

PAPADONIKOLAKI, E., LEON, M. and MAHAMADU, A.M. 2018. BIM solutions for construction lifecycle: a myth or a tangible future? In Karlshoj, J. and Scherer, R (eds.) eWork and ebusiness in architecture, engineering and construction: proceedings of the 12th European conference on product and process modelling 2018 (ECPPM 2018), 12-14 September 2018, Copenhagen, Denmark. Boca Raton: CRC Press, pages 321-328. Available from: <https://doi.org/10.1201/9780429506215>

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2018

This is an Accepted Manuscript of a book chapter published by CRC Press in eWork and ebusiness in architecture, engineering and construction on 21/8/2018, available online: <http://www.crcpress.com/10.1201/9780429506215>.

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BIM solutions for construction lifecycle: A myth or a tangible future?

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ABSTRACT: Building information Modelling (BIM) lies at the centre of construction industry's interest nowadays, with a revolutionary impact on the ways that professionals work, collaborate and conduct business. The application of BIM is not as straightforward as it sounds though, with numerous software solutions available, various implementation processes across the project lifecycle, which challenges the interoperability and how information flows throughout the various project stages. This paper performs and presents a systematic review of the BIM software landscape currently available for the construction industry across the various project phases and in alignment with the 2013 RIBA Plan of Works. A gap analysis is conducted among these BIM solutions to examine the different software application areas, software architecture, interoperability possibilities, accessibility and affordability, by applying descriptive statistics. Surprisingly, the BIM software ecosystem is fragmented across the different project stages and highly proprietary and further hindered by the large number of specialised and highly sophisticated solutions addressed to advanced computer users. To this end, the paper aims to inform the industry's stakeholders, policy makers and software vendors, while shedding light on the extent that sophisticated BIM solutions can be disseminated to the market.

Keywords: Building information Modelling (BIM), lifecycle, digital twin, software, interoperability

1 INTRODUCTION

Building information Modelling (BIM) and information digitisation are ubiquitous within construction projects for overall project efficiency and effectiveness. BIM and digitisation have been touted as revolutionary forces in the Architecture, Engineering and Construction (AEC) industry. BIM and digitalisation initiatives are further supported in the United Kingdom (UK) and European markets due to various government mandates for implementation (GCCG, 2011). Such mandates and the general market demand for BIM require an inclusive solution to the many persistent challenges of the construction sector, i.e. low productivity, fragmented information flows, poor collaboration and inefficiencies in time and costs. The construction industry is increasingly implementing various BIM software to tackle these challenges and so far, the results have been more than promising.

At the same time, and in addition to being an inclusive solution to construction challenges, BIM has been presented as a technology and process that can radically digitise the construction lifecycle, from inception to operation of an asset (HMG, 2015). The

BIM software ecosystem is abundant with both commercial and non-commercial solutions with functionalities that support various tasks across the lifecycle phases. We define BIM software ecosystem as the set of commercial and non-commercial (i.e. non-profit or freeware) software tools available for the generation, sharing and management of building information in the AEC. However, no sufficient effort has been placed in providing a holistic BIM solution encompassing all the life-cycle functions (Hallberg and Tarandi, 2011). Nwodo *et al.* (2017) identified challenges in BIM for life-cycle assessment at early stages, highlighting the disconnect between BIM for design and whole life-cycle.

Nevertheless, BIM has been placed at the forefront of digital transformation with the promise that it greatly improves construction life-cycle (Eadie *et al.*, 2013, Rezgui *et al.*, 2013). Apart from the recent BIM-related mandates in the UK and the various Publicly Available Specifications (PAS) that specify BIM use, various professional associations such as the Royal Institute of British Architects (RIBA) have adjusted their processes to align with BIM with recommendations of functions needed to be delivered at the

various lifecycle phases of facilities, i.e. the 2013 Royal Institute of British Architects (RIBA) Plan of works overlay (RIBA, 2013). Despite these propositions, there is lack of knowledge of how existing BIM solutions address the functional needs of the lifecycle of an asset. This study sought to bridge this gap by reviewing BIM software to establish the extent to which these functionalities are relevant at the various lifecycle phases of construction projects.

This paper is structured as follows. Following this introduction, firstly, it will present the research and industry background of this work and relevant research. Secondly, it will present the research methodology and subsequently, it will present the data, results and findings. In the ensuing section, the findings will be discussed with reference to relevant scientific literature and state-of-the-art in the industry. Afterwards, the paper will conclude by summarising the main points, outlining implications for practice and policy and setting the agenda for further research.

2 BACKGROUND AND RELATED RESEARCH

2.1 Digitisation in the Built Environment via BIM

The fourth industrial revolution, also known as industry 4.0, is changing the way manufacturing and construction industries are perceiving efficiency, productivity and data exchange. The UK BIM Level 2, which supports data interoperability within a project's lifecycle, and Level 3, which focuses on the smooth data transition from concept to operational stages, are another manifestation of the impact of this revolution within construction and infrastructure (HMG, 2015). The interconnected cyber-physical systems that allow the life-cycle representation, monitoring and re-calibration define the progression of the industry, and, as a result, represent the future of the everyday practice for the sector, towards the so called *Digital Twin*.

According to Whyte and Hartmann (2017) a number of national construction standards have been developed worldwide for managing delivery, operations, handover and data classification with the main target being to achieve smooth information transitions and fluidity. For example, BIM is not entirely new for construction as it has emerged through long-standing institutional processes and efforts for structuring and consistently representing initiatives and knowledge about building artefacts (Papadonikolaki, 2017), which was a predominant line of thought in the 1970s (Eastman, 1999).

2.2 Standardisation

The statement "*BIM is about sharing structured data*" is the motto of BuildingSMART (2018), the organisation which is the leader in defining, identifying and supporting the implementation of the construction industry standards related to the application of BIM. Standards are set to define best practice, usability, safety and promote greater efficiency, as decided by an extensive engagement with different group of experts, government bodies, businesses, trade associations, etc. (BSI, 2017). In the case of BIM, the standards ensure the ways construction professionals share, structure and define information and data.

Sharing information could be paralleled with passing the baton in a relay race, with the different construction professionals and stakeholders exchanging information among them (ISO/FDIS 29481-1:2010). BuildingSMART (2018) is responsible for maintaining the structure of data related to the Industry Foundation Classes (IFC), an object-based file format that is open, neutral and available for the OpenBIM initiative (ISO 16739:2013). OpenBIM promises work in a BIM environment not dictated by the software solutions used, but based on open file formats. BuildingSMART (2018) is also providing the template for the adaptation of the IFC format for the construction industry. As a result, compliance with IFC standards allows products and applications that can operate in any platform and device and that are compatible with other systems that are developed with the same standards. Furthermore, IFC format can facilitate both geometric and contextual/ non-geometric data.

2.3 Types of interoperability

Interoperability is divided into organisational, semantic, syntactic and technical, according to the European Telecommunication Standards Institute (ETSI), while there is a strict hierarchy, which means that in order to achieve the organisational one, all the others have to be in place (Veer and Wiles, 2008). Technical interoperability "*covers the technical issues of linking computer systems and services. It includes key aspects such as open interfaces, interconnection services, data integration and middleware, data presentation and exchange, accessibility and security services*" (Kubicek *et al.*, 2011). Syntactic interoperability is focused on data formats, and it supports the use of well-defined syntax and messages encoding. Semantic interoperability concerns the precision of the exchanged information for it to be understood in a meaningful manner by other applications that do not share the same developers. Finally, according to Kubicek *et al.* (2011) organisational interoperability

focuses on the common descriptions of inter-organisational processes and can be achieved through common enterprise architectures and securing technical, syntactic and semantic interoperability.

According to BuildingSMART (2018), interoperability, that is the systems' property to exchange information in a shared data schema, is key aspect of working with BIM. OpenBIM is based on open standards and workflows and it promotes and supports these aspects by ensuring data interoperability among project teams and collaborators irrespectively of types of software they use and by applying non-proprietary, neutral file formats. It also contributed to the requirement and development of the IFC format and the Construction Operations Building Information Exchange (COBie).

According to the National BIM Survey (NBS, 2018), 72% of UK construction professionals have adopted the IFC format, to achieve projects' coordination, in terms of models, documents and overall information. The reason for the extensive level of adoption is that conflicting information can risk a project's realisation, thus, causing potential disputes (thus, loss in cost and time) among different stakeholders.

COBie is another non-proprietary data format that includes non-geometric information, which can be easily published, usually with a spreadsheet format. The COBie output is typically focused on informing the client regularly regarding the project progression and the operation and it also ties with the project delivery and the asset operation and management data. Only 41% of the UK construction industry professionals are actually producing COBie data, and according to NBS (2018) the reason for this is the lack of clients' awareness and the fact that BIM Level 2 mandate concerns only public projects.

2.4 Research gap, research aim and question

Shafiq *et al.* (2013) reviewed available BIM collaboration systems in order to identify their ability to support intra-disciplinary collaboration as well as integrated practice. Their review concluded that while BIM solutions for construction industry collaboration exist, they offer inter-disciplinary functionality to different extents and capacities. Furthermore, no solution provided a comprehensive functionality for inter-disciplinary integration. Given this study was conducted before 2013 it is unclear whether the landscape has changed in terms of functionalities BIM solutions offer. Some of the criteria used for assessing collaboration and integration functions of BIM solutions in the work by Shafiq *et al.* (2013) were: multiple user supported model content management, content creation, viewing and reporting, and system

administration including data exchange protocols access control among others.

However, this study was focused on server related BIM solutions rather than all potential applications. Some other studies have reviewed BIM software capability and functionality for only specific disciplines including quantity surveying (Wu *et al.*, 2014), risk management (Zou *et al.*, 2017) and safety management (Martínez-Aires *et al.*, 2018). Despite these developments, however, no study has comprehensively reviewed a wide range of BIM software in relation to the relevance of their functions for each lifecycle phase of a facility.

This paper complements previous work done by Papadonikolaki *et al.* (2014), which attempted to map out the relation between the acclaimed benefits and usability of BIM software for construction Project Management (PM) and the actual impact of BIM solutions on delivering these benefits. In a similar spirit, this study focuses on the whole lifecycle of the AEC to investigate the extent to which BIM solutions support a whole lifecycle consideration of digitisation in the built environment. The main research question can be thus formulated as follows:

To what extent the existing ecosystem of BIM solutions addresses the promise of a whole lifecycle BIM?

3 METHODOLOGY

3.1 Rationale and research setting

This paper presents a systematic review of the BIM software ecosystem currently available for the construction industry. Due to the practical nature of the research aim and question, the review will not focus on scientific literature, but on software instead. This study places interoperability in the epicentre of BIM work, given that it enables various actors to collaborate with BIM across project lifecycle. Thus, only BIM solutions which allow interoperability and the generation and exchange of open industry standards are reviewed. Additionally, the type of software, e.g. stand-alone, plug-in and their platform, e.g. mobile or desktop affect the collaborative potential of BIM tools and create 'hard' transition points. Nevertheless, the study will employ scientific methods to collect and analyse the data.

As the construction industry moves gradually from paper-based to data-driven, this review will increase the understanding of the degree to which the BIM software ecosystem can support the promise of a whole lifecycle and fully interoperable AEC. To operationalise the concept of lifecycle thinking in the AEC, the 2013 RIBA Plan of Works stages (RIBA,

2013) have been used as a guideline. The various solutions of the BIM software ecosystem will be analysed against their applicability to the 2013 RIBA Plan of Works, which are as follows:

Table 1. RIBA Plan of Work Stages and Objectives.

RIBA Plan of Work Stages	Core Objectives
Stage 0: <i>Strategic Definition</i>	Business Case, Strategic Brief
Stage 1: <i>Preparation and Brief</i>	Project objectives, Quality Objectives, Project Outcomes, Sustainability Aspirations, Initial Project Brief, Feasibility studies, Site Information.
Stage 2: <i>Concept Design</i>	Concept Design, Cost Information, Project Strategies, Design Programme, Final Project Brief.
Stage 3: <i>Developed Design</i>	Developed Design, Cost Information, Project Strategies, Design programme.
Stage 4: <i>Technical Design</i>	Technical Design, Design Responsibility Matrix, Project Strategies, Design Programme.
Stage 5: <i>Construction</i>	Construction, Construction Programme, Design Queries
Stage 6: <i>Handover and Close Out</i>	Building Contracts
Stage 7: <i>In Use</i>	In Use, Schedule of Services, Post-occupancy and Project Performance evaluation

The alignment between the different software and their applicability within the RIBA Plan of Work stages is based on identifying the core objectives of each stage and ensuring that the different types of software can provide solutions to these objectives, as presented in Table 1. The study features a gap analysis between the proclaimed BIM solutions and BIM

application areas throughout the construction lifecycle and their availability in commercial solutions. To this end, the study will attempt to highlight any lack of applications focusing on specific stages of the construction projects' lifecycle with the ultimate aim to propose new areas for Research and Development (R&D), knowledge transfer and ad-hoc solutions for efficient management of construction projects.

3.2 Data and methods

The data on BIM solutions are collected from readily publicly available information from relevant databases, e.g. certified software by BuildingSMART (2018), and from the webpages of the software manufacturers. This database was selected because it contains a record of the BIM-tools that allow the import and export of IFC format, the only widely-used open data format. Before the analysis, this dataset was 'cleaned'. From the 205 BIM software in the database, 31 tools were discontinued, as no information could be found about them online or irrelevant as no IFC import/export functionality was supported. On the contrary, 2 new tools were added to the dataset. In total, 173 BIM applications took part in the analysis.

The data analysis was performed through coding of the data on BIM software using a priori sets of codes. These codes were set according to the BIM software application areas, relevant RIBA stages within they might be applied, their software architecture, interoperability and collaboration possibilities, business model, accessibility and affordability, by applying descriptive statistics. All authors were involved in the coding for internal validation of the analysis and performing two rounds of coding.



Figure 1: Demographics of IFC-compliant BIM software ecosystem per (a) software type, (b) functionality of IFC, (c) license type and (d) business model.

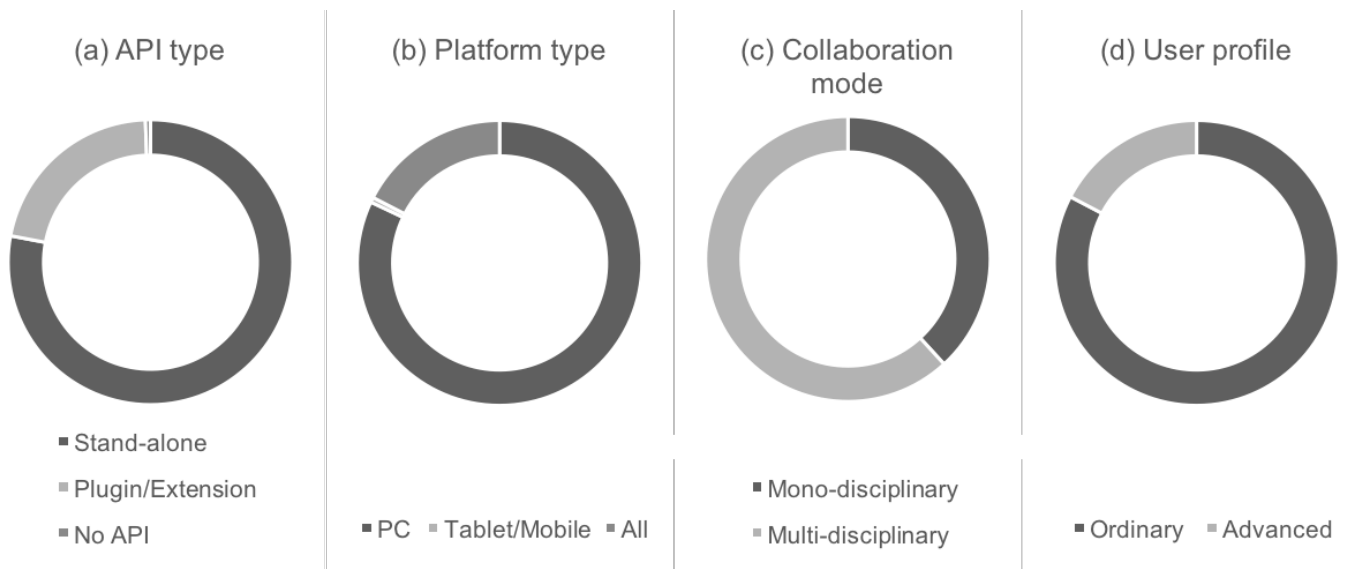


Figure 2: Usability profile of BIM-related software per (a) application programming interface (API), (b) platform type, (c) potential use collaboration mode and (d) expected application user profile.

4 DATA PRESENTATION AND ANALYSIS

4.1 Demographics of IFC-compliant software

The first level of analysis of the BIM software ecosystem relates to the descriptive data about the tools as derived by BuildingSMART (2018). This data is presented in Figure 1, which consists of four parts. Figure 1(a) includes the BuildingSMART (2018) categorisation of the software into architectural, building performance energy analysis and simulation, building services, construction management, data servers, development tools, facility management, modelling tools, Geographic Information Systems (GIS), model viewer and structural BIM tools. Based on this analysis, the majority of BIM software is of structural use (25 tools), followed by architectural (22 tools).

Drawing upon the data from BuildingSMART (2018), Figure 1(b) presents the IFC functionality of the BIM tools. Most of the tools ($n=83$) allow both import and export functionality, followed by tools that allow only import ($n=72$) and only 18 tools allow only export of IFC files. Figure 1(c) illustrates whether the tools are proprietary or free. Out of the 173 tools, 148 are proprietary with commercial interests and requiring license, and only 25 tools are free-ware, either completely open source or free versions of limited functionality of commercial software. Figure 1(d) presents the type of license of the BIM tools, that is whether they have a Software-as-a-Product (SaaS), Software-as-a-Service (SaaS) or Platform-as-a-Service (PaaS) business model, the majority of which have a SaaS model.

4.2 User-friendliness of BIM-related software

Apart from analysing the types of license, and the fairly descriptive characteristics of how BIM tools could be procured and accessed, the study also focused on the usability profile of the various BIM solutions. In particular, the Application Programming Interface (API) of the various BIM software is mostly stand-alone software ($n=135$), followed by extensions and plug-in solutions and a handful of software did not have API, as shown in Figure 2(a). Figure 2 (b) shows that the majority of BIM solutions are based on personal computers (PC) ($n=142$), followed by several applications that run on both PC and tablets and mobile ($n=30$), whereas one application is only mobile.

As BIM has been widely acknowledged for its collaborative way of working, the data on the rest of Figure 2 focus on the users. In Figure 2(c), the software was analysed based on its capacity to allow multi-disciplinary work. From the sample, 110 BIM software applications were found to be able to support collaborative work among more than one disciplines, whereas the rest, was software primarily addressed to specialists. Following upon this point, the software was also analysed with regards to the computer or digital skills of the users that the BIM software was addressed to. Figure 2(d) shows that the BIM software was addressed primarily to ordinary computer users, whereas a part of the sample is addressed to advanced computer users ($n=27$), who might need to be familiar with specialised technical knowledge to set-up data servers or engage to additional programming.

BIM Solutions applicability per RIBA Stage

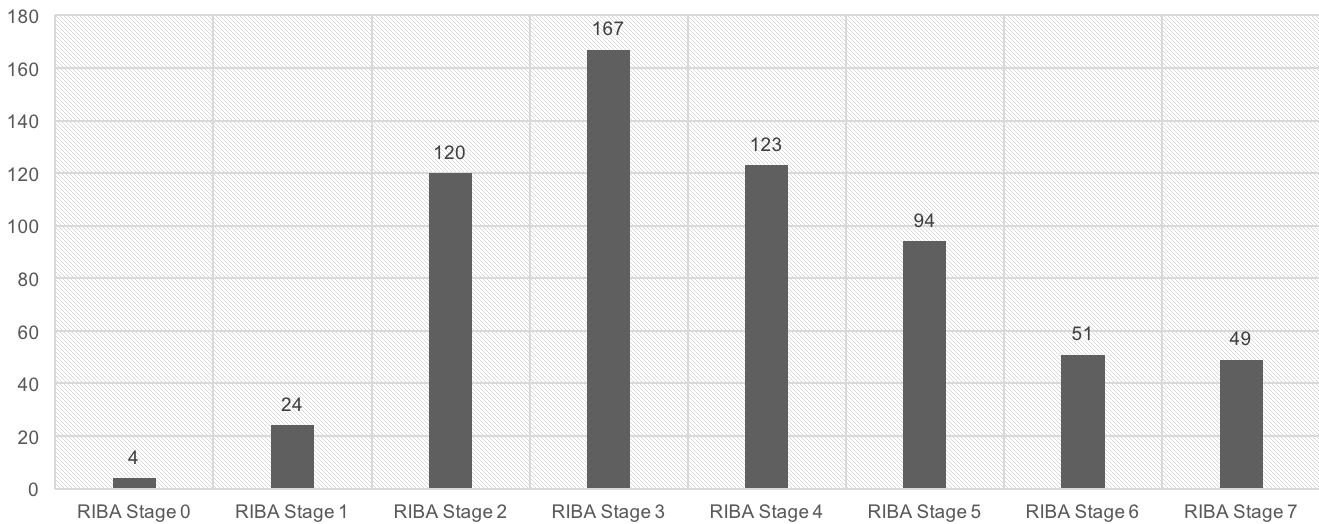


Figure 3: Number of BIM software applicable across the various RIBA stages.

4.3 Phasing and lifecycle fragmentation

Figures 3 and 4 show how different types of software support the various RIBA stages in a bar chart and a heat map respectively. A staggering 96.5% of the software ($n=167$) is actually targeting the Developed Design Stage 3 of RIBA Plan of Works, as illustrated in Figure 3, followed by a 71% ($n=123$) of the software targeting Technical Design Stage 4 and 69.4% ($n=120$) focusing on Concept Design Stage 2. Only 2.3% ($n=4$) of the software is actually tackling the strategic definition Stage 0 of a project, which resonates with the fact that each project is tackled as a business case while this stage is mostly focused on the client and investor, information typically hosted in Data Servers. However, only 25% of these data servers concern the whole project lifecycle, which means that the information within Stage 0 is not followed throughout the project (see Figure 4). That translates into issues with time and cost, as the initial decisions are not followed through the project.

Furthermore, a mere 13.9% ($n=24$) is supporting Preparation and Brief Development Stage 1, which also questions the focus and understanding of the project team on the objectives of the project. Following the technical design, a 54.3% of software ($n=94$) is dealing with Construction, project completion and mobilisation Stage 5, an aspect of the industry that is typically the most time consuming, where typically issues with cost and time occur. A 29.5% of the software ($n=51$) is tackling the Handover and Closeout Stage 6, and a 28.3% ($n=49$) examines the “In-Use” and post-occupancy evaluation Stage 7.

5 Discussion

5.1 BIM as a digital platform across the lifecycle

The analysis shows that the construction sector is experiencing a major digital transition underpinned by numerous solutions of BIM-related software available along with a number of supporting software and infrastructure, e.g. servers. Although the mapping of the BIM software across RIBA stages shows that there are available software solutions across the construction lifecycle, only 18 tools allow both import and export of IFC files (Figure 1), thus hindering interoperability among software. Also, only 4 of the total software concern the Stage 0, which means that the information is not followed throughout the project (Figure 3). While construction disputes and issues with cost and time typically occur within Stage 5 and 6, the fact that Stages 0 and 1 are barely supported does not help with projects’ efficiency, as the initial decisions are not followed throughout the project. The support of BIM across the project lifecycle remains fragmented into specialised pieces of software (Figure 4) some of which are addressed to advanced users not allowing for multi-disciplinary work.

Small software developing firms enter the market, to provide specialised or more affordable solutions. Whereas this plethora of BIM tools and the top-down policy push in the UK cause a radical innovation in construction (Papadonikolaki, 2017) the industry is ready from disruption by new players entering the market and changing the BIM software ecosystem. Importantly, there is a major difference between radical and disruptive innovation, the former being at a

RIBA stages per software category

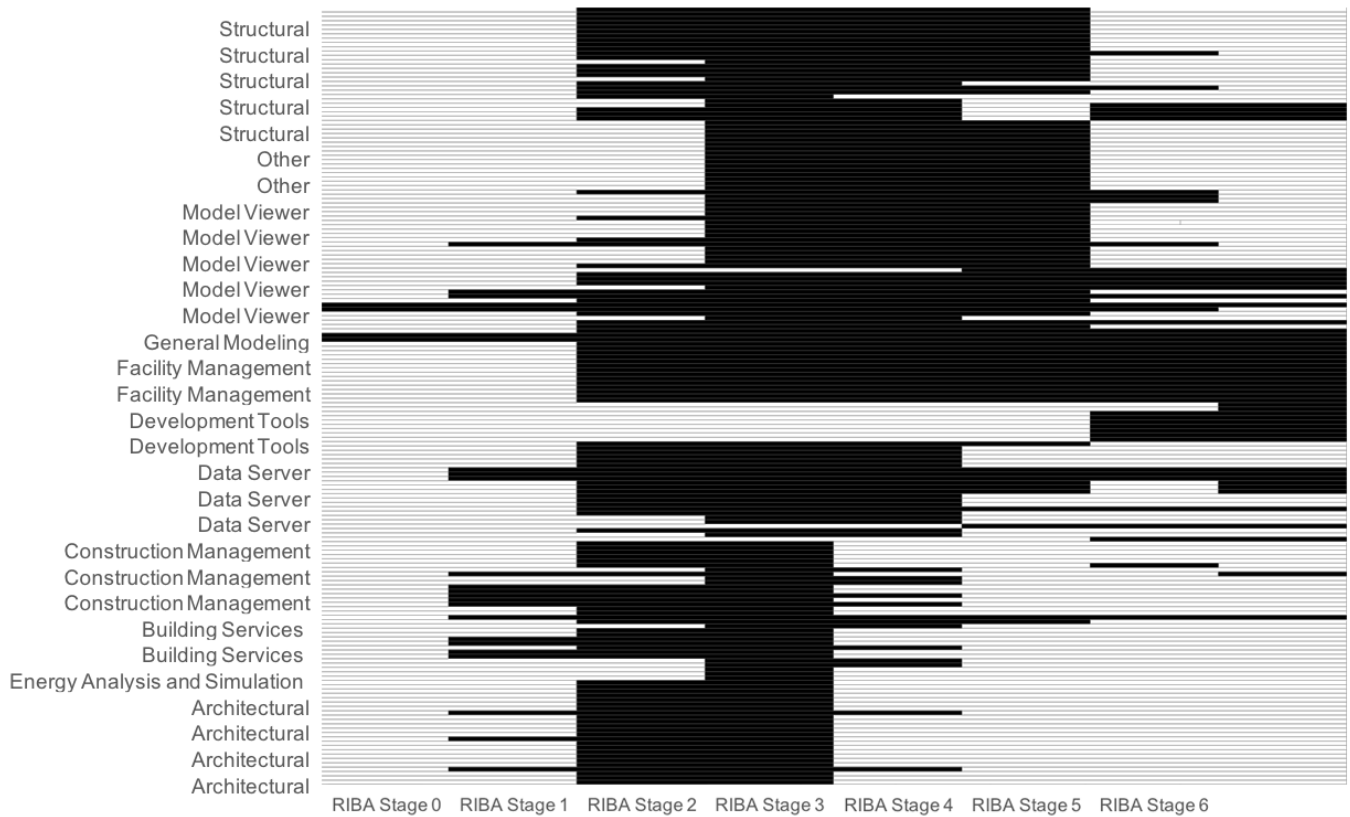


Figure 4: Heat map of applicable RIBA stages per types of BIM software.

micro level, whereas the latter at a macro level (Hopp *et al.*). To this end, construction is more susceptible to new technologies and business innovation from other industries now more than ever, as reorganisation and restructuring for the commercialisation of breakthrough ideas takes place at a higher rate. According to Figure 1d, the BIM ecosystem transits towards servitisation, where new business models reshape BIM software provision as Software-as-a-Service, rather than the traditional SaaS model.

5.2 Bridging the policy and industry mismatch

The contribution of the study is twofold. Firstly, the data could be utilised for decision-making on BIM software from construction industry stakeholders, such as contractors, consultants and clients. Secondly, after confronting the data with relevant public mandates and perceptions about BIM solutions from existing scientific and market research (NBS, 2018), especially from the UK where BIM use is mandated in public procurement, the findings would potentially mobilise software vendors and industry consortia towards expanding Research and Development (R&D) on BIM. Importantly, the study targets policy-makers and enriches the BIM debate by presenting a new evidence-based paradigm on the accessibility and affordability of BIM solutions, while shedding light on

the extent that sophisticated BIM solutions can be disseminated to the market.

This research also identified a mismatch in relation to the adherence with the industry standards and the available BIM software solutions, especially within the UK. Not only there is a lack of clear link between BIM standards and their actual application, most importantly, the lack of clear regulations on BIM is highly contradicting the BIM mandate. As a result, the UK industry is falling behind in BIM implementation within the supply chain (NBS, 2018).

5.3 Research limitations and future research

A number of limitations are acknowledged within this research with first and foremost concerning the fact that not all types of projects and procurement methods can follow the RIBA stages, nor these Stages are applicable in a worldwide scale, thus the relevance of this study is limited to building projects. The analysis is also considering that the RIBA stages are aligned with Level of Details (LoDs); thus, the software alignment with the different stages is compliant not only to the core objectives of each stage but also to the expected LoDs. However, LoDs are quite often dependant of the different companies' policies and procurement methods. An additional and important barrier is the potential researchers' bias, as there has

been no usability testing applied as such. As a result, future research will include triangulation of data from other sources, e.g. users and software manufacturers.

6 CONCLUSIONS

How can we ensure that we do not end up with a mythical “chimera” of BIM software? It seems that there is no easy answer to that. Data and systems’ interoperability and usability, especially among interdisciplinary professional project teams, have been proclaimed for a long time but not fully achieved. This paper performed a BIM software review and revealed the gaps in provision of BIM software across project lifecycle. Whereas interoperability via IFC has been the strength of various BIM software, it is hardly achieved due to the high specialisation and sophistication of the solutions and the fragmentation of software packages across lifecycle stages.

To this end, the Digital Twin development is becoming more and more of an elusive goal for construction although it is feasible in manufacturing. At the same time, BIM strategies are often government-led like in the UK, thus revealing a disconnect not only between practice and policy, but also between AEC and software vendors. Finally, this underlines the need for the informed client, who is aware of the value of data, over and above the COBie requirements for realising the full potential of built assets through whole lifecycle BIM and digitalisation.

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