classified fixed BDO approaches without parametric features into two dichotomous groups, namely: i) made-to-stock (MTS) manufactured products that are already in stock and ready to purchase; and ii) made-to-order (MTO) products that can be ordered from the manufacturer's catalogue. These classifications restrict customer choice when selecting standardised and fixed items from the products catalogue provided by manufacturers (*ibid*). Conversely, engineered-to-order (ETO) provides an opportunity to facilitate product customisations through parametric changes via BDO implementation (Holzer, 2016; NBS, 2018). BDOs engender bi-directional relationships of cooperation between customers and manufacturers through the use of shared information and workflow (Mirarchi *et al.,* 2017). From the architect's and the general contractor's perspective, a customised ETO facilitates changes and modifications to the BDO prior to ordering building components during the design and construction phases (so called 'upstream' supply chain activities). From the manufacturer's perspective using ETO accommodates bespoke client changes during the manufacturing design, production and construction phases (so called 'downstream' supply chain activities). Failure to streamline the design process within up- and downstream activities, leads to project delays, cost overruns, design errors and re-work (Eastman *et al.,* 2011).

Given this prevailing contextual setting, this case study investigates how BDO utilisation can optimise the dialogue between manufacturers and customers (i.e. contractors and architects). Concomitant research objectives are to: i) identify current trends of using BDOs in the literature; ii) define and delineate issues that hinder the use of BDO by SME manufacturers; and iii) develop a conceptual 'proof of concept' framework for maximising BDO usage to enable the development of ETO that incorporates both parametric and customised features. This latter process will include extracting semantic data and information from architectural designs to input into manufacturing planning processes and computer numerical control (CNC) machinery.

RESEARCH METHODOLOGY

An inductive methodological approach was adopted that sought to report upon current processes and procedures utilised for integrating digital design into manufacturing (Imenda, 2014). Within this overarching design, elements of interpretivism and the metatheoretical stance post positivism (Fox, 2008) were applied (Edirisingha, 2012). The interpretivist stance was used to examine and interpret extant literature but also identify similar or related studies that could inform the ensuing direction of study (Ritchie *et al.,* 2014). From this body of knowledge (BoK) accrued, the post positivist critical realist stance adopted then questions any theories or observations uncovered. For the case study, a small-to-medium sized (SME) manufacturing company (entitled Excelsior Panelling Systems Ltd – herein thereafter simply referred to as Excelsior) provided the case study setting and units of analysis (Yin, 2009). Units of analysis constituted members of the senior management team, including the: Managing Director, Commercial Director, Contracts Manager and Operations Director. Excelsior design, manufacture, supply and install bespoke and/or modular washroom products (such as toilet cubicles, vanity units and integrated panelling systems) for a wide range of industrial premises, including new building construction and retrofit or refurbishment building projects. The company has a turnover of £6 million per annum, currently employs 53 staff and is located in the Black Country region at the heart of the West Midlands industrial conurbation, UK. The lead researcher was employed by the company as part of a Knowledge Transfer Partnership (KTP) agreement (GOV, 2018). The first stages of participant action research (PAR) were implemented to develop conceptual models of contemporary manufacturing processes and procedures, and specify future implementation of BDO and ETO within this typical SME organisation that is embedded within the construction supply chain (Garst *et al.,* 2012; Phillips *et al.,* 2010; Siew *et al.,* 2013).

Research Methods and Data Collection Techniques

Both qualitative and quantitative data sources were utilised within a four-phase ‘waterfall’ operational programme of research (Balaji *et al.,* 2011) – *viz*:

- *Phase one – literature diagnosis*: the software VOSViewer was utilised to conduct an interpretivist and qualitative bibliometric analysis of extant literature (Jan *et al*., 2017) to identify pertinent theories and previous research conducted regarding to BDO.

- *Phase two – recording contemporary practice:* a 'snap-shot' of current business operations was conducted using secondary data (such as: quality procedures, non-conformance reports (NCRs) and pertinent computer-aided design (CAD) drawings and standards) to map prevailing system procedures; report upon how different departments within the business operate; and identify issues regarding BIM implementation within the design and manufacturing process.
- *Phase three – mapping manufacturing workflow and procedures*: a process map was developed to record Excelsior's production workflow within downstream and up-stream activities. Primary qualitative data was collected through focus group discussion held to elucidate upon prevailing practices and generate ideas for revising and optimising these. The focus group method was chosen because it provides an environment to discuss ideas, perceptions and concepts (Krueger and Casey, 2000). The focus group consisted of key managers and decision makers within the company *viz*: CAD Team Leader (CL); two CAD Technicians ($CADT_1$, $CADT_2$); Production Manager (PM); Operational Director (OD); Inventory Manager (IM); CNC Technician (CNCT); Two Project Managers (PM_1, PM_2); Contract Manager (CM); and Estimation Manager (EM).
- *Phase Four – evaluation and proof of concept development:* a conceptual framework (as a 'proof of concept') was developed and subsequently evaluated through a second focus group discussion. The participants' feedback helped to shape the conceptual model and report upon the lessons learnt from the findings.

Phase One - Literature Diagnosis

The bibliometric analysis utilised the Scopus database to search for pertinent BIM-related keywords search terms *viz*: *'BIM' and 'Manufacturing'; 'BIM' and 'IFC'; 'BIM Object'; 'BIM' and 'Engineer-To-Order'*. These keywords were identified from an initial manual literature review to contextualise this study's boundaries. Sample literature was confined to peer-review journal and conference papers written in the English language and published within the last four years between (2014-2018) to capture the 'latest' *vis-à-vis* 'historical' developments in a rapidly developing area of construction and computer science. Preliminary results retrieved consisted of 603 publications that included a wide diversity of research conducted - much of which were superfluous to the specific area under investigation

Consequently, a filtering process was employed to refine and focus publications onto BDO within the context of manufacturing - this reduced the sample size to 137 publication results (refer to Figure 1).

<Insert Figure about 1 here >

These filtered results were then analysed in depth using VOSviewer via several analysis techniques adopted, namely: i) bibliographic coupling with documents as a unit of analysis – where the relatedness of studies is determined by how many times these studies cited each other; and ii) text data analysis with co-occurrence of text in title and abstract. The bibliographic coupling analysis created by VOSviewer relies on grouping studies together once these studies have a common third reference in their bibliographies. VOSviewer visualised most cited studies at the centre of the map, where the nodes scattering is based on their closeness in citation to each other. The visualised font and circle sizes are correlated with the frequency of paper citations (Jan *et al.,* 2017). Bibliographic coupling analysis was deemed as a suitable approach to explore the most promulgated trending studies within this chosen field because it helped to identify the most influential studies by visualising them with bigger circle size compared to less frequently cited studies (Dawson and Gašević, 2014).

To provide a holistic understanding of the trending topics within literature, text data analysis was chosen as the method to identify reoccurring key words discussed in titles and abstracts (refer to Figure 2). The analysis known as 'co-occurrences in the network' and the 'binary method' was selected to filter the key words appearing at a minimum of 10 occurrences while a 60% threshold was configured by VOSviewer for terms with highest relevance, as recommended for software users (cf. Jan *et al.,* 2017). All of the selected studies were subsequently reviewed individually in an in-depth manner to identify reoccurring leitmotifs to aid conceptualisation of the BDO framework.

<Insert Figure 2 about here>

Interpretation of the Literature

To interpret the literature, colour coding from VOSviewer was used as an *aide memoire* for the BDO framework. A total of 40 keywords were identified, which were grouped by VOSviewer into three clusters displayed as *red, green* and *blue* nodes and connectors. Figure

2 illustrates that downstream manufacturing activity related terms were thematically grouped in *green* key words such as *'BIM technology', 'limitation', 'error', 'quality'* accumulated the lowest text-occurrences based on their small node circles and font sizes. The analysis illustrates that such downstream terms are currently discussed but with less emphasis in the literature. Interestingly, upstream cluster terms displayed keywords such as *'problem', 'understanding'* and *'lack'* which accentuate the current issues commonly expressed by architects when interpreting and using BIM objects supplied from supply chain manufacturers. Keywords deemed to be optimisation activities were visualised as a red cluster included: *'automation', '3d object', 'real time', 'gap', 'value', 'relation', 'automation'* and *'workflow*'. These keywords showed the lowest text-occurrence counts compared to their counterparts from the same category such as '*algorithm', 'planning'* and *'information modelling'.* The aforementioned cluster analysis substantiates the need to develop a proprietary workflow or a conceptual framework to bridge the gap between the upstream and downstream manufacturing activities with BDOs.

In order to develop the conceptual framework, all 137 identified papers were manually reviewed in detail. This was because VOSviewer's clustering method used in bibliographic analysis that is based upon grouping a minimum of two studies under one cluster if they have been cited by a third study. Hence, the VOSviewer approach lacks the ability to identify studies that focus on the same subject. Therefore, whilst VOSviewer's clustering method was useful to visualise the extant literature 'at a glance', it failed to adequately quantify the studies in their corresponding clusters. Therefore, further manual analysis sought to re-group the studies and categorise them in their appropriate cluster based on their purpose of study (refer to Table 1).

<Insert Table 1 about here>

The majority of thematic clusters discussed in Table 1 have focussed on upstream activities. Only a relatively small fraction of these studies discussed downstream activities such as: '*3D printing and additive manufacturing', 'fabrication'* and *'mixed realities'*. Furthermore, the thematic groups were fragmented and consequently, lacked a comprehensive framework in the literature to connect these core clusters together for manufacturing. The findings from the bibliometric analysis provide a theoretical basis for the ensuing case study analysis.

Phase two – Recording Issues Occurring in Contemporary Practice

It was important to factually record re-occurring issues facing Excelsior so that the problem domain was clearly defined and delineated (as a first step towards developing a robust solution). A manual review of Excelsior's quality management documentation (particularly non-conformance reports (NCRs)) was used a viable secondary data source to identify issues occurring. The NCRs articulate problems commonly occurring during business (such as errors or omissions recorded during sales and client interface) and manufacturing operations. Hence, NCRs, CAD drawings and job records were chosen as key information sources needed to develop a causality map and assess current workflows adopted in the business. Current issues arising were then manually classified (following consultation with Excelsior Directors and senior staff) under their associated groups to create a logical workflow of activities, namely:

- *Estimation*: inaccurate quotation and estimation;
- *CAD*: errors in drawings; wrong colour assigned to the manufacturing; inconsistent drawings; inaccurate specification assigned to products for production;
- *Production*: wrong cutting of components; damaged item(s) during production; lack of quality check; mismatch of materials with CAD drawings; wrong materials assigned to products;
- *Transportation*: delay(s) in transportation; items damaged during loading; missed items from delivery; and
- *Installations*: fitting delays; items installed in the wrong location; damaged items; items lost on site and during installation.

Phase three – Mapping Manufacturing Workflow and Procedures:

The third phase encompassed the development of a combined stakeholder and process map to capture ongoing business procedures, technical systems and file exchange formats used throughout the manufacturing process. However, prior to this development a theoretical two axis stakeholder matrix was created (again using informal discussions with Directors and other senior staff) and sought to determine the placement of stakeholders within the business where: the *x*-axis represents the level of interest of stakeholders and the *y*-axis represents the stakeholders' level of power (Mendelow, 1981) – refer to Figure 3. This stakeholder matrix was quintessentially important to help identify relevant participants for the ensuing focus group discussions.

<Insert Figure 3 about here>

A process map was then developed by the lead researcher and validated through a focus group discussion (where the latter consisted of the: Contract Manager (CM); Operational director OD; Estimating Manager (EM); Inventory Manager (IM); CAD Team Leader (CL); CAD Technicians (CADT1,CADT2); Project Manager (PM_1, PM_2); CNC Technician (CNCT) and Production Manager (PM). Validation was conducted by reaching consensus on the diagram visualisation from the focus group. After validating the process map, the group participants were asked to provide feedback on the current manufacturing processes and procedures adopted. An information delivery manual (IDM) was chosen as a method to identify and record discrete processes (as well as product attributes, entities and components) that are undertaken as part of Excelsior's manufacturing 'workflow' processes (e.g. design and production). IDM is typically used by software developers to solve interoperability issues associated with open BIM standards/ industry foundation classes (IFC) but can only be used in the context described here (Buildingsmart, 2007). New knowledge generated from the IDM mapping sought to identify information requirements for the upstream and downstream manufacturing activities. Multiple scenarios (e.g. product cancellation, product approval subject to revision, product approval without revised comments) were considered to ensure that the IDM workflow diagram represented real business scenarios for Excelsior. The IDM incorporated visual 'pool lanes' that represented actors or stakeholders involved in different stages of a project lifecycle (refer to Figure 4). Upon finalisation of the IDM process map diagram, focus group members were asked to describe current issues they most identified with from the workflow of existing company procedures. The ensuing discourse was transcribed and summarised in Table 2.

<Insert Figure 4 and Table 2 about here>

To identify exiting problems within the IDM workflow, information exchange requirements (IER - which represents the type of data exchange between stakeholders) were analysed using the functional parts method as recommended by Buildingsmart (2007). The functional parts represents the detailed information or components that are enclosed in the information requirements swim lanes within the IDM workflow (*ibid*). As such, the functional parts approach describes the technical specifications of a product's manufacturing elements that are part of a single or multiple unit(s) of IER. Functional parts therefore describe detailed technical characteristics of the information exchanged between stakeholders (e.g. colour, finish, height), whereas the swim lane (designated for the IER in an IDM's workflow) describe the non-technical design specifications such as cad files, bills of quantities, quotations and orders. Cumulatively, the functional parts assessment and the IDM workflow map capture a snapshot of current company procedures. For example, a sample of the functional parts assessed for a vanity unit bill of quantities will consist of: *name of the product range; identified manufactured element/component; material; finish; width; height; depth; quantity; and comments.* At present, most of the information within the existing workflow is manually entered and frequently subject to human acts, errors or omissions (via information loss or work duplication) (refer to Table 2). Hence, there is a need to automate these procedures to mitigate erroneous human intervention within the manufacturer's current workflow processes.

Phase Four – Evaluation and Proof of Concept Development

Phase four focused on the evaluation and development of a proof of concept model for utilising BDO by construction manufacturers; where the model evaluation was achieved through a focus group discussion with supply chain participants. The findings from VOSviewer's analysis helped to direct suitable open-ended discussions with focus group members and elicit their views and opinions on potential solutions to issues observed/ reported upon. The conceptual model was visualised using a unified modelling language (UML) to depict relationships between identified concepts in the conceptual model (Gomaa, 2011) - refer to Figure 5. To fully understand the conceptual model, it was important to break down the model into iterative steps, viz:

<Insert Figure 5 about here>

- *Order*: an order will be requested from the manufacturer with a list of attributes that define the requirements for delivering the asset/product throughout its whole lifecycle.
- *Interoperability*: IER will be defined internally within the manufacturer's departments and externally with various actors (such as the architect and the client). This activity must

establish the file extension, the parties using the file and the purpose of use e.g. extracting 2D drawings and bill of quantities for production.

- *Model Parameters*: BDO parameters (i.e. length, width, height, material colour) will be prepared in the BIM authoring software. The use of BDO parameters should eliminate any misconceptions associated with using CAD drawings as the model has the same dimensions in all views.
- *Topology Identification*: algorithms will be developed and designed to enhance user experience in buildings by providing greater accessibility to products' location and specification via the BDO.
- *Radio Frequency Identification (RFID) Tags*: bar codes will be created using algorithms for each BDO's component. The bar codes should be attached to the BDO during the whole downstream activity (production and installations) to enable the real time tracking of components and ultimately, enhance the quality of manufactured products.
- *Costing 5D*: a cost database will be developed and integrated within BDOs using algorithms. This database includes multiple scenarios of BDO configurations and material specifications. Once the database is linked with the BDO, the client/architect can configure the model dimensions and access the calculated cost instantaneously. This significantly reduces both time and resources utilised to estimate the cost of BDOs.
- *Security*: a special authorisation code will be generated for sensitive BDO parameters which require certain authorised users to access them. For example, security measures such as door accessibility or CCTV operation.
- *Model verification*: BDOs will be checked against certain criteria prior to production. For example, automating check-up routines through using algorithms and programming scripts. These can be employed in the BDO via applications programming interfaces (APIs) and plugins.
- *Fabrications*: BDO parameters will be translated into CNC machining language such as G-code. The BDO components associated with CNC activities can therefore be exported from BIM software as a text readable file to the CNC. This eliminates unnecessary errors that occur during the exporting of CAD drawings in Drawing eXchange Format (DXF) files to the objects that can be further processed by CNC software such as WoodWop (Hamid *et al.,* 2018).
- *Augmented Reality (AR)*: Augmented reality will be used to develop BDOs for fabrication to assist labour visualise the product during factory assembly in the production stages.

- Delivery: RFID tagging procedures (developed for BDO) will be applied during product delivery to ensure safe and complete handover on site using bespoke mobile scanners or mobile phone applications.
- *Scheduling 4D*: photogrammetry and CCTV recording assigned on site will be used to check the progress of the scheduling live. This system will be linked with a real time platform to facilitate collaboration and decision making between stakeholders.
- *Product Checking*: products will be checked during various life cycle stages. For example, different RFID tags will be attached to the manufacturing assembly to enable its tracking and checking upon completion of each stage of manufacturing and installation.
- *Scan to BIM*: hand held laser scanners will be used to update the BDO to capture any design changes. Such an approach is useful when the cost of re-modelling the object is expensive or complex.
- *Virtual Reality (VR)*: scanning the product's BAR codes will facilitate VR access to non-graphical information (e.g. Construction Operations Building Information Exchange (COBie) and maintenance and operation (O&M) manuals) via mobile device applications. Accessing products information virtually enables facility mangers and building owners to update asset information during its whole lifecycle.

CONCEPTUAL FRAMEWORK VALIDATION

The proposed BDO conceptual framework was validated by arranging a focus group discussion with experts from Excelsior (consisting of: CM; PM; PM_1; PM_2; CL). The UML diagram was converted to a user-friendly diagram, for ease of readability and interpretation by focus group participants (refer to Figure 6). Additionally, the issues identified from phase two were tabulated and presented to the group to demonstrate their current position the current workflow against potential proposed solutions. Participants verbally validated the conceptual model and provided their feedback on how these solutions could be incorporated to enhance the use of BDO within the construction manufacturer supply chain. Extracts from this discourse complement the ensuing narrative.

<Insert Figure 6 about here>

Autonomous Function

Automation will be used to enable the self-detection of BDO within its BIM environment, so it can interact with other BDOs in the project in a smart and efficient manner. Common consensus was reached by the focus group to embed the autonomous function for BDOs to mitigate errors caused by design clashes. The CL said:

> *"Obviously we position our items within the rooms. If this column or anything else is in the way, you know, we have to design around it…. the smart objects need to have that functionality to be able to identify any potential clashes in the project."*

A CM echoed similar views:

> *"You also have product ranges that we do - you know that you easily identify clashes with other smart objects as in with the M&E [mechanical and engineering] contractor….so it would identify the fact that they can't go there because there's something in the way of them. So, you get that early detection which is an absolute key for the success of the project."*

Value Engineering

Maximising quality and eliminating the production cost of BDOs will be established using a value engineering database that is integrated with the BIM authoring software in the form of an API plugin. Applying this solution will determine the ideal dimension and materials for the BDO so it can be utilised efficiently in the project. The focus group welcomed the use of value engineering during the design stage of manufacturing and stressed that optimised value engineering should be determined based on factors such as material and cost. The CM said:

> *"I mean you basically, at this stage, starting up with a wish list that the clients got. Such as sizes etc. and then you bring in your knowledge value engineering, you're looking at it being one."*

Cumulatively, encapsulating the knowledge engineering in BDO can potentially save huge amounts of time, maximise productivity and profit for manufacturers.

Sensors

Sensors' parameters are developed for BDOs using BIM authoring software - these parameters can control the function of sensors in BDO such as (temperature logger, cameras and accessibility). Use of sensors enables real time interaction of building users and BDOs.

According to the focus group the use of sensors in BDO products is beneficial as it solves the problem of identifying early product defect(s). These can be can be controlled by certain factors such as the humidity level – the PM_1 said:

> *"Distortion of the board. You know, when you are building a full-height boxed in cubicle ... You want to know what's the temperature difference between the inside and the outside face of the cubicle…it can be a way of monitoring the products."*

Model Verification

The importance of including a checkmark to indicate when the model is error free and ready for production was also emphasised. In addition, it was stressed that any revision considered by the client needs to be evaluated by value engineering and subsequently, submitted to a process of model verification to ensure all changes are checked prior to production. The PM_2 said:

> *"Well you still need to do a check ... any checks would need to be reset at that point as well. Okay, because then when you start the process again, you want everything to be unchecked again"*

The model verification as echoed by the PM_2 should incorporate checking the BDO against possible codes, regulations, requirements and customised rule sets for a particular project. Checking against these requirements can eliminate project delays and enhance the product's quality.

Topology

The focus group envisaged using topology functionality for the benefit of end users and/or architects, including checking the design aspect in the final project design. For instance, planning authorities might impose certain rules that dictate spatial orientation of functional spaces inside the project. Such may include ensuring that the location of toilets is within short proximity to food serving zones or commercial zones. Therefore, this function can be utilised to help architects determine the BDO proximity to other zones or spaces within the project. The CL envisaged another example where accessibility is determined through the topology function viz:

"The architects for example can question why would they put the disabled toilet at this one end of the building when the lifts are down the other end of the building? So that's a good function from an outside perspective on using the smart model of ours."

Fabrications

Focus group participants agreed that any replications associated with processing the information from CAD to fabrication could be reduced by translating BIM data into production processes. In essence, the BDO can translate and relay its data to CNC machines. Furthermore, all processes associated with production of the BDO should be embedded within the model (e.g. post-forming or painting of the material to eliminate the production manager from manually identifying these processes for every product). The PM_2 said:

"Every component of that model will be exported as information… this will eliminate human error and take it out from the operational process."

AR and RFID Tracking

The AR function was explained to participants and it was stressed that using such technologies could help to eliminate problems associated with quality assurance. Additionally, participants were interested in using RFID technology to ensure that products are traceable from product requests through to the production and installation stage. The PM_1 said:

"We want to track all the items from start to finish and by finished we mean installation on site."

Tracking the BDO using barcodes will eliminate all quality issues associated with missing product's items during the dispatch and installation stage.

Spatial Recognition and 4D Scheduling

The spatial positioning of BDO components are identified using Cartesian points - this might include linking the BDO with a graphical information system (GIS). Utilising this functionality enables tracking of the BDO on site. All participants agreed on the importance of using spatial recognition to aid the process of installation of manufactured products on site.

Some argued that such approach could ultimately eliminate the need for clash detection. The PM_1 said:

> *"If you are going far into a project where BIM is being used to that level - clash detection would be determined at a very early stage of the project and it shouldn't be required because all 'that' [clash detection] would have been known before you even got into the room."*

Regarding to the use of 4D scheduling, the focus group emphasised the importance of using cameras to track completion percentages of the installed products on site. The CM and PM_2 suggested that the use of CCTV (as live tracking) is inextricably linked to barcode tracking.

Utilising Virtual Reality

The implementation of VR was discussed with focus group participants and they all emphasised the importance of using it after the installation stage. Participants suggested linking VR with the products' bar codes, and for these bar codes to be placed in a discretionary location to ensure that only asset managers can scan and access them. Using VR will link the model with all the BDO's semantic information such as COBie, product life cycle and warranty date. The CM said:

> *"From an asset management point of view, it isn't critical information that we need to have out the end... They [the asset manager] want to have links. They want COBie sheets. They want to have the links to be able to know what the product is."*

RESEARCH LIMITATIONS

There are two key limitations of this research. First, this research applied an interpretivist methodology which is prone to subjectivity as it relies upon interpreting the research problem from the participants' and the researchers' lenses. Additionally, there is little known about how the conceptual framework will perform on real manufacturing projects – at this juncture, the model is based purely upon the subjective views and opinions of focus group participants. Therefore, longitudinal testing of the conceptual framework's implementation is needed to validate its result and to eliminate any subjectivity introduced via focus group discussions. Second, Vosviewer's clustering analysis is technically limited because it cannot group studies based upon their sole purpose of study. Future research should therefore seek to identify alternative bibliometric software tools that are able to address this observed weakness.

CONCLUSION

Extant literature is replete with endorsement for BIM, which is seen to expedite design and production of construction supply chain manufacturing via improved BDO data management throughout design and construction phases. The increased demand for BIM based design data management in the supply chain sector has pushed for a shift in existing processes of supply chain collaboration with BDO's and manufacturing procedures. This has specifically impacted upon the way in which suppliers and manufacturers deliver and install building products. SME's in the construction manufacturer supply chain are now faced with the task of having to adopt BIM or perish under technologically advanced competitor suppliers who have adapted to embrace innovation stipulated from clients. Importantly, BDO developed by designers and construction suppliers can greatly benefit supply chain productivity by integrating this data into upstream (i.e. design) and downstream manufacturing (i.e. manufacturing) activities. Inherent complexity of construction supply chain manufacturing procedures presents exciting opportunities for enhancing supply chain activities. Consequently, efficient utilisation of BDO's in manufacturing poses new challenges for SMEs. Three fundamental reasons are apparent. First, BIM adoption in practice is steadily increasing and hence, keeping abreast of the latest knowledge and developments presents a major challenge for SMEs. Second, SME's have had an overreliance on 2D information in their upstream and downstream manufacturing activities, which can also indicate a lack of understanding of how BDO's can improve such activities in the design and production stages. Third, data within BDOs is not fully exploited for the inherent utility for manufacturing and production, therefore the opportunity to enhance construction supply chain performance using rich BIM data is lost.

These aforementioned issues are further exacerbated, by a reluctance to adopt to new ways of working and workflow changes in manufacturing. Yet, the broad range of information embedded in BDOs points towards the potential to augment manufacturing activities and improve decision making via hybridization with other emerging technologies (i.e. RFIDs, sensors, laser scanners, and computer vision – so called 'coalescence of digital technologies'). The extant literature and focus group findings suggest the need for automation in the construction supply chain, which can be a catalyst for BDO integration into manufacturing procedures. The extant literature also revealed a paucity of discussion of downstream activities and the interrelationship with upstream activities in construction manufacturing supply chain.

This research paper forms as part of a larger longitudinal case study of applied design research Knowledge Transfer Project (KTP) with Excelsior. The outcomes of application of this conceptual model into existing manufacturing processes will be published in the second phase of this longitudinal study. Future research is however needed to further substantiate the potential benefits afforded by BDO conceptualisation using real life case-studies. Yet to date, case studies of practice-based initiatives are scant or provide only rudimentary insight into the myriad of opportunities available to the construction supply chain.

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Figure 1 - Documents coupling from VOSviewer with 137 studies after filtering the preliminary result

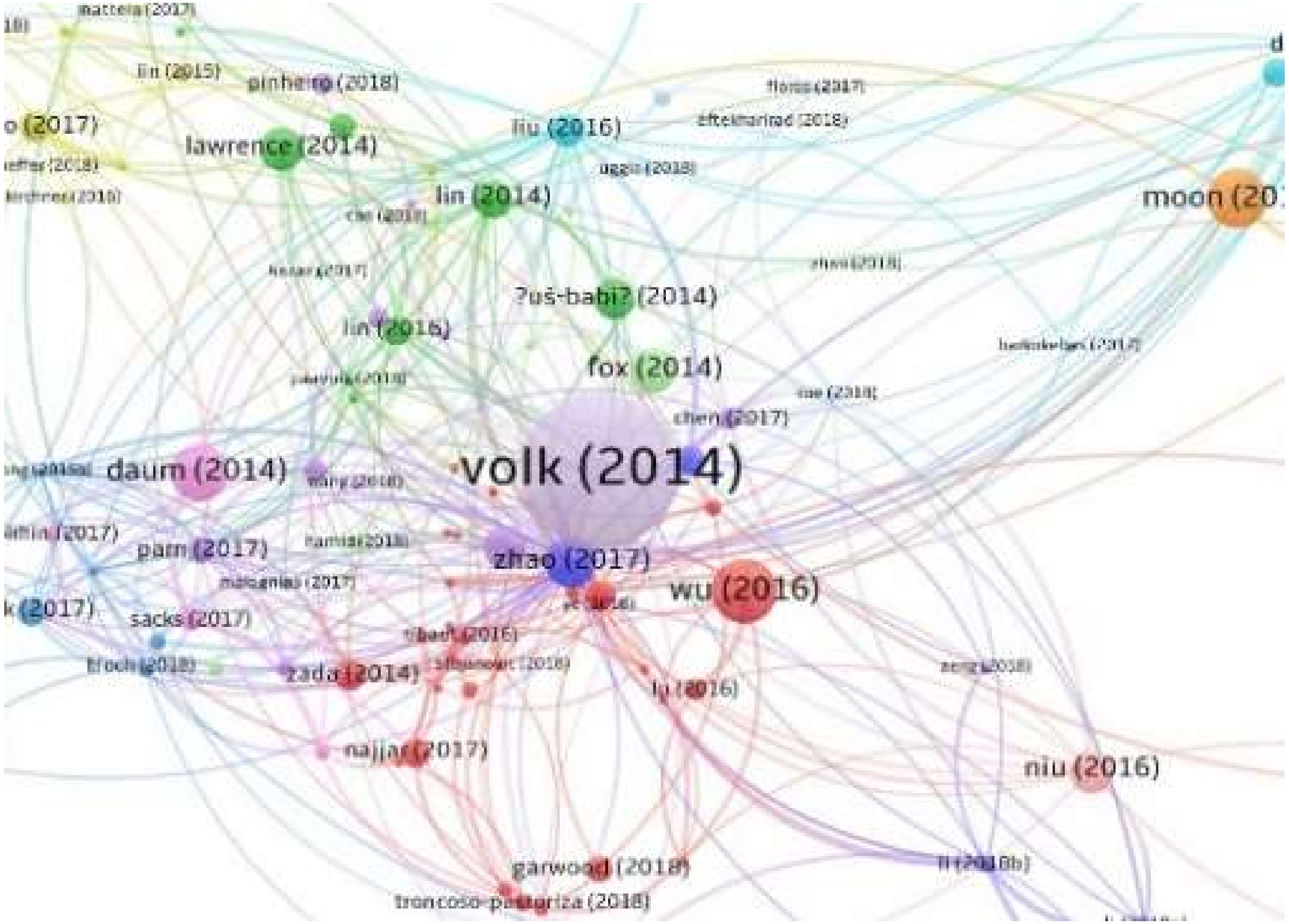

Figure 2 – Text data analysis

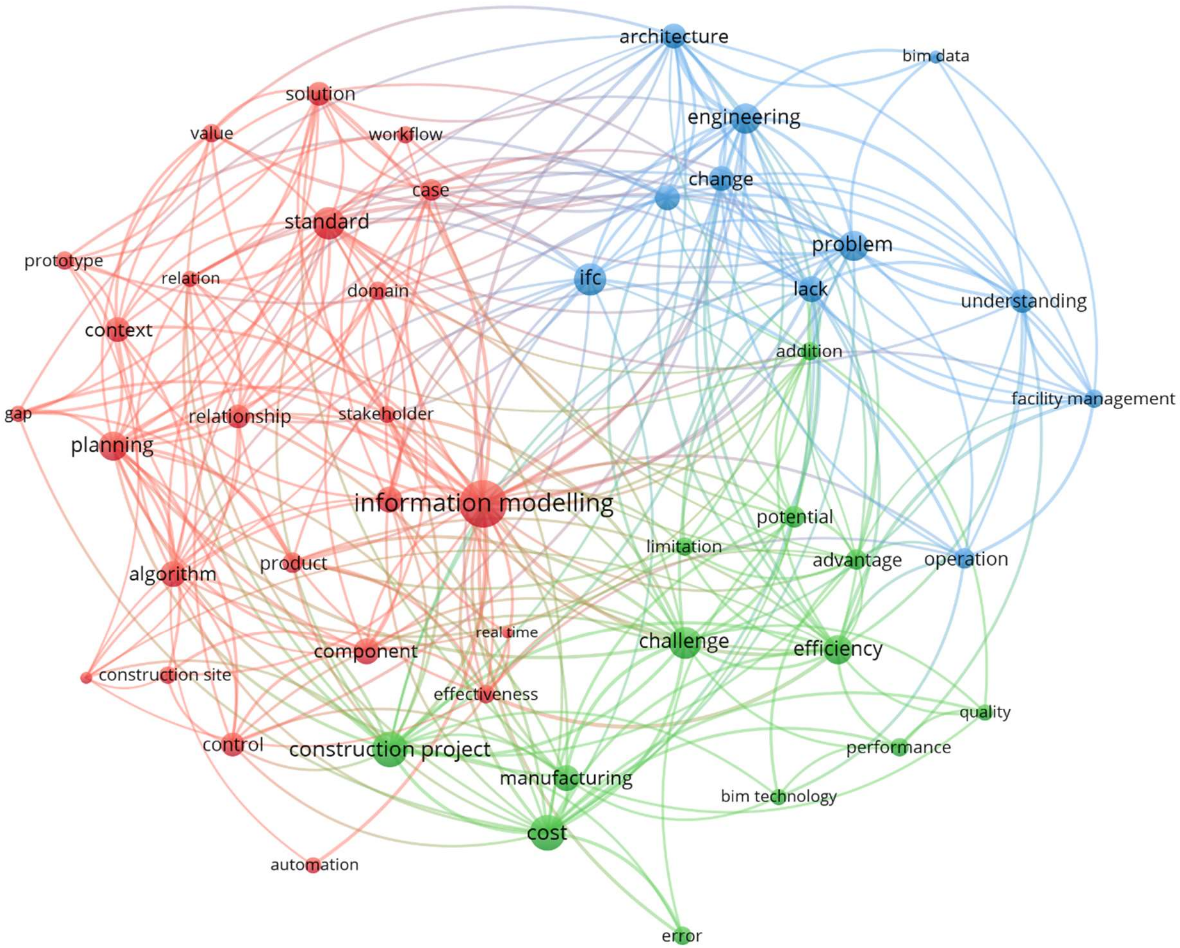

Figure 3 - Stakeholder mapping

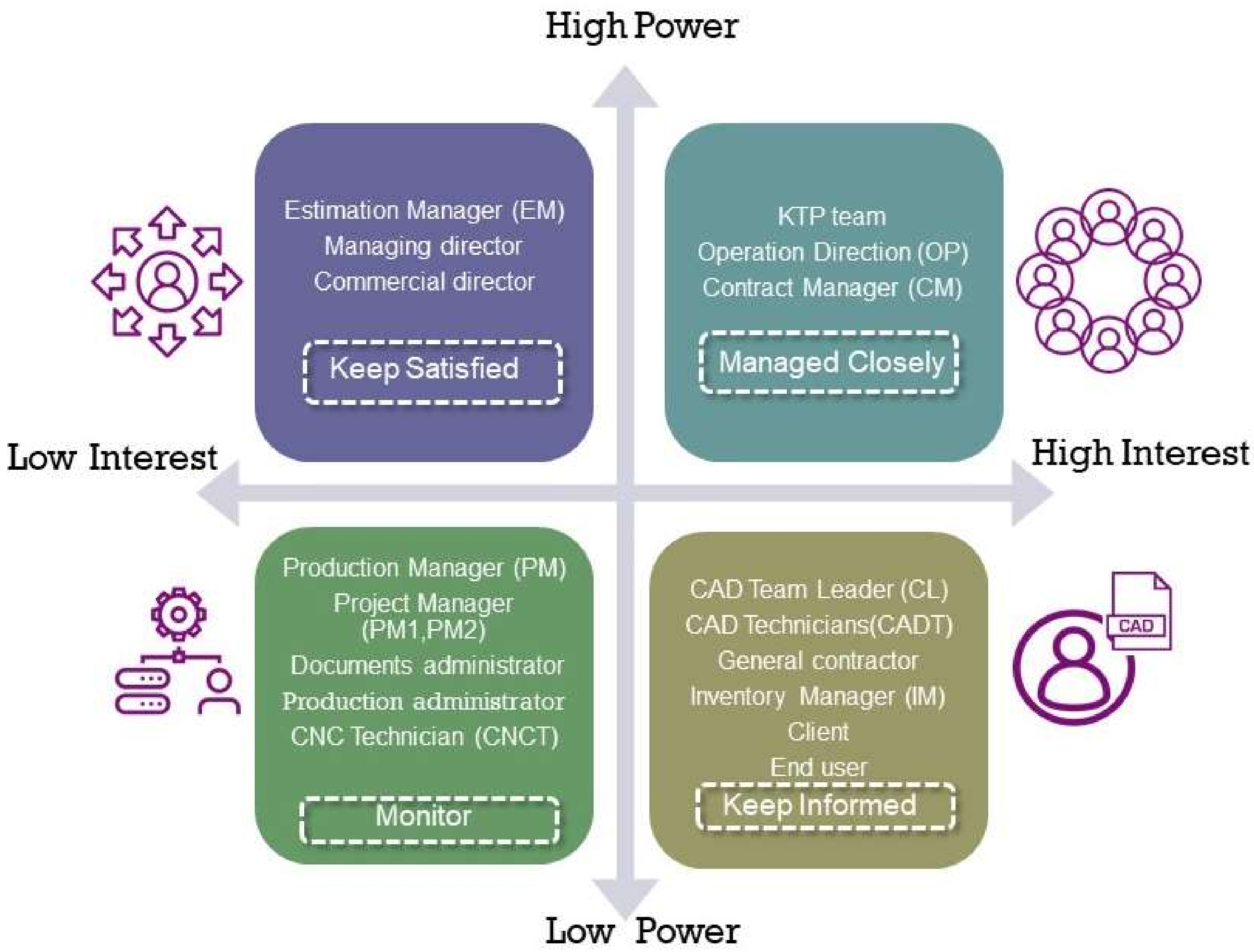

Table 1 - Review of BIM object literature

Thematic clusters	Description	Authors
Scan to BIM.	BIM objects are referred to as–built BIM objects that can be monitored and retrieved via point cloud data via laser scanning and photogrammetry. These studies sought to enhance the quality monitoring, model checking and tracking of as-built design changes over the project's lifecycle.	(Adán *et al.,* 2018; Agapaki *et al.,* 2018); Dietze *et al.,* 2013; *Franz et al.,* 2018; Stojanovic *et al.,* 2018; Kalyan *et al.,* 2016).
Interoperability.	BIM objects are discussed in the context of stakeholder information exchange interoperability. Research conducted developed a plethora of process maps to identify potential BIM users and information exchange requirements (IER). Typically, this is done by: i) generating industry foundation class (IFC) as an open data standard; and ii) using model view definition (MVD) as a technical interoperability solution to extract relevant information from the IFC file. This approach requires expertise and knowledge-based engineering to extract relevant information from IFC to MVD. Therefore, it lacks the flexibility required by AECO users.	(Arayici *et al.,* 2018; Miller *et al.,* 2017; Nizam and Zhang, 2016; Tibaut *et al.,* 2016).
Internet of Things (IoT) and security.	BIM objects are presented as a 'digital twin' of built assets that can be monitored using sensor-based technologies and connected via a network to engender the IoT.	(Dave *et al.,* 2018; Kirstein and Ruiz-Zafra, 2018).
Value engineering and performance optimisation.	The focus of these group of studies is optimising the performance of BIM objects in buildings through use of algorithms (e.g. via API's, visual programming). These algorithms are proffered to enhance the environmental, energy and lifecycle analysis (LCA) of the building.	(Gallego-Fernández *et al.,* 2018; Najjar *et al.,* 2017; Abanda *et al.,* 2017; Salimzadeh *et al.,* 2018; Troncoso-Pastoriza *et al.,* 2018).
Clash detection and error detections.	Clash and error detection can be achieved using: i) visual representations (e.g. Solibri clash detection software); and ii) non-visual representations such as rules, codes and specifications (e.g. speech recognition as code checking method that is verified by BIM object users).	(Matejka *et al.,* 2018; Ismail *et al.*, 2017; Lee *et al.,* 2018).
Spatial and geo-referencing.	BIM object location is undertaken via geo-referencing that integrates IFC schema with GIS.	(Plume *et al.,* 2017; Kang, 2018).
Graph theory and building topology.	BIM data is extracted from IFC file exchange to visualise data in the form of nodes and lines to visualise escape routes, fire escape and accessibility for disabled building users.	(Ismail *et al.,* 2017; Ismail *et al.,* 2018; Strug and Ślusarczyk, 2017).
Radio frequency identification (RFID) and real time monitoring.	RFIDs are utilised to: i) track BIM objects throughout their lifecycle; and ii) link object data on site with BIM database or cloud system to empower stakeholder collaboration.	(Li *et al.,* 2018; Xue *et al.,* 2018).
4D and 5D scheduling and cost.	4D and 5D automated scheduling is developed through processing of BIM object parameters using algorithms and bespoke APIs.	(Xue *et al.,* 2015; Wang *et al.,* 2016).
Smart and autonomous objects.	Autonomous 'context aware' BIM objects are recommended. This includes the ability of BIM objects to encompass interactive parameters such as: becoming aware of regulations and policies, and autonomous interaction with building elements.	(Wang and Cho, 2015).
3D printing and additive	BIM objects are discussed in the context of additive manufacturing. This is achieved by	(Correa, 2016; Goessens *et al.,* 2018). (Lu

manufacturing.	exporting the relevant BIM object data to stereolithography (STL) files in order to be utilised by 3D printing. The integration of 3D printing and BIM in manufacturing is a new area of research that has not been explored fully.	*et al.,* 2016).
Mixed reality (VR and AR).	Visualising graphical data (such as BIM objects) can be used for real time scheduling of 4D.	(Patacas *et al.,* 2016; Kim *et al.*, 2018).
Fabrications.	Data extraction from BIM objects is used for fabrication purposes through the following two approaches: i) exporting the data into MS Excel and converting it into readable format by CNC machines; ii) exporting the BIM components into DXF file to be processed further by CNC software prior to their fabrication which include cutting, drilling and nailing.	(Hamid *et al.,* 2018; Wang *et al.,* 2016).

Table 2 – Summarised discussion with the focus group

Activity	Description	Participants	Identified issues by the stakeholders
Order request.	A file is created with an order number once the order is approved by the customer. All relevant information associated with the order will be embedded within this file.	CM, OD	The file is created in paper format and is difficult to track and retrieve the information. Consequently, there is no auditing trail to track changes which can cause ambiguity and confusion.
Quotation generated.	A quote is generated by entering the dimensions and quantities of the product in quotation software known as 'QuoteWerks'.	EM, CM	The quotes become invalid if the customer or the CAD team modify the drawings and specifications. Therefore, the process of generating quotes is repeated and updated frequently which is time and resource consuming.
Order approved with revisions requested.	A revision of drawings by the CAD team may be required if requested by the customer.	CL, PM1, PM_2, CM, $CADT_1$,$CADT_2$	The procedure of revision consumes time and resources as the customer needs to make changes and these changes need to be re-drawn and approved by the customer in order to proceed for production.
Bill of quantities.	Because of CAD drawings, the company relies on entering the product's relevant information manually into an MS Excel sheet to generate the components needed for production.	$CADT_1$,$CADT_2$ PM1, PM_2, PM	The procedure is assigned to one technician for the whole year to process the drawings and convert them into bill of quantities. The process is prone to human error and this inflates cost, protracts the process and causes quality issues.
Job breakdown into activities and time assigned for each one.	The Production Manager breaks down the job into smaller tasks and also plans these tasks. This programme of works is created in MS Project and is circulated to different parties within the production department.	IM, PM, CM	This manual process engenders a lack of coordination and transparency between the CAD team and the production department.
CNC programming.	Any drawings that require CNC processing are exported as a DXF file by the CAD team and then processed by the CNC Manager in ASPAN software.	CNCT, PM, CM	This process is time consuming and duplicated as the cutting is redrawn by the CNC Technician in order to be converted into a G-code for the CNC machinery.
Bonding.	The finishing material is bonded to the laminate base material using machines.	PM, CM	Materials are not stocked in logical order therefore; a great effort is needed to select the right material for bonding in an efficient way.
Assembly.	Components associated with the final product are assembled.	PM, CM	The assembly requires the correct sizes, shapes and colours of materials generated from various production stages. Any production errors occurring during manufacturing might not be identified during the assembly process.
Transportation.	Products are delivered to site prior to the installation and fitting.	PM, CM	Items (such as door furniture) are often missing due to lack of quality checks prior to dispatch.
Fittings.	Product installation on site.	PM, CM	Several issues are apparent including: fitters missing the delivery; and lack of tracking of this activity because the company relies on the fitters' invoice as a notification for closing the job.

Figure 4 - Information delivery manual (IDM) process map

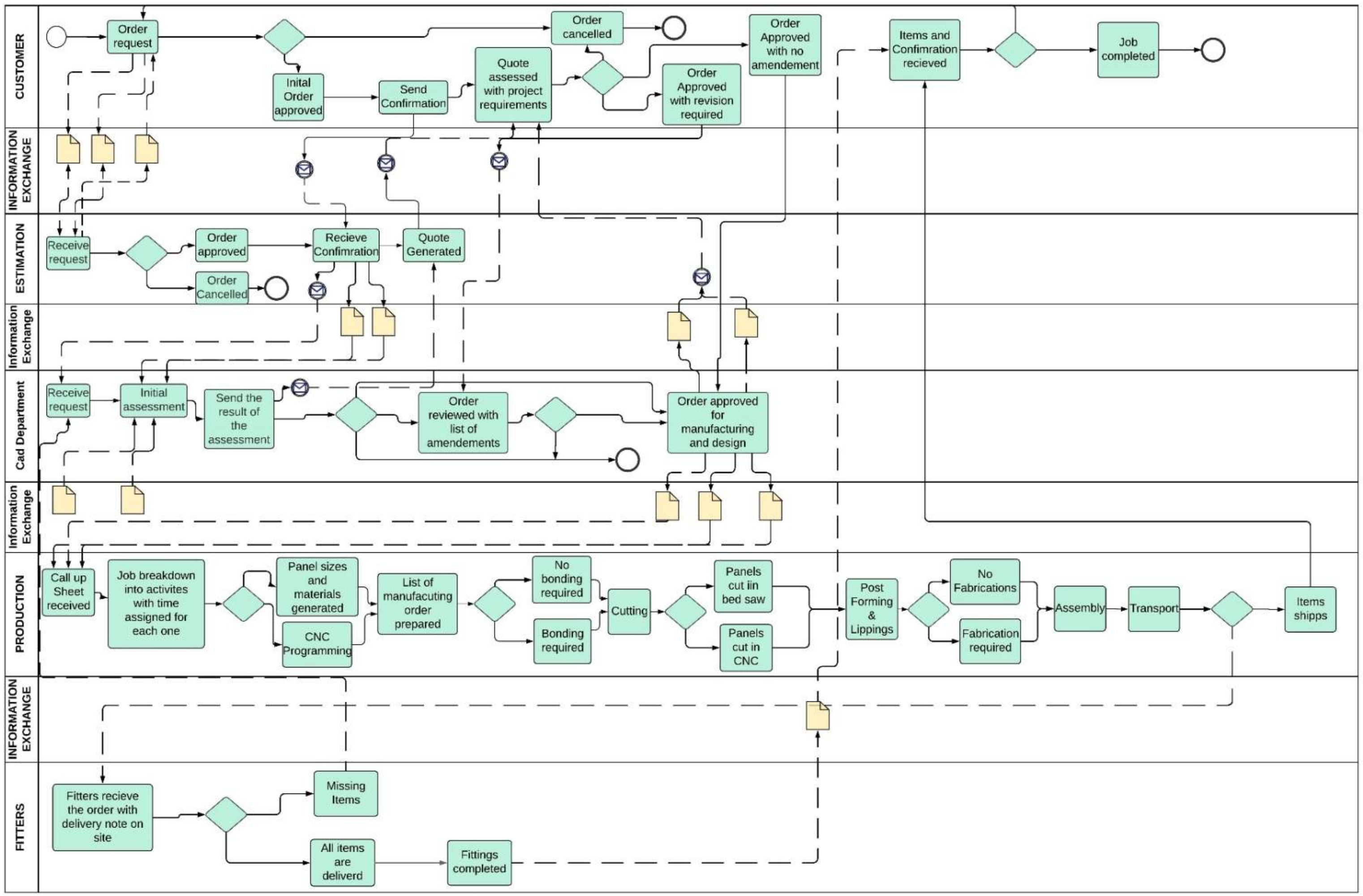

Figure 5 - UML diagram representing the conceptual model

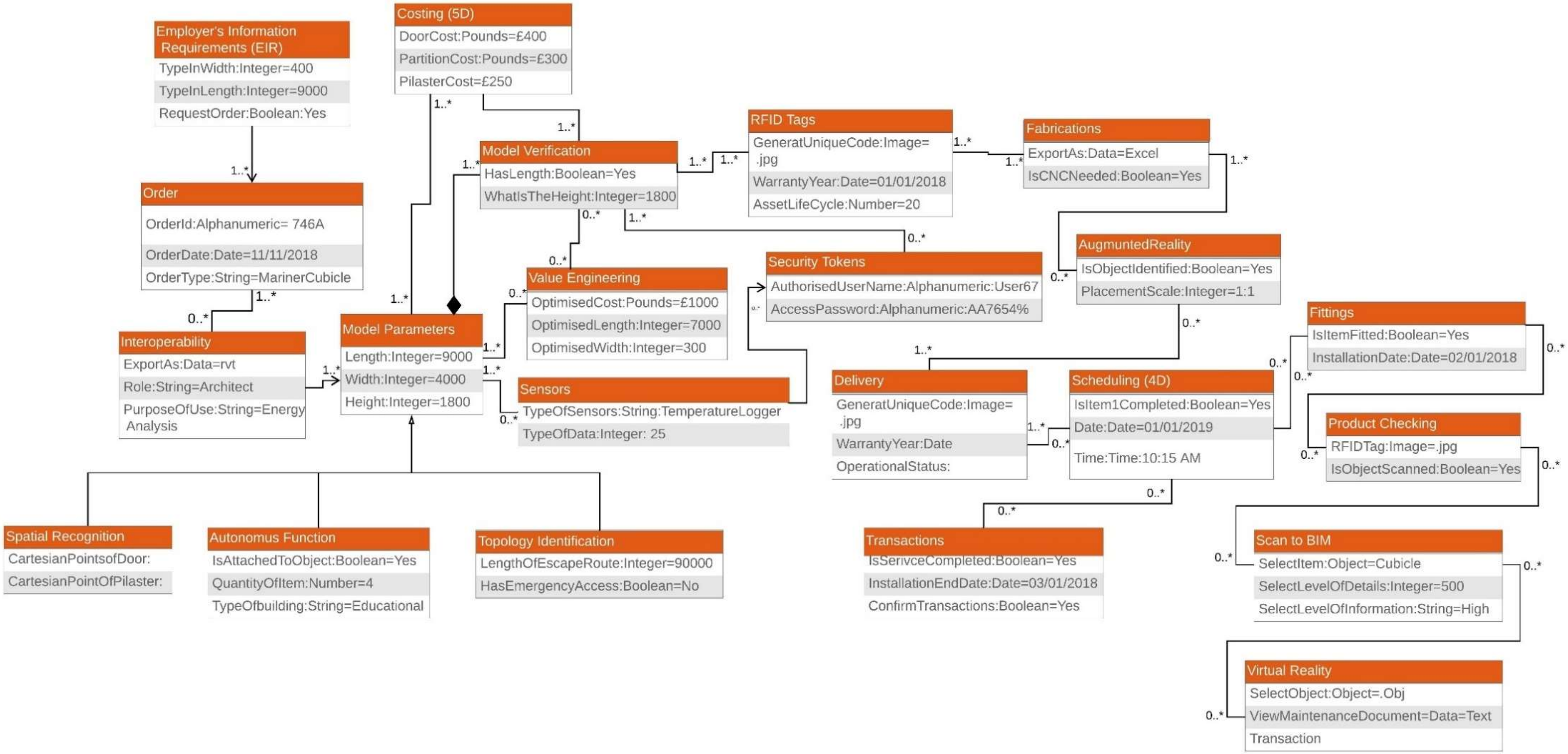

Figure 6 - Flow chart of the conceptual model